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RESEARCH ARTICLE

Study on Distributed Consistent Cooperative Control of Multi-ART in Automated Container Terminals

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ABSTRACT In order to address the congestion problem of vehicles in quay of automated container terminal with parallel layout and side-loading operations, the study regards the terminal operation system as a multi-agent system (MAS). Then, A dynamic cooperative speed regulation strategy for a group intelligence-oriented multi-ART (Artificial Intelligence Robot of Transportation) is proposed to realize the smart and distributed traffic control of container terminals. Via the real-time data interchange and message passing with ART group, the individual ART implements the collaborative speed regulation with the combination of the dynamic speed regulation strategy. Through the above-mentioned method, the sequence of ARTs arriving at the quay can be adjusted, which can decrease the waiting time of ARTs at the quay. Considering the consistency problem of individual and group agent among the dynamic speed regulation of ARTs, a novel distributed consensus protocol is established to assure that the individual status of ART will tend to converge basically during the collaborative speed regulation process, and the convergence of system can be guaranteed. Based on the case of automated container terminal of Tianjin Port, the paper establishes a multi-agent based simulation model, and simulates the decision-making process, and validates the effectiveness of mentioned model and strategy. The results demonstrate that the strategy can decrease the waiting time of ARTs under uncertainty environment of terminal and improve the operation efficiency of system.

INDEX TERMS Agent-based simulation, automated container terminals, dynamic speed regulation, multi-agent systems, transport operations.

I. INTRODUCTION

With the container shipping industry stepping into a phase of rapid development, the volume of container transportation is growing recently. Serving as a comprehensive logistics hub for container shipment, terminals are facing a tough challenge to expand their throughput capability to match fast-growing demand. Hence the terminal operators around the world are seeking for new transport operations paradigms, new scheme of layout in order to improve the productivity of system and the intelligence of operations. Due to the climb in labor cost and labor shortage, the construction of automated container terminals (ACTs) has attracted more and more attention in China.

Dozens of ACTs have been completed and put into operation recently, with the majority of them belonging to perpendicular layout of yard block with end-loading operations, namely the vehicles will carry and store the container at the end of yard. As the world largest scale of automated container terminal, ACT of Yangshan Port Phase IV chooses the intelligent unmanned horizontal transport system for container transfer between the sea-side and land-side areas. Under the end-loading operation mode, the less loading and unloading points for horizontal vehicles tend to concentrate, and more likely lead to congestions at the landside. Due to the longer distance for transferring containers, the energy consumption

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FIGURE 1. Intelligent container terminal of section C, Tianjin Port.

by Automated Rail Mounted Gantry Crane (ARMG) in the yard will increase.

The loading and unloading style for the majority of current traditional container terminals among China is parallel layout with side-loading operations, such as the Pacific International Container Terminal of Tianjin port, which means the vehicles will drive directly into the blocks area for storage and retrieval jobs.

In order to push the full automated upgrading of traditional container terminals, a novel fully automated container terminal with parallel layout and side-loading operations is planned and constructed by Tianjin Port as shown in Fig. 1. Compared with perpendicular layout of yard block, the new mode can separate the land-side operation from sea-side and shorten the moving distance of yard crane with container, which benefit the organization and operation management of transportation in terminals. With the purpose of improving unmanned and intelligent level of inner terminal, a novel artificial intelligence robot of transportation (ART) is invented and serves as the horizontal transport vehicle responsible for the fully driverless transportation of containers.

During the loading jobs for outbound containers of ACT Section C, Tianjin Port, unreasonable loading sequence of containers would result in the reshuffling operation in the yard and the bays for moving the obstacle boxes. Three kinds of loading modes (strict loading, loose loading, and free loading mode) are designed to decrease reshuffling operation times and improve the unloading efficiency. Strict loading mode requires that each container must be placed in the specified position in strict order during loading operation. Cross-bay, cross-row and cross-tier are not allowed between containers. Loose loading mode allows containers to be loaded in different bays according to the flow direction, empty/weight, destination port, size, and other attributes of the container. Cross-row and cross-tier are allowed between containers, but cross-bay is not allowed. The free loading style that adopts the strategy of FIFO, namely fist-in and first-out, has the least requirements among the three modes, and is usually applied to large-volume container loading operations.

Because of the numerous types of containers for transshipment in the ACT of Tianjin Port, these containers should be allocated to different bays and tiers according to their respective attributes. So the strict loading mode is adopted, which is the most common and default one for almost majority of terminal operating systems around the world. Under this strict loading mode, each container should be carried by ART from the dedicated location in yard to the corresponding area of quay. The ART that matches the loading sequence will work first, and the other ARTs that fail to match the sequence will line up and wait. In practice, due to the congestion and reshuffling operations exist unavoidably, some ARTs cannot arrive at the planned location as scheduled in time and the loading sequence needs to be adjusted, resulting in increased ART waiting time and reduced system operation efficiency.

The mentioned situations give rise to the study of effective control on ARTs that adopt the strict loading mode under parallel layout and side-loading operations. In the effective control of ARTs, the waiting time of ART's adjustment of loading sequence at quay can be reduced and the smoothness of operation in ACT can be improved finally. The study is regarded as of great importance for improving operating efficiency of automated container terminals.

In a word, the contributions made by this study are as follows:

(1) The vehicles control problem is discussed under the circumstance of parallel layout of ACTs and the strict loading mode is chosen for loading jobs. The distributed cooperative control method of multi-ART is studied for the first time with the purpose of smart transportation control.

(2) Regarding the distributed and intelligent features of ARTs, a MAS-based dynamic speed-regulation simulation model for ACTs is established to decrease the waiting time of ART at quay in strict loading mode by designing a dynamic speed regulation strategy to control the speed of ART and so as to adjust the sequence of ART arriving at the quay.

(3) For the purpose of improving stability and convergence of system, and addressing the consensus problem which is the basic one in the studies of distributed heterogeneous multi-agents, a novel distributed consensus control protocol is proposed to overcome the consensus problem among the speed regulations of ART, and make sure that the status of agents group will tend to consistency gradually.

II. LITERATURE REVIEW

From the following three aspects, the existing literature is reviewed in the paper. Firstly, the optimization of horizontal transportation of ACTs provides the direction for this study. Secondly, the application of agent in port planning field is reviewed. Lastly, the current studies on consistency sheds a new light on the convergence of speed regulation model for this paper.

A. OPTIMIZATION OF HORIZONTAL TRANSPORT IN ACTs

The horizontal transport operations play an important role in container terminals by linking and bridging the berth and the storage yard area. The optimization of transfer system for keeping the consistency between tasks and improving the whole operation effectivity has been the main target for numerous scholars.

Rashidi et al. regarded and formulated the scheduling problem for automated guided vehicles in container terminals as a special case of minimum cost flow problem [1]. The experimental results show that compared with incomplete algorithm Greedy Vehicle Search, NSA+, namely extended the standard Network Simplex Algorithm, is efficient and effective in minimizing both the waiting and travelling times of the vehicles. Hu et al. investigated the operational control of Automated Guided Vehicles (AGVs) and Autonomous Land Vehicles (ALVs) and proposed a three-stage decomposition method to address the vehicles scheduling and stacking sequences of containers [2]. Yang et al. investigated the problem of integrated scheduling of Quay Cranes (QC), AGVs and ARMGs for simultaneous loading and unloading operations, and applied a mixed integer programming model to solve conflictive problems and proposed a bi-level general algorithm based on the preventive congestion rule to simulate actual situations of ACTs that handle numerous containers [3]. Considering the travel speed, running time and collision distance of AGV, Guo et al. established a conflict-free path planning model for multiple AGVs in ACTs, and an improved interactive protocol based on blackboard model is used as the communication method of AGV [4]. Xu et al. proposed a reinforcement learning based hyper-heuristic genetic algorithm to address the integrated scheduling optimization problem, which can eliminate the waiting time during the interaction between AGV and dual cantilever rail crane [5]. Aiming to minimize the energy consumption, Yue et al. introduced the constraints of stability, available laytime, precedence, safety margin, buffer size, and AGV's endurance time constraints, then proposed an improved genetic algorithm to get the optimal operation sequence of AGVs [6].

Xu et al. proposed a load-in-load-out AGV route planning mode with the help of a buffer zone AGV which can provide two-way loading between the dock and the container yard and thus improves the efficiency of container terminals [7]. Zhong et al. established a mixed integer programming model based on path optimization, and conflicts and dead-locks to minimize AGVs delay time and realize the integrated scheduling of multi-AGV with conflict-free path planning [8]. Zhao et al. established a collaborative scheduling model adopting a two-stage taboo search algorithm for AQCs and AGVs and the capacity limitation of the transfer platform on AQCs is considered in the model with the purpose of the minimum total energy consumption of AQCs and AGVs [9]. Singh et al. considered the problem of scheduling AGVs with battery constraints, and proposed an adaptive large neighborhood search algorithm for heterogeneous AGV fleets with different transportation capacities and costs to solve the problem of assignment the AGV transport and charging requests with the objective of minimizing a weighted sum of the tardiness costs of transport requests and travel costs of AGVs [10]. Considering the buffer capacity constraint and the operation interference of the automated stacking crane (ASC), Zhang et al. introduced the design of handshake area and developed a collaborative scheduling model of AGV and ASC based on the genetic algorithm which was proved to be able to minimize the AGV waiting time and the ASC running time. [11]. Roy et al. used the theory of regenerative processes and Markov chain analysis to analyze a stochastic stylized semi-open queuing network model with bulk arrivals (of containers on trains), shared stack crane resources, and multi-class containers, and the proposed network solution algorithm worked for large-scale systems and yields sufficiently accurate estimates for performance measurement of the system [12]. Jia et al. presented the novel roll-on roll-off dual cycling problem which was solved with a novel heuristic strategy by a generalized random key algorithm with the objective to minimize the total makespan of discharging and loading operations [13]. Jonker et al. developed a comprehensive model to represent the waterside operations of a container terminal taking the form of a hybrid flow shop, and then solved it by means of a tailored simulated annealing algorithm that balances solution quality and computational time [14]. Fragapane et al. presented the application of autonomous mobile robots (AMRs) in logistics systems such as terminals. Compared to AGVs under central control unit, AMRs can communicate and negotiate independently with other resources such as machines and systems, thus decentralize the decision-making process [15]. Ahmed et al. proposed a double-cycling strategy to minimize the number of empty travel trips of yard trucks, and verified the enhanced efficiency of the proposed strategy by comparing the simulation models of standard single-cycling and double-cycling [16].

However, the ahead-mentioned literatures mainly focused on the perpendicular layout of yard block which had a lower requirement for AGV's cooperative control during the transportation because the AGVs did not need to enter the yard and consequently had a shorter routing distance relatively. By contrast, the AGVs under the parallel layout should move into the storage yard for unloading which means a longer travel distance. Hence, the mentioned methods cannot be applicable anymore because they will deliberately neglect the cooperative operation benefits during the long travel distance and the impacts of vehicle speed on the operation efficiency of the system as a whole. In addition, the current literature published focuses mainly on the scheduling and path planning of AGVs, leaving room for the speed-monitoring of unmanned vehicles during horizontal transportation in ACTs which may lead to disability of adjustment of arriving sequence of AGV at quay and many containers will be delayed on the quay for loading. Controlling of vehicle speed makes it possible to adjust the sequence and concrete time timely for vehicles according to the requirement and the sequence of loading operation, which can relieve the congestion problem in quay.

In the horizontal transportation system of ACT, Section C of Tianjin Port, ARTs can make decisions autonomously and adjust speed cooperatively in the running time, which provides condition for distributed speed control of horizontal transportation. However, the traditional way of terminal operation system usually chooses a kind of centralized method to give instructions for devices by centralized system. Due to the lack of flexibility and deep dependence on the computability of control center, the system cannot meet the requirement of dynamic control, neither effectively simulate the autonomous decision-making behavior and distributed intelligent control of ART in the dynamic operating environment. Hence, the agent technology with autonomous and cooperative features opens a new way for device scheduling of ACTs.

B. APPLICATION OF AGENT TECHNOLOGIES IN PORT PLANNING

As for the combination of MAS with port scheduling problem, vehicles for horizontal transportation are conceptualized as agent and then designed into MAS cooperative models, which can effectively solve the terminal operation scheduling supported by the new technologies. Compared with single agent which is regarded as a computing entity with the function of decision making autonomously and sustainably in the distributed environment, the MAS is a distributed system which consists of multi-agents. Differing from traditional way of centralized scheduling, MAS can make dynamic distributed decision.

Yin et al. proposed a distributed agent system for port planning and scheduling which was built on the communication and cooperation among the port planning manager, berth control agent, shuttle allocation agent, and yard storage agent [17]. The system has shown to be able to effectively work out the near optimal berth allocation and ship loading-and-unloading schedule. Rekik and Elkosantini suggested a multi-agent approach for the reactive and decentralized control of container stacking in an uncertain and disturbed environment. They proposed a belief-desire-intention (BDI) model for the development of the different agents constituting the system in order to select the most appropriate storage strategy and determine the most suitable container location [18]. For solving re-scheduling problems in port container terminals, Chargui et al. proposed a reactive MAS which contains a heuristic scheduling agent for simultaneous re-scheduling on real time once a perturbation occurs. Simulation study showed that the reactive approach provides less deviation between planned and actual schedules [19]. Muravrv et al. developed a set of agent-based hybrid simulation models to investigate a two-stage optimization of intermodal terminals main parameters [20]. Tang et al. established an agent-based simulation model to visualize the power demands of QCs with double cycling [21]. The computational experiments results show that the policy of limiting maximal energy demands of QCs performs better which reduces the maximum energy demand as well as protects electrical equipment. Regarding of the stochastic and dynamic operation processes in ACTs, Li et al. developed an agent-simulation-based energy consumption and cost models to provide more precise and practical reference for terminal operators to make decisions on layout design in the planning phases of ACTs [22]. Abourraja et al. built a simulation model based on a distributed architecture to evaluate the handling capacity of a Ro-Ro terminal under different flow scenarios so as to determine the number of resources required and to identify the potential bottlenecks that happen mostly inside the terminal [23]. Mnasri et al. presented a set of techniques involving the negotiation protocol, the multi-agent interactions and Worst-Fit arrangement technique to propose a detailed modeling of the discrete and dynamic problem of berth allocation in maritime terminals with heuristic and multi-agent methodology [24]. Jiménez et al. presented a multi-agent based software platform named HADES where agents involved in vessel arrivals share meaningful but limited information, which utility leaded to alleviate the potential congestion in multi-client liquid bulk terminals and the overall reduction in congestion anchoring [25].

With the development of Internet of Things (IoT) and the 5G technologies, gigantic real-time data are generated during the terminal operations. Some scholars conduct lots of researches about the effective fusion of real-time data and dynamic scheduling in MAS. To address the classic flexible job shop scheduling problem (FJSP), Zhu et al. proposed a novel adaptive real-time scheduling method for MAS so as to make each job agent be able to select the most suitable dispatching rules according to the environment state [26]. Du et al. developed a dynamic decision support framework based on a genetic algorithm and MAS which can propose corresponding dynamic scheduling method according to the different types of uncertainty factors, and finally improve the suitability of the production schedule for the actual production environment [27]. In order to effectively respond to unpredictable exceptions, Wang et al. proposed a new multiagent-based real-time scheduling architecture for an IoT-enabled flexible job shop. A bargaining-game-based negotiation mechanism then was developed to make sure that the scheduling method can optimally assign operations to machines according to their real-time status [28]. Zhu et al. proposed a hierarchical heterogeneous hybrid MAS-based control architecture and designed a MAS-based shop floor scheduling model for manufacturing system which can realize a distributed control and a dynamic schedule based on MAS according to the real-time status in manufacturing shop floor [29].

However, few studies can be found about the real-time running data of transfer vehicles, neither the optimization of horizontal transportation based on vehicles real-time data. Insufficient researches were undertaken considering the agents consistency during dynamic scheduling by MAS. As the consistency of system as a whole is closely related to the stability of MAS, it is hard to assure the stability and convergence of production system if only the MAS structure and scheduling policies were taken into consideration and designed. Therefore, it is necessary to optimize the control policy from the perspective of distributed consistency.

C. CONSENSUS CONTROL FOR MULTIAGENT SYSTEMS

As for the coordinated control of MAS, the active research field originated from the research by Vicsek et al. in 1995 which focused on one-order discrete-time model and the study about the synchronization of directions of the agents motion [30]. And then the results about one-order MAS were generalized to the consensus tracking for higher order MAS [31], [32], [33]. Zuo et al. investigated the adaptive output containment control of general linear heterogeneous MAS and then checked the effectiveness of two distributed control protocols using state-feedback and dynamic output-feedback [34]. Su and Lin proposed a control protocol of information consensus for MAS with higher-order controllable linear agent dynamics under dynamically changing directed interaction topologies and weighting factors [35]. This research showed that information consensus can be achieved asymptotically by the group of agents under proposed distributed control protocols.

The consistence problem is regarded as the fundamental and also the most discussed one for distributed multiagent research. Via the design of distributed consensus protocol, the agents can exchange the status information with each other and then update their status data, pushing the agent group to arrive at common state so as to guarantee the convergence of system and improve the converge velocity at the same time. But few studies are dedicated to address the consistency problem of operating system of ACT under high uncertainty.

Basing on the review of current literatures, shortcomings as described as below:

(1) Few studies paid attention to the congestion problem of horizontal transportation vehicles at the quay under the strict loading mode. And most of the related literature piled in the field of AGV scheduling of perpendicular layout and end-loading operations. However, there are few researches about the parallel layout with side-loading, cooperative control with ART.

(2) Under the situation of parallel layout of storage yard and side-loading operations, the travel distance of ART will increase and the fixed speed of ART may lead to the inefficiency and the worsening congestion of ARTs in terminal. A new strategy to dynamically regulate the speed of ART based on real-time data to adjust the sequence of ARTs arriving at the quay, which can decrease the waiting time of ART at the quay under the strict loading mode, has not been taken into consideration up to now.

(3) The majority of current research about MAS of ACTs just focused on the system architecture and scheduling policies and left a blank area for considering consensus problem of agents which cannot guarantee the convergency of system.

Aiming at the mentioned three problems, with the scenario of parallel layout and side-loading operations of yard, the study firstly focuses on the vehicle congestion problem of ARTs under the strict loading mode. In order to decrease the waiting time of ARTs at quay, a dynamical speed regulating policy for swarm-intelligence-based ARTs is proposed to adjust the travel speed during running time. In addition, the consistency problem of agents during dynamic speed regulation is also investigated by designing a distributed consistent cooperative control of a multi-ARTs. Supported by the ART cluster cooperative simulation environment, the proposed system simulates the process of speed regulating decision making cooperatively and autonomously of ART cluster which can realize the breakthrough in distributed and smart control of transportation in ACTs. Finally, different simulation scenarios are set for the effective validations of swarm intelligence decision making for ART's dynamic speed regulation, which is followed by the sensitive analysis of decision-making system facing the uncertainty such as the device operating time.

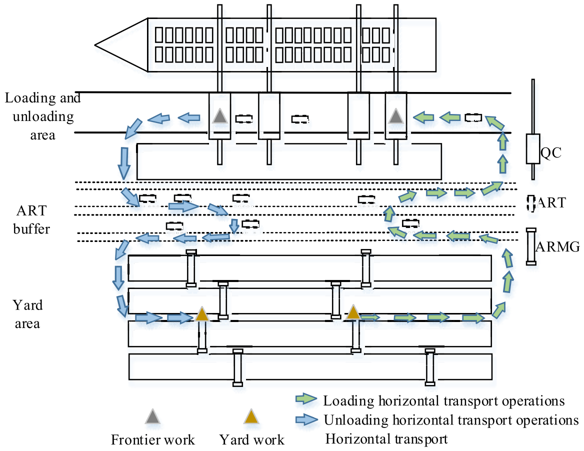

FIGURE 2. Loading and unloading process layout of automated container terminal.

III. PROBLEM DESCRIPTION

The operation process of the fully automated container terminal with parallel layout and side-loading operations as shown in Fig. 2 is described as follows. As for the job of loading containers to vessel, it mainly contains three steps.

Step 1-Yard operation: When the ART arrives at the specified loading area, the ARMG will lift the container from the yard slot and place it on the ART;

Step 2-Horizontal transport task: the ART will transport containers from the yard to the designated QC;

Step 3-Seaside operation: After the ART enters into the buffer zone, if the QC is labeled free and matches the loading sequence, the ART will be guided to enter the QC loading area, then the QC dismounts the container from the ART and loads it onto the vessel. Otherwise, the ART needs to stay in the buffer zone and keep waiting.

As for the unloading jobs, the QC will unload the containers from the vessel and put them on the ARTs. ART will then transport these containers from the front area of port to the planned unloading area of the yard, and then the ARMG will lift the containers from the ART and put them on the specified storage position.

Basing on the above description and analysis, the job of container loading and unloading operations under strict load-

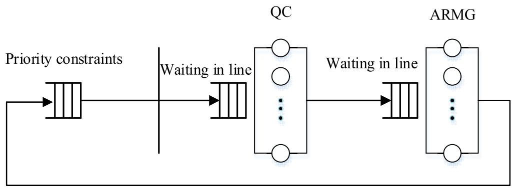

FIGURE 3. Automated container terminal queuing network model.

ing mode can be mapped to a closed queuing network model with priority as shown in Fig. 3. The QCs and ARMGs in this model can be regarded as two kinds of service stations, and the ART in this model is regarded as the customer. The ART that performs the loading and unloading jobs arrives at the service station to receive dedicated services; the total number of customers, namely ARTs, in this system is fixed and the customer will not just leave because of the overlength queuing time. Therein the terminal operation system (TOS) will formulate the loading sequence for the export containers according to the vessel stowage plan and the current state of yard storage. Constraints such as container weight, the destination port and the strength of the vessel are taken into considerations, so as to determine the job's priority among the customers (ART) according the loading sequence. If the container being transported is planned to loaded to the vessel in a more advanced order, the operation by the ART will conducted in a higher priority.

As the ART arrives at the service desk (namely QC), it will accept the service immediately if the ART has the highest priority and the QC is free, otherwise the ART will have to wait in front of the other ART with the secondary priority.

During the process of terminal operation, the waiting time of ART at the quay is an important factor that affects the efficiency of loading and unloading jobs. The waiting time W_{qk} of ART with the k^{th} priority at the quay is composed of three elements: 1) the sum of the average service time T_1 of ART waiting for service from the first priority to the $(k-1)^{th}$ priority; 2) the sum of waiting time T_2 that is caused by queue-jumping with preference of ART from the first priority to the $(k-1)^{th}$ level that arrive successively; 3) the average waiting time T_3 of ART waiting for the QCs in service to be free. The formula is as follows:

$$W_{qk} = T_1 + T_2 + T_3 \tag{1}$$

The average time of ARTs (customers) of the first priority to the k^{th} priority stay at the Quay, $W_{s,1-k}$, is defined as follows:

$$W_{s,1-k} = \frac{1}{\mu - \sum_{i=1}^{k} \lambda_i} \tag{2}$$

where λ_i is the average arrival rate of the customers and $1/\mu$ is the average service time of the QCs.

Since the strong dynamics and randomness of the ART interactive speed regulation system exist and the presence of obstacle containers during the process of loading and unloading jobs, the reshuffling operation for moving the obstacle

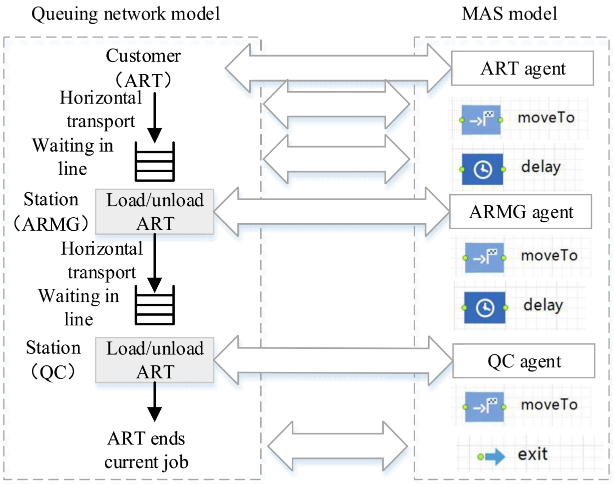

FIGURE 4. Mapping relationship between queuing network model and multi-agent system model.

boxes is necessary which may result in the uncertainty of the average service time of QCs and ARMGs. The traditional queuing theory and mathematical model are difficult to describe the service state of system and the autonomous decision-making behaviors of ART in a dynamic environment. Whereas agent-based simulation method can not only effectively simulate the dynamic and random operation process of terminal, but also collect and analyze the waiting time related data of the queuing system.

During the process of simulation, due to the time-driven characteristic of the simulation model, the W_{qk} value can be accurately obtained by calculating the difference between the time T_{EA} when the ART enters into the quay and the time T_{EB} when the ART enters into the buffer area, as shown in Equation (3).

$$W_{qk} = T_{EB} - T_{EA} \tag{3}$$

Similarly, by calculating the waiting time of each ART and taking the average value of them, $W_{s,1-k}$ value can be obtained, as shown in Equation (4).

$$W_{s,1-k} = \frac{\sum_{i=1}^{k} \mathrm{W}_{qk}}{k} \tag{4}$$

Due to the similarity between the agent and the equipment in port like ARTs that have the features such as autonomy and intelligence, the terminal operation system is abstracted as a multi-agent system (MAS). The system mapping relationship is shown in Fig. 4.

The customers (ARTs) and the service desks (QCs and ARMGs) are abstracted into agents. The simulation modules of discrete events such as the behaviors moveTo, delay and exit are designed to simulate the horizontal transportation of the ART, the queuing behavior of the ART at the QC and the ARMG area, and the behavior of the ART finishing the current job and entering the next round for loading and unloading operation.

IV. MAS SIMULATION MODEL

Combined with the above analysis of the queuing network of system, and the mapping relationship between the queuing system with MAS, a discrete event system simulation model based on MAS and Anylogic platform is developed. Among the model, the discrete event system is used to describe the operation process in ACTs; MAS is dedicated for simulating the distributed production environment of port, the inner structure and the running state of ARTs.

A. ARCHITECTURE OF MAS SYSTEM

The simulation model of MAS consists of Main Agent, QC Agent, ARMG Agent and their environment. The main interaction process among these agents in the model is shown in Fig. 5. When the vessels arrive at the terminal, the operation task information of loading and unloading containers generated by Main Agent is then delivered to the QC and ARMG. Subsequently, the task will be assigned by terminal operating system (TOS) to the vehicles management system (VMS); When receiving the horizontal transportation tasks dispatched by the VMS, the ART agent acquires the attributes data of containers including the container type, the initial location and end location of this task, and then updates its job state as busy, sends the signals of task being received to QC or ARMG.

Once performing the transportation task, the ART obtains the real-time environmental information including the real-time moving speed, priority data and job execution status of other ART agents, and then modulates the working speed according to the speed regulation strategy to reduce the waiting time caused by the loading order adjustment at the quay. As the speed regulated by individual ART, the running state of the group of ART in the environment changes simultaneously. Hence the environment information needs to be updated timely as a reaction to every speed modification of one ART. As the transportation task be completed, the ART updates its job state as available and waits for other horizontal transport job dispatched by VMS so as to shift to the next job round. The information interchange and the collaborative decision among the different devices make it possible for adaptive control of ACTs.

B. MULTIAGENT MODEL

1) MAIN AGENT

As a comprehensive agent in the simulation model, the Main agent is responsible mainly for realizing the design of simulation interface, initiating the parameters of simulation, control of the creating of other kinds of agent, and generating discrete events according to the dynamic variables triggered by the simulation clock, then activating the interactions and cooperations between agents. Three prime functions are set in the Main Agent, which respectively is dedicated to realizing the initialization of container type, the initialization of container storage location, and ending the simulation process then outputting the simulation data. In addition, according to the actual driving path of ART in Tianjin port, the ART road network and the guiding path structure are drawn in Main agent, as shown in Fig. 6 below. The green dashed line in the figure is the ART road network and ART travels in the counterclockwise direction. The actual driving lane consists of the operation lane and the overtaking lane. ART drives normally in the operation lane and overtakes through the overtaking lane when it needs to overtake. The solid black line in the figure is the ART guiding path. When ART performs the loading/unloading task, it determines the guiding path based on the shortest operation path according to the starting and ending positions of the loading/unloading task and the real-time position of ART. The guiding path consists of connecting lines of key path points, where the key path points include ART current position, task start position, end position and turn position. The ART buffer area is located between the yard and the QC operation area. If the ART meets the loading sequence before entering the quay crane, it will directly enter the QC operation area for loading operations without entering the buffer area. If the ART does not meet the loading sequence before entering the quay crane, it will drive to the ART buffer area and wait until the loading sequence is met.

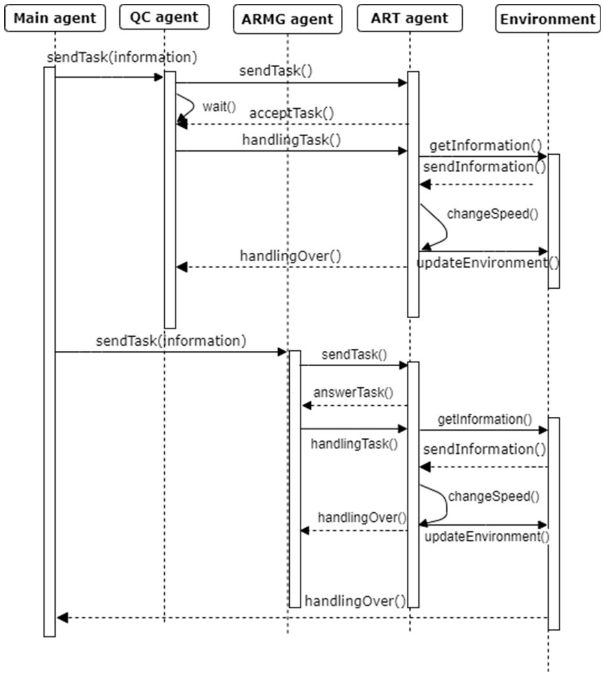

FIGURE 5. **Framework of simulation model.**

2) ENVIRONMENT

The entity Environment can function mainly as an object composed of variables and methods to describe the state data and interaction information of agents. The methods of getSpeed, changeSpeed, getDistanceTo are set in the Environment entity to obtain the speed, change the speed and obtain the location information of the ART agent respectively. The variables such as taskType and taskFinished are defined in the

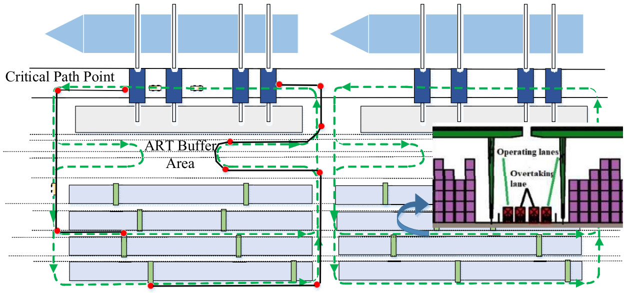

FIGURE 6. ART driving path.

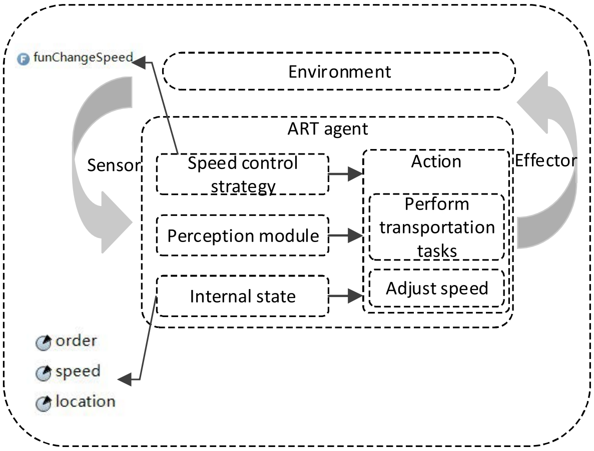

FIGURE 7. Structure of ART agent.

Environment to describe the type and the completion status of horizontal transport tasks. The defined communication methods are utilized by the ART agents to communicate with each other. The communication with the Environment entity enables the ART agents to perceive the outside and change the position and their status in the environment.

3) ART AGENT

Supported by the Internet of Things (IoT) and 5G technology, the ART can perceive other ARTs' state during job execution and respond instantly based on the combination of the external information with its own strategies. Considering the features like ART's quick response to the external environment and the intelligent characteristic of decision-making autonomously, a kind of hybrid agent is selected for modeling the operation equipment like ART. The internal structure of ART Agent is shown in Fig. 7.

After receiving the horizontal transportation task assigned by VMS, the ART acquires its internal status data such as the current position, speed, task priority, and the task-related information such as starting position of task, ending position of task through the Perception module, and then automatically generates vehicle routing path and performs horizontal transportation jobs. During the process of transportation, the ART agent obtains the running status data of vehicle and performs the coordinated modification of velocity basing on dynamic speed regulation strategy. At the same time, the vehicle status information after modification is fed back to the Environment through Effector, with the environmental information be updated correspondingly.

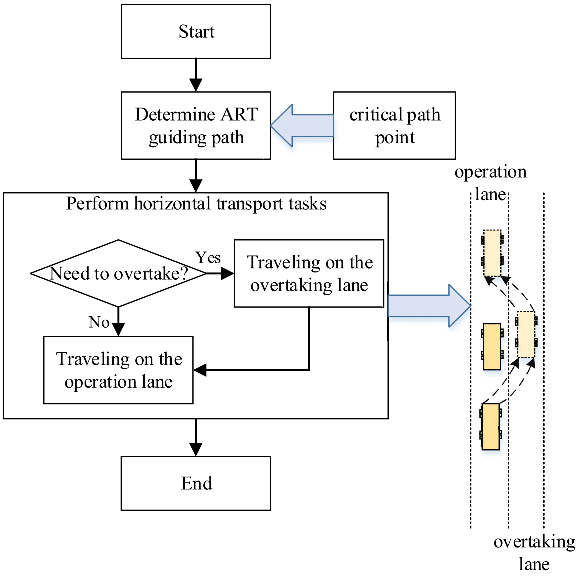

FIGURE 8. Process of ART movement.

The ART movement module is established in the simulation, and the process of movement is shown in Fig. 8. The ART moves from one critical path point to the next critical path point at a set speed according to the guiding path. The traveling speed of ART is decided by the speed control strategy, and the global state sharing mechanism is used to realize the driving state perception and distributed speed control among the ARTs. Under the global state sharing mechanism, each ART has access to global resource state information and can adjust its own traveling speed according to the speed control strategy. In the process of horizontal transportation, when the speed of the rear vehicle is higher than the speed of the front vehicle, the rear vehicle can complete the overtaking action through the overtaking lane and then return to the operation lane to drive normally until the current transportation task is completed.

4) QC AGENT

The QC agent is responsible for container loading and unloading on shore. As the vessel moored at the berth, a job of containers loading or unloading will be assigned to the specified QC agent. The QC adds the corresponding container to the current job list and then sends the task request to the ART agent. When the ART agent that responds to the request arrives at the designated quay crane, the QC agent will unload the container from the ART and load it onto the vessel, or unload the container from the vessel to the ART. The quantity and location of QC agent are specified by the attributes of size and location of the resource pool, and the time delay module is designed to set the cycle time of operation to simulate the QC operating process.

5) ARMG AGENT

ARMG agent is responsible for container loading and unloading in the storage yard. Under the parallel layout of storage yard and the side-loading mode, the ART can move directly to the loading and unloading points inside the yard, and the ARMGs can perform the loading or unloading job to or from the ART on both sides of the yard. If the ARMG is labeled as busy, the ART will be pushed into the queue and wait until the equipment is free. Similarly, the number and location of ARMG agent are set by resource pool, and the ARMG operating process of container loading and unloading is simulated by the time delay module.

V. DISTRIBUTED CONSISTENT COOPERATIVE SPEED REGULATION ALGORITHM

In order to adjust the order and time of vehicles arriving at the quay crane in time through vehicle speed regulation, we propose a distributed consistency-based ART cooperative speed regulation algorithm. The algorithm mainly consists of three parts: ART dynamic speed regulation, multi-ART dynamic topology construction based on graph theory and multi-ART consensus control protocol based on multi-agent consistency.

Aiming at the terminal loading and unloading operations under the strict loading mode, the ART dynamic speed regulation strategy is firstly designed to adjust the travel speed of the ART in real time during the horizontal transportation process. The goal of this startegy is to realize the coordinated speed regulation decision between the individual ART and the ARTs group, so as to reduce the waiting time caused by the ART adjusting the loading order at the QC operation area and improve the system operation efficiency. Secondly, the graph theory is introduced to construct the dynamic topology structure of ART in the process of information interchange, so as to limit the real-time interaction objects of ART. Finally, as for handling the stability and convergence problems of the multi-ART distributed cooperative control system during runtime, a consensus control protocol is embedded into the algorithm to ensure that the state of the ARTs group tends to be gradually consistent during their operation process. The flow chart of the algorithm is shown in Fig. 9.

A. DYNAMIC SPEED REGULATION OF ART

During the horizontal transportation, each ART agent interchanges the real-time information with other ARTs and the external environment. The ART running status and task information are updated in real time. By judging the exact position information of individual vehicles in the internal road environment and among the surrounding vehicles, they make dynamic speed regulation decisions according to the priority attributes, so as to change the order of ARTs arriving at the quay. When an individual ART makes a speed regulation decision, it not only changes the speed itself, but also sends a request for coordinated speed regulation to other ART agents in the environment. After receiving the speed regulation request, other ARTs will decide to accept or reject the collaborative speed regulation request according to their current states, and reply the response information to the previous agent which initiate the process. The flow chart of dynamic speed control strategy is shown in Fig. 10.

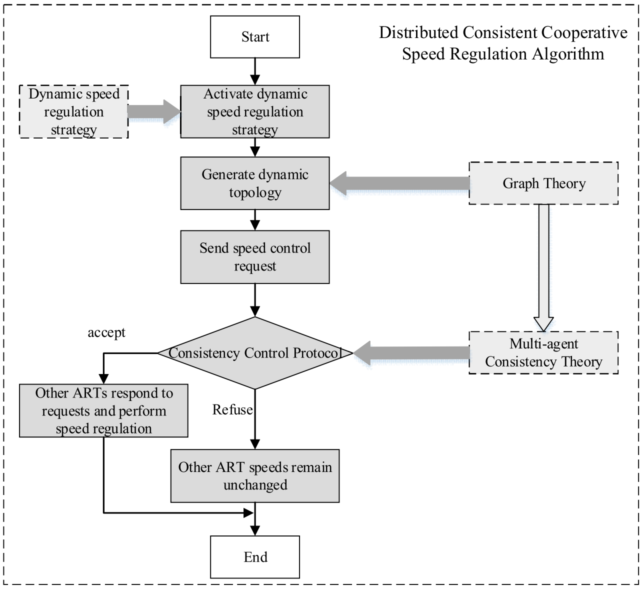

FIGURE 9. Flow chart of distributed consistent cooperative speed regulation algorithm.

On the way to the QC operation area after picking up containers from the storage yard, the ART performing the current highest priority task will obtain the exact position information of other ARTs performing the loading task. If there is an ART ahead with lower priority, it accordingly increases its speed and sends a speed reduction request to the ART ahead simultaneously. The ART will receive the speed reduction request and make its own judgment upon collaborating or not. After finishing the current operating task that will then be removed from the current transport job list, the ART will step into the next round of coordinated speed regulation cycle until all the horizontal transportation tasks are completed.

B. ART DYNAMIC TOPOLOGY CONSTRUCTION BASED ON GRAPH THEORY

Considering the dynamic speed regulation system is composed of multiple ART agents, the communication network among the ARTs in the ACT can be represented by the graph $G = (V, E, A)$. $V = \{v_1, v_2, \cdot \ldots, v_i, \ldots, v_n\}$ denotes the set of nodes (ART agent); $E \in V \times V$ denotes the edges of the network topology graph. The adjacency matrix $A = [a_{ij}]$, where $i, j = 1, \ldots n$, $(v_j, v_i) \in E$ denotes an edge from node v_j to v_i. If $(v_j, v_i) \in E$, then $a_{ij} > 0$, otherwise $a_{ij} = 0$. Furthermore, the neighbor set of node v_i is defined as $N_i = \{v_j : (v_j, v_i) \in E\}$. The degree matrix D of G is defined as $D = diag(d_i)$, $d_i = \sum_{j=1}^{n} a_{ij}$ is the weighted degree of node v_i, which indicates that the number of neighbors connected to the current ART agent. The ART network topology diagram is shown in Figure 11.

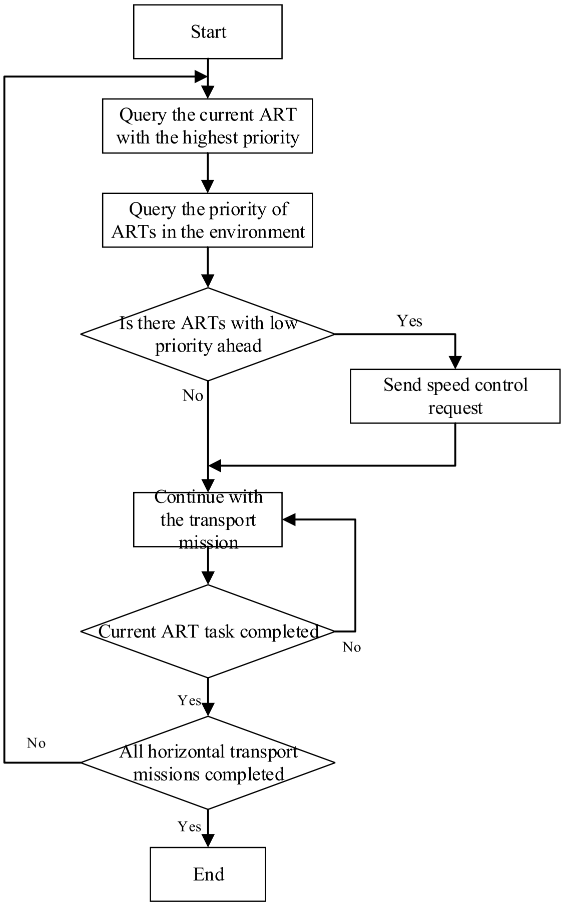

FIGURE 10. Dynamic speed control strategy process.

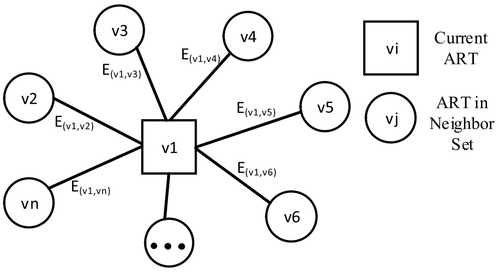

FIGURE 11. ART network topology diagram.

The ahead mentioned dynamic speed regulation policy comes to the conclusion that the information interactions between agents of a MAS made up of multi-ARTs is time-varying and the neighbor set of each ART agent changes dynamically according to the running status of the MAS which behaves as a dynamic topology.

When the MAS is running, ART can obtain the operation information of other ARTs from the environment. After comparing the information with its own operation status, the current ART will add the ART ahead with lower priority into its neighbor set, and then makes collaborative speed regulation decision with the ARTs in the neighbor set via the message sending mechanism. As the current task for the ART be completed, the network connection with ART in its neighbor set will be disconnected and the neighbor set will be regenerated in the next job cycle and a new round of information interaction will take place correspondingly as shown in Fig. 12.

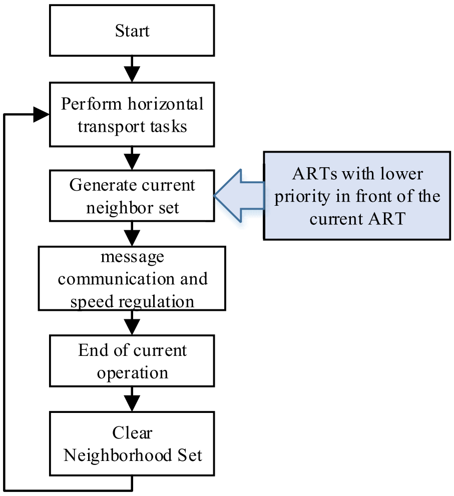

FIGURE 12. Dynamic topology construction process.

C. CONSENSUS CONTROL PROTOCOL OF MULTI-ARTS BASING ON MULTIAGENT CONSISTENCY

For the consistency problem of leaderless MAS, the following linear discrete-time multi-agent system is considered:

$$\begin{aligned} x_i[t+1] &= x_i[t] + u_i[t] \\ u_i[t] &= \eta \sum\nolimits_{v_j \in N_i} a_{ij}(x_j[t] - x_i[t]) \end{aligned}$$

where $x_i[t]$ and $u_i[t]$ are the state of agent i at time t and the corresponding control input, N_i is the neighborhood of agent i, and η is the coupling coefficient. At this time, the consistency problem of the MAS is to design the local control protocol u_i according to the local information of each agent and its neighboring agents so that the states of all agents tend to be consistent, that is, for $\forall i, j = 1, \ldots n$, $\lim_{t\to\infty} x_i[t] = x_j[t]$.

In the ART dynamic speed regulation system of this paper, $x_i[t]$ is considered as the average travel speed of this ART at the current moment, and $u_i[t]$ represents the consistency policy choice made by the ART after receiving the speed regulation request, and the combination of them forms the status of the ART at the next moment, namely, embodying the average travel speed at the next moment. The emphasis of the consistency policy in the dynamic speed regulation strategy is directly related to whether the change of the individual ART agent state will tend to be aligned with the group of ARTs' states as time goes on.

Herein, a consensus control protocol is embedded into the dynamic speed regulation strategy. Via this protocol, the ART agent can make suitable choice based on the relationship between the current state of individual ART and that of the group of the ARTs and ensure the converging from unite state to group state with the aim to improve the stability of the whole system.

The consensus control protocol is designed as follows: the average travel speed of all ARTs is regarded as a consistency variable; every agent interacts and exchanges the information with each other according to the dynamic topology, making sure that average travel speed v can converge to a fixed value. The consensus policy selection can be described as below:

$$\begin{cases} u_i = 0, & \upsilon \le \upsilon^* \\ u_i = 1, & \upsilon > \upsilon^* \end{cases}$$

where v is the current average travel speed of the ART, and v^* is the average driving speed of the group of ARTs. The parameter policy $u_i = 0$ means the ART rejects the collaborative speed request received, whereas policy $u_i = 1$ means the collaborative speed request is accepted and the corresponding speed adjustment action is made by the ART at the same time. Via the continuous interactions and collaborations between the individual with the group, the fluency and efficiency of system operations as whole can be improved on the premise of ensuring their own operating efficiency and stability of individual ART.

VI. EXPERIMENTAL ANALYSIS

Taking the ACT of Section C, Tianjin Port as an example, the model and algorithm proposed in this paper are verified through simulation experiments on the Anylogic platform, including the verification of effectiveness and the sensitivity analysis of the distributed consistent coordinated speed regulation algorithm. And the impact of speed regulation algorithm on terminal operation performance is also evaluated.

A. CONFIGURATION OF MODEL PARAMETERS

The working condition for simulation is designed according to the planning documents of Tianjin Port Section C ACT, and the key parameters and kinematics, such as total length and depth of quay wall, total number of equipment, single operation time of equipment and running speed of ART, are shown as follows.

1) TERMINAL AREA AND EQUIPMENT

1,200 meters berth with 600 meters in land area, the equipment of 12 QC, 42 ARMG and 76 ART deployed.

2) OPERATION TIME AND KINEMATICS

Based on the historical operation data of the port, the operation time of the QC and ARMG conform approximately to the trigonometric distribution function, namely triangular (93,103,113) seconds and triangular (102,144,216) seconds respectively. The average speeds for ARMG are 2.5m/s for empty travel and 1.25m/s for loaded travel respectively.

3) ART SPEED

According to the actual operating data of the port, the average speed of ART is 6m/s, and the maximum driving speed is not more than 10m/s. Therefore, the initial speed, secondary speed and maximum speed of ART are set as 6m/s, 3m/s and 10m/s respectively. Among of them, the initial speed is the normal move speed of ART, and the secondary and maximum speed correspond to the deceleration speed and acceleration speed of ART respectively.

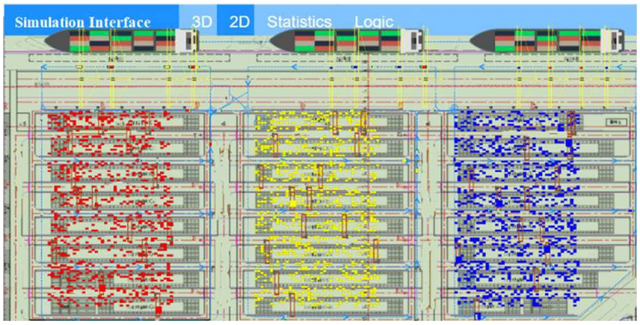

FIGURE 13. Screenshot of simulation interface.

4) SIMULATION TIME

The simulation time was set to 24 hours.

The screenshot of the simulation graphical interface, as shown in Fig.13, demonstrates the running result of simulation model. The correctness of the model is supported and verified by checking the running tracks of ART during loading and unloading operations, the operation time of QC and ARMG each time, and the storage positions of containers with different types.

In addition, in order to ensure that the behaviors and the results of the simulation model are similar to that of the actual scenario of operation system, the average driving distance for each cycle of the ART in the model is tested. The mean test is performed on the simulated and actual data. The null hypotheses H_0 is $\mu_1 = \mu_2$, and the alternative hypotheses H_1 is $\mu_1 \neq \mu_2$. The test statistic and p-value are calculated by the following equation:

$$T = \frac{\bar{X} - \bar{Y}}{S_w \sqrt{1/n_1 + 1/n_2}} \sim t(n_1 + n_2 - 2)$$
$$p = P(|T| \ge |t_0|)$$

where t_0 is the observed value. The results of the statistical tests are shown in Table 1, where $p = 0.69 > 0.05$, so the hypothesis H_0 is accepted at the significance level of 0.05. It is considered that there is no significant difference between the mean value of the simulation system and the actual system.

B. VALIDATION OF EFFECTIVENESS

With the aim to validate the effectiveness of the distributed consistent coordinated speed regulation algorithm, two kinds of scenarios for simulation are set up: 1) the first scenario that applies the distributed consistent coordinated speed regulation algorithm; and 2) the second scenario that applies the non-distributed consistent coordinated speed regulation algorithm, which are represented by scenarios s_sra and s_base respectively. The simulation and analysis are conducted in

TABLE 1. **Validation of Data in Simulation Model.**

Mean Value (m) Simulation Model	confidence intervals ($\alpha = 0.01$)	Actual data	p-value
1419.58	[1385.04,1454.13]	1443.75	0.69

TABLE 2. **Simulation data of speed regulation mode and speed without-regulation mode.**

Scenario		Index for System Performance			
		Loaded Containers	Unloaded Containers	U_{qc}	U_{armg}
s_sra	mean	3525	1565	0.9494	0.2708
	confidence intervals	[3497.05,3553.35]	[1557.19,1572.81]	[0.9409,0.9579]	[0.2683,0.2732]
s_base	mean	3373	1526	0.9092	0.2634
	confidence intervals	[3347.60,3398.80]	[1512.48,1540.72]	[0.9035,0.9149]	[0.2608,0.2640]

these two different scenarios. In term of the system without the speed regulation policy, each ART will run independently at a constant speed at initialization.

1) SYSTEM RUNNING EFFICIENCY

To explore the impact that the consistency of distributed collaborative speed regulation algorithm has on the system performance of ACTs, the simulation duration is set as 24 hours, and the simulation cycles is set as 5 times. At a significant level α of 0.01, the simulation output parameters including the number of containers loading and unloading to/from the ships and the rate of equipment utilization, are calculated and collected as shown in Tab. 2. Among them, the formula for the utilization ratio of equipment is as follows.

Utilization rate for QC:

$$U_{qc} = \frac{T_q}{T_t} \times 100\% \tag{5}$$

Utilization rate for ARMG:

$$U_{armg} = \frac{T_r}{T_t} \times 100\% \tag{6}$$

where, T_q and T_r are the average operation time of QC and ARMG in practice respectively, and T_t represents the total simulation time.

In the scenario s_sra, the containers be loaded and unloaded are increased by about 4.5% and 2.5% respectively compared with the scenario without speed regulation (s_base), indicating that the collaborative speed regulation algorithm can improve the operating efficiency of the system to some extent. At the same time, the utilization rate of QC and ARMG are increased minorly by 4.0% and 3.2% respectively.

Owe to the real-time perception of the running states of itself and the group of ARTs during their moving process, the ART can adjust the speed according to its current location and the task priority and respond simultaneously to the collaborative control requests from other ARTs based on the consistency control protocol. The mechanism designed assures the order of horizontal transportation jobs, the decrease of the QC's spare time due to waiting for the shipping order adjustment, and finally improves the utilization rate of load/unload equipment. Thus, the smoothness and productivity of ship loading and unloading operations are improved as a whole.

2) OPTIMIZATION OF WAITING TIME

Further analysis is then conducted for evaluating the influence of the algorithm proposed in this paper on the queuing network of horizontal transportation system. The simulation duration is set as 24 hours and the preheating time is 2 hours. With the simulation data be stable, the average waiting time ($W_{s,1-k}$) of ARTs transferring the containers with the priority from 1 to k (k<=1000) in the two different scenarios are collected according to equation (3) and equation (4) in part III. As the data shown in Fig. 14, the time for the system steps into stable under the speed regulation mode is significantly earlier than that under the speed non-regulation mode, indicating that ART in the former scenario can improve the stability of the system through the collaborative speed regulation decision.

With the system arriving at a stabilized phase, the average waiting time of ART in speed regulation mode is reduced by 22.8% compared with that in speed non-regulation mode. The dynamic speed regulation policy applied to ART answers the mentioned great improvement of system performance. Supported by the dynamic speed regulation strategy, the ART can interact and exchange the real-time data with the environment and other ART agents; it can obtain the location data and the priority information of the surrounding vehicles, and then performs coordinated speed regulation with surrounding vehicles according to its own priority. Via the intelligence decisions of dynamic speed regulation by the individual and group of ART, the ARTs group in the dynamic changing operation environment can adjust themselves adaptively, changing the sequence of arriving at the quay according to the loading order and reducing their own waiting time, so as to ensure the high efficiency and smoothness of the operating system.

3) OUTPUT SYNCHRONIZATION

The average travel speed of each ART is regarded as the measurement of consistency variable, and then the output of speed data is collected under the two different situations as adopting or without the distributed consistency control protocol as shown in Fig. 15 and Fig. 16. As for the system without consistency protocol, the ART unconditionally accepts all the collaborative speed regulation requests it received. After the system being stable, its relative variance of output synchronization is larger, which fails to meet the requirements of state consistency for agent.

After the distributed consistency protocol been embedded into the ART speed regulation policy, the ART can deal with the received speed regulation requests through the consistency protocol based on the state feedback, and respond to

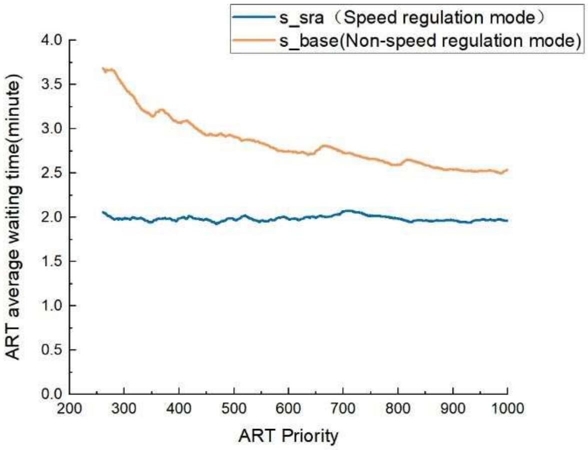

FIGURE 14. ART average waiting time.

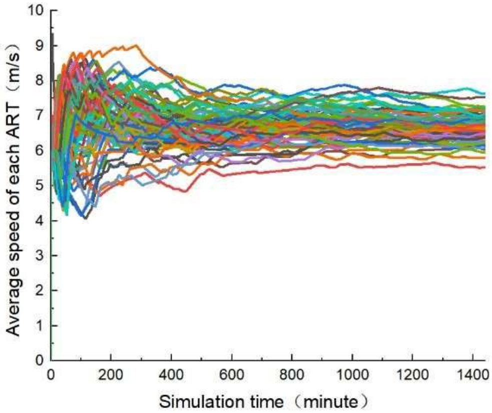

FIGURE 15. ART consistency output (no consistency strategy).

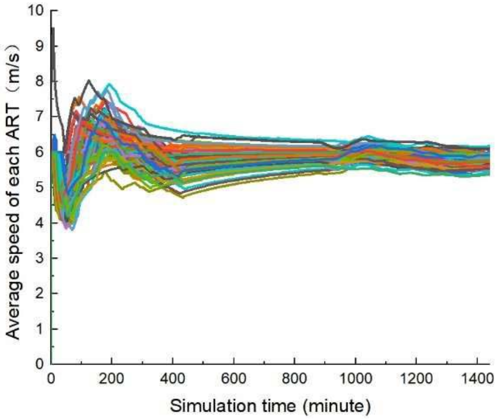

FIGURE 16. ART consistency output (under consistency strategy).

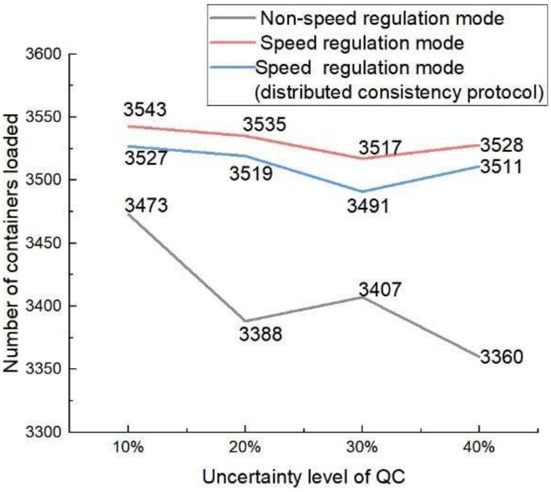

FIGURE 17. Number of containers loaded under different quay crane uncertainty levels.

the requests for speed regulation according to the obtained consistency policy. In the specified scenario, the consistency variables of ART gradually tend to be consistent and the variance is small, indicating that all the ARTs can realize the mutual convergence of agent states after the system arrives at stable situation.

C. SENSITIVITY ANALYSIS

In order to investigate the adaptivity of the coordinated speed regulation algorithm for the uncertainty of operating time by QCs and ARMGs, the study selects the number of loading containers as an index to test the performance under the four levels of uncertainty for three different scenarios (namely, speed non-regulation mode, speed regulation mode but without consistency control protocol, and speed regulation mode based on distributed consistency control protocol). The figures in vertical axis as shown in Fig. 17 and Fig. 18 respectively are the numbers of containers loaded to the vessel during the average operation time (±10%-40%) of QCs and ARMGs. The increase of the degree of uncertainty leads to a wider fluctuation range of volume of loading containers under the mode without speed regulation with the max value reaching 3.4% and 3.2% respectively. However, the numbers of loading container under the other two modes with speed regulation change more gently, and the fluctuation range are significantly lower than that under the mode of speed non-regulation.

The volumes of loading container under the two modes of speed regulation surpass that under the mode without speed regulation. With the distributed consistency control protocol being applied, the efficiency performance of system operation is slightly lower than the system without consistency policy. The difference comes from the policy which ART has chosen. Because the ART may refuse to receive any speed regulation requests from the other ARTs based on its running state among the cooperative speed regulation process, so as to assure the stability of itself and finally lead to a minor decrease in the productivity of the system as a whole.

In order to analysis the impact of the ART scale on the operation performance of system furtherly, the quantity of ART is set to 70, 80, 90, 100 and 110 respectively. The number of containers loaded on board is regarded as an index of simulation results, and its values are shown in Fig. 19. When the number of ART increase, the change in containers loading volumes under the mentioned three modes draws similar trend curves, all of which rise at first and then flatten

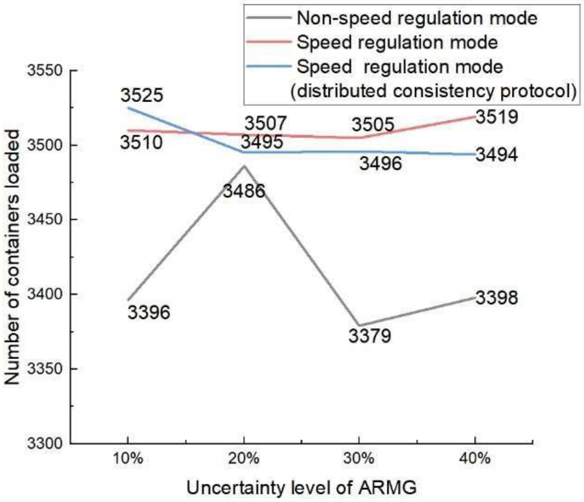

FIGURE 18. Number of containers loaded under different ARMG uncertainty levels.

gradually, and it is close to the peak when the number of ART is 100. All of the loading containers with the speed regulation mode at the four levels of uncertainty are always higher than that of mode without speed regulation. If the average container number of the system under the five types of configurations is regarded as the base value, the base value of the system with a consistent policy is about 2.5% higher than that of the speed non-regulation mode.

If the number of loading container tends to reach the saturation point as the ART's scale enlarges, indicating that the number of ART has reached saturation. The excessive ARTs otherwise will aggravate the congestion of the ACT and finally lead to the decrease of the operating efficiency of the whole system. At the same time, the performance of system under the two modes of speed regulation reflects a better stability when the system has a lot of ART. Via the decisions of dynamic speed regulation basing on group intelligence, the group of ART can decrease the impact of the number of equipment has on the operating performance of system as whole. When the number of ART is not saturated in the system, the operating efficiency of the system applying the distributed consistency control protocol is slightly higher than that of the system without consistency protocol, indicating that distributed consistency control protocol is helpful in maintaining the stability of the system and improving the operating efficiency of the system to a certain extent when the ART is sufficient.

D. COMPARISON WITH EXISTING METHOD

To further demonstrate the effectiveness of the algorithm proposed in this paper, the system operation efficiency and ART waiting time under the distributed consistent cooperative speed regulation algorithm (DCSPA) are compared with the real ship test data under the existing method at the terminal. For the strict loading mode, the terminal currently uses a composite vehicle sequence control strategy (CVSCS) for loading operations, which consists of a scheduling sequencing strategy and a buffer sequencing strategy. Before ART starts to perform tasks, the scheduling sequencing strategy is used to assign loading operation tasks to ART, and initial planning is performed based on task priority, ART location and travel distance to ensure the most basic loading sequence. Before the ART arrives at the QC, the buffer sequencing strategy is used and the ART adjusts the sequence in the buffer area. The comparison data is shown in Tab. 3.

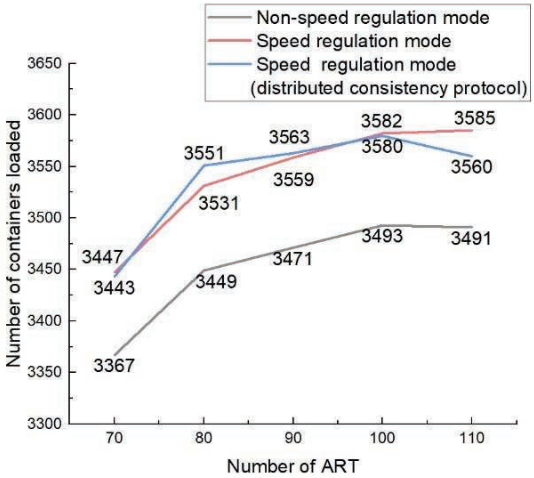

FIGURE 19. Number of containers loaded under different ART quantities.

TABLE 3. Comparison data with existing method.

Method	Data for comparison			
	Number of QC	Containers	Working hours	Percentage of waiting time
DCSPA	12	5090	24	9.1%
CVSCS	2	353	10.5	11%

Compared with the composite vehicle sequence control strategy, the system under distributed consistent cooperative speed regulation algorithm has more containers handled per unit time per QC, and the operation efficiency is improved by about 4.8%. In addition, due to the cooperative speed regulation decision of ARTs, the sequence of containers arriving at the QC operation area is controlled to some extent. The waiting time of ART at the buffer area is reduced, and the proportion of waiting time in ART operation running time is reduced from 11% to 9.1%, thus improving the coherence of system operation.

VII. CONCLUSION

In this paper, the problem of the dynamic speed regulation for the multi-ARTs under strict loading mode in automated container terminals is discussed, which aims to reduce the required waiting time of the ART due to its adjusting the sequence for loading containers at the quay, and also seeks to relieve the congestions occurring among inner terminals. Herein a dynamic speed regulation policy for multi-ARTs based on distributed consistent cooperative control is proposed.

In order to realize the method proposed, a simulation model of dynamic speed regulation of the automated container terminals based on MAS is established, which includes the internal structure of ART agents and information interaction between the agents.

The unique points that differ this paper from the previous studies are as follows: Firstly, the congestion problem of multi-ART in the fully automated container terminals with parallel layout and side-loading operations is taken into consideration for study. Secondly, based on the distributed and intelligent characteristics of new devices such as ART, the multi-ARTs collaborative speed regulation mode is studied, and the ART's speed regulation is completed through the interactions and exchanges of the information between different ARTs. Finally, the agent consistency problem during the process of dynamic collaborative speed regulation of ART agent is considered, and the distributed consistency protocol is then embedded in to make sure that the agent state will tend to be aligned with the group of ARTs.

The simulation results show that the dynamic speed regulation strategy for multi-ARTs based on distributed consistent cooperative control can reduce the waiting time of ART at the QCs working area by 22.8% and to a certain extent improve the loading and unloading efficiency. Therefore, it is fully demonstrated by the simulation that the ahead-mentioned strategy can adapt to the requirements of new terminal operations, effectively utilize the operation characteristics of intelligent equipment such as ART, and improve the operation efficiency of horizontal layout and side loading ACTs under strict loading mode.

As the literatures shows, the optimization of operation in ACTs involves many interrelated and interactive aspects. In this paper, the waiting time of ART is mainly considered. But the joint optimization of the ART scheduling and container storage location should be taken into consideration in the future, so as to reduce the driving distance of the ART and the moving distance of the ARMG. In addition, in order to focus on the design of MAS and cooperative control strategy, it is assumed that the job priority is determined in advance. In future research, it can be considered to determine the priority according to the actual attributes of the containers. Finally, the findings shown in this paper indicate that the operation conditions of QCs and ARMGs will have an impact on the operation efficiency of the ARTs, which finally affects the overall operation efficiency of the ACT. So the collaborative scheduling problem between the ARTs, QC and ARMG should be added to the research list for the next steps.

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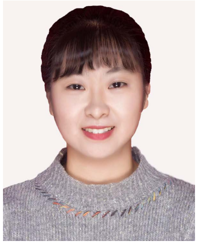

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