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A Review of Recent Advances in Automated Guided Vehicle Technologies: Integration Challenges and Research Areas for 5G-Based Smart Manufacturing Applications

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ABSTRACT In industrial environments, over several decades, Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs) have served to improve efficiencies of intralogistics and material handling tasks. However, for system integrators, the choice and effective deployment of improved, suitable and reliable communication and control technologies for these unmanned vehicles remains a very challenging task. Specifics of communication for AGVs and AMRs imposes stringent performance requirements on latency and reliability of communication links which many existing wireless technologies struggle to satisfy. In this paper, a review of latest AGVs and AMRs research results in the past decade is presented. The review encompasses results from different past and present research domains of AGVs. In addition, performance requirements of communication networks in terms of their latencies and reliabilities when they are deployed for AGVs and AMRs coordination, control and fleet management in smart manufacturing environments are discussed. Integration challenges and limitations of present state-of-the-art AGV and AMR technologies when those technologies are used for facilitating AGV-based smart manufacturing and factory of the future applications are also thoroughly discussed. The paper also presents a thorough discussion of areas in need of further research regarding the application of 5G networks for AGVs and AMRs fleet management in smart manufacturing environments. In addition, novel integration ideas by which tactile Internet, 5G network slicing and virtual reality applications can be used to facilitate AGV and AMR based factory of the future (FoF) and smart manufacturing applications were motivated.

INDEX TERMS Intelligent factory, factory of the future, 5G, smart manufacturing, industry 4.0, autonomous industrial equipment, AGV, AMR, tactile Internet, virtual reality, lean manufacturing.

I. INTRODUCTION

The first known Automated Guided Vehicle (AGV), was introduced by Barret Electronics of Northbrook, Illinois, USA in 1953; and since then, AGVs have been used extensively to simplify intralogistics and material handling pro-

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cesses in industrial environments [1]. Also, in the past few decades, Autonomous Mobile Robots (AMRs) have continued to be widely integrated and used in industrial environments. AMRs are often taken to indicate material handling vehicles that can autonomously navigate from place-to-place to accomplish specific tasks. They are usually in form of robots' arms and actuators that are built on top of mobile platforms. AGVs on the other hand are most often used in

industrial applications to move materials around the manufacturing floor or in a warehouse [2], [3]. In some instances, an AMR can be constructed with an AGV serving as the mobile base to accomplish set objectives. In most modern applications however, both AMRs and AGVs are often used interchangeably to mean autonomous devices that can accomplish industrial tasks [4] which can include material handling, research activities, collaborative work with humans (cobots), or cooperative activities with another AGV or AMR [5]. In the case of AMRs, the mobile base and the robot arm can be viewed as separate subsystems that collectively form the complex AMR system. The base, which can be an AGV is often used to cart, dock or park the robot arm to a location where the arm is needed to accomplish a specific task [4]. Thus, in general, AMRs are an advanced [6] form of AGVs; and they can be integrated in a factory environment without any supporting infrastructure, such as wires, optical markers, magnets etc. An AGV often must navigate with the aid of supporting infrastructures while an AMR can autonomously navigate using only onboard intelligence [7]. In view of their wide range of uses and applications for smart manufacturing, AGVs and technologies that support them have been projected to generate close to \$7 billion (USD) in revenue by the year 2022 [8]. Also, AGV and AMR technologies have been projected to become pivotal for actualizing smart manufacturing. They will also be central to the success of factory of the future (FoF) initiatives [9] in several factories round the world.

Due to their centrality to achieving smart manufacturing, matrixed production and FoF, AGV and AMR fleets must be optimized to achieve better performance on the factory floor. Development of advanced AGV/AMR systems that can be robustly and painlessly integrated into the entire factory production architecture must be accomplished for the success of FoF and smart manufacturing. A reactive, scalable FoF and smart manufacturing can only be achieved by exploiting and harmonizing technological breakthroughs in 5G communication, Industrial IoT, AGV/AMR technologies and in general robotics applications [10], [11], [27], [28].

In view of this, this paper presents a comprehensive review of advances in research and industrial applications of AGV technologies in the last decade. Our review, in part, also present important timelines, milestones flowcharts, implementation examples and relevant pictures that summarizes key advances in AGV/AMR research and utilizations from the conception of their technologies, through the last decade, until present time. The complete contribution of this paper and its comparison with other existing AGV/AMR review papers is summarized in Table 1. In Table 1, it is notable that the scope of existing AGV and AMR review publications does not provide any in-depth discussion on how 5G communication system, which is projected to be a key enabler [10], [11], [27], [28] of smart manufacturing and FoF applications can be applied to provide for better AGV fleet management, control and general fleet mission optimization in a factory environment. In summary, methods of implementing FoF and

TABLE 1. Summary of existing survey articles on AGV and their contributions.

Aspect	SURVEY PAPERS	Contributions
Localization Navigation & Control. Algorithms	[12], [13], [14], [15], [16], [17], [18], [19], [20], [21]	Survey of localization, mapping, navigation and control technologies currently in use on commercial AGVs. Important localization technologies developed by research communities are also provided. A review of AGV docking methodologies was provided.
Applications, design and use cases	[22], [23], [24]	Review of Autonomous Industrial Mobile Manipulation (AIMM) system use cases as mobile manufacturing assistants in the industry. AGV material handling processes.
	[25], [26]	Literature review about scheduling problems of AGV in job shops, flow shops and container terminals. Mobile manipulator research review with applications example.
	[27], [29], [30]	Trend in AGV industrial applications. Review of key AGV application technologies. AGVs design review
Wireless Technologies	[7], [31], [32]	A review of enabling communication technologies and AGVs use cases for flexible production. Review of flexible Wi-Fi architecture for AGVs and other mobile robots.
	[33]	Comprehensive review of two wireless standards in use before 2014 for AGV systems: ZigBee and IEEE 802.11. Emphasis was placed on low-latency and reliability as being vital to successful management of cyber-physical-systems-based AGVs integration architecture.
Scheduling & path-planning algorithms	[34]	Literature review of exiting routing and scheduling problems and applicable algorithms.
This article		<ul style="list-style-type: none"> - A review of the timeline of AGV and AMR developments from conception of their technologies. Important development milestones with relevant example and pictures are presented. - A review of state-of-the-art research results in AGV technologies. The review presents important results from the past decade until present time. - Research areas and open challenges regarding the application of 5G technology for AGVs and AMRs fleet management in smart manufacturing environment are explored in detail. Possible future applications are provided.

smart manufacturing with regards to AGVs and AMRs using 5G communication networks are missing in other review works and in most other existing AGVs/AMRs research publications.

It is therefore critical to provide a review publication that explores past AGV research achievements and reveal present methods by which 5G networks can be utilized to provide better AGVs/AMRs utilization and fleet management strategies. Since AGVs research works are extensive, our review will provide researchers the depth and reach of existing

research works in different domains of AGVs utilization. In addition, we examined integration challenges and inadequacies of different types of existing technologies that are in use for AGVs control, path-planning and fleet management. Examples of examined technologies include, laser guidance systems, Radio Frequency Identification (RFID), barcode technology, etc. We also present relevant areas of research (AoR) that are necessary for 5G communication networks to be fully utilizable for AGVs fleet management in smart manufacturing environments.

These topics are timely due to the recent advances of 5G technology and the simultaneous advances in AGV and AMR technologies for FoF and smart manufacturing applications. The rest of the paper is organized as follows. In section 2, we present a review of AGV research works in the past decade, and we also provide brief summaries of their contributions in a table. Flowcharts of timelines and graphical illustrations of important development in both AGV and AMR researches and of factory implementations are also presented. In section 3, we examine challenges militating against a robust deployment of AGV fleets in manufacturing environments. In section 4, since it is envisaged that 5G networks will be a key enabler for robust integration of AGVs and AMRs into smart manufacturing environments [8], [10], [11], [27], [28], we discuss important AoRs that must be comprehensively explored for 5G systems to be fully utilizable for AGV fleet management. We also examine essential AGV/AMR communication needs such as: communication needs for time-critical AGV/AMR processes, non-time-critical AGV/AMR processes, and communication needs for AGVs and AMRs that are integrated as part of enterprise communication systems for smart manufacturing applications. The full range of important AoRs discussed in this paper is as summarized in Figure 1. In section 5, we present a conclusion and possible future directions of our work regarding 5G utilization for integrating AGVs and AMRs for smart manufacturing applications in industrial environments.

II. REVIEW OF AGV RESEARCH WORKS IN THE PAST DECADE

In previous decades, researchers seeking to optimize logistics and industrial processes commenced works on automating material handling activities in several industries. As mentioned earlier, an AGV was introduced in 1953, and in the following years, AGVs were integrated into warehousing and logistic activities using track guided magnetic systems, optical sensors and color strips as AGV guidance technologies [1]. Advancing technologies brought about the use of transistors, vacuum tubes, microprocessors, microcomputers [38], infrared, radio signal guidance and programmable logic controllers (PLC) [1].

In the immediate past decade, based on examined published works, the use of wireless networks as a means of controlling and managing AGV fleets became widespread [39], [41], [42]. Also common is the integration of artificial intelligence (AI) technologies and the use

of open source software such as Robot Operating Systems (ROS) [43], [44]. The complete timeline of development and examples of AGVs that highlights the integration of each technology mentioned are shown in the flowchart of Figure 2 and the development timeline of Figure 4 [45]–[47]. Examples shown in Figure 4 were sourced from different applications and AGV research domains in the academia and the industry. They are examples of important achievements in AGV research and integration examples through the decades from inception of AGV technologies until present time.

The first patent regarding an AMR was issued in 1987 [9], [48]. However, before that time, researchers have been working on systems that were not fully autonomous, but that were the forerunners of AMRs. Complete flowchart illustrating relevant AMRs research timelines is as shown in Figure 3. Timeline of AMRs development, showcasing relevant examples of AMRs developed over many decades is shown in Figure 5 [49]–[51]. As shown in Figure 5, example of mobile robots that were not fully autonomous but led the way in AMR developments are Little Helper [52], Virgule [53] and MF3 Manipulator [54]. These robots are different from modern day fully autonomous AMRs in that they have cables that tether them to factory infrastructures. Some robots, such as Virgule and MF3 Manipulator are remotely controlled and although they are classified as mobile manipulators, they are not fully autonomous. Development of AMRs are similar to AGVs development since researchers tend to use time-prevailing technologies to develop AMRs. Generally, from the 1980's onward, AMRs that can navigate in dynamic environments were developed. Accompanying technologies include the use of sensor-based navigation; proportional integral (PI) and fuzzy control methods also came into widespread use. Generally, in the past decade, developments in AMR and AGV technologies became more interrelated, with AMRs generally having more onboard intelligence than AGVs [55]. In the past decade, majority of research works regarding FoF have consistently reiterated the need for equipment in factory floors including AGV systems to be more agile, reactive and operable in a dynamic factory environment [80]–[82]. In industry 4.0 or smart manufacturing environments, different complex systems that constitute a smart factory will employ industrial Internet of Things (IIoT), fault-tolerant systems, distributed edge computing, multi-access or mobile edge computing systems and low-latency wireless networks to institute a reliable and resilient FoF systems [83]–[86]. Our review method in this paper is synonymous with review methods adopted by researchers in [87] and [88]. Our review is focused on understanding the state-of-the-art and gaps in existing body of AGV research knowledge in:

- Localization, scheduling and AGV path-planning; and type of algorithms in use in these AGV research domains
- Navigation, control and AGV guidance algorithms
- Wireless communication and its uses for AGV fleet management and control

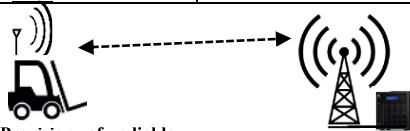
Processes	Examples	Latency Requirements	5G Implementation & Challenges	Potential benefit in the industry	
Time-critical AGV & AMR Processes	AGV and AMR fleet management, AGV motion control (e.g. AGV docking & process synchronization with conveyor belts & packaging machines). AGV fleet cooperative motion control.		Between 1 ms and sub-1 ms latencies for the tactile sensor on top of the AGV. Cooperative motion control. [56] [57], [58]	 Reliable 5G Network Slicing: For biomimetic AMR, both the AGV base and the biomimetic gripper or tactile robot will need reliable close-loop control that may be actualized using reliable, low-latency communication network. 5G network slicing will be needed here. The lower latency slice for the biomimetic gripper while the higher latency slice may be used by the AGV to navigate and dock.	For reliable remote control of tactile and biomimetic grippers on top of AGV working in hostile environments 
	Tactile robots, forklift AGVs, biomimetic arms, mobile cranes, biomimetic grippers, and sensors on top of AGVs		4-8 ms latency needed between the AGV navigation controller and the AGV base vehicle. [59], [56]	 Latency for critical machine type communication (MTC): 0.25-10 ms; PER of 10^{-9} [58] ms	For reliable and agile collaborative working with humans. AGV base will need to be very precise in docking, in free navigation and other types of movements to ensure stability of both the AGV and the collaborative robot (cobot) arm on top of the AGV
Non-time critical AGV & AMR processes	Tracking products for ad-hoc AGV transportation. This is useful for customized production for certain customers. AGV waypoint selection in dynamic factory environment AGV sensors' data acquisition; e.g. periodic battery level sensor data acquisition Application of AGV and AMR for nonurgent remote inspection and diagnostics	  Latency for massive machine type communication (mMTC). Process monitoring (> 50 ms; PER of 10^{-5}) [52], [58]	Latency for non-critical MTC. Remote inspection, diagnostics (> 50 ms [57]) 5G mMTC challenges involves redesigning existing communication networks uplink and downlink [60] to support small packets (and their overheads) coming from numerous machine sensors such as AGV sensors	Real-time monitoring of AGV sensors such as battery sensors to reduce time expended by AGV to navigate from their current task(s) to battery-charging stations. End-to-end monitoring of AGV & AMR sensors to reduce downtimes. Predictive maintenance. Prescriptive analytics	
AGV & AMR communication with industry enterprise network	Intralogistics and integration of AGV specific data with factory inventory management system Integration of AGV data with factory warehouse databases Integration of AGV data with cloud repositories. This is useful for both predictive and prescriptive analytics using both on-premise and cloud-based analytics platforms		Latency between MEC and AGV fleets. Process automation – video operated remote control (10-100 ms) [59], [56]	 Provision of reliable 5G MEC platform and robust integration of MEC-based analytics software with cloud-based analytics software e.g.	Improved business operation. Real-time actionable intelligence for AGV-based intralogistics optimization

FIGURE 1. Benefits and challenges associated with 5G applications for AGV deployment in the industry.

- Virtual Reality (VR) and Augmented Reality (AR) applications for AGVs; and
- AGV design and wireless power transfer (WPT) systems for AGVs. Applications and use cases.

In our study, we have selected large scientific sources and repositories such as IEEE Xplore (<http://ieeexplore.ieee.org/xplore/>) Google Scholar (<http://scholar.google.com>) and repositories of well-known research organizations from the

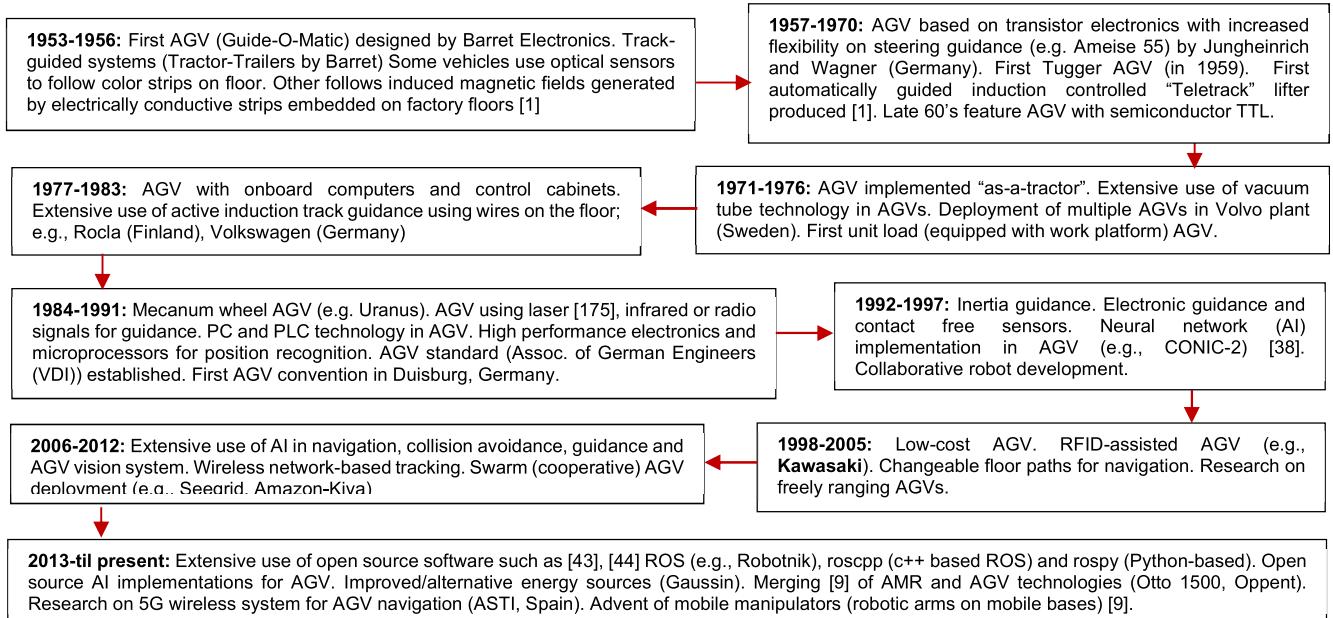


FIGURE 2. Timeline of development and research works on AGVs.

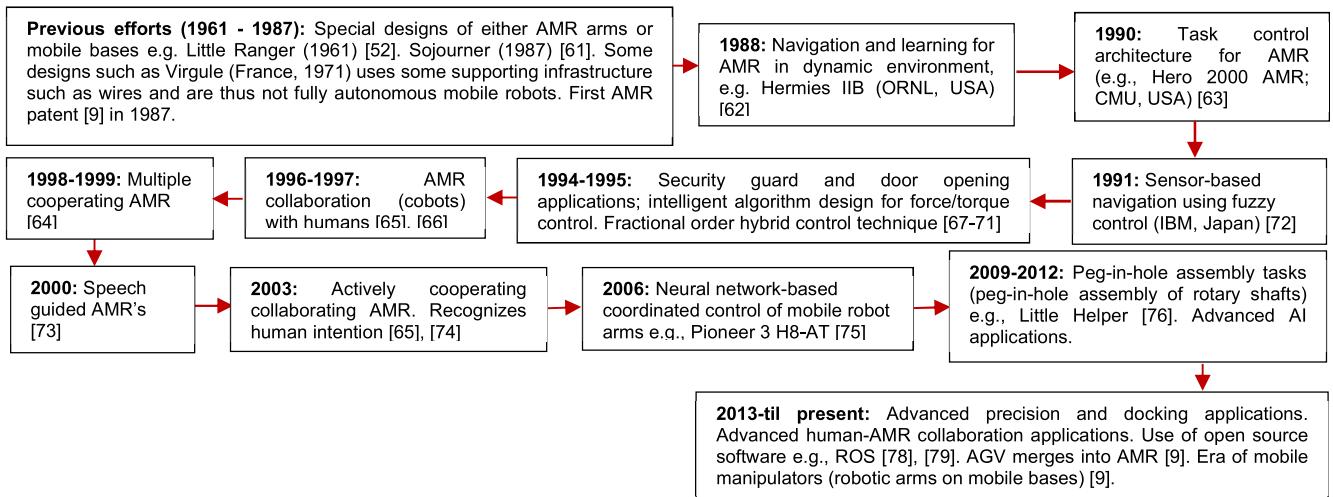


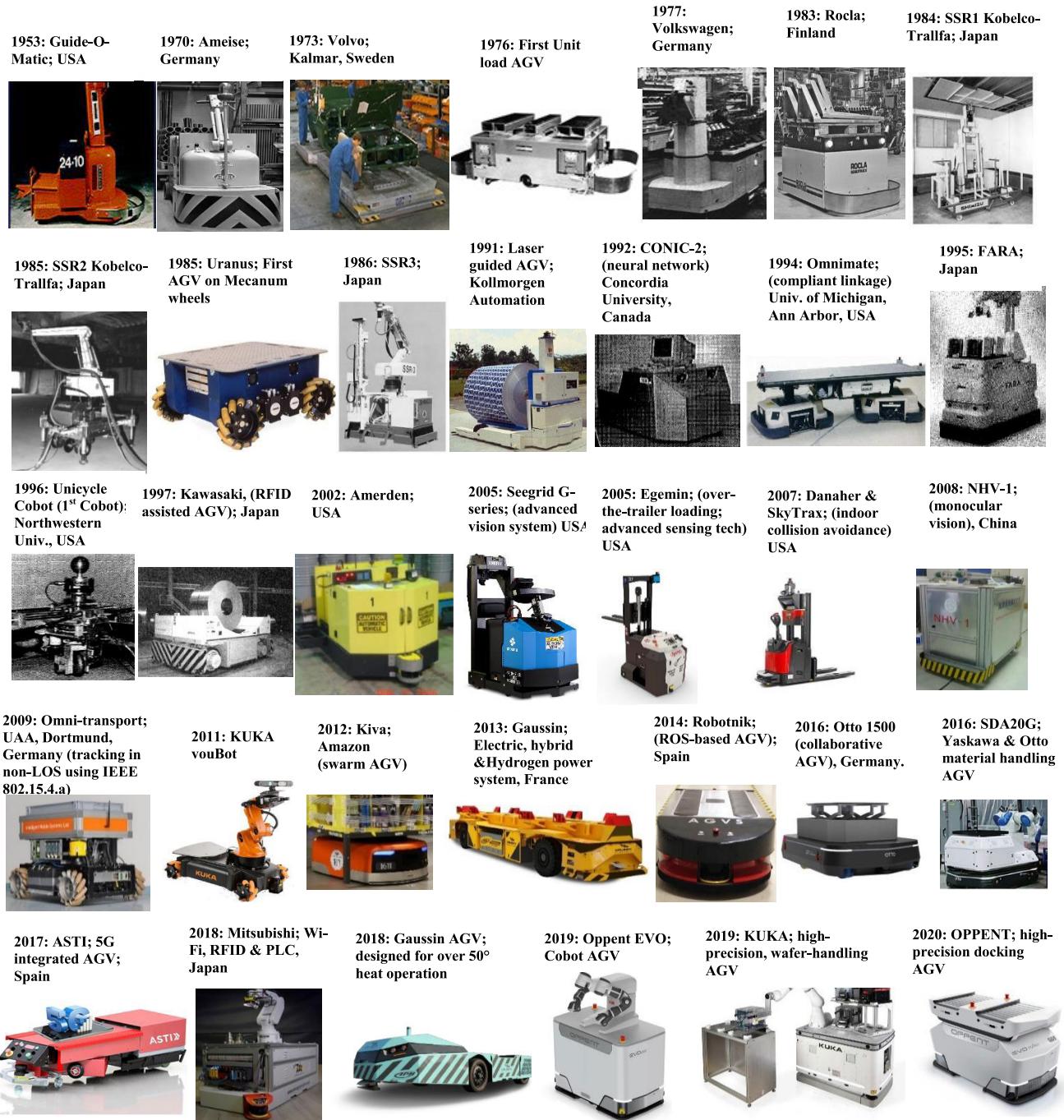
FIGURE 3. Timeline of development and research works on AMR.

academia and government research agencies. Published peer-reviewed articles in the five AGV research areas mentioned above are selected from the year 2010 to 2020 using inclusion and exclusion selection criteria listed in Table 2 [87], [88]. A total 893 AGV research articles were obtained from different mentioned sources, and from these, 207 published works were eventually selected using inclusion criteria of Table 2. In the past decade, most research works from academia and from industrial perspective regarding AGV integration and their deployments in the industry can be summarized as discussed below.

A. LOCALIZATION, SCHEDULING AND PATH PLANNING ALGORITHMS

AGV localization involves determining AGV position without a priori AGV position information [41]. For more effec-

tive and agile integration of AGVs in the manufacturing environments, localization, path planning and reactive AGVs scheduling is of paramount importance. As such, these areas have commanded appreciable amount of research works in the last decade. In [89], [90] and [91], the D* Lite algorithm was applied for AGVs path planning. The D* Lite algorithm was also applied with backstepping method for obstacle avoidance in [92]. Authors in [89] also discusses different strategies that AGVs can use in industrial environments to avoid obstacles that suddenly appears in front of on-motion AGVs. Such strategies include using obstacle avoidance algorithms such as curvature velocity method, dynamic window approach, and using the geometry of the obstacle to successfully navigate around it. In addition, authors in [89] discusses the importance of AGV trajectory tracking. It was emphasized that in the industrial environment, when an optimal

**FIGURE 4.** Timeline and recent advances in Automated Guided Vehicles (AGV) development.

AGV trajectory is mapped out, a control or trajectory tracking algorithm will then be used by the AGV to track an optimal path. Such control algorithm includes feedback control laws, fuzzy proportional-integral-derivative (PID), and the sliding mode control theory. Hence, in their report, authors in [89] proposed using Simultaneous Localization and Mapping (SLAM) algorithm that was based on Extended Kalman Filter (EKF) for AGV positioning. The D* Lite algorithm based on a given factory floor map in combination with laser scan data

of important floor locations was used for AGV path planning. Backstepping control method based on Lyapunov stability approach was used for reducing AGV tracking errors.

In [93], and [94], authors used A* algorithm combined with Dijkstra algorithm to plan optimal paths for AGVs navigation. A* algorithm was also used in [95] for AGVs path planning. In [115], authors utilized a combination of the artificial potential field algorithm and A* algorithm for AGV path planning. The objective of the work in [115]

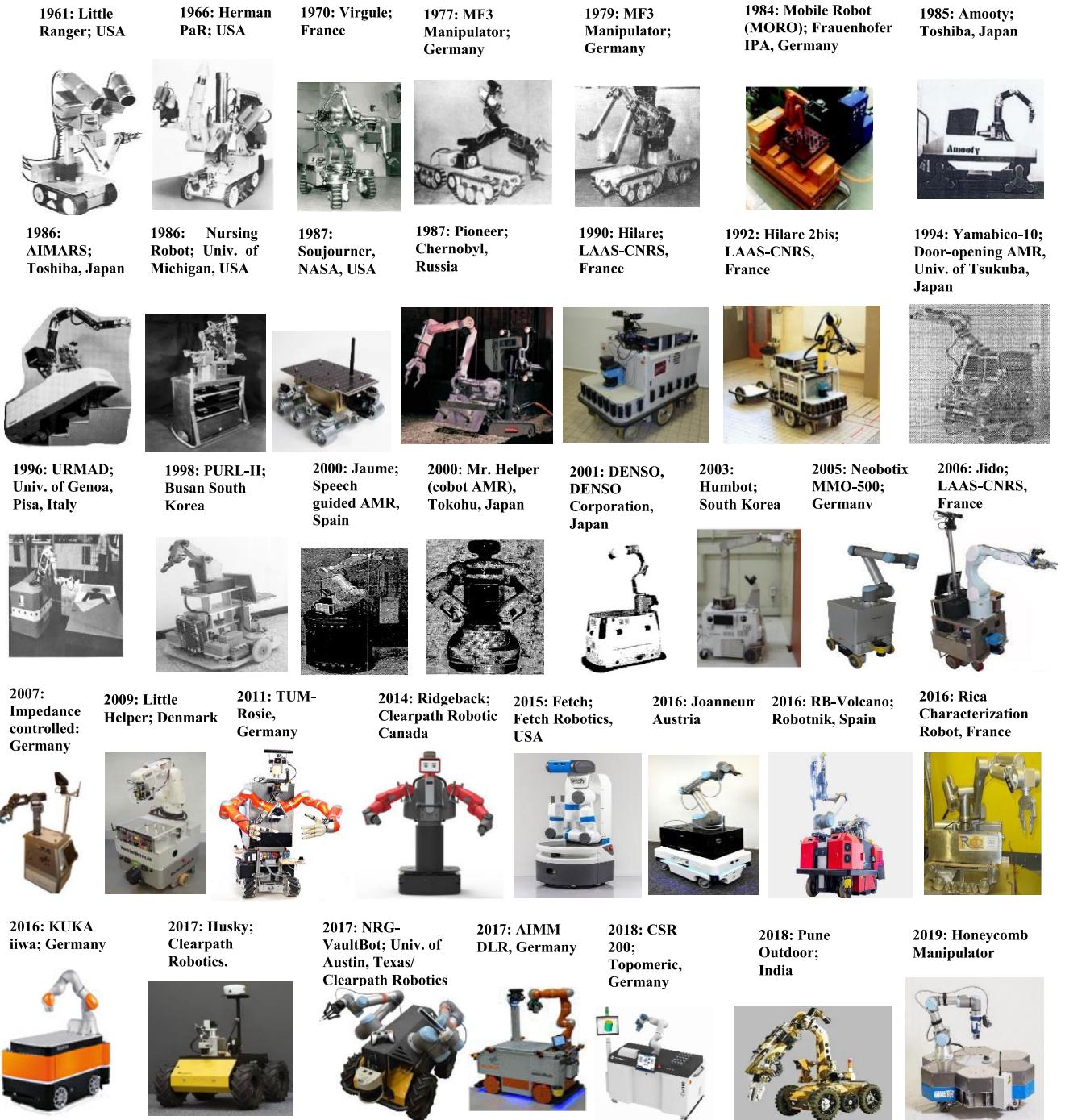


FIGURE 5. Timeline and recent advances in autonomous mobile robots' (AMR) development.

was to solve the problem of path planning for AGVs that are used in warehouses and large storage facilities. Using a decision module, the proposed algorithm achieves the goal of finding the optimal path relating to different storage environments. Authors also emphasized in [115] that classical A* algorithms for global AGV path planning applications have the problem of generating large computation overheads; leading to poor real time performances. Thus, classical A*

algorithm may not be suitable for path planning applications in complex environments such as a future FoF environment that may have changing layouts and dynamic arrangements. Dijkstra algorithm was used for AGVs path planning in [96], while improved Dijkstra algorithm was applied to path planning in [97] and [98]. Specifically, Dijkstra algorithm was used to resolve AGV conflict in [98] where authors classified conflicts that AGVs may experience as cross conflict,

TABLE 2. Inclusion and exclusion criteria or review articles.

Inclusion	Exclusion
Articles focusing on AGV localization, scheduling, path-planning, navigation, control, wireless communication for AGV, VR, AR, AGV design and use cases Articles written only in English are considered	Articles that does not have AGV as focus of study or articles which does not focus on localization, scheduling, path-planning, wireless communication for AGV, navigation, control, VR, AR, AGV design and use cases. Articles not written in English
Peer-reviewed articles or articles published in scientific databases such as IEEE Xplore, government research agencies and educational institutions	Articles not peer-reviewed or published by in scientific repositories, academic or government research institution

path-occupancy conflict and head-on conflict. Cross conflict can occur when a single path node falls into the navigation path of two AGVs. Example of such a node can include an intersection at a factory floor. Path-occupancy conflict can occur when an AGV travels on a path that is included in the route of another AGV while head-on conflict can occur when two AGVs travel on the same path, but in opposite directions. To implement the improved Dijkstra algorithm developed in [98], the factory environment considered was described using an adjacency matrix with a 2D coordinate using MySQL. Conflict-free routing paths was used to populate the Dijkstra algorithm matrix. An adaptive conflict resolution strategy was used to improve the performance of the Dijkstra algorithm. The improved Dijkstra algorithm showed a marked improvement over the classical Dijkstra algorithm in terms of AGV routing efficiency for AGV based automated warehouse system.

Similar to [98], in [99], improved Dijkstra algorithm was used for global path planning while heuristic-based Monte Carlo algorithm was used for local path planning for AGVs. A heuristic approach was used for cell based AGV guide path design as discussed in [100] while another heuristic algorithm that can be used to accomplish just-in-time (JIT) routing for AGVs, and also useful in reducing AGVs earliness or tardiness was discussed in [101].

A scheduling optimization algorithm to reduce AGVs earliness and tardiness was also presented in [102]. Another AGVs path planning heuristic algorithm was presented in [103], while in [104], authors worked on a heuristic-based decentralized control with collision avoidance for multiple

AGVs. Specifically, in [103], the problem of planning navigation paths for multiple heterogenous AGVs was solved by transforming routing and AGVs dispatching as a heterogeneous Hamiltonian path problem. The heuristics relating to the Hamiltonian transformation was a non-deterministic, polynomial-hard (NP-hard) problem and solutions generated was similar to solutions for the traveling salesman problem which is also an NP-hard problem. Authors evaluated their solutions using four different AGVs. The heuristic was found to work very well since a fast AGV that can handle small payload was deployed for jobs requiring transporting small payloads over long distances. The heuristics formed using the Hamiltonian heuristic approach also could be used to dispatch and route AGVs using a short computation time. In [105], a combination of Bellman-Ford and A* algorithms were used with a fuzzy inference systems that incorporates the knowledge of AGVs system planners.

In [106], authors applied improved genetic algorithm for multi-AGV path planning challenges. More optimal offspring were obtained by using three-exchange crossovers in the heuristic algorithm design as opposed to the traditional two-exchange heuristic algorithm crossover operators. Also, by using double-path constraints that includes minimizing the total path distance of all AGVs and also minimizing each AGV's travel distance, the shortest travel distance for all AGVs considered were obtained. To evaluate the genetic algorithm designed, five AGVs and fifty workstations were considered. The heuristic algorithm population size was set to 200. Results showed improved performance of the designed genetic algorithm with a total path distance of 72 as opposed to a total path distance of 86 obtained for the traditional genetic algorithm. In [107], authors applied a combination of genetic algorithm and Dijkstra algorithm to study AGVs path planning problem in a conflict-free flexible manufacturing environment where the number of deployed AGVs are dynamic. Tri-string chromosome coding method [107] was applied to ensure the feasibility and computational tractability of the genetic algorithm-based solution. In [108], authors presented a method using passive RFID tags and B-spline based algorithm to track indoor positions of an AGV. The B-spline algorithm was preferred to other processing intensive method such as using lookup tables (LUTs). In [109], the dynamic banker algorithm, a resource allocation and deadlock avoidance algorithm was applied for AGVs scheduling. To improve AGV scheduling, the applied dynamic banker scheduling was modified in three ways. First, if an AGV path is unoccupied, an AGV can navigate in that path without giving considerations to safety measures [109]. Secondly, some unsafe states may be allowed in some instances if it will improve overall AGV scheduling and thirdly, AGV mission paths may be split into several sub-paths if it will improve overall AGV scheduling. With this approach, AGV mission waiting time is reduced, time required for releasing a path for AGV navigation is also reduced [109]. A third benefit is that more traveling spaces will be available for overall AGV fleet.

In [110], authors proposed and evaluated a decision making and synchronization algorithm that consider errors of the particle filter of a 2D laser range finder (LRF) and AGVs localization using dead reckoning method. A three-step process which included using (i) dead-reckoning to estimate an AGV, (ii) Bayesian probabilistic technique and nonparametric particle filter to compensate for odometry error that can result from using dead reckoning method; and (iii) building a 2D map using a LRF and the iterative closest point (ICP) algorithm. For evaluation of the decision making and synchronization algorithm, an AGV platform equipped with an LMS-100 LRF was used the 2D map generation and for AGV localization. Results shows that the designed algorithm can solve the problem of cumulative errors from dead reckoning and the uncertainty of the particle filter. In [111], authors proposed and designed a priority-based path routing algorithms for AGVs. The algorithm was based on priorities of locations that each AGV will visit on the global factory floor map. For the priority-based routing algorithm to work, the map of the factory floor is available as an input to the priority algorithm, and the AGV can utilize the map to make path tracking decisions. In their implementation as reported in [111], authors decided to use a LUT to store priorities of the factory floor path nodes. An Arduino Uno that is based on the ATmega328 MCU was used to automate AGV control activities. Using the designed priority algorithm, the AGV was found to follow optima path based on the priorities stored in the LUT.

In [112], performances of two separate mathematical models that are applicable for AGV path planning were compared. The reduced-parameter multi-commodity model was found to perform equally as well as the detailed-parameter model. In [113], a computationally efficient stochastic Markov chain model was used to evaluate the cost and risk associated with deploying an AGV in a small-scale manufacturing environment. The Markov chain model allows for the analytical optimization of the capacity of an AGV in a close-loop multi-machine stochastic system. In [114], researchers designed and tested a mathematical model that may be executed in polynomial time. The model can be used for dynamic simultaneous scheduling of factory machines and AGVs. In [116], an algebraic algorithm was designed, with its iteration steps based on direct distance matrix computation. Its path planning performance was found to be better than the path planning performance of Dijkstra algorithm.

In [117], authors reported the design of a dynamic, time estimation based AGVs scheduling algorithm. Its performance was evaluated using a simulated AGV model built with AnyLogic software. AnyLogic software was selected since it has widespread applications in logistics and manufacturing. It also provides Java programming interface such that simulations can be easily modified and customized. The implemented dynamic, time estimation algorithm shows its benefit by allowing AGVs to avoid congestion, avoid frequent start and stop instances and enhance overall AGV fleet utilization. In [118], authors proposed a new real-time scheduling strat-

egy by which an AGV transport entire shelves to pickers in logistic warehouses. Productivity was improved and picking time was reduced since sorting shelves can be transported to pickers even if the sorting shelf is still engaged in item sorting. In [119], authors proposed using Yen's algorithm to optimize AGV storage and retriever process in logistic warehouses. Authors pointed out a shortcoming of the classical Dijkstra algorithm as being useful in finding the shortest path without considering other shortest paths that have same length. This demerit can lead to possible conflicts and AGV deadlocks when Dijkstra algorithm is used for AGV path finding solutions. Thus, authors proposed using two strategies that includes finding multiple potential paths and inserting waiting nodes where AGVs can temporarily wait to resolve conflicts that are encountered during AGV navigation. The Yen algorithm is an adapted version of the k shortest path algorithm. To design the Yen algorithm, k shortest paths between two nodes were sorted in non-decreasing order of lengths. Feasibilities of paths were checked for paths that may possibly have discontinuities. The Yen algorithm was found to perform better than the classical Dijkstra algorithm in terms of avoiding conflicts and finding optimal paths from a source to a destination.

In [120], authors applied deep reinforcement learning to assist AGVs to select closest task among other multiple material handling tasks in a warehouse. Likewise, authors in [121] applied deep learning algorithm to AGVs route planning. However, researchers in [121] uses high-dimensional map as input to the deep-learning algorithm in lieu of hand-engineered low-dimensional state representations. In [122], a prototype sensor and a localization method for AGVs was proposed. A small imaging Light Detection and Ranging (LIDAR) named Single-Photon Avalanche Diode (SPAD) LIDAR which uses a time-of-flight method and SPAD arrays was used for AGVs localization. Researchers in [122] also introduced a deep-learning and fusion-based localization method named SPAD + DCNN (Deep Convolutional Neural Network). To improve AGV localization, SPAD + DCNN can be used to fuse the output of SPAD and LIDAR including range image, monocular image and peak intensity data. In [123], authors applied neural network to assist in tuning PID gains to improve on an AGV speed regulation whenever the AGV is navigating around a corner or when moving in an arc. Using neural networks to tune PID control gains led to reliable speed control of AGV brushless DC Motors (BLDCM). Using neural networks for PID tuning also led to achieving excellent AGV speed response at full AGV loads. Authors uses a two-step method in [124] to estimate the appropriate number of AGVs suitable for deployment in a fleet for flexible manufacturing system (FMS). The two-step approach consists of using a mathematical model to estimate the fleet size and then using simulation to determine the number of AGVs that can be reliably deployed. The two-step approach was found to be more computationally efficient and reliable than applying each methods individually. In [125], researchers applied linear programming method

to determine the transportation throughput of AGVs in a logistics center. Linear programming was used since using it results to shorter processing time when compared with using integer programming. Results obtained in [125] by using the linear programming approach is useful for determining the appropriate number of AGVs that can satisfy a customer requirements. Cost of trials, assessment and evaluation of an AGV fleet to be used for satisfying material handling needs of a logistic center are also reduced.

In [126], authors demonstrated the application of quantum Ising model in solving the problem of controlling many AGVs in industrial environments. The problem of controlling a sizable number of AGVs was formulated as a low-parameter quadratic unconstrained binary optimization (QUBO) problem. Parameters were reduced so that the problem can be solved using the D-Wave 2000Q quantum computer. Results demonstrated the applicability of quantum Ising model to the problem of AGVs traffic control. In [127], a time Petri net-based scheduling method coupled with an AGVs flow path control system was proposed for developing an AGV material handling flow path (MHFP) system. To overcome the problem of AGV congestion and deadlocks especially at intersections, dwell point, which are points where AGVs can timely interrupt service routines and revert back to former known states along a unidirectional AGV loop system when deadlocks happen are considered. With dwell points included in AGV loop paths, the MHFP system becomes an extended material flow matrix. For a particular AGV work order, the AGV route can be modelled as a marked graph. When transition times are included with the marked workflow graph, it will become a special type of timed petri net. The timed petri net approach advocated in [127] made possible the simulation of different routing and deadlock scenarios. Thus, intelligent decision making which incorporate the knowledge of most possible AGV workflow, congestion and deadlock scenarios will be incorporated into the MHFP system.

Also, in [128], authors introduced the design of a material handling flow path control system in a partitioned zone using timed Petri nets. A Petri net decomposition method, in which the entire Petri net is decomposed into task and AGV subnets was discussed in [129]. Petri net was also used to design programmable logic controller (PLC) for solving path planning problem to prevent collision among AGVs in [130] and in [131]. In [132], colored Petri net and D* Lite algorithm were applied to collision-free navigation and traffic control for AGVs. In [133], authors proposed a hierarchical AGVs traffic control algorithm useful for implementing path planning on a two-layer architecture. The topmost layer describes the topological interrelationship among different areas of the factory. The lower layer contains information about fixed routes along which AGVs must traverse. Each AGV in a factory floor will autonomously computes its navigation path using both layers. The entire AGV fleet was coordinated by exploiting shared resources using both centralized coordination and local negotiation (decentralized coordination).

Kalman filter (KF) was applied in [134] to prevent slipping of AGVs running on Mecanum wheels during navigation. KF was used to fuse data of StarGazer and ENCODER sensors and thus combine advantages and mitigate the shortcomings of both sensors. StarGazer can produce large errors when used to measure absolute localization values whereas ENCODER sensor can accumulate errors due to the presence of integral term and due to disadvantages brought about by the Mecanum wheel slip phenomenon. In [135], authors also applied KF to the problem of online control cost estimation. Control costs that are considered include task completion rate, energy and robot speed. In [136], a deep learning based deep belief network was applied to learn the innovation sequence of KF in a bid to improve accuracy and robustness of KF used for AGVs positioning. In [137], KF was used to fuse data of an AGV inertia system encoder and the inertia measurement unit while using RFID tags to assist in positioning the AGV. The aim of researchers in [137] was to develop a reliable but low-cost inertia guidance system for AGVs. Thus, the AGV inertia guidance system was made to rely on the inertia measurement unit (IMU). Errors accumulated by inertia sensors are eliminated with the aid of magnetic nail (MN) positioning method. The entire solution for designing the low-cost inertia guidance system including the use of RFID was named the combinatorial inertia guidance system (CIGS). KF was used for filtering data from several sensors and units of the CIGS. An AGV kinematic model was used to evaluate to CIGS and it was found to be more effective than ordinary AGV inertia guidance system.

In [138], KF was applied to the fusion of an AGV odometric sensor data and RSSI (Received Signal Strength Indicator) data from RFID tags; while it was applied for AGVs localization in [139]. In [140], AGVs localization, position and orientation were determined using KF state space model. In [141], SLAM-based EKF is used for AGV navigations; while in [142], EKF was applied to the problem of sensor fusion of a wireless ultra-wideband wireless system and an inertia navigation system (INS) for AGVs navigation. The applied multi-rate EKF fuses delayed data that has been compensated for position measurement and the INS data.

It could be observed from the foregoing that algorithm design and implementation for AGV localization, scheduling and path planning is still an ongoing area and it has enjoyed much research attention in the last decade. Using classical algorithms such as A* and Dijkstra have been known to lead to the problem of generating large computation overheads and routing inefficiency respectively. Thus, researchers have been examining hybrid and improved algorithms such as combination of artificial potential field algorithm and A* algorithm, improved Dijkstra, improved D* Lite and Yen's algorithm. Other classical algorithms such as KF and EKF for AGV data fusion applications have also enjoyed much attention in the last decade. In the near future, the utilization of 5G MEC and its high-speed computing resources may be useful in faster processing for some of these classical algorithms and their variations if those algorithms are installed in the 5G MEC

for the purpose of AGV path planning, localization and AGV mission scheduling.

B. NAVIGATION, CONTROL AND GUIDANCE

In [143], a control algorithm was proposed based on the concept of virtual platoon. The algorithm can aid AGVs to avoid jumps in velocity and acceleration while merging. The effectiveness of the algorithm was verified through simulation. In [144], authors examined the feasibility of using ant algorithm to AGVs design and control. A case was made for the introduction of an ant inspired adaptive routing algorithm known as AntHocNet. AntHocNet was suggested as an algorithm that can be applied to solve the problem of frequent unexpected topology changes that are always encountered when AGVs are navigating on mobile ad hoc networks (MANETS). In [145], authors presented an algorithm that can be applied for an AGV velocity control. The FIREBIRD IV and ATMEGA microcontrollers (MCUs) were used to emulate the AGV while ZigBee was used to establish communication between a central controller and the AGV. In [146], authors applied a combination of laser-based tracking and pure pursuit algorithm for AGVs tracking in indoor environment. Movement of the AGV was determined using a mathematical model which was based on direct AGV kinematics. AGV localization was accomplished using AUTO-NAV200 laser sensor. By using the pure pursuit-based trajectory tracking algorithm, AGV experienced less than 5% error in its position over its entire motion over a defined trajectory. Also, in [147], authors applied laser-based guidance to avoid unknown obstacles in AGVs path. In their implementation, an algorithm was designed that enables AGVs to be able to detect an obstacle and circumvent the obstacle in industrial environments. The designed algorithm can be used by different types of AGVs, it avoids heavy computation in its implementation and it can work with limited perception of its environment. In [148], authors developed a three-wheel differential drive mobile robot to test a model that uses feedback-based controller algorithm designed to prevent AGVs from capsizing during navigation.

In [149], authors proposed and evaluated the use of a USB camera to sense the position of an AGV. The impact of image resolution obtained by the camera, image processing parameters and the cameras frame rate on the AGV's PID control system were evaluated. It was discovered that the USB camera is adequate for sensing AGV position. A magnetic guidance method was used in [150] for indoor AGV navigation. Existing AGV guidance method involves the use dead reckoning, gyro sensors and encoders for calibrating against AGV steering angle errors. However, research efforts in [150] involves the use of magnetic spot guidance, Hall-effect sensors, counter and encoders which are used to achieve AGV guidance. Skidding errors are corrected in real-time using a fuzzy logic controller. The magnetic spot guidance method was evaluated in a ceramic and steel manufacturing plant and it was found to be robust against skidding and other tracking disturbances.

In [151], to improve positioning accuracy of an AGV, authors proposed the use of a magnetic nail that can be easily tracked by a 2D sensor array. A hybrid optimization algorithm that utilizes both Levenberg-Marquardt and particle swarm algorithms was used together with the 2D sensor array to determine the location and orientation of the magnetic nail. To establish the improved performance of the suggested method over the traditional 1D magnetic sensor array method, a N35 neodymium nail was used. Positioning accuracy was $\pm 1.69\text{mm}$ as opposed to the greater than $\pm 5\text{mm}$ positioning accuracy normally obtainable from the traditional 1D sensor array. In [152], buried magnets were used with an appropriate control strategy to ensure the stability of an AGV, to aid its navigation and to assist the AGV to decide on the appropriate path to select at factory floor intersections. In [153], a decentralized path planning and AGVs control algorithm that can run independently on free-ranging AGVs was proposed. The algorithm can deduce the shortest feasible path that an AGV can follow while running missions.

In [154] and [155], researchers applied fuzzy inference algorithm and also utilized the weight of a trolley attached to an AGV to enhance movement control of the AGV, while in [156], authors applied a variant of fuzzy inference algorithm called parallel cascade fuzzy algorithm to assist AGVs to avoid obstacles while navigating. Fuzzy algorithm was also applied to the design of an AGV in [157] and to AGVs trajectory tracking in [158]. In [157], it was emphasized that the objective of the fuzzy controller algorithm was to produce monotonous AGV control with minimum fluctuations and to achieve AGV stability within the allocated AGV movement time. The inference system of the fuzzy controller was designed using if-then rules. Using the designed fuzzy controller, the AGV was robust to unplanned changes along its movement track. In [158], the fuzzy controller algorithm was designed using Linear Matrix Inequality (LMI) solver to guarantee its stability. PID control was used to obtain AGV input torque. The use of Lyapunov's LMI solver to ensure AGV stability was quite beneficial as the AGV can track sudden big orientation changes from the AGV reference trajectory. Authors in [159] proposed and evaluated a collision avoidance algorithm that scales robustly with the number of AGVs. The algorithm can also be effectively used to resolve AGVs deadlock situations. In [160], researchers explored methods of using colored sensors for AGVs navigation and established that colored sensors, due to their low cost, ease of installation and their effectiveness in AGV line navigation can be very useful for AGVs navigation. In [161], authors applied a fuzzy inference method and combined it with a PID control method to achieve stability and speed control for an AGV. In [162], authors utilized the hierarchical sliding mode control (HSMC) algorithm for an AGV obstacle avoidance and target approach. A single hardware/software platform which was also used for RGB-D vision-based image processing and PWM-based driving control was used for implementing the HSMC control solution.

In [163], a continuous form of sliding mode control (SMC) was used to control an AGV that has complex navigation references. The AGV also have extra load and it experiences instant disturbances. Result of experiment show that the proposed SMC was adaptive to changing conditions resulting from initial AGV disturbances. It also robustly controls AGV velocity and direction of movement angle. In [164], an optimization approach which also include the use of SMC and PID algorithms are applied for the AGV trajectory tracking. In that study [164], genetic algorithm was used to tune parameters of the SMC. The optimization algorithm presented in [164] also utilized an intermediate sliding surface to minimize the error between the desired and the actual AGV's trajectory. In [165], authors presented an algorithm that can be used in real-time to solve precision problems related to arc path tracking when AGVs are implementing using dual differential driving mode system. In [166], researchers developed a software-based image processing system capable of acquiring image, processing the image and recognizing glyphs. The image processing system can be used for AGV motion control. In [167], an AGV path-deviation parameters were obtained from image processing unit on the AGV. Obtained parameters were used to actualize improved AGV vision navigation using fuzzy control algorithm. In [168], an improved camera calibration technique whereby intrinsic, radial distortion and camera external parameters were used in camera calibration for vision guided AGVs was presented. In [169], to be able to introduce reliable free-ranging AGV system, a vision-based range finder which include a laser transmitter and image sensor was applied to AGVs navigation. The laser transmitter emits a line-shaped laser and an image of the line-shaped laser was produced by the laser image sensor. Distance between objects in AGVs' navigation path and the AGV range finder is estimated based on the height of the laser image in the image sensor. The laser vision range finder has a reported navigation error of less than 1%.

In [170], authors reported the design of a constrained path-following controller for an AGV navigation. The AGV close loop signals were bounded by state constraints which are approximated by Lyapunov functionals. The state constraints are AGV path lane boundaries detected by a vision computer on the AGV. In [171], an algorithm that can be used to extract lane edge features from an AGV-based vision camera was designed. The extracted lane features can be used by the algorithm to estimate the optimal AGV's trajectory. In [172], an algorithm that can be used for 3D point cloud information extraction when only partial scanning data is available was developed. The algorithm can be used to solve the problem of partial detection of objects in AGV movement path. When compared with other LIDAR methods, the 3D point detection algorithm has clear advantage. It has lesser processing steps, it has lesser implementation restrictions since it is not model based, and it is rotation invariant which makes it to be able to detect objects in unusual positions such as overturned cars. In [173], a remote controller was used for the control of a lawn mowing AGV, and in [174], non-

uniform illumination resulting from the use of LED arrays in AGV vision guidance systems was reduced using Levenberg-Marquardt algorithm. It is however worthy to note that in [173], the lawn mowing AGV was teleoperated using a 5G customer premise equipment (CPE) that was connected to a 28GHz 5G/2.1GHz antenna that was using a 5G core network and a 5G base station. A direct benefit of using 5G networks for the AGV teleoperation is the low latency that exist between the microcontroller module and the AGV. However, as emphasized by authors in [173], the performance of the AGV can be improved using an advanced control system. In [175], a chronicle of the evolution of laser-based AGVs navigation products by AutoNavigator AB since the 1980's till the year 2013 was conducted. Authors emphasized that AGV laser navigation system introduced in 1991 was the first of its type that can accomplish simple identical targets using anonymous stripes of retro-reflective tapes. AGV Laser navigations systems was thus considered as a disruptive technology since it enables Kollmorgen Särö AB, an AGV company and its partner firms to have significant market shares in the AGV market. In [176], authors designed a Corresponding Vector Sampling and Consensus (CVSAC) based algorithm for robots and mobile vehicles' pose estimation. The designed CVSAC algorithm took advantage of ICP and random sampling and consensus (RANSAC) scan matching algorithms for robot's localization and mapping for safe robot movement.

In [177], an event driven model of an AGV was used to study AGV design and control methods. Routing algorithm that reduces AGV transportation time and travel distance in a grid path layout was also developed. In [178], authors revealed how a navigation method based on potential field around an AGV could be used to improve the ability of AGVs for obstacle detection. Similar to using a Lyapunov function as was done in [170], a Lyapunov function was also used for AGVs control application in [179] where an AGV control strategy that uses a reference point for rear steered AGVs was presented. The considered AGV was conditioned to track the given reference and minimize the AGV to reference distance. Barrier Lyapunov Function (BLF) was selected for ensuring the stability of the proposed control approach. In [180] and [292], fuzzy inference (IF-THEN) methods were proposed and applied for AGVs control. Specifically, in [180], the fuzzy control algorithm has two parts which consist of moving toward the destination and obstacle avoidance. In the first part of the fuzzy algorithm, to move towards a destination, AGV movement angle, angle variation and AGV distance to destination are inputs to the fuzzy controller. When AGV sensors detect an obstacle in AGV path, the obstacle distance to the AGV and the locations of obstacles' corner points with respect to the AGV are calculated and used as input to the fuzzy system. Two AGVs can prevent collision by each of the AGV calculating the movement speed, distance and movement angle of the other AGV. These variables are also used as inputs to the fuzzy system. The designed AGV control algorithm using IF-THEN fuzzy controller was found to be

robust against different type of obstacles when evaluated in a new unknown environment. In [181] authors evaluated three control techniques: vector pursuit, flatness-based and fuzzy method. Their effects in ensuring low jerk variations in AGV docking operations were also examined. A data driven model of the vector pursuit control algorithm was combined with differential flatness control technique to obtain a new control strategy. Evaluation through simulation shows encouraging control result as the AGV was able to overcome skidding effects in industrial environments. In [182], performance of a model predictive control (MPC) based tracking and trajectory planning algorithm for AGVs was implemented with ROS and tested in a manufacturing plant. Simulation was built with Stage Map. Interior Point Optimizer was used as solver for the MPC algorithm. Performance of MPC-based planning for AGVs tracking was compared to the performance of – (i) MPC and PID control; and also compared to the performance of – (ii) MPC and A* global path planning algorithm. The MPC based planning and tracking method showed better overall tracking and control performance. In [183], authors presented a low computational complexity control method by which feedback control deviation errors introduced by AGVs skidding can be corrected. The cascade control system that was implemented works with AGVs wheel encoders to detect AGVs skidding on slippery surfaces. In [184], authors applied a model-based systems engineering approach to develop an AGV-based material handling system. The AGV controller was designed in system modelling environment using Visual Paradigm software. In [185], authors proposed an approach by which multiple AGVs can be coordinated, especially at intersections, while considering AGV fleet dynamics in view of communication constraints. A decentralized navigation function (DNF) that considers AGV's dynamic constraints was used for multi-AGV coordination. Performance of the DNF was evaluated by simulation through Matlab. The DNF method was compared with classical methods of AGV intersection management such as using traffic light, roundabout and give-way rules. The DNF method enable multiple AGVs to improve fleet flow, reduce travel times and also reduce the number of stops.

In [186], authors proposed the use of neural network, fuzzy and bang-bang control methods to design an intelligent control method for steering a moving AGV. The designed controller can control operating status and parameters of the AGV. A feedback linearization method for an AGV trajectory control was proposed in [187]. A time-scaling mechanism was used to adapt AGV reference trajectory to desired trajectory in real-time. This allows the AGV to be able to achieve collision avoidance through braking. The control method yielded small position errors when evaluated using a real AGV. In [188], the STM32 microcontroller was used to implement control options such as space vector pulse width modulation (PWM) and fuzzy PID control for a Permanent Magnet Synchronous Motor (PMSM) based controller for AGVs. The PMSM was selected due to its reported excellent speed regulation performance in robots and industrial control

machine tools. Experimental test reveals an AGV control system that shows good dynamic quality and stable performance. Also, evaluation using a dual pulse experiment indicates that switching system for the PMSM control circuit have low power consumption. In [189], the active disturbance rejection control (ADRC) based backstepping control method was used to offset the effect of a moving AGV that has uncertain linear and angular velocities. Tuning law based on feedback gain was used to ensure compensation for uncertainties derived from uncertain AGV linear and angular velocities. Time-scaling mechanism was used to adapt a reference trajectory to the AGV velocity in a desired trajectory. Breaking mechanism for collision avoidance was also implemented. In [190], researchers applied the STM32F103VET6 MCU to transfer remote control instructions to an AGV's direct current (dc) motor. The NRFI24I01 transceiver module was employed to transmit control instructions and updates to the STM32F103VET6 chip. Evaluation of the STM32F103VET6 MCU based remote AGV controller shows that the designed system is easy to operate and it has marked flexibility since it can be reliable used to actualize forward, backward, sideway turns, stop, acceleration and deceleration functions for an AGV.

In [191], a high precision AGV path-tracking method based on using color difference threshold segmentation was proposed and used as input to AGV's close-loop control method when an AGV is navigating. Authors advanced a method through which AGV deviations from its navigation paths can be extracted using the threshold segmentation of chromatic aberration of floor path colors that are being used to guide AGVs during navigation [191]. These deviations are used as inputs to the AGV path tracking controller. Experimental result indicates that the visual navigation method considered enables the AGV to navigate smoothly with high path tracking precision. In [192], researchers applied an unconstrained optimization method based on continuous curvature steering to generate reliable waypoints for AGVs. Waypoints are precise points from which an AGV can start off an explicit docking maneuver for load transfer operations [192]. Authors in [193] motivated an approach by which data from low-cost external and AGV onboard sensors can be fused together to assist in AGV localization and mapping in both indoor and outdoor environments. In [194], authors presented methods by which SLAM based localization and mapping for mobile robots was accomplished using Bayesian method. According to researchers in [194], SLAM algorithm works by creating two maps using trajectory and positioning data collected through AGV sensors. The first map is known as the metric map. This map is created from selected factory floor point of interests or position of obstacles. The second map is the local map and it is created from AGV perception of current AGV position. Both maps are then merged to create the general factory floor environment map. The AGV will then move through a trajectory and update the map based on new data obtained through AGV sensors until the area of interest is completely mapped. In [195], as part of the

Plug-and-Navigate Robots (PAN-Robots) initiative, a new approach by which AGVs utilize 3D maps of factory floor and factory landmarks to navigate was discussed. AGVs were equipped with reliable perception systems that can monitor the entire 360° area around an AGV. The perception system was made up of two cameras, two omnidirectional lenses mounted on top of an AGV and multiple lasers scanners that are positioned around the AGV. The new AGV perception system promises to aid pervasive diffusion of AGV systems in the factory. It will also lead to improved and safe working environment when multiple AGVs are deployed to work with humans in industrial environments.

In this subsection, AGVs navigation, control and guidance technologies that enjoyed wide research attention within the past decade are discussed. It could be observed that fuzzy inference, PID, MPC, SLAM, PWM and Lyapunov function-based control methods and algorithms commanded wide attention from research communities. These algorithms were widely applied for solving a variety of control, navigation and guidance problems within the last decade. Laser based vision systems are used with some of these algorithms and methods in some instances. Authors in [175] emphasized that introduction of laser-based solution proved to be highly significant in some segment of the AGV industry. Researchers are still actively attempting to improve existing solutions to problems such as AGV skidding, minimization of errors between the desired and actual AGV trajectory and AGV motion control. The use of 5G networks as a means of transmitting or exchanging control data is still in its infancy and only one author in [173] mentioned a preliminary work in this area. From the foregoing, it could be deduced that AGV navigation, control and guidance problems are still being largely solved using variants of classical algorithms such as PID and fuzzy inference algorithms. Open challenges still exist in the area of AGV motion control, and AGV skidding during movement. Avenues of using 5G communication networks as a reliable means of exchanging AGV control data still largely remain un-explored.

C. VISION AND IMAGE PROCESSING HARDWARE AND ALGORITHMS FOR AGV CONTROL APPLICATIONS

In [196], authors presented a high-performance algorithm that utilized real-time 2D image captured by a charge-coupled device (CCD) camera. The algorithm was designed to assist the NH1-V AGV in docking and navigation activities using artificial landmarks as a guide for the AGV. In [227], images from two CCD cameras which are used to obtain images for path tracking prediction and positioning are processed using the Texas Instruments' TMS320DM642 digital signal processor (DSP). Output of the software development platform based on the TMS320DM642 DSP are used with RFID tags for an AGV path planning and workstation identification. In [197], an AGV-based vision system was used with support vector machine (SVM) and principal component analysis (PCA) to detect nearby AGVs so as to prevent collision. In [198], researchers working on the European PAN-Robots

project presented a system level overview of the main technologies developed during the project. Of importance is the development of an advanced sensing system that AGVs can use to classify objects and humans in dynamic FoF environments. The developed sensing system will enable a reliable human-robot activities' collaboration in a FoF environment that have many AGVs working with humans. Authors in [199] presented an AGV navigation approach by which overhead cameras can be used for AGV navigation. The approach is useful for controlling a fairly large number of AGVs in a small manufacturing environment.

In [200], researchers designed and evaluated the performance of a new laser based AGV navigation positioning method that can be applied to underdetermined laser tags cases. For laser navigation to work as intended for AGVs, a minimum of three reflector tags are needed. In underdetermined cases however, some of the reflectors may be missing or have their signals occluded. The method used to overcome underdetermined laser condition in [200] revolves around combining known navigation roadmaps with an AGV 2-axis accelerometers to augment inputs from available reflectors. Evaluation of the designed system shows that it can be useful for rectifying problems resulting from cases of underdetermined laser reflectors in AGVs navigation. In [201], to improve performance of AGV fleets used for logistics operations, authors proposed using an advanced central sensor fusion technique that can receive signals from both AGV onboard laser sensors and lasers sensors installed on factory infrastructure. Laser sensors installed for factory infrastructures can be used to monitor existing blind spots on the factory floor. These sensors are capable of providing a 360° view of the entire area near a roving AGV, thus improving on the AGV security and navigational abilities.

This subsection extends the discussion of the last subsection and it focuses specifically on the impact and uses of camera, laser and vision systems for AGV control and navigation. An important lesson of this subsection is that when lasers and other vision systems that are installed on AGVs and on the factory structure works together, then AGV fleets will have improved navigation, security and safety performances.

D. WPT FOR AGV, AGV POWER CONSUMPTION AND MANAGEMENT

Power management, AGVs WPT and battery conservation methods are very important aspects of AGVs fleet management and these aspects has commanded an appreciable level of research in the past decade. Distance and time of travel to and from an AGV present location and the location of the AGV battery charging port are important parameters for AGV fleet optimization. Also important are the sizing and type of battery in use, types of charging employed (namely contact and contactless battery charging), life cycle of battery and possible integration of alternative energy sources in AGVs and AMRs [202]–[204]. In [205], a WPT method based on magnetic coupling resonance for AGV was proposed. By using a soft switching strategy for

the WPT inverter and by careful selection of the resonance parameters, the wireless charging system achieves a constant charging current of 30 A for a 48V AGV Lithium battery.

A PWM inverter with voltage booster for an AGV WPT system was proposed in [206]. The WPT system was equipped with a permanent magnet (PM) motor, and a voltage booster that can work with either a 24 V or a 48 V low voltage battery. The voltage booster works to keep the battery charging current constant. The WPT dc link can be controlled and made constant by adjusting distance between the transmitting and receiving power coils. In [207], a charging control method based on noncontact charging method for AGVs was proposed. The control method entails the use of variable frequency control which can be used to realize a close loop current control in the presence of misalignment. Researchers in [208] developed a system that was used to drive an induction motor and charge an AGV battery using WPT. The system enables a constant output voltage from the WPT system by constantly moving the receiving coil and adjusting gap length. In [209], a modular on-road WPT system which facilitate interoperable power adjustment was proposed to enhance the capability of on-road charging while an AGV run missions. The power adjustment module was based on detected impedance, and it was used to adjust power output from each AGV WPT transmission module in a flexible way.

In [210], an 80% efficiency at 600 W power transmission level was recorded when a Class E push-pull inverter was developed for outputting between 300 W to 600 W power to drive large AGVs. The 80% efficiency resulted from reducing the apparent inductance of the transmission circuit using compensation capacitor. AGVs power system researchers in [211] proposed a repeater-aided dual output WPT system with extended power transmission gap. The resonant behavior of a WPT dual output system was studied in-depth and theoretical analysis of system behavior was conducted. A WPT resonant circuit simulator was built and its frequency response confirms outputs of the theoretical analysis. In [212], an AGV WPT system was designed to solve the problem of long AGV charging time. A proportional-integral passivity-based-controller (PI-PBC) control strategy was proposed to reduce effective charging time of an AGV during time spent at docking ports. A 1.5 kW model of an AGV WPT system was constructed using PLECS software. The output voltage of the PI-PBC control strategy has no steady state error and its dynamic performance is better than using only PI control.

Authors in [213] designed a system that can be used to estimate state of charge of AGV batteries while authors in [214] reported on a retrofitting effort to mitigate harmonics and improve on power quality of a 480 V power system for large AGVs at a container terminal. In [215], a linear programming heuristic method was proposed for use in determining when an AGV need battery change while a proposal for a WPT with two receiving coils was put forward in

[216]. During AGV movements, system output voltage and coupling effect can be easily adjusted and stabilized using the two-coil system. To improve on system topology, new brushed dc motors which can be used to better drive the shaft and wheel system was incorporated into an AGV design in [217]. AGV batteries can be charged as the AGV follows magnetic lines on the factory floor. AGV motor controllers were replaced so that line-following performance and AGV stability can be improved. In [218], a parameterized simulation model of an AGV with battery management was built. The model made provision for designing a FMS with the objective of understanding the relationship between the FMS, number of deployed AGVs and the battery management system. An AGV energy consumption model using experimental data and the trajectories of AGV translational and rotational motion was employed to estimate the rate of energy usage of AGVs in [219].

A move and charge (MAC) system was designed for AGVs in [220]. The system employs a dc-dc converter to maintain an AGV equivalent load resistance at a certain level, and then detect the charging current variation in view of constant AC input for the magnetic rail transmitter. An 83% efficiency was reported by using the design. A series-series compensation topology useful for realizing a low-voltage and high-current inductive power transfer (IPT) system for AGVs was proposed in [221] using a magnetic coupler size of 200 m × 220 m × 10 mm. The system was able to transfer 1.8 kW power at 89.9% dc-dc efficiency from a 400 Vdc source to a 24 Vdc load at a 10 mm air gap. A similar system was proposed in [222], however, the system can only achieve an 86.1% efficiency when transferring 1.78 kW power from a 300 Vdc to a 24 V battery at an air gap of 15 mm. In [223], the use of an energy shaping controller for AGV WPTs using dc-dc output voltage transformation. The study in [224] was used to establish that the series/series-parallel (S/SP) output voltage compensation circuit is better than series-parallel (SP) for AGV WPT circuits. In [225], a new magnetic design for an IPT pad called the bipolar pad (BPP) was proposed. BPP's performance was compared to the performance of double-D quadrature pad (DDQP), and both were found to be suitable for AGV IPT applications.

Since power provisioning is very important for reliable AGV fleet operation, research works on AGV power transfer systems have wide coverage in the past decade. WPT technologies were shown to be very important for a reactive AGV power system, and various aspect of this technology was focused on in the past decade. State of charge estimation and various circuits for improving AGV WPT systems enjoyed prime research focus in the past decade. This review does not focus on battery types and different type of AGV power sources. It is however envisaged that AGV power transfer circuits, methods of minimizing AGV power system harmonics and WPT technologies will continue to improve as new and improved AGV power sources and battery technologies are discovered.

E. WIRELESS COMMUNICATION FOR AGV/AMR APPLICATIONS

In the industry, wireless technologies-based solutions are applied extensively for AGVs control and fleet management [33]. However, the scope of technology and type of applications have continued to expand. For example, in [80], RFID tags were used for AGVs motion control applications taking into consideration factory floor issues that are crucial to instituting smart AGV systems such as: reconfigurability, flexibility, and customizability. In [81], authors reported the use of the Wireless Network for Industrial Factory Automation (WIA-FA) for actuating a real-time communication network that connect AGVs. WIA-FA system architecture, network topology, system management, protocols stack and key supporting technologies are discussed. Practical applications regarding the utilization of WIA-FA for monitoring and controlling industrial robots are explored. Deployment of WIA-FA as a communication network that connect AGVs for sorting applications in a logistic warehouse was also explored. WIA-FA was also employed for coordinating multiple cooperative AGVs that are used for transporting large and complex industrial components. In [226], communication among swarm of AGV was used to implement collision avoidance. Importance of communication network among AGV swarm was established through the fact that effectiveness of collision avoidance among is improved if more AGVs participate in exchanging their position information. In [227], RFID tags are used in conjunction with AGVs vision system for workstation identification. The Texas Instruments' TMS320DM642 DSP was used as the AGV image processor and the ARM LPC2210 was used as AGV controller. Factory floor images obtained by two CCD cameras on the AGV are received on the DSP. Position information obtained by RFID tags are used together with CCD camera images for workstation identification and for AGV navigation. Experimental results show that the DSP based workstation identification and AGV navigation solution advanced by researchers in [227] is robust and works well in industrial environment. In [228], authors combine NodeMCU located on an AGV with ultrasonic sensors for AGVs obstacle avoidance using voice commands from Android smartphones that are transmitted over Wi-Fi communication channel. A TDMA-based vehicle to infrastructure (V2I) MAC protocol was designed for use in an AGV control system in [229]. The TDMA-based MAC protocol features strict communication requirements for low transmission delay and for high reliability; and its performance was found to be better in terms of end-to-end latency when compared with the performance of the IEEE 802.11p standard. In [230], a trigonometrical algorithm was designed for AGV path planning; also, hardware needs for building an AGV that can use ultra-wideband wireless position sensors for obstacle avoidance was discussed in detail. The trigonometrical algorithm was found to be more computationally efficient for AGV path planning than conventional A* and D* algorithms.

Authors in [231] reported on a non-optical method that can be used to localize an AGV. The method employs channels state information (CSI) which could be easily extracted from most wireless cards on Wi-Fi communication transceiver interfaces. Reports in [232] and [233] features discussions on several ways through which an AGV can use wireless means to obtain its position information using a ZigBee network especially in high radio frequency (RF) interference environment such as IIoT environments. Specifically, in [232], an AGV can obtain its position using RFID. The AGV can also obtain details of its schedule priority and navigation route from a central coordinating tower. AGVs can also send their status details to the coordinating tower using small and in-expensive ZigBee radios. With these data from ZigBee and RFID nodes, an AGV can avoid collision with other AGVs by using: RFID nodes, ZigBee nodes and a central coordinating tower. Reports in [233] focuses on the application of ZigBee networks as a means of coordinating AGVs in container ports. Effects of the number of routers on the quality of ZigBee communication networks are examined. Channel quality parameters considered include RSSI and Link Quality Indicator (LQI). ZigBee channel qualities are examined between two ZigBee nodes on mobile AGVs and a fixed coordinator node while number of ZigBee routers are varied. It was deduced that ZigBee is a good communication network that can be reliably used in AGV based automated container ports. However, it was envisaged that due to ping-pong handover effect, the number of ZigBee routers must be limited. Nature of propagation channels in IIoT environments was discussed in [234]. Wireless channel between the sensor and control center becomes time-varying when the mechanical robot arms (MRAs) on top of mobile AGV bases are working and the AGV is also moving. To assist in further studying the channel, a 2D geometrical model for the MRA and a mathematical model of random Doppler offset for AGVs are provided to depict these Doppler frequency trajectories in the industrial wireless communication environment [234]. Simulated result of the geometrical model and random Doppler offset basically agrees with measurement results.

Similar to works reported in [232] and [233], authors in [235] examined RFID performance when used on conveyor belt applications. Studies in [235] focused on using AGVs to emulate conveyor belts in industrial environments. A test was conducted to determine the relationship between RFID tag reading rate and AGV speed. Another test was conducted to examine the impact of antenna height on tag reading rate. Yet another test was conducted to determine the impact of antenna's Azimuth on RFID tag reading rate. Study results indicate that RFIDs can be very useful for conveyor belt applications. RFIDs can also be reliably integrated with AGV based conveyor belts applications in industrial environments. Authors in [236] also examined the performance of RFIDs for AGV based operations in industrial environments. A unit load AGV was considered and the AGV can locate itself using RFID tags on the factory load stands. The RFID solution in [236] work along with a PLC solution that can detect the

docking point of an AGV and that of a workstation stand. The PLC can adjust the movement of AGV load-transfer mechanism with the aid of a stepper motor and a push rod. The effective performance of RFID and PLC based solutions was confirmed by an AGV navigation and load transfer experiment.

In [237] and [238], RFID and Wi-Fi-based paradigms through which AGVs can be better controlled to improve collaboration between cobots on AGVs and workers in industrial environments are presented. Specifically, authors in [237] discusses the benefit of using passive RFID technology as being a cost-effective means of aiding AGVs navigation in factory floors with large areas. They evaluated the performance of three AGVs that works with KUKA KR15 robots in an industrial environment. The KUKA KR15 gripper arm will pick an object and it will signify the completion of that task (picking an object) by sending a signal to an HMI using Wi-Fi. The AGV will navigate and dock at a receiving point using RFID and the KUKA KR15 will drop the picked object onto the AGV. The AGV will then navigate away to another point to deliver the object. Authors in [238] also discusses the importance of using Wi-Fi technology in enabling AGVs to be able to cooperate effectively with other AGVs and to be able to work safely in places that are populated with humans by being able to perceive the environment. They [238] also discussed the design of a cheap Wi-Fi based AGV called Cheap Cooperative AGV (CCAGV). CCAGV uses the ESP8266 Wi-Fi module. ESP8266 operates in the 2.4 GHz frequency region and supports the 802.11 b/g/n Wi-Fi protocols. It was emphasized in [238] that the strength of the CCAGV design lies in its being low-cost. Also, ESP8266 Wi-Fi module selected for AGV communication in [238] can interface with many variants of the Wi-Fi standard. In [239], researchers examined the application of QR codes and RFIDs for robot navigation in an industrial environment. Authors stressed the importance of using a combination of QR codes and RFID tags to ensure that AGVs navigates and successfully accomplish their tasks in the industrial environment. It was observed that even though QR codes can be utilized to accomplish precise positioning for AGVs, if the AGV increases speed, then the motion blur of the camera on the AGV can make the QR decoder on the AGV to fail, thus leading to imprecise decoding of AGV position. Thus, authors motivated the idea of using QR codes to determine the AGV angle and high-speed passive RFID tags to determine AGV position.

The design of a new omnidirectional AGV system was presented in [240]. Differential MY3 wheels installed on the AGV are equipped with wireless infrared and ultrasonic range-finding modules so that the AGV can avoid obstacles with minimal errors. A cyber physical system (CPS) based smart control model capable of reliably working on factory floors was designed in [241]. AGVs and antenna nodes on the factory floor can interact and share real-time information online. Using the smart control model, multiple AGVs can communicate, thus extending the range of each vehicle's

perception. Collision avoidance is improved since possible collisions between AGVs can be predicted using communication antennas. With the model, intersection negotiation time between AGVs are shorter leading to overall AGV fleet optimization. For reliability of interaction between AGVs that are relying on communication networks, authors in [242] focuses on the need to minimize packet errors to ensure quality of control (QoC) and thus improve on system reliability. Researchers in [243] studied the prediction of RSSI at a receiver that tracks an AGV as it moves along a factory floor. Machine learning was used with a sliding window pattern of RSSI signal leading to further improvement of prediction performance by multiple AGVs.

Authors in [42], presented a method of using WSN nodes that are attached to AGVs to monitor and record object that are transported by AGVs. Recorded data are to be sent onto a factory database on the warehouse management system (WMS). A nanoLOC wireless device with five sensor nodes was used along with EKF for trilateration to estimate AGV position. Some sensors on the nanoLOC device are also used to read data on pallets being transported by AGVs. Recorded data are transmitted onto a database on the WMS. Authors suggested the inclusion of more sensors to improve the accuracy of the EKF trilateration and to improve reading of data on objects picked by AGVs. Researchers in [244] presents real-time communication and localization strategies for swarms of mobile AGVs used for transporting Euro bins in logistic centers. Localization was realized by trilateration method; using laser range measurement that are obtained from IEEE 802.15.4a and IEEE 802.15.4a CSS networks. Research work in [245] also involves fusing data from sensors and laser range finders that are transmitting data over IEEE 802.15.4a networks. AGV localization and tracking was accomplished by fusing laser range finder data using a Monte Carlo particle filter. Similar to the approach in [42], authors in [246] also uses nanoLOC sensors for AGV range measurement. However, an EKF was used to combat the effect of noise introduced when AGVs navigates in industrial NLOS environment in [246]. In [247], a 1-km range Angled Physical Contact (APC) transceiver onboard an AGV was used to establish a network environment for understanding network behavior during packet transmission session. It was deduced that ideal transmission rates at the 434 MHz frequency and at a baud rate of 19200 bps was found to be 25 ms between each 56 bytes data packets. Authors in [248] presented a wireless network-based control strategy for AGVs. Their work features KF as a wireless network delay estimator. The estimator is useful for mitigating effect of channel disturbance that may jeopardize the robustness of the close loop wireless-based AGV networked control system. Authors emphasized that although AGV controls are traditionally implemented locally on the AGV, however benefits of implementing wireless communication based networked control system for AGV include better fleet management and improved task coordination that can lead to the actualization of a reliable FMS [248]. In [249], authors proposed the use

of IEEE 802.15.4a CSS (chirp spread spectrum) to improve on swarm AGV global localization in an industrial environment. To improve on localization and tracking of a swarm of AGVs in the industrial environment, authors' uses the IEEE 802.15.4a CSS to fuse wheel encoder data from a sensor in conjunction with AGV range measurement.

Researchers in [250] considered the problem of locating an AGV which moves on a plane by means of Ultra-Wide Band (UWB) signaling from fixed anchor nodes (AN) situated in 3D space. An analytical approach that can be used for optimizing placement of ANs used to locate an AGV was proposed. A local network cooperative control architecture for industrial robots in the Fog Radio Access Network (F-RAN) environment was proposed in [251]. The aim of the work in [251] was to increase the efficiency of issuing work orders and executing them when multiple AGVs are utilized in an industrial environment. In a multiple AGV environment, it is inefficient if AGV orders are processed sequentially (i.e., one after the other). If an AGV is conditioned to start processing work orders only when all other orders by other AGVs are considered, then efficiency and agility of the whole system will be jeopardized. If, however all others are speedily processed without an appropriate coordination policy, then the problem of conflict and deadlocks may be escalated [251]. To improve coordination and improve efficiency of a multi-AGV system scheduling, a new recurrent neural network (RNN) empowered coordination policy that involves the prediction of future orders was proposed. The coordination policy was presumed on the fact that when an AGV is currently executing a work order, if the RNN network can predict the starting location of the next order, then an idle AGV can be sent to the next order location in advance; thus minimizing AGV idle times, and improve on efficiency of the whole system. Time-window-based dynamic path scheduling algorithm (DPSTW) was used along with the RNN network to prevent conflicts and thus avoid AGV deadlocks.

To evaluate the RNN based multi-AGV coordination policy proposed in [251], a testbed for multiple AGV coordination in F-RAN environment was designed and implemented. The RNN-deep learning-based controller that can predict future AGV orders was deployed as an application in the fog access point (F-AP) of AGVs in the multi-AGV system. Work order predictions are based on historical records of prior orders. The RNN-deep learning predictor consists of an input layer, multiple long short-term memory (LSTM)-based middle layers, and an output layer that was fully connected. Input to the system are historical records of past orders and the outputs are the predicted starting points of next AGV work orders. Results showed that the method advanced using RNN based multi-AGV scheduling and coordination policy in F-RAN environment can improve AGV scheduling efficiency up to 35%.

In [252], an android smartphone was deployed to make voice commands work on an android phone for AGVs direction movement using Wi-Fi communication. In [253], authors described using probabilistic neural network (PNN) to predict

the most likely signal received along a fading channel as the AGV moves in a fixed-route format in a factory. The PNN was used to predict the most likely signal to be received by the AGV by using pattern matching between a stored signal and a currently received signal. In [254], a multiple degree of freedom (DOF) device was designed and fixed on the roof of a factory. The device can communicate with an ultra-sonic receiving device on an AGV. It can track the AGV in real-time; and thus, assist the AGV to reduce positioning errors in network-blind segments of the factory floor.

Observation and study of published research works in the past decade reveals the wireless network systems can be used to significantly improve AGVs fleet management, scheduling and coordination policies. RFID, QR codes, ZigBee and Wi-Fi technologies enjoys prime positions when it comes to AGV applications. However, 5G communication networks which have been projected to be an important enabler of smart manufacturing applications in industrial domains is yet to be widely used to improve AGV coordination and fleet management in industrial environment. Research results of modeling, simulation and actual implementation of AGV fleet scheduling and coordination policies with 5G networks are not widely available in literature and in actual practice domains. Thus, there exist a huge gap in the current understanding of the impact and challenges of applying 5G networks towards AGV fleet management and scheduling in industrial environments.

F. VIRTUAL REALITY APPLICATIONS FOR AGV AND AMR

Emerging technologies such as VR and AR coupled with AGV and AMR systems are now being applied to optimization of factory intralogistics. AR and VR technologies are also being applied in novel ways for AGV-based smart manufacturing and FoF initiatives. In [255], an immersive and interactive VR desktop was presented for 3D visualization of an AGV moving along a specified path in a factory environment model. The model consists of a large-scale point cloud obtained through Terrestrial Laser Scanning (TLS). In [256], authors presented a setup that integrates humans using motion capturing devices. The VR system also emulates a smart-watch as interaction device. The VR-based setup enables the validation of human-robot collaboration (HRS) functionalization of an AGV via virtual commissioning. In [257], 3D models are designed using the Autodesk Inventor 3D CAD software. Path tracking and collision avoidance were enabled in AGVs using Autodesk Inventor and KUKA KR5 robot. The introduced method is capable of enabling visual and virtual control of an AGV. Wi-Fi was used for communication. In [258], authors presented a visual representation approach to modeling an AGV-based logistic facility. The presented approach is useful for measuring and visualizing the performance, the availability and the reactivity of the facility within a VR environment. 3D laser scans were used to create a visual representation of the facility and mechanical components were modeled using simulation system's kinematic mechanism. Overall system was validated with a

simulation model of an agent-based facility logistic system. The system validation technique was also used to determine system's performance and availability.

Even though AR and VR technologies are being widely used in other domains of manufacturing such as for training, they are yet to be widely utilized for AGV/AMR applications. This conclusion is based on the few number of published works in this domain when compared to other domains such as the application of wireless technologies for AGV/AMR purposes. However, it is expected that due to current advances in AR, VR and other related technologies, manufacturing and intralogistics may very soon experience wider applications of AR and VR technologies for smart manufacturing applications.

G. APPLICATIONS AND USE CASES

In [259], authors proposed a mathematical model of an AGV applicable to FMS designs. The proposed model took into considering restrictions in plant layout and the AGV load constraints. In [260], authors catalogued the weaknesses of existing AGV systems that limits their deployment in FMS applications. To install AGVs successfully in a FoF system, authors emphasized the importance of installing flexible AGVs that relies less on installed factory infrastructures such as magnetic grids and RFID tags. In [261], authors examined how AGVs may be used to replace conveyor belts in clinical laboratories. A clinical lab where AGVs are used to transport clinical sample tube racks was simulated. Throughput of the systems was examined to ascertain if AGVs overall throughput exceeds capacity of clinical sample analyzers. Local traffic controllers that accept few inputs and output semaphores were used to control AGV traffic intersections. Simulation results show that AGVs can be used to profitably replace conveyor belts in clinical sample laboratories. Semaphores are also used as part of AGVs traffic control algorithms that are useful for resolving conflicts and deadlocks in [262].

In [263], researchers highlighted the application of multiple LMS500 laser scanners which are used in place of SLAM applications to achieve 3D mapping in a warehouse environment. However, some weaknesses, such as the poor perception of pallets on racks and poor perception of dynamic objects such as walking humans were observed with the 3D mapping of the warehouse environment when laser scanners are used. Similar to researchers' approach in [195], researchers in [264] employed 3D representations of the factory floor to assist operators using Human Machine Interface (HMI) to interact effectively with AGV fleets [264]. The designed HMI allows operators to supply inputs that can influence the behavior of AGV fleets. A central data fusion system which contains data of both static and dynamic elements of the factory floor provides the HMI operator an almost real-time feed of the situation of the factory floor. Based on data supplied by the data fusion system, the HMI operator can then influence the behavior of AGVs on the factory floor. An AGV was designed to specific customer requirements in [265]. Emphasis was placed on a low-

complexity AGV design capable of working along a conveyor belt. Also, in [266], emphasis was placed on a trust-based, human-AGV HMI system than is useful for AGV designers in crafting holistically trusted HMI interfaces. In [267], researchers showed methods of protecting AGV systems from cyber-attacks using AI-based Danger Theory. Heuristic approaches by which AGVs lateness at wafer fabrication stations can be minimized was discussed in [268]. In [269], the Hungarian algorithm was applied to the execution of consensus-based control for multiple AGVs. The algorithm prioritizes AGV activities by assigning the nearest task destination to each AGV. In [270], authors applied both static and dynamic methods involving discrete event simulation to determine the appropriate number of AGVs needed for transportation tasks in the photolithography section of a semiconductor manufacturing facility. For semiconductor manufacturing facilities, advantages and disadvantages of different layout topologies through which AGV can be deployed are discussed in [271]. Due to the special nature of semiconductor manufacturing facilities, different types of AGV topologies for integrating AGVs including: segregated, unified and supported topologies are discussed in [271]. In segregated topologies, the entire factory floor area is divided into zones, and workflow of each zone are serviced by one or more AGVs. AGVs in a segregated system cannot leave their assigned zone of work, hence overhead hoist transport (OHT) system must be used along with AGVs if materials must be transported from one zone to another. In supported topology, AGVs can help with workflow schedule of other zones. There are no zones assigned AGVs in a unified topology system. However, due to the huge expense and initial capital involved with semiconductor fabrication plants, there are still needs for extensive research so as to be able to optimize performances of AGV systems.

In [272], authors presented detailed methodology of designing AGVs that are useful for teaching students in a campus environment. Authors focused on the use of low-cost hardware such as Arduino for the steering, obstacle detection and speed control systems. The design process involves designing a small-scale version of the Kampus Cart AGV to test reliabilities of each software and hardware modules. Reliable performance of the large-scale version of the Kampus Cart AGV showed that the design methodology adopted is useful for designing reliable but low-cost AGVs. In [273], researchers worked to develop a suite of software useful in driving the Powerlink interface. The Powerlink interface enable direct data transmission between ROS and hardware that are compatible with the Powerlink interface. The developed solution can work with state-of-the-art LIDAR and other software stacks useful for mapping, localization and navigation for a newly developed AGV called Pathfinder. Pathfinder was designed for AGV duties in the hospital environment. Specifically, for usage in hospital environment, an AGV design based on a hybrid between a towing and a loading AGV was also proposed in [274]. Implementation for mixed used cases confirms that such a hybrid design is suitable for

use in many applications in hospital environments. In [275], authors reported methods applicable to the complete design of an AGV with all its modules communicating through network communication elements. Benefits of simulating the number of needed AGVs before committing them to production were discussed in [276]. By simulating a process before deploying AGVs for a workflow, authors showed the importance of simulation since wastages and overheads were reduced due to simulation before actual deployment. Benefits of simulation were also highlighted in [277]. Through the use of simulation, it was emphasized in [277] that optimal set of deployed AGVs in a warehouse depends on factory size, dimensions, workflow process and layout structure of the factory.

In [278], the Social Force Model (SFM) was used to analyze AGVs motion and improve the efficiency or traffic management on the industrial floor. The SFM was found to work well as it was discovered that improved efficiency (lack of tardiness) in production was noticed since AGVs were able to avoid collision while moving at a speed of 0.6 m/s. In [279], authors presented a bilevel heuristic algorithm that can be used to optimize AGV efficiency and energy consumption at container terminals. In [280], to be able to investigate critical AGV safety and reliability issues, researchers modeled AGV transport system as a phased mission system using Fault Tree Analysis (FTA) to understand possible phase failures in AGV missions. The model allows for establishing the probability of success or otherwise for each AGV mission phase. In [281], authors developed a flexible mobile manipulator capable of performing different functions in the industrial environment.

A summary of published research works in the past decade reveal that, for AMRs, many researchers are currently focusing on how to develop collaborative vehicles that can work safely and robustly with humans in a shared workspace environment [282]. For AGVs however, many researchers are interested in improving their performances and thus, expand their capabilities to be able to feature intelligent AMR functionalities [283] while still being used solely for AGV duties such as pallet moving. To ensure a cohesive industry-wide standard for measuring AGV performances, authors in [284] informed on the development of the ASTM F45 Driverless Automatic Guided Vehicles performance standard since 2014. The standard is being developed to measure navigation and docking performances of AGVs, AMRs, mobile robots and mobile manipulators. The standard also includes relevant terminologies that will be used industry-wide to understand performances of these machines. Standard test methods for measuring vehicle performance are also being developed so that manufacturers and system users can easily replicate reported performance measurements in their own facilities and with minimal cost and efforts. Authors also provided a comparison of ground truth (GT) measurement to support the standard test method being developed in the ASTM F45. For dynamic AGV performance measurement, an optical tracking system was used to provide a suitable GT measurement comparable to the standard test method being developed in

ASTM F45. In terms of existing AGV and mobile robot safety standards, authors in [285] stressed the importance of making available an industry standard that will ensure that humans, AGVs, AMRs and other type of mobile robots will work safely together on a factory floor.

In the past decade, researchers in areas of AGV applications and interfaces designs placed emphasis on designing HMI interfaces that can produce more holistic view of the industrial floor in real-time. This paradigm of HMI designs has enabled industrial and floor plant managers to be able to effect ongoing actions almost in real-time. Benefit of this paradigm include being able to supply HMI inputs that will optimize AGV/AMR performances in almost real-time. It is envisaged that developments in HMI interfaces designs will continue due to its advantages and benefits to factory intralogistics. Summaries of reviewed papers are shown in Table 3. It is notable from reviewed published works in Table 3 that there are many open challenges in the five broad areas of AGV researches covered in this review. It can also be observed that methods through which 5G communication networks can be useful for AGVs and AMRs integration in the industry are yet to be researched and fully explored.

III. CHALLENGES WITH EXISTING AGV/AMR TECHNOLOGIES FOR AGV-BASED SMART MANUFACTURING APPLICATIONS

A. LASER NAVIGATION SYSTEM

For effective AGV navigation, deployed localization methods must be reliable and robust to factory floor disturbances. Many popular laser based AGV navigation systems uses artificial landmarks for localization and navigation [41]. Even though a laser navigation system is quite good for AGV localization due to its reported accuracy, the use of artificial landmarks may sometimes be a disadvantage to factory operational safety. To guarantee operational safety, laser range finders may need to be installed on the factory floor [41]. However, installing new infrastructures may not be a very good option for FoF initiatives since new installations may impose high construction costs on the environment. Also, with laser guidance, an AGV will not be able to accurately estimate its position if insufficient laser reflectors are detected or if position estimates are acquired at a very low rate. A minimum of three reflectors are always needed for effective AGV navigation when lasers are used [200]. Also, laser does not work well for AGVs navigation in cluttered or loss of sight (LOS) environments [286].

B. WIRELESS SENSOR NETWORKS

Using conventional wireless sensor networks (WSN) such as the IEEE 802.15.4a for AGVs fleet management and control may not be a very good option for applications requiring high-level precision such as AGVs docking due to issues with accuracy, reliability, bandwidth availability and the already high users' traffic existing on such wireless communication systems. As established by [41], existing WSNs have two

distinct drawbacks when used for AGV localization and position estimation. One is that there exists the issue of an AGV position uncertainty due to noisy data resulting from multipath fading and from non-line-of-sight (NLOS) distance measurement. Another shortcoming of using existing WSNs is the difficulty inherent with estimating WSN tag orientation. Yet another problem with applying existing wireless communication networks (different from 5G networks) for AGV fleet management is the issue of high latency (cycle times) between the AGV and the communication network transceivers that are used for AGVs control and fleet management [285]. In [248], authors emphasized that utilizing existing wireless communication systems such as IEEE 802.11 (Wi-Fi) for AGV control and fleet management may be challenging since network parameters such as reliability, latency and AGV timeliness are significantly more challenging to satisfy for AGV control applications. In Wi-Fi, radio channel properties such as path loss, channel errors and low available bandwidth (due to high number of users) causes network delays. As such, in many instances, data packets are often needed to be retransmitted. Also, in Wi-Fi systems, implementation of the medium access control is often based on carrier sense multiple access (CSMA) protocol. Using CSMA protocol always result in random and long access delays in the presence of network traffic load [248]. In a 5G system, due to its nature, many of the shortcomings of existing wireless systems such as low bandwidth and high latency will not occur [287]. This will make 5G-based wireless networks more useful for AGV control and fleet management applications.

C. BARCODES AND RFID

Barcodes systems are similar to RFID systems in terms of implementation. To use barcodes, optically detectable barcodes are placed on the factory floor and the barcodes can be read by barcode readers that are attached to moving AGVs. RFID systems consist of transponders. A transponder is essentially a tag having a chip and an antenna [288], [289]. The chip can store information about a particular segment of the factory being navigated by the AGV. The antenna can transmit the stored information to a reader attached to an AGV. The AGV can then use the obtained information to navigate around the factory floor. Barcodes are lighter and cheaper than RFIDs, but RFIDs have been found to be more reliable than barcodes. While these technologies have been found to be relatively reliable, metal, oil and other liquids commonly found in many factories have been known to interfere with RFIDs. A well-known problem with both technologies is the problem of size, weight and power consumption of the reader attached to an AGV [289]. Yet another challenge relating to using RFIDs, QR codes, lasers and other LOS methods is that most factory areas and warehouses are not always dust-free [231]. Dust can easily occlude the LOS between the AGV and guiding tags, leading to possible failure of these technologies.

D. INDUCTIVE GUIDANCE SYSTEM

In most inductive guidance implementations, the AGV guidance solenoid detects electromagnetic wires buried on the factory floor [285]. Navigation at junctions are achieved by embedding many wires and activating whichever wire will guide the AGV to its desired destination [12]. Installing inductive guidance systems always results in huge logistic problems and it does not support FoF initiatives since digging up factory floors always involves moving machines and reworking the factory layout.

E. OPTICAL GUIDANCE SYSTEM

To use optical guidance systems, either visible or invisible fluorescent paints are used to mark out AGVs flow paths on the factory floor [285]. AGVs navigating with optical guidance systems always have ultraviolet light emitter and detectors that works with the fluorescent paint on the factory floor [12]. Optical guidance systems allow easy modifications of AGV routes by simply repainting the factory floor at low cost. However, system robustness may be jeopardized when lines on the floor are erased or obscured by other objects or spilled liquids on factory floors. Also, AGVs using this method to navigate are always restricted to fixed navigation paths [12].

F. VISION GUIDANCE SYSTEM

In vision guidance system, AGVs work with charge coupled device (CCD) cameras, and they compare the current image acquired by their cameras to stored factory maps. This method is known to suffer from accuracy issues resulting from signal reflections in the industrial environment [293].

G. ULTRASONIC GUIDANCE SYSTEM

With this method, AGVs rely on ultrasonic signal reflectors that are located on the factory floor to reflect transmitted ultrasonic signals. While this method is known to be very flexible and amenable to changes to AGV paths, it has been reported to be very susceptible to interference resulting from signals reflecting off metallic objects on the factory floor [293].

H. INERTIA GUIDANCE SYSTEM

AGV inertia guidance system works by calculating a gyroscope's bias signal and by acquiring ground position signals. The ground position signal is useful for determining an AGV's orientation and its position [293]. Then the bias signal and the ground position signal are then collectively used to guide the AGV. Performance issues regarding accuracy of AGVs positioning have been reported with using this method [293]. Also, gyroscopes are known to be very sensitive to vibration. In addition, this method is known to be quite costly to install.

I. GPS GUIDANCE SYSTEM

With this method, an AGV acquires GPS satellite signal, and uses the signal to establish its own position. It will then track

TABLE 3. Summary of existing research works on AGVs, AMRs and their intralogistics applications in the past decade.

Theme	Reference	Major Contribution
Localization, scheduling, docking, and path planning algorithms	Dijkstra, Genetic, Banker, Bellman-Ford, A* & D* algorithms: [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [105], [109], [115], [117], [268], [269]	[89], [90], [91] D* Lite algorithm was applied for AGVs path planning and [92] path re-planning using backstepping method. [93], [94] A* algorithm combined with Dijkstra algorithm to plan optimal paths for AGVs navigation. [96] Dijkstra algorithm was used to find local optima path for AGVs. [109] Dynamic Banker algorithm used for AGVs scheduling. [105] Bellman-Ford, A* algorithm and fuzzy inference system for path planning. [97], [98] Path planning using a combination of Dijkstra, improved Dijkstra and A* [95] algorithm. [117] Dynamic time-estimation based algorithm. [115] A combination of improved artificial potential field algorithm and A* was used for path planning. [99] Improved Dijkstra was used with heuristic Monte Carlo algorithm for AGVs path planning. [268] Heuristic-based approaches by which AGVs lateness at wafer-fabrication station can be minimized. [269] Hungarian algorithm used to assign the nearest destination to AGVs.
	Mathematical & Optimization models: [112], [114], [113], [124], [125], [126]	[112] Reduced parameter model work equally as well as detailed model for AGVs path planning. [113] Stochastic model based on Markov chain for performance evaluation in relation to cost of AGVs deployment. [114] Heuristic model for dynamic scheduling of machines and AGVs. [124] Applies a two-step method: (i) mathematical method to estimate fleet size and (ii) simulation method to determine appropriate number of AGVs for FMS. [125] Uses linear programming to ascertain the transportation throughput of AGVs in logistic center. [126] Using quantum annealing and the D-Wave 2000Q quantum computer to solve AGVs traffic control problem.
	Data fusion, KF & EKF: [193], [194], [285]	[193] Low-cost laser and external sensor data fusion for AGVs localization and mapping. [194] Localization and mapping using Bayesian Method. [285] Applies EKF to fuse AGVs position estimates from a commercial laser navigation system with dead-reckoning information.
	AI: [120], [121], [123]	[120] Uses deep reinforcement learning to assist AGVs in selecting the closest task among other multiple tasks. [121] Deep learning using high-dimensional map as input. [123] Use neural network to compensate PID gains for AGVs speed regulation.
	Petri Nets: [116], [127], [128], [129], [130], [131], [132], [133]	[116] Algebraic based path planning algorithm using direct distance matrix method. [127], [128] Path planning and AGVs flow path control and scheduling using Petri nets. [129] Petri net decomposition. [130], [131] Petri net for designing PLC to prevent AGVs collision. [132] Colored Petri net and D* Lite Algorithm used for collision free navigation and AGVs traffic control. [133] Proposed two-layer architecture for coordinating AGVs in industrial environment.
	Scheduling & Path planning: [101], [103], [104], [116], [118], [119], [153], [165]	[101], [103], [104] Heuristics routing algorithms for AGVs. [116] Compared two mathematical models applicable for AGVs path planning. [118] Real-time scheduling strategy by which AGVs transport order shelves to pickers in real-time in logistic warehouses. [119] Proposed using Yen's algorithm to find the optimal storage and retrieval processes for AGVs. [153] Decentralized path planning algorithm that can run independently in multiple AGVs was designed. [165] Algorithm for solving precision problem relating to arc path tracking when AGVs are implementing a dual differential driving mode system.
	Vision System: [77], [80], [196], [197]	[77] Developed vision guidance system for AGVs using fiduciary markers. [80] Texas Instruments TMS320DM642 processor used with 2 CCD cameras and RFID tags for path prediction, accurate positioning and workstation identification. [196] High-performance algorithm based on 2D image processing was applied to guidance and docking using the NHV-1 AGV. [197] Vision system used with SVM and PCA to detect nearby AGVs.
Wireless Communication	[33], [40], [41], [42], [80], [81], [108], [145], [226], [227], [228], [229], [230], [232], [233], [234], [235], [236], [237], [238], [239], [240], [241], [242], [243], [246], [247], [248], [249], [250], [251], [252], [253], [254], [257].	[33] Survey of wireless communication technologies used for AGV applications [40], [41], [42], [244], [245], [246] Communication and localization strategies for AGVs. [80] RFID used for AGV motion control. [81] WIA-FA for connecting AGVs. [108] Passive RFID tags used for indoor position tracking. [145] ZigBee used for AGV communication between central controller and the AGV. [226] Communication used for collision avoidance in AMR swarm [227] RFID used for workstation identification. [228] NodeMCU for obstacle avoidance. [229] TDMA-based V2I (vehicle to infrastructure) MAC protocol was designed for use in AGV control system. [230] Hardware needs for building an AGV that can use ultra-wideband wireless position sensors. [232], [233] Methods of using ZigBee to obtain AGV position information. [234] IIoT propagation channel. [235] RFID performance for conveyor belts applications. [236], [237] RFID, Wi-Fi [238] for AGV cobot applications. [239] QR codes and RFID applied to robot navigation in industrial environment. [240] Wireless ultrasonic range-finding modules design for AGVs. [241] CPS-based smart control model.

TABLE 3. (Continued.) Summary of existing research works on AGVs, AMRs and their intralogistics applications in the past decade.

		[242] Methods of improving QoS. [243] RSSI prediction. [246] Global localization and AGVs position tracking using IEEE 802.15.4a WSN. [247] AGV communication using APC transceiver. [250] How to locate AGVs using UWB signaling. [248] Wireless network-based control strategy using KF [249] Proposed using IEEE 802.15.4a CSS to improve AGV swarm localization. [251] AGV Cooperative control strategies in FRAN environment. [252] Smartphone was used in voice-based commands for an AGV control. [253] Applies PNN to predict most likely signal as an AGV moves in a fixed-route format in factory. [254] Designed a multi-DOF receiving device to assist AGVs to reduce positioning errors. [257] Wi-Fi VR applications for AGVs
Navigation, Control & Guidance Algorithms	KF: [107], [134], [135], [136], [137], [138], [139], [140]	[107] Fused CCD camera data used for an AGV path prediction. [134] Sensor fusion technique using KF to prevent Mecanum wheel slipping during AGVs navigation. [135] Online AGV control cost estimation. [136] Deep learning applied to improve robustness and accuracy of KF in AGVs tracking. [137] KF generally applied to AGVs sensor fusion. [138] KF used to fuse RSSI and odometric sensor data. RFID tags used for workstation identification. [139] AGVs localization using KF. [140] AGVs position and orientation are estimated using state space KF model.
	EKF: [89], [141], [142]	[89] Fusing encoder positioning result and landmark positions obtained from laser scanner using EKF. [141] SLAM-based EKF used for AGV navigation. [142] Sensor fusion of an ultra-wideband wireless system and an inertia navigation system for AGVs navigation using EKF.
	Mathematical & Optimization models: [111], [192], [259]	[111] Priority based routing algorithm for AGVs. [192] Applies unconstrained optimization model to the problem of selecting AGVs docking waypoints in FMS environment. [259] Mathematical model for the design of AGVs was presented.
	Control [120], [143], [144], [145], [148], [150], [152], [154], [155], [156], [157], [158], [159], [162], [164], [181], [182], [183], [184], [185], [186], [187], [188], [180], [189], [190], [292]	[120] Event driven model of AGVs used to study AGVs control using zone control approach. [143] A control algorithm that can aid AGVs to avoid velocity and acceleration jumps while merging was proposed [144] Ant algorithm for AGVs design and control. Algorithm for AGVs velocity control was presented. [148] Model-based and feedback-based controllers were used to implement anti-capsize algorithm for AGVs. [150] Magnetic guidance system used with control system to aid AGV navigation. [152] Bipolar magnetic guidance system for AGVs. [154], [157] Fuzzy inference-based control of vehicle movement. [155] Fuzzy inference algorithm. Algorithm that can correct deviation in dual differential driving mode was implemented. AGVs movement control. [156] Cascade fuzzy inference-based algorithm for obstacle avoidance was evaluated. [158] Fuzzy control algorithm used to track AGVs trajectory. [159] Scalable collision avoidance algorithm. [162] Vision system based hierarchical sliding mode control for obstacle avoidance and target control. [164] SMC and PID algorithm used to minimize error in AGVs trajectory. Three control techniques: fuzzy, flatness-based and vector pursuit methods are considered. - Fuzzy PID for speed control. [180], [292] Fuzzy inference based AGV control method. [181] Comparison of control techniques: fuzzy, vector pursuit, and flatness-based and their effects on stable AGV docking. [182] MPC based control for AGVs. [183] Cascade control system that can aid an AGV to correct for deviation errors caused by skidding in the control loop. [184] Used system modeling language to design AGVs controller. [185] Control method for multiple robot coordination is designed. [186] Used fuzzy, neural network and bang-bang controller to design a new AGV steering control method. [187] A feedback linearization method for an AGV trajectory control was proposed. [188] The STM32 microcontroller was used to design control strategy based on PMSM for AGVs. [189] Uses ADRC backstepping control method to offset effect of AGVs uncertain linear and angular velocities. [190] STM32F103VET6 chip is used as a controller for the AGVs dc motor
	Laser: [110], [146], [147], [176], [193]	[110], [146] Laser-based AGVs applications. [147] Unknown obstacle detection and avoidance using laser-based navigation. [176] Laser scan matching CVSAC-based algorithm for robot pose estimation. [193] Laser-based sensor fusion.
	Magnetic Guidance: [178], [291]	[178] Potential field method used for AGVs obstacle detection ability. [291] AGVs magnetic navigation method

and guide itself along the factory floor using the acquired signal and its own established position. GPS signals have

been known to be very good for outdoor applications, and less useful for indoor applications including for AGV navigation

TABLE 3. (Continued.) Summary of existing research works on AGVs, AMRs and their intralogistics applications in the past decade.

	Vision systems & sensors for control: [149], [160], [167], [168], [169], [170], [171], [172], [173], [174], [191], [198], [199], [200], [201]	[149] USB camera is used as an AGV position sensor. [160] Color sensors are applied for an AGV navigation. Software-based vision system that can be applied to an AGV motion control. [167] Used vision navigation with fuzzy control algorithm for an AGV control. [168] Vision calibration method for vision guided AGVs. [169] AGVs navigation implemented with vision-based range finder and image sensor. [170] Designed constrained path following controller with close-loop signals bounded by state constraints. [171] Algorithm that can be used to extract lane edge features for AGVs vision-based guidance was designed. [172] Algorithm for 3D point cloud information extraction when only partial scanning data is available was developed. [173] Vision-based remote controller was used for AGVs control. [174] Non-uniform illumination resulting from the use of LED arrays in AGV vision guidance systems was reduced using Levenberg-Marquardt algorithm [191] Designed path-tracking controller using color difference threshold to correct AGVs path-deviation [198] Design of advanced sensing and classification systems useful for human-AGV coexistence in dynamic FoF environment. [199] AGVs navigation using overhead camera. [200] Designed a method that combines available roadmap, 2-axis accelerometers inputs with a less than three laser reflectors for AGVs navigation [201] Proposed central fusion system that fuses laser data from onboard AGVs and factory infrastructure.
WPT for AGV, power consumption and management	[188], [205], [206], [207], [208], [209], [210], [211], [212], [213], [214], [215], [216], [217], [218], [219], [220], [221], [222], [223], [224], [225]	[188] PMSM control system. [205] WPT charging method based on magnetic coupling resonance. [206] WPT with inverter voltage booster. [207] WPT based on variable frequency control [208] Move WPT receiving coil constantly, adjust gap length. [209] Detected impedance used to adjust WPT circuit power output. [210] Reduce apparent inductance of WPT circuit using compensation capacitor. [211] Repeater-aided dual output WPT system with extended power transmission gap. [212] PI-PBC used to reduce effective charging time of AGVs. [213] Battery state of charge estimator. [214] Retrofit AGVs power system to reduce harmonics. [215] Linear programming used to determine battery change time. [216] AGVs WPT with two receiving coils. [217] Brushed dc-motor for improved shaft driving. [218] Simulation based model of AGVs with battery management. [219] AGVs energy consumption model. [220] MAC system for AGVs. [221], [222] Series-series compensation topology for AGVs IPT system. [224] Comparison of SP and S/SP constant voltage output compensation circuit for AGV WPT circuits. [223] Energy shaping controller for AGV WPT system. [225] BPP for AGVs IPT
VR and AR Applications	[255], [256], [257], [258]	[255] Immersive and interactive VR desktop was presented for 3D visualization of AGVs moving along specified path in warehouse environment. [256] Presented a setup that enables the validation of HRC functionalization of an AGV via virtual commissioning. [257] 3D models were designed using the Autodesk Inventor 3D CAD software. Wi-Fi was used for communication. [258] Presented an approach to model an AGV-based logistic facility to measure and visualize performance of the system within VR environment.
AGV/AMR Design and Applications	[43], [35], [49], [50], [260], [261], [262], [264], [265], [266], [267], [268], [278], [270], [271], [272], [273], [276], [277], [279], [280], [284]	[43] ROS based design [50] Mobile manipulator design for research and education. [35], [49], [50] Designed for educational applications. [260] Explores the weaknesses of present AGV systems for FMS. [261] Proposed the use of AGVs as replacement for conveyor belts in clinical laboratories. [262] Application of semaphores to AGVs intersection management and traffic control. [263], [264] A 3D mapping of factory environment is used in interacting with HMI to assist in AGVs fleet control. [265] Design of low-cost PLC-based AGVs according to customer specification. [266] Design of a trust-based HMI interface for AGV designers. [267] Danger-based theory and its AGV application. [268] Heuristic scheduling for flexible AGV allocation in wafer (semiconductor) manufacturing. [278] SFM was used to reduce AGV and product tardiness when AGVs are moving at a speed of 0.6 m/s. [270], [271] Applies static and dynamic discrete vent simulation to determine appropriate number of AGVs in semiconductor manufacturing. [272] AGVs design for teaching (campus) environment. [273] Developed a suite of software and hardware solution for the Pathfinder AGVs useful in the hospital environment. [276], [277] Benefits of simulation before using AGVs in production. [279] A bilevel heuristic algorithm to optimize AGVs efficiency and reduce energy consumption at container terminals. [280] Uses FTA to model causes and phases of AGV failures. [284] ASTM F45 industrial standard for AGVs.

due to reported low reliability of the GPS signals in indoor locations [293].

J. USING ELECTROMAGNETIC GRIDS AND MAGNETIC TRANSPONDERS

These methods also involve installing hardware (magnets, transponders etc.) on the factory floor. Factory floors must be extensively augmented for this method to work [12]. After the initial floor work, AGVs are then equipped with sensors that can detect buried magnets. This method allows AGV to freely range insofar as the AGV remains in the general area delineated by installed magnetic markers [12]. For agile or smart manufacturing initiatives, installations of additional hardware of any kind on the factory floor may jeopardize quick plant remodeling and restructuring. Also, modifications of flow paths when AGV paths changes may require pausing or stopping the plants' material handling system (MHS), and this may lead to adverse economic cost for the factory [285].

K. FREE-RANGING VS FIXED-PATH NAVIGATION

Majority of navigation methods discussed above only allows AGVs to navigate using fixed paths. With fixed-path navigation, for example by using an inductive guidance system, AGVs are restricted only to some selected paths in the factory. With free-ranging navigation, which can be provided by methods such as laser navigation systems, AGVs can follow arbitrary paths to avoid obstacles on the factory floor. Free-ranging mode also allows an AGV to move from point to point using shorter routes in the allowed AGV navigation paths [12], [294].

L. POTENTIAL BENEFITS OF AGV FLEET MANAGEMENT

OPTION USING 5G RADIO AND MEC

In most of the methods examined above, AGVs are restricted to fixed navigation paths, and it may require extensive infrastructure reworking to make AGVs to navigate new paths. Also, none of the methods examined above have strong architectural models through which AGVs fleet data and sensors readings can be completely integrated with the factory enterprise management system for entire factory system optimization without incurring additional cost. If a factory already has 5G communication system installed, then the same system can be further utilized for AGV fleet management, control, warehouse integration and for real-time analytics. For example, by using a 5G-based MEC system and by collecting AGVs data, some AGVs can be selectively demobilized based on varying volume of work and current production status. This will provide a cost saving and dynamic manufacturing option.

1) AGV WORKFLOW ARBITRATION, DEADLOCK AVOIDANCE AND MISSION PLANNING USING 5G RADIO AND MEC

With 5G radio system and MEC, the abundant bandwidth provided in the millimeter wave region will allow for better system throughput. There are basically two methods of AGV

fleet control [94], [99] or fleet management namely: centralized and distributed. With centralized fleet management, a central control platform (which in the case of 5G, may be based on a MEC platform) maintains the status of the entire fleet and determines the path that each AGV should traverse to avoid collision or deadlocks. There can also be a decentralized coordination scenario whereby AGVs communicate and arbitrate missions with one another using distributed antenna system over 5G networks. By using 5G MEC, AGVs can communicate and exchange data with a central factory job scheduler, workstations and other machines to minimize transportation time using the closest AGV to a scheduled task to execute the task.

In deadlock situations, an AGV will attempt to resolve the deadlock by exchanging data with other AGVs when they are in decentralized fleet management mode. In centralized management mode, all AGVs will attempt to resolve the deadlock by exchanging data with the central controller. Both situations can lead to excessive data exchange that only a fleet management system with enough memory bank such as a 5G MEC can handle. Current algorithms used for AGV decentralized coordination always do not have global fleet information [295]. Due to this problem, it is always harder for AGVs to collectively reach a global optimal solution. With 5G systems in place, it will be easier to use the 5G MEC resources to enable an AGV to have global navigation and location information of other AGVs, leading to better system optimization. Also, it will be easier to configure AGVs to navigate in a free-ranging mode since the availability of a reliable network for example, a 5G massive MIMO antenna network in a factory may provide a pervasive and reliable network coverage than what is currently available with pre-5G communication networks.

2) 5G MEC APPLICATION FOR AGV COMPUTATIONAL, AND DATA PROCESSING ISSUES IN SMART MANUFACTURING ENVIRONMENT

In conventional AGV deployments, most onboard hardware units for AGV/AMR navigation may have limitations with available data processing power [296]. Thus, the functionality of the onboard processors may not be further available for FoF purposes. With availability of 5G MEC to support AGV-based smart manufacturing applications, data and processing functions can be offloaded to the MEC. In many factories, there are many instances whereby AGVs are deployed outdoors to work on semitrailers, trailers and other articulated vehicles that are parked arbitrarily in places where factory infrastructures cannot be installed. AGVs that relies on conventional indoor infrastructures such as lasers, RFIDs magnetic grids etc., cannot be used to accomplish such functions [103]. However, 5G infrastructures with their wider coverages can be used to control such AGVs; thus, extending the reach of indoor FoF applications to the outside extremity of the plant. However, for 5G to work seamlessly with AGV and AMR swarms on the factory floor, there are still numerous issues that needs to be researched and refined for better

system optimization. Section IV entails detailed discussion of such open research challenges.

IV. AGV/AMR FLEET INTEGRATION FOR SMART MANUFACTURING: OPEN CHALLENGES AND AREA OF RESEARCH FOR 5G-BASED APPLICATIONS

A. FLEET MANAGEMENT AND CONTROL

1) AGV FLEET MANAGEMENT USING 5G RADIO AND MEC PLATFORM – OPEN CHALLENGES

In conventional AGV deployments, communication networks are always used for exchanging information among AGVs, and between AGVs and the fleet control system [33]. An AGV localization system is applicable for detecting the AGV positional changes using a set of AGV sensors. An AGV control and fleet management system coordinates the movement of all AGVs on the factory floor to prevent collisions, task duplication, deadlocks and to limit traffic congestions. For reliable AGV fleet management, effective AGVs global localization, robust tracking of positions, and reliable communication within AGV swarms are of utmost importance. These can be achieved using control platforms situated on the 5G MEC. However, such a MEC may ultimately represent a single point of failure [295] for the entire AGV fleet if it fails. A potential solution to a MEC single point of failure scenario may include making provisions for a secondary MEC platform as a back-up. Some AoRs regarding utilizing 5G MECs and their backups for AGV control and fleet management are as discussed below.

An AoR regarding the use of 5G MEC for AGV control and fleet management is the need for researching and defining reliable hand-off strategies useful for preventing information losses when the primary 5G MEC fails or when it transfers operation to a back-up MEC platform. MEC failures can potentially lead to loss of an AGV fleet status. Loss of fleet status or loss of present fleet state information when AGVs are used for critical operations or when they are used for JIT operations in smart manufacturing environment may lead to painful revenue losses in FoF applications [297].

An important AoR is how to ensure that 5G signal penetration losses on the factory floor when 5G networks are used for AGV fleet management, does not cause AGV collisions. To prevent AGV collisions, AGV sensors always detect obstacles in front of AGVs. In centralized fleet management systems, the central control system always calculates the distance between two AGVs; and stop or reroute one of them when the separating distance is within collision range. A robust controller warehoused on the 5G MEC platform must be reactive enough and work seamlessly with the 5G radio to ensure that in the presence of 5G signal penetration losses, an AGV with a lower priority schedule ‘pauses’ or ‘stop’ in its track until collision distance between two AGVs on a possible collision course becomes big enough. Only then should the AGV with the lower priority mission resumes its mission.

2) INTELLIGENT AGV TRAFFIC COORDINATION AND INTERSECTION MANAGEMENT ON THE FACTORY FLOOR – OPEN CHALLENGES

An important AoR for robust AGV fleet management is how to avoid collision and resolve AGV deadlock situations. Traffic management at factory intersections is crucial to maintaining an accident free factory floor. If AGVs and AMRs are to work seamlessly with humans in an accident free environment, they must be able to identify humans and class them differently from other objects in the factory workspace. AGVs and AMRs must be equipped with intelligent devices that can identify humans and other AGVs and AMRs. Most other machines in the industrial workspace are in most cases situated in a stationary position. Thus, AGVs can always successfully navigate around such machines and continue to run their missions. However, humans and other AGVs can always move arbitrarily when an AGV under observation is moving to navigate around them. This can lead to collisions and accidents with humans or with other AGVs especially at intersections on the factory floor. Successful human identification using 5G MEC based AI solutions and cameras installed on AGVs will be crucial to being able to successfully identify humans in a manufacturing environment.

B. AGV/AMR FLEET INTEGRATION WITH 5G MEC FOR FACTORY OF THE FUTURE APPLICATIONS - AoRs

Numerous avenues for FoF applications linked to the use of AGVs and AMRs exist in the industry. AGVs and AMRs can be monitored and controlled as they operate in remote, difficult to access or hazardous areas using 5G-based remote monitoring platforms. Operators can remotely interact with AGVs and AMRs being monitored and control them to run special missions that may not be included in day-to-day operations of the factory. Since executing those types of operations are rare, only a small amount of data relating to such operations may be available. Designing reliable remote-control interfaces when AGVs and AMRs are deployed for such unusual missions may include application of AI paradigms that support using small amount of available data sets and interpretable models. Example of such AI paradigms include explainable AI (XAI) [86], [298], deterministic AI algorithms [290], exact algorithms, reliable, low complexity fuzzy inference systems [292], [299], collaborative and predictive AI models [318], [320]. Design of these types of AI systems for AGVs and AMRs interfacing in real-time with humans continues to be important AoRs worldwide. Conventional factory floors are always designed with precise segments allocated for specific uses. However, such grid or segment-based factory designs may prevent an optimal deployment of AGVs and AMRs in FoF applications. An AoR is how to equip AGVs with enough intelligence such that they will be able to freely navigate in the presence of humans and other machines – in free-ranging mode in a segment-based factory design. Other types of AGV/AMR scheduling and mission running that will need extensive research if AGV and AMR

will successfully participate in FoF scenarios are explained below.

1) AGV BATTERY, POWER MANAGEMENT AND INRUSH CURRENT ISSUES ON AGV – OPEN CHALLENGES

Battery charging and power management continues to remain a painful bottleneck for optimal utilization for AGVs and AMRs in the industry. A well-known problem in this regard is that due to the segmented nature of most factory floors, there is always a considerable distance between AGV/AMR mission workstations and the location of the battery charging station. For FoF implementation, an AoR is how to design a 5G MEC based optimization strategy by which a trade-off scheme can be established for minimizing the distance between the present location of an AGV and the nearest battery charging station. The cost of the distance to the battery charging station can also be compared with the priority of an assigned task, the present AGV battery level and the existence of another AGV with a higher battery usage level which also can handle the task assigned to the AGV under consideration. The routine for the tradeoff assessment can be stored on the 5G MEC while control commands resulting from the routine decision can be communicated to the respective AGV using 5G communication links.

Due to design constraints and the need for space management on some AGVs, the AGV onboard motor may share the same power source with the wireless communication device on the AGV. Such wireless device may however be damaged by inrush current generated by AGV onboard motors and possibly leading to failure of the wireless device. An AoR in this regard is the design of an effective harmonics and inrush current-limiting method that can insulate a 5G wireless device from onboard motor inrush current. Such problem can also be resolved by an improved design method of integrating AGV 5G wireless devices with AGV onboard motors [300].

2) AGV FOR HARVESTING FACTORY FLOOR DATA FOR 5G MEC MULTIMEDIA DATABASES APPLICATIONS – OPEN CHALLENGES

Since AGV and AMR traverses the factory floors, their presence can be leveraged for harvesting data related to almost all segments of the factory. AGVs can also be equipped with RFID readers dedicated to harvesting data from finished and unfinished products as AGVs haul those products from one workstation to another. Strategic placement of those RFID readers on AGVs so that they can capture data from different load type is an import AGV design AoR.

Video data of the factory floor from a camera attached to an AGV can also be streamed to a 5G MEC for better all-round vision of the entire factory. By transmitting such video dataset, the AGV or AMR will be able to function as a security patrol or monitor robot while also performing its other dedicated functions. An AoR in this case is how to design a dynamic uplink and downlink radio resource scheduler through which large-sized data such as video [301] data can be successfully transmitted alongside other small mMTC

dataset from other AGV sensors. Also, video data from monitoring cameras attached to an AGV must be successfully transmitted alongside other video data such as visual navigation video data being transmitted from other parts of the mobile AGV.

An AoR is the design of a video database systems that can successful receive and separate different video datasets from the same AMR or AGV and route received datasets to the appropriate segment of the 5G MEC for further data processing. Since various type of datasets are being transmitted from multiple AGVs, the 5G MEC database must be designed for dynamic storage, buffering or forwarding various multimedia datasets to other parts of the MEC for further processing and analytics. In [302], it is projected that by the year 2020, smart connected factories in vertical industrial sectors will be able generate approximately 1 PB (petabyte) of data per day. An immediate relating to this huge data generation phenomenon is how to be able to store and analyze such huge data sets on time to be able to derive actionable intelligence from the data. Cloud-based data repositories and data lakes such as Amazon S3 buckets is being used as a provided service to store huge data sets. An AoR relating to the use of cloud repositories is how to forward vertical industry and proprietary factory data to a cloud repository such as Amazon S3 bucket and at the same time, be able to maintain appropriate and reliable internal Internet security and data encryption for the 5G system. Such Internet security method must also provide for a reliable and fully secured automated data exchange from the AGV fleet, to the MEC and onward to the cloud repository and vice-versa. Yet another AoR is how to apportion required AGV analytics tasks between a 5G MEC analytic software and a cloud-based analytics software such as Databricks for a reactive and robust real-time analytics.

3) AGV AND AMR FLEET INTEGRATION WITH INDUSTRIAL TACTILE INTERNET AND SHARED HAPTICS VIRTUAL ENVIRONMENT – OPEN CHALLENGES

The advent of 5G with its promises of sub 1 ms latency has been propelling researches into tactile and VR Internet applications by which AGV and AMR can be teleoperated by humans using haptic devices as shown in Figure 6 [51], [302], [304]. Human operators can interact with remote AGV/AMR using a virtual but immersive multimodal teleoperation via video feeds provided by VR devices. Haptic or tactile devices can provide remotely located human operators a sense of touch and vibration comparable to actually touching remotely located AGVs. The VR device can provide the human an immersive environment with a 360° video view of a remote machine [305]. Operators can alternately choose to observe the performance of the tactile device using near visual aids or use a VR device to have a 360° view of a remote AGV or AMR as shown in Figure 6 [302], [303]. Thus, tactile Internet and VR can make possible a high-fidelity human-robot collaborative shared-task environment. In such a smart manufacturing environment, humans' skills

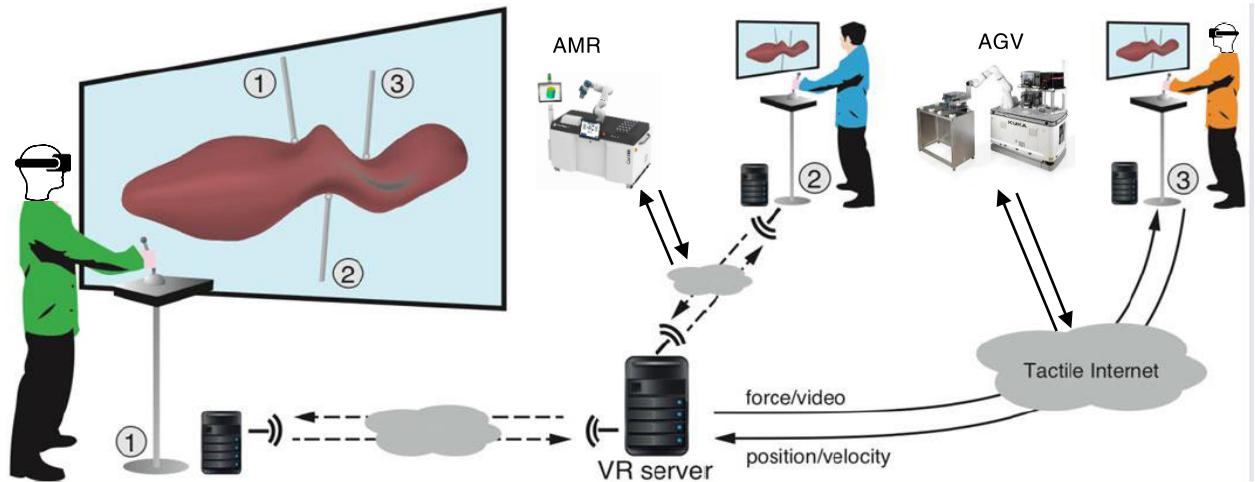


FIGURE 6. Reliable and high-fidelity AGV/AMR multi-user tactile Internet and virtual reality industrial applications is an intensive AoR for 5G networks. Adapted from [51] and [303].

from geographically dispersed engineers can be delivered without boundaries, and highly expensive and specialized AGV or AMR can be used round the clock over high-fidelity 5G communication networks.

Also, remote teleoperation of an AMR or an AGV that must operate in highly hazardous part of a plant will be realizable. Human operators with certain skillsets who must transfer their skills through the use of a collaborative AGV/AMR robot located in another part of the world will also be able to operate. JIT production can also be achieved by controlling AGVs via tactile Internet applications. By introducing reliable tactile Internet based JIT production, AGVs that are running dynamic missions along production lines can work with remote operators who are aided by immersive audio-visual VR inputs [305]. Such AGVs can be used to pick unfinished products for customized finishing. AGV missions for JIT production may be challenging to schedule since JIT products and their demands may require a lot of flexibility in production [319]. Hence, a dedicated human can work with several AGVs using 5G tactile Internet to execute customized requests as soon as those requests are logged. Using tactile interfaces, several remotely located humans can also utilize a central VR server to send control commands to different AGVs located in different parts of the same factory or factories in different location as shown in Figure 6.

An AoR is how to design such VR servers to be reliable and scalable so that they can take into consideration possible imprecise AGV and AMR workstation dockings. Another AoR is how to ensure that distributed haptic feedback, distributed VR and distributed sense of touch in a shared virtual environment is achieved in synchrony with docked AGVs or AMRs such that sensitive industrial object manipulation, or application needing high level of precision and sensitivity can be reliably executed. Design of high-quality VR video streaming system that can provide useful immersive visual feed of tactile Internet for such applications is still an ongoing AoR [305]–[307]. Yet another AoR in this

scenario is how existing, 5G ultra-low latency communication (URLLC) implementations can be robustly utilized for effecting a multi-agent, shared-haptic, virtual reality operations whereby different human agents can work seamlessly over 5G networks with the same or different AGV/AMR in a smart manufacturing environment as shown in Figure 6. For effective human-machine teleoperation, cycle times for such collaborative tactile Internet based VR environment must be lower than 5 ms since a greater than 5 ms latency will be detectable to the human eye [305]. Also, not to be overlooked as an AoR in this case is how to reliably solve problem of multimedia data association occasioned by direct coupling of multi-user VR datasets since such data sets can feed into one another at haptic machine interfaces [303].

4) DIGITAL TWIN SYSTEM FOR AGV AND AMR APPLICATIONS

A crucial AoR for FoF implementation using AGV and AMR fleets is the design of effective factory digital twin model that can be warehoused on the 5G MEC for better fleet coordination on the factory floor [8]. The virtual factory representation in form of a digital twin can be applied for real-time process monitoring, mapping and surveillance operations on the factory floor. By designing an effective factory model, its digital twin could theoretically be linked to the physical factory for real-time monitoring of industrial and AGV activities. Current data harvested by AGVs as they run missions can be correlated with the digital map located on the 5G MEC almost in real-time. Disparities between the current factory situation and the digital map projections can be detected and relevant alarms raised in almost real-time [321]. Such an AGV/AMR and 5G MEC based factory digital twin system can be applied for intrusion detection what-if scenarios testing [321], almost real-time critical process monitoring [308] and surveillance applications.

5) AGVs AND AMRs AS PART OF INDUSTRIAL SURVEILLANCE AND EMERGENCY RESPONSE TEAM

As AGVs and AMRs run missions on the factory floor, cameras installed on those AGVs and AMRs can be used to identify foreign objects or liquid spills on the factory floor. Precise coordinates of a detected foreign object or of the liquid spill location can be sent with an alarm to an appropriate segment of the 5G MEC database for onward delivery to plant's emergency squad. 5G MEC based AI solutions that ingest data from the AGV cameras may also be programmed to track mobile foreign objects that are located in any segment of the factory. An AGV swarm can also be automatically summoned to collectively track and send video feeds of identified foreign objects when those AGVs have low priority tasks to accomplish. How to determine task priorities and balance those priorities with the need for using AGVs for further security and surveillance applications are important AoRs. Designing intelligent AI-based vision systems that can work robustly on factory floors where significant 5G signal penetration losses exist is also an important AoR.

6) INTEGRATING AGV SENSORS' DATA WITH THE WAREHOUSE MANAGEMENT SYSTEM

JIT inventory management with short production cycles requires flexible material flow. It also requires the use of small and agile transportation units [319]. For updates and inventory management, AGVs and AMRs can be utilized, as possible backups for existing factory tracking systems to track products from the production line, through warehousing and storage; and through final dispatch to consumers or to other production units. Methods by which AGVs and AMRs can be dynamically and adaptively configured so as to be able to handle different types of loads and painlessly harvest 5G-MEC bound data from such loads is an important AoR.

C. RELIABLE AND PRECISE DOCKING FOR AGVs IN FACTORY OF THE FUTURE ENVIRONMENT – AGV WAYPOINT SELECTION OPEN CHALLENGES

For applications that require high-level precision such as peg-in-hole machine assembly tasks, mobile AGV bases that may be used to support AMR robot arms for such tasks must be able to move robot arms and pegs precisely within millimeters of the peg holes while mobile AGV base must also be precisely docked. When movement of peg-in-hole assembly AMRs or AGVs are coordinated over 5G networks, movements of both the supporting AGV mobile base and the robot arm on top of the AGV base must be precisely and reliably coordinated. An AoR, especially in the presence of a dynamically changing FoF environment is the problem of waypoint selection for AGVs. Docking waypoint selection for AGVs is a very challenging problem that remains a persistent AoR [192]. Waypoint selection problem will even more be a challenging AoR in a dynamic FoF manufacturing environment wherein factory layout may be continually modified to allow for flexible manufacturing.

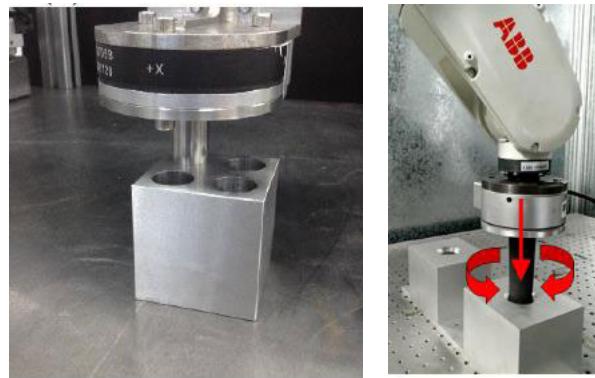


FIGURE 7. Typical peg-in-hole assembly tasks [309], [310].

D. RELIABLE 5G NETWORK SLICING AND NETWORK RESOURCE ALLOCATION FOR AGV/AMR APPLICATIONS – OPEN CHALLENGES

A composite system that supports high level precision tasks such as peg-in-hole machine assembly (e.g., Figure 7 [309], [310]), time-critical AGV/AMR docking applications, multi-AGV tactile Internet applications [311] and other AGV/AMR FoF applications as shown in Figure 8 may be supported by different vertical slices of 5G radio resource having different reliability and network latency specifications. In 5G Radio Access Networks (RAN), the flexibility that 5G New Radio (NR) applications provide can make different latency frame slices available in a 5G wideband channel [322]. For example, 5G NR can be used to divide a wideband channel into 10 ms frames and 1 ms subframes [322]. To ensure accuracy and precision in a peg-in-hole machine assembly task, both the mobile AGV base and the robot arm on top of the AGV base may be supported by 5G signal transmission frames that have 1 ms latency. After the movement and precise docking by the AGV mobile base, the 1 ms network portion that supports the mobile base may be robustly released and reassigned to support the robot arm being used for the peg-in-hole application.

AoR in this case is the design of reliable and robust, service-oriented, 5G [306] radio resource allocation scheme at the appropriate layer of the 5G radio network; specifically, for AGV and AMR applications. Since AGVs and AMRs represent composite systems that have different subsystems, another AoR is the design of a network softwarization technique by which a composite AGV or AMR can be taken as a user equipment (UE) at one end of the loop as shown in Figure 6. Network softwarization describes an overall transformation blueprint capable of ensuring a design, an implementation, a deployment and a model for maintaining network equipment and components by instituting a software programming approach that factors in flexibility, agility and rapidity of design [314]. If an AGV can be adequately represented as a UE in a softwarization framework, then different data sets corresponding to different parts of the UE can be robustly communicated across 5G channels from the

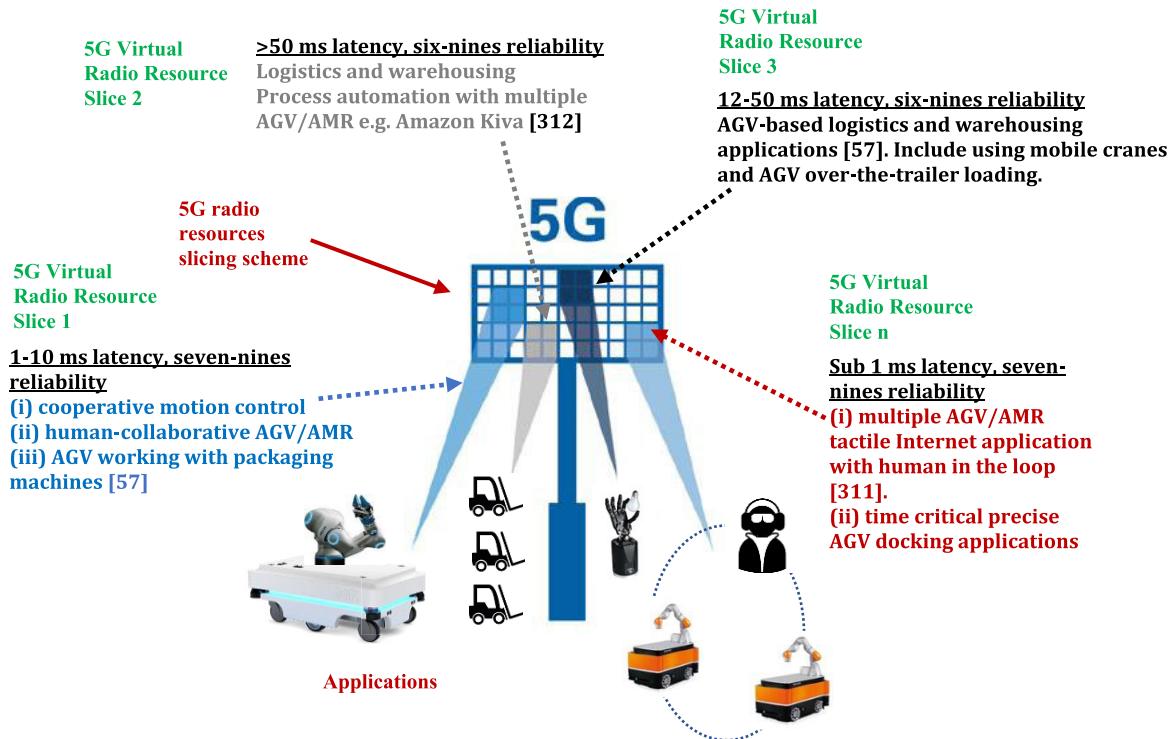


FIGURE 8. Design of a virtualization-based 5G radio resource slicing scheme that can selectively allocate radio resources based on AGV/AMR functions and needs is an important AoR.

transmitting to the receiving end. The employed softwarization technique must be capable of an effective end-to-end transmission of different types of data e.g. large data packets such as VR video, and small packets such as AMR/AGV velocity, vibration data [313] and tactile Internet dataset for remote control applications.

E. OPEN CHALLENGES WITH WIRELESS COMMUNICATION AND SENSORS' MACHINE TYPE COMMUNICATION OVER 5G NETWORKS

An AoR when 5G is utilized to deploy WSNs for AGV navigation is a method of reducing power consumption on the WSNs supported by a 5G network. Protocols and strategies for deploying WSNs mandates low energy consumption in WSNs driven by pre-5G wireless networks. However, existing 5G solutions still consumes more power than the low-energy approaches available in WSNs that are based on previous (pre-5G) communication systems [315], [323]. Another AoR regarding the use of wireless communication technologies involve the scalability of communication system performance when large number of AGVs are deployed in a tightly scheduled industrial process [33]. As an example, suppose the latency required for an AGV scheduling activity is fixed at 20 ms. Method of maintaining the required 20 ms when the number of AGVs increases in a tightly scheduled industrial process is an important AoR. It is well-reported in literature that the complexity of AGV path planning and fleet management ramps up exponentially when the number of deployed AGVs increases [33]. A most pressing AoR

regarding the use of 5G wireless communication technology for AGVs fleet management is how to ensure the six-nines reliability and availability needed for AGV and AMR applications such as motion control in the presence of wireless signal penetration losses that are always encountered in manufacturing environments [57].

Most wireless systems including 5G networks are always designed to provide for high data rates to support large packet downloads. Standard assumptions for most networks are for the designed link budget to support high data rates in both the uplink and the downlink [316]. However, most AGV and AMR sensors always send small packets containing MTC data types. An example of this is the odometry data of the AGV. Other examples include battery level information and other sensors' MTC data in the AGV. For 5G networks to adequately support AGV/AMR navigation, coordination and fleet management, there is a need to modify the standard assumption regarding network link budget designs to include link design specifications for both large and small mMTC datasets. Thus, for effective AGV and AMR fleet management, 5G network design that support mMTC in a reactive and highly scalable format is needed. This is a most crucial AoR needed for reliable 5G-based AGV/AMR smart manufacturing applications.

Another AoR regarding MTC data types is that MTC data types requires deterministic data packet delivery [302]. MTC data types also requires low latency and high reliability guarantees even though MTC data may be transmitted infrequently, and in small data bursts [317]. For other

data types that are different from MTC and IIoT datasets, the classic communication theory assumption is that packets payloads can always be increased without bound [302]. In IIoT wireless channel links, MTC or machine-to-machine (M2M) [317], [323] data often have minimal payloads, typically of only a few bytes. In such cases, the classic communication theory assumption does not hold. In current Internet networks, the problem of deterministic data delivery and QoS assurance for IIoT is being resolved by the introduction of Ultra-Low Latency (ULL) standards such as the IEEE Time Sensitive Networking (TSN) and the Internet Engineering Task Force's (IETF) Deterministic Networking (DetNet) standards. Specifically, the IEEE 802.1Qat was designed for providing a Stream Reservation Protocol (SRP) for distributed resource reservation and the IEEE 802.1AS was designed for ensuring time synchronization among IIoT devices. Also, IEEE 802.1Q was designed as a Local Area Network/Metropolitan Area Network (LAN/MAN) standard for bridging LANs while the IEEE 802.1CM was designed to ensure that the fronthaul segment of 5G networks deliver reliable QoS for TSNs [324]–[326]. However, as discussed in [324], there are numerous AoRs for TSN and DetNet standards to be thoroughly effective for handling MTC datasets across disparate networks. For networks that handle heterogeneous AGV/AMR datasets such as shown in Figure 6, effective inter-scheduler coordination for TSN operations need to be ensured. In TSN networks, each network node in the flow path of a communication instance must guarantee time sensitive characteristics that are applicable to TSN standards. If a node fails to enforce TSN networks' end-to-end flow characteristics due to mistiming or scheduling inaccuracies, then TSN network reliability will be compromised. Thus, an AoR relating to this issue is the design of a robust TSN inter-scheduler coordination scheme.

In TSN networks, data generated from synchronizing network nodes, setting up and tearing down connections, communication flow management are collectively referred to as control plane data. Generally, control plane data are always transported along with the Control Data Traffic [324]. New TSN use cases corresponding to sensors' data from automated drones, robotics applications, and by extension, AGV/AMR smart manufacturing applications may be in need of establishing short TSN flow instances. Such short flow instances will increase control plane activities especially in the in-band control plane of CDT resource reservation scheme [324]. An AoR in this case includes the design of a new resource reservation scheme that schedule resources for excessive control plane data that are generated by AGV/AMR and other robot type sensors in the in-band control plane of CDT resource reservation scheme. For TSN networks nodes to reliably transfer high priority sensors' data, sensors from AGVs/AMRs that generates low priority data set may be preempted several times during a transmission instance by TSN network nodes. An open challenge regarding this is the design of new TSN data forwarding mechanism that can ensure an acceptable lower bound for the worst-case delay for such low

priority sensors since data from such sensors may be applied for smart manufacturing and FoF activities. Also, there is need for in-depth studies of the impact of synchronization inaccuracies on the QoS of TSN networks. Numerous IIoT, edge computing and smart manufacturing initiatives in FoFs will be executed using low-cost devices [327]–[329]. For such low-cost devices and sensors, especially those that are applied in large scale networks and in remote applications such as the remote control of AGVs shown in Figure 6, synchronization schemes employed by TSN networks may not be quite accurate [323]. Hence, detailed studies regarding the effects TSN networks' synchronization inaccuracies on when such low-cost devices are in use is needed.

Typically, TSN networks are always implemented in closed industrial environments. Connecting to remote applications across different geographical locations such as shown in Figure 6 will require the use of external communication connections. Since large scale applications such as shown in Figure 6 may require using TSN and non-TSN networks due to the geographical spread of such applications, an AoR is the design of a common inter-operation platform for harmonizing workflows across TSN and non-TSN networks.

An AoR regarding the use of DetNet networks is the design of a resource arbitration scheme that can ensure an acceptable balance between packet replication, packet delivery latency and the network bandwidth required for packet replications. Also, similar to TSN networks, arbitrating and harmonizing communication workflow between a DetNet and a non-DetNet network is still an open AoR.

From the foregoing, it could be inferred that even though 5G networks are projected to be key enablers [10], [11], [27], [28] of AGV/AMR based smart manufacturing and FoF applications, there are still numerous AoRs and open challenges for 5G networks to adequately fulfill their promises of providing adequate QoS assurance needed for realizing the full benefits of 5G network integration in industrial environments.

V. CONCLUSION

This paper is a review of research results from different AGVs and AMRs research domains in the past decade. Timelines of important achievements from the conception of AGV and AMR technologies are shown in form of flowcharts and pictures. Important AGVs research results in the past decade are reviewed, and it was deduced that there is need for more research to fully understand how the benefits of 5G communications networks may be leveraged to make AGVs and AMRs more reactive and useful in smart manufacturing environments. Areas of research that must be explored for AGVs and AMRs to be fully useful for smart manufacturing activities are comprehensively explored. The paper also provides a thorough and broad overview of different AGVs/AMRs enabling technologies. In addition, novel integration ideas by which tactile Internet, 5G network slicing and virtual reality applications can be used to facilitate AGV and AMR based factory of the future and smart manufacturing applications are advanced and discussed. Limitations of current technologies

that are used to enable AGVs and AMRs in the industrial environments are highlighted. Possible uses of AGVs and AMRs for FoF activities and their uses for smart manufacturing initiatives are also thoroughly discussed.

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