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Three-layer Architecture for Control and Routing of AGVs in the Mega Transshipment Automated Container Terminal

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Abstract

In the mega transshipment automated container terminal (mega-ACT), the operation scale of Automated Guided Vehicle (AGV) carrying the containers from the quayside to the yard-side or vice versa becomes very large and may cause a lot of potential conflicts, congestion and deadlock. A good scheme for control and routing of AGVs is thus needed to address these issues and should also have a positive impact on system efficiency and operation performance in terms of container throughput. In this paper, we propose a novel three-layer control architecture, which includes the global path direction design, dynamic junction coordination, and adaptive local junction control. The mathematical models in each layer are built to achieve the certain goals. Experiment study is conducted to verify the effectiveness of the overall model, from which related insights can be obtained for decision making by terminal operators. The results showed that the three-layer control architecture is promising in minimizing conflicts and congestion and improving system efficiency and operation performance.

Keywords
Automated Guided Vehicle, Large scale, Routing, Control architecture

1. Introduction
The introduction of high density mega automated container terminal (mega-ACT) shows several benefits on improving the terminal operation efficiency, reducing the handling costs and meeting the increasing demand in marine transportation [1]. Such a system contributes to a positive development of the operation mode which facilitates a fast transshipment of containers to and from the ships. When mega-ACT has been introduced, the corresponding automated equipment used in the system also needs to adjust their operations and control modes for it in order to obtain the efficiency.

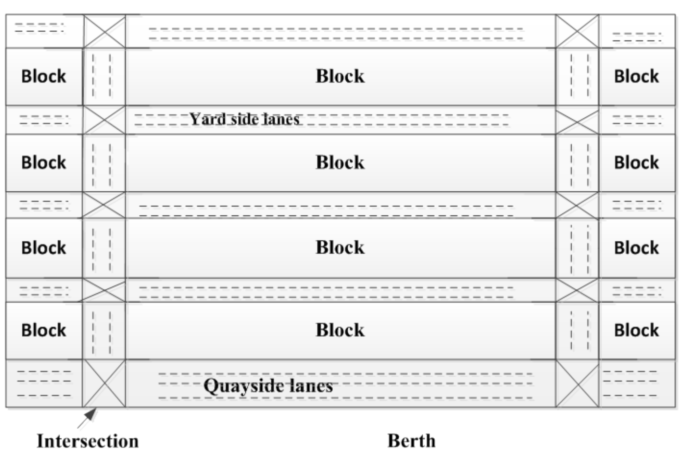

Figure 1 Part of the path network (AGVs System) showing one berth

The efficiency of automated container terminal highly depends on the smooth and efficient transporting of containers. Automated Guided Vehicles (AGVs) as the main automated transportation equipment are used in the automated container terminal (ACT) to carry the containers from the quayside to the yard storage area or vice versa. Due to the scale of terminal and complexity of AGV operations, a lot of potential conflicts, congestion and deadlock may be easily caused without proper control for these AGVs. In addition, transportation operations by AGVs play an important role for synchronizing operations of other automated equipment like cranes in port [2]. Therefore, to ensure a fast transshipment process, especially in such a mega terminal, a good control scheme for efficiency and a high degree of coordination is of major importance.

As shown in the Figure 1, the mega automated container terminal has particularly complex grid-like path topology with so many AGVs and much potential AGV interference. Three main factors, a large number of AGVs, a large number of alternative routes and a lot of safety constraints ensuring a conflict-free system, lead to new challenges for researchers and port operators. To the very best of our knowledge, there has been no study considering free-ranging AGV routing in such a large scale [3-5]. Moreover, an effective control mechanism for AGVs under a large scale problem were absent in these studies [6-10]. This study attempts to fill this gap, by considering free-ranging AGV routing in a large scale. Meanwhile, a new approach with three-layer architecture is proposed for control and routing of AGVs in the mega automated terminal to carry out the container transporting operations in an efficient way.

The rest of paper is organized as follows. The next section discusses the novel three-layer control architecture for control and routing of AGVs. In Section 4 numerical experiments are carried out and results are presented. Finally, the paper's findings and conclusions are reported in Section 5.

2. Methodology

The study proposes an approach with three-layer architecture (see Figure 2) in order to achieve good control of AGVs and the efficiency of system. First, layer one of path direction design is implemented globally not only to optimize the network design but also to balance the traffic flow over the whole network. Then, layer two introduces concept of "virtual traffic light" to facilitate the AGV movements in each junction and applies a coordination mechanism among these junctions to reduce delay and the number of stops for AGVs. The last layer is adaptive local junction control which is adopted to make sure each junction responsive to traffic flow and generate lane-based patterns to guide AGV and reduce the corresponding interactions among AGVs. These three layers are highly integrated from the view of system to control a large number of AGVs so that smooth and efficient transporting operations by AGVs can be finally achieved.

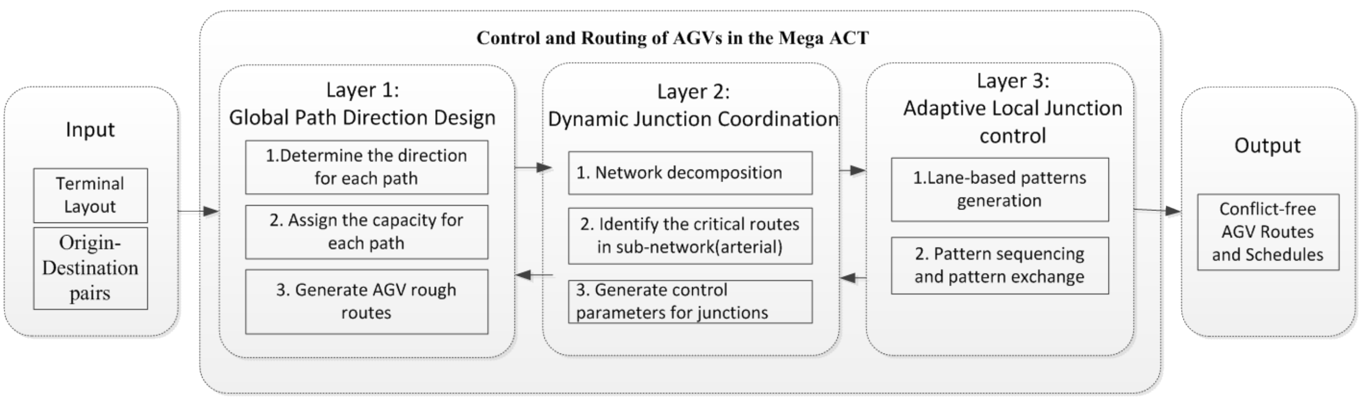

Figure 2: An overview of the approach with three-layer architecture

2.1 Layer 1: Global Path Direction Design

In layer one, an overall model is presented to determine the directions for all the paths given the input of transportation requests with Origin-Destination (O-D) pairs and terminal layout. The capacity plan for paths and the rough route (referring to traveling path with the absent of exact traveling lane and schedule) for O-D pairs are also determined by the model. The objective of the model is to minimize the total travel time. Three decision variables are introduced to control the path direction, to generate the capacity level and to decide the routes, respectively. A

set of constraints is introduced to establish the connections between the path direction and selected route and also enforces a traffic flow limit on the relevant paths. The related two-loop algorithm is used to efficiently solve above model.
The design of paths directions in the whole network (see Figure 3) is optimized to minimize the total travel time with the aim of reducing potential conflicts among AGVs in the terminal. The AGVs used in the system are fully free-ranging among tremendous routes. Thus, the potential conflicts among AGVs can be frequently caused because of completely routing freedom. The regulation of only allowing one direction for AGVs to travel on path then creates room for reduction of these conflicts among AGVs.

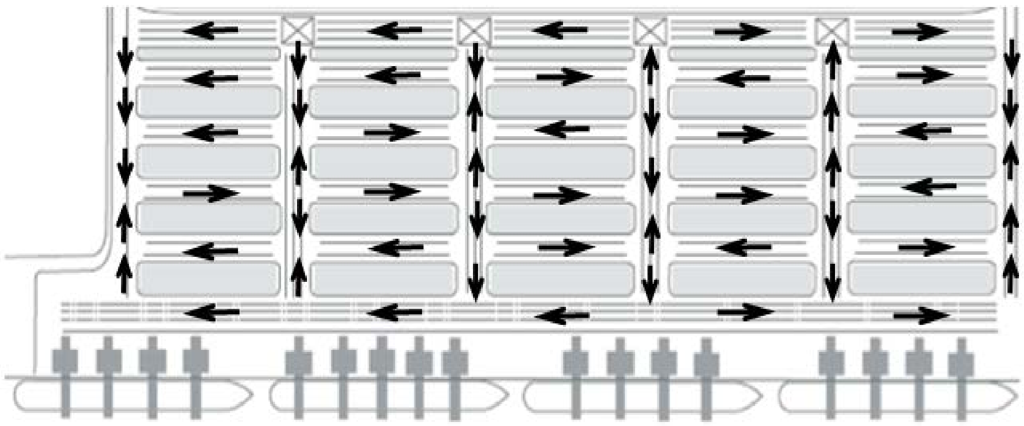

Figure 3: One sample of path direction design in the AGV-based mega automated container terminal.

To further mitigate congestion over the network, the other technique of workload balancing is also adopted in this layer. The balance of workload is then achieved by determining the capacity level for each path so that the AGVs are spread out over the whole network instead of concentrating on a few specific paths. To model of above AGV flow congestion, the estimated link travel time as a key indicator to reflect congestion is investigated. A combination of probabilistic and physics-based models for AGV interruptions is then used for evaluation of the expected link travel time [11].

The two techniques of directing paths and balancing workloads used in this planning layer not only allow modeling of congestion from the view of system and but also lay a foundation for the effectiveness and efficiency of routing AGVs in the latter execution layers.

2.2 Layer 2: Dynamic Junction Coordination
In layer two, the study mainly develops a model to coordinate the virtual “traffic lights” at junctions (see Figure 4). To well address traffic congestion at junctions, traffic control was regarded as one of the most efficient and effective ways [12-13]. Thus the virtual “traffic light” concept is naturally introduced in the study to guide AGVs pass the junction. Without coordination among these junctions, the delays and the number of stops for AGVs at junctions may still be great. The coordination model then becomes necessary to make virtual “traffic lights” function well and help facilitate the AGVs at junctions.

The overall coordination model includes two parts: network decomposition and a multi-route progression model. The solution generated from layer one is used as the input for the model in layer 2. The first part of network decomposition is about decomposing the network to several critical subnetworks or arterials. To partition the network, the priority index is introduced first. Then a decomposition algorithm is provided to order the principle subnetworks according to the priority index of each identified subnetwork [14]. The subnetwork with the highest index is continuously picked up until the whole network is formed.

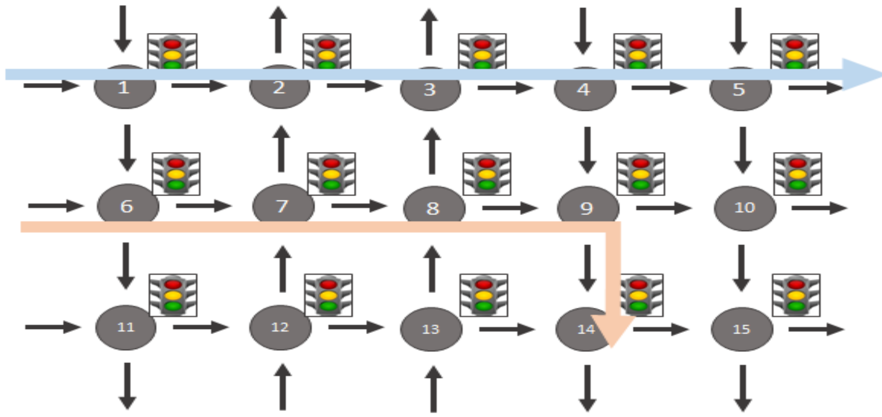

Figure 4: The progression provided for AGVs on two direction-oriented subnetworks (arterials).

The second part of the multi-route progression model is established to provide progression for AGVs on the specific direction-oriented subnetwork or arterial. In this multi-route progression model, the critical routes on each subnetwork or arterial are selected first according to their traffic flows and then green waves are provided for some of these routes on the subnetwork. For instance, in the Figure 4, two critical routes are selected and provided the progression on the subnetwork. The control parameters used to regulate these virtual "traffic lights" are treated as decision variables determined by the progression model, including the bandwidth, traffic patterns (see Figure 5) and pattern sequence.

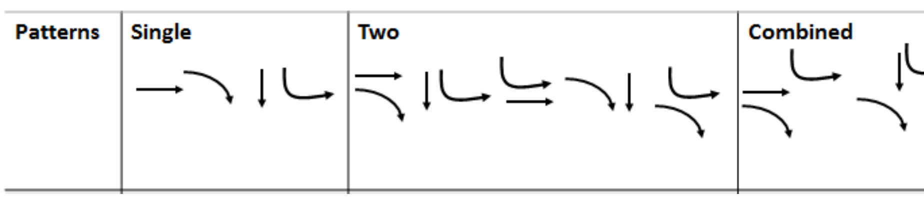

Figure 5: Some traffic patterns

2.3 Layer 3: Local Junction Traffic Control

The model in layer three mainly features a real time traffic control. The optimal control parameters including the lane-based patterns, their lengths and sequence are calculated for a short period. To minimize the performance measures, such as AGV delays or completion time can be the objectives of the model. Meanwhile, an exchange scheme for pattern sequence is developed to provide the flexibility to control the coming AGVs so that the delays and the number of stops is further reduced.

The current technology of real-time detection of AGV location makes the local junction traffic control becomes a practical and applicable strategy to help with the AGVs' guidance. As for the implementation of junction control, the junction reservation is used. The junction reservation is responsible for allocating time slots and movements calculated by the above mentioned model to coming AGVs.

2.4 Interaction Mechanism between Layers

The proposed approach with the three-layer architecture is highly integrated as shown in Figure 6. The main goal of this interaction mechanism is to guarantee the good control and routing of AGVs can be obtained through the comprehensive approach. First, the interaction mechanism helps with communication between layer 1 and 2. The path directions, capacity plan and rough routes for each O-D pair determined by layer 1 are used as the input for layer 2. The dynamic feedback information such as control parameters from layer 2 are sent to layer 1 to request for rerouting and redesigning. Similarly, a connection is built by the interaction mechanism between layer 2 and 3 to exchange the control parameters and status of AGV flow. The actual flow in each link can be captured from layer 3 to update the priority index for routes and then applies to the coordination model again.

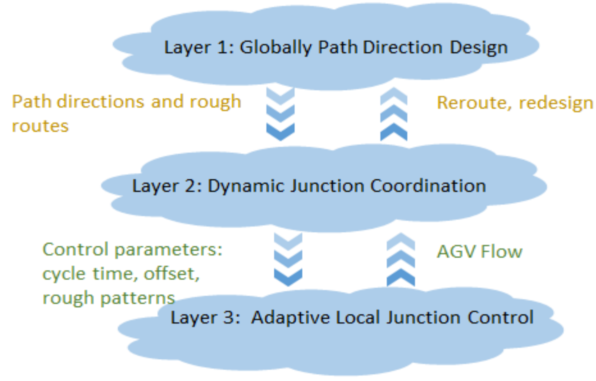

Figure 6: The interaction between layers

3. Experiment and Results

Due to the scope of this paper, the experiment and results presented here are limited to analyzing and evaluating the control and routing strategies in the first two layers with further analysis reserved for future work. Up to date, the proposed path directing and junction coordination to improve system efficiency has been implemented through simulation. The strategy of adaptive local control junction is awaiting further test. The test case used to evaluate the proposed strategies is shown in Table 1. A simulation of the path directing and coordination strategies was carried out to compare with the simulation of normal bidirectional paths and non-coordination. Table 2 shows a higher system performance resulting from the application of the path directing and coordination strategies. The range of average travel time changed from 482.36s to 411.48s, a reduction of 14.7%. Results from the simulation suggested that the control and routing strategies of path directing and coordination were effective to reduce congestion and improve the system performance.

Table 1: The details of test case

The area of each block	300 m * 70 m	The number of junctions	96
Length of one intersection	24m	The number of AGVs	96
Travel speed	4m/s	Turning speed	2m/s

Table 2: System performance under the path directing and coordination strategies

Measurements	Simulation without the path directing and coordination strategies	Simulation with the path directing and coordination strategies
Average travel time	482.36s	411.48s

4. Conclusions

The paper proposes a novel approach with three-layer architecture for control and routing AGVs in the mega transshipment automated container terminal. A simulation was carried out to illustrate the control strategies of path directing and junction coordination was a promising way to improve the system efficiency and reduce routing conflicts and congestion. At this moment, there are some limitations for current work and more future study is needed. One of the limitations is the setting of capacity levels of path which may need more information from the port operators to verify. Another limitation may result from the lack of simulation of adaptive local junction control strategy. A future study could consider carrying out the simulation of the integrated strategies in three layers so that we can obtain a more comprehensive understanding of the proposed overall approach.

Acknowledgement

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