Control Strategy of RGV Operation Blockage and Deadlock in Plane Mobile Stereo Garage

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Abstract. Aiming at the safety requirements of multi-RGV and multi-lift planar mobile stereo garage access vehicles, a time window-based system RGV operation blocking and deadlock control strategy is proposed. Combining the improved banker algorithm with the time window principle, the banker algorithm is used to evaluate the security of the RGV running path. If an unsafe state is detected, the RGV operation blocking and deadlock control strategy based on the time window algorithm is given. The verification is detailed through specific cases. The results show that the RGV operation blocking and deadlock control strategy proposed in this paper can improve the RGV operation efficiency while increasing the system security.

1. Introduction
Plane mobile stereo garage play an increasingly important role in solving urban static traffic problems. The increasing number of cars and the scarcity of land resources have promoted the development of plane mobile stereo garage. At the same time, Plane mobile stereo garage has shortened the access time of vehicles to a certain extent and reduced the waste of resources. However, it also has certain limitations. For example, many Rail Guided Vehicles (RGV) have blocking and deadlock problems during operation, resulting in low garage operation efficiency and long customer waiting time.

Regarding the blocking and deadlock of the RGV in the AVS/RS system, Yunsoo Ha et al. [1] explained the reasons for the above problems. Zhao Ning et al. [2] proposed to set all aisles to one-way operation in the plane mobile stereo garage system to avoid system deadlock. Martina et al. [3] reduced the blocking in the system by changing the running speed of RGV. He Lina et al. [4] used time windows to generate multi-RGV conflict-free paths. Wu Changqing et al. [5] proposed a deadlock control method based on Petri net and directed graph in order to prevent the loop deadlock phenomenon of the track guidance car in the automatic car access system.

This paper proposes an improved banker algorithm combined with the time window model to improve the operating efficiency of the Plane mobile stereo garage while avoiding blocking and deadlock. First, the operation path is obtained according to the allocation of each access vehicle operation; then the improved banker algorithm is used to detect whether RGV is blocked or deadlocked at a certain path or node; finally, the time window method is used to eliminate the occurrence of the operation process. The blocking and deadlock phenomenon ensures the safety and efficient operation of the garage.

2. Description of Movement State of Stereo Garage
This paper takes a plane mobile stereo garage in Beijing as an example. The structure of the garage is shown in figure 1. It consists of 9 rows and 21 columns with 2 rows of parking spaces. RGV is used to
realize the horizontal movement of the vehicle on each floor of the Aisle. There are 4 RGVs, \( RGV_1 \), \( RGV_2 \), \( RGV_3 \) and \( RGV_4 \) in the garage. Lifts are on both sides of the garage, which are used for loading RGV and car cross-layer movement between different floors.

**Figure 1.** Plane mobile stereo garage schematic.

In the AVS/RS system, there are two types of operations: customer storage operations and customer pickup operations. Customer storage refers to cooperating with the lift to transport the vehicles to be stored from the I/O port location to the designated storage garage location; customer pickup is to transport the vehicle to be removed from the designated storage garage location to the I/O port location [6]. It can be seen that RGV is one of the core equipment for the operation of a plane mobile stereo garage, which has a direct impact on the operation efficiency of the garage. Therefore, reducing the blocking of RGV in the garage and eliminating the deadlock of RGV in the garage are the guarantee of the plane mobile stereo garage. In the AVS/RS system, all storage tasks start from the I/O port, and the storage of the vehicle to the designated parking space ends. All car pickup tasks start from the storage location, and the transportation of the vehicle to the I/O port ends. The flow chart of the access car operation process is shown in figure 2 and figure 3.

**Figure 2.** flow chart of car storage operation.  
**Figure 3.** flow chart of car picking operation.

3. Multi-RGV Environment Generation of Stereo Garage  
In this paper, the driving environment of the RGV route is based on graph theory and uses a directed graph \( G=(V,E) \), where
$V = \{n_1, n_2, n_3, \ldots, n_n\}$ Represents a series of nodes, $E = \{a_1, a_2, a_3, \ldots, a_n\}$ Represents a series of weighted edges [7]. Compared with the plane mobile stereo garage, the node $V$ represents the upper and lower station points, and the edge weight $E$ is the length of the effective path between each node. The following provisions are made in the article:

1. All road sections in the plane mobile stereo garage are single-way roads that can run in both directions. RGV can only occupy one road section in the same time period.
2. In a certain state on the route, the vehicle travels at a constant speed.
3. The load capacity of RGV is 1, and after receiving a request to store or pick up a car, the next command can only be received after completing the task.
4. It is irrespective of the deceleration time and acceleration time of RGV traveling to or from the intersection.
5. It does not consider the time for RGV to load and unload vehicles during work.

4. Conflict Detection based on Banker Algorithm System

4.1. Bankers Algorithm

Bankers Algorithm is a well-known algorithm designed by T.H.E to avoid deadlocks in 1965 by Izig Dijkstra [8]. When the basic banker algorithm is used to detect the system, it will detect whether the RGV is blocked or deadlocked with other RGVs in a certain section of the path, that is, the security assessment of the specified RGV operating path. If an unsafe condition is detected, that is, a conflict will occur between RGVs of a certain path, the algorithm needs to select other alternative paths. Once all alternative paths are unqualified, it is necessary to return to find the feasible path again. The blocking and deadlock between RGVs in the system are avoided, but the amount of online calculation is increased, so this algorithm cannot meet the flexibility requirements of the multi-RGV multi-lift system in the plane mobile stereo garage.

4.2. Improved Banker Algorithm

In the example of the plane mobile stereo garage mentioned in this article, each layer of the system contains 65 directional paths $l_1, l_2, l_3, \ldots, l_{65}$ and 66 nodes $A_1, A_2, A_3, \ldots, A_{66}$. The local node path of the first floor of the garage is shown in figure 4.

![Figure 4. Garage single floor plan.](image)

Suppose $L_i$ is the path traversed by the $i$ th RGV and $N_i$ is the path matrix of the $i$ th RGV. The path usage of the RGV on the first floor in the garage is represented by the first row of the path matrix, and the path usage of the second floor represented by the second row, and so on, each row of the matrix has 65 elements, representing 65 paths of the layer. $H_i$ is the first path occupation matrix. The elements of the above matrix are all represented in binary, and the occupied road sections are represented by "1", otherwise, they are represented by "0". For example, if the $RGV_i$ on the first level wants to reach $A_{38}$ from $A_1$, then the path it passes through is $L_1 = \{l_1, l_{23}, l_{24}, l_{25}, l_{47}\}$, and the
1, 23, 24, 25, and 47 elements in the first row of its path matrix $N_i$ are "1", and the rest The elements are all "0". The 1, 12, 24, and 35 elements in the first row of the path occupancy matrix $H_i$ at the current position are "1", and the remaining elements are "0", then comparing the path matrix $N_i$ and the path occupancy matrix $H_i$, $RGV_i$ There may be conflicts with other RGVs on section $l_i$ and section $l_{24}$. Although the above algorithm can determine whether the RGV operation blocking and deadlock will occur in the same road segment in a certain operation stage, it cannot determine the RGV deadlock at the node.

For example, the existing $RGV_1$ and $RGV_2$ are located on the first floor of the garage. In the same time period, the former must go from $A_i$ to $A_{46}$ and the latter from $A_{25}$ to $A_2$. There is no conflict in the running paths of the two, but it may happen at node $A_{24}$. Therefore, this paper introduces a node matrix. The RGV with a higher path length priority has priority to occupy the node, and the RGV with a lower priority waits for the former to pass before entering the node.

In the above algorithm, the path matrix and the node matrix are introduced, which not only detects the collision of the road segment and the node that the RGV passes, but also reduces the amount of online calculation of the system.

4.3. Judgment of Blocking and Deadlock Types

The blocking and deadlock phenomenon in the plane mobile stereo garage was described in this paper. Referring to the phenomenon that two or more RGVs overlap on the path (node) on the same floor of the garage at the same time period [9], the operation of RGV The types of blocking and deadlock are mainly divided into 5 categories, as shown in figure 5.

(a) Node deadlock (the number of identical nodes is 1)
(b) Single path is blocked (the number of the same path is 1 and the order of the same node is the same)
(c) Single path deadlock (the number of the same path is 1 and the order of the same node is reversed)
(d) Multiple paths are blocked (the number of identical paths is greater than 1 and the order of the same nodes is the same)
(e) Multiple path deadlocks (the number of the same path is greater than 1 and the order of the same nodes is reversed)

![Figure 5. Single layer conflict type.](image)

5. Time Window-based Blocking and Deadlock Elimination

5.1. Time Window Model

In order to avoid RGV operation jams and deadlocks in the two-way single-lane plane mobile stereo garage, it is necessary to determine the time period occupied by each RGV operation on the road segment. The meaning refers to the time period from when RGV enters a certain path to when it leaves
the path, during which RGV is given the right to use the path in a certain direction [10].

The core of the time window model is the starting time point of RGV entering a road segment and the ending time point of leaving the road segment [11], so the time window model after determining the RGV working path in this article is as follows:

\[ T = \left\{ t^m_{jk} = [t^{ms}_{jk}, t^{me}_{jk}] \right\} \] (1)

where \( t^m_{jk} \) is the \( m \)th time window of the path \( jk \); \( t^{ms}_{jk} \) is the start time of the \( m \)th time window of the path \( jk \); \( t^{me}_{jk} \) is the end time of the \( m \)th time window of the path \( jk \).

### 5.2. Time Window Calculation

The basic condition of the time window is an accurate time point, so the calculation of time is crucial [12]. This article assumes that the RGV travels at a constant speed of \( V_S \) and its own length is \( L_R \). If two or more RGVs meet at an intersection, a node deadlock will occur, then the time after passing this node is recorded as:

\[ t_n = \frac{L_n + \frac{L_R}{2}}{V_S} \] (2)

In the above equation, \( L_n \) is the path length RGV traverses.

Next, the time taken by RGV to pass through the straight line segment is given. Suppose that the length of the road segment between RGV passing through \( ij \) is \( L(i, j) \), and the time it takes to pass through the road segment is \( t_{ij} \), then the equation for calculating \( t_{ij} \) is as follows:

\[ t_{ij} = \frac{L(i, j) - L_R}{V_S} \] (3)

### 5.3. RGV Operation Blocking and Deadlock Solution

In this paper, the method of extending the time window and setting the priority of the path length is used to eliminate the blocking and deadlock in the garage. Each RGV receives different access vehicle tasks, and their running paths and distances are also different. Then, according to the length of their running paths, the priority is sorted. The longest running path has the highest priority, and vice versa. The extended time window is to let the low priority RGV wait at the node when a conflict occurs so that the higher priority RGV first passes through the overlapping path (node), but the running speed of the RGV does not change throughout the process.

For node deadlock, since the RGV only conflicts with a certain node during the entire operation process, the RGV with a lower priority of the extension path length can pass the time window of the path between the deadlock node and the previous node. The extension time is the time of the path.

For a single path blocking (deadlock), because the RGV conflicts between a certain path and the nodes included in the path during the entire operation process, the RGV with a lower priority of the extension path length is on the node. Where the blocking (deadlock) occurs A node's time window is sufficient, and the extension time is the time through overlapping paths.

For multiple path congestion, since the path of RGV conflict and the number of nodes included in the path are greater than 1, the length of the RGV with the lower priority of the extended path length is the time of the previous node of the first blocked node. And the extension time is the time through all overlapping paths.

For multiple path deadlocks, consider two cases. The path of RGV conflict and the number of nodes included in the path are greater than 1. If the running path of a certain RGV is short, it is only owned by another RGV. For a part of the running path, the latter should be passed first, that is, the time...
The window of the former node at the first deadlock node should be extended, and the extended time should be the time for the latter to pass through all overlapping paths; if the two are only partially present, when the path nodes overlap, the time window of the previous node of the first deadlocked RGV with a lower priority is extended, and the extended time is the time for the latter to pass all overlapping paths.

The extended time window is to let the lower priority RGV wait at the previous node (path) of the conflicting node (path), and in the waiting process, the RGV may occur at the node (path) with other RGVs. Therefore, when updating the path matrix, path occupancy matrix, and node matrix of the RGV in a planar mobile three-dimensional garage, the previous node (path) of the node (path) that may have conflicted is also marked as occupied.

6. RGV Operation Blocking and Deadlock Control Strategy

From the analysis in the previous section, we can see that when the operating plan of the system is given, blocking and deadlock detection are required and corresponding solutions are given.

6.1. RGV Operation Blocking and Deadlock Control Strategy

Step 1: Determine each operation path in the plane mobile three-dimensional garage, and obtain each path and node, occupied path and occupied node matrix according to the improved banker algorithm described in Section 3.2 in the article.

Step 2: Compare each path matrix and path occupancy matrix, node matrix and node occupancy matrix. If there is a phenomenon of overlapping nodes or paths, judge according to the types of blocking and deadlock mentioned in Section 3.3. If there is no such situation, then exit the program.

Step 3: Find the previous node (path) of the conflicting node (path) and set the node (path) to the occupied state.

Step 4: Adjust the time window according to the method described in Section 4.3 until all paths (nodes) are free of blocking and deadlock. If not, exit the program.

6.2. Algorithm Example Verification

This article gives examples of the five types of blocking and deadlock that may occur in the plane mobile three-dimensional garage given in Section 3.3, and eliminates them according to the methods described in Section 4.3.

The \( i \) th task \( M_i \) defined first is \( M_i = \{ O_i, d_i, L_i, P_i(t), R_k \} \).

In the equation: \( O_i \) and \( d_i \) are the start and end of the RGV running path, \( R_k \) is the number of the RGV undertaking the task, \( L_i \) is the running path of the entire RGV operation process, and \( P_i(t) \) is the dynamic priority of the \( i \) th RGV running path length, value. The larger the priority, the higher the priority.

Intercepting the task parameters in the garage during certain periods of time are:

First group: \( M_1 = \{ P_6A_6, P_1A_1, L_4, 2, RGV_1 \} \), \( M_2 = \{ P_6A_6, P_1A_1, L_2, 1, RGV_2 \} \)

Second Group: \( M_2 = \{ P_6A_6, P_1A_1, L_2, 1, RGV_2 \} \), \( M_3 = \{ P_3A_2, P_1A_1, L_3, 2, RGV_3 \} \)

The third group: \( M_1 = \{ P_3A_3, P_1A_1, L_4, 1, RGV_1 \} \), \( M_4 = \{ P_1A_1, P_1A_1, L_4, 2, RGV_4 \} \)

Fourth group: \( M_2 = \{ P_3A_3, P_3A_4, L_4, 2, RGV_2 \} \), \( M_4 = \{ P_3A_3, P_1A_1, L_4, 1, RGV_4 \} \)

Fifth group: \( M_2 = \{ P_3A_3, P_3A_4, L_4, 2, RGV_2 \} \), \( M_3 = \{ P_3A_3, P_1A_1, L_3, 1, RGV_3 \} \)

Among them, for the task \( M_1 \) in the first group, the starting position of \( RGV_1 \) is \( P_6A_6 \) (node 6 of layer 6), and the final arrival position is \( P_1A_1 \), the current position of \( RGV_1 \) is \( P_6A_6 \), and the task priority is 2.
During these time periods, the system is found to be pre-blocked or pre-deadlocked. The time window for the blocked or deadlocked path (node) is shown in figure 6.

As shown in (a) of figure 6, $RGV_1$ and $RGV_3$ will have node deadlock at $P_6A_{28}$. According to Section 5.1, the time window of $RGV_1$ at node $P_6A_6$ needs to be extended by 2s.

It can be seen from (b) that $RGV_2$ and $RGV_4$ are deadlocked at $P_1A_{43} - P_1A_{44}$, so the time window of RGV3 at $P_1A_9$ node should be extended by 6 s, and the time window of $RGV_3$'s subsequent road sections should be updated at the same time.

From (c), it can be seen that $RGV_1$ and $RGV_4$ are blocked in $P_2A_{33} - P_2A_{32}$, so $RGV_4$ should be allowed to wait for 18s at node $P_2A_{23}$ (node $P_2A_{23}$ is the starting operating position of $RGV_4$), and the time window of the previous node on the conflicting node cannot be extended. So wait at the starting position) and update the time window of the subsequent road segment of $RGV_4$ at the same time.

It can be seen from (d) that $RGV_2$ and $RGV_4$ are blocked at $P_4A_{40} - P_4A_{44}$ and $P_4A_{44} - P_4A_{43}$, so the time window of $RGV_2$ at node $P_4A_{39}$ should be extended by 12s, and the time window of the subsequent road segments of $RGV_2$ should be updated at the same time.

Figure 6. Conflicts and deadlocks judgment based on time window.
It can be seen from (e) that $RGV_2$ and $RGV_3$ have two deadlocks at different times in the $P_6A_43 \sim P_6A_35$ segments, so the time window of $RGV_2$ at the node $P_6A_43$ should be extended by 12 s, and at the same time update the $RGV_2$ subsequent segment time window.

The above five types of blocking and deadlock phenomenon elimination results are shown in figure 7.

![Node deadlock elimination result](image)

(a) Node deadlock elimination result

![Single path deadlock elimination result](image)

(b) Single path deadlock elimination result

![Single path blocking elimination result](image)

(c) Single path blocking elimination result

![Multiple path blocking elimination result](image)

(d) Multiple path blocking elimination result

![Multiple path deadlock elimination result](image)

(e) Multiple path deadlock elimination result

**Figure 7.** Conflicts and deadlocks eliminate results based on the time window.

It can be seen from the above figure that the RGV operation blocking and deadlock control strategy based on the improved banker algorithm combined with the time window can effectively solve the problem of conflicts between RGVs in the plane mobile stereo garage.

**7. Conclusion**

This paper proposes a control strategy for RGV operation blocking and deadlock based on improved banker algorithm combined with time window method. Use the improved banker algorithm to detect the blocking and deadlock in the system and make a pre-judgment, and then use the method of extending the time window to eliminate the blocking and deadlock. This method increases the operating efficiency of RGV and also improve system safety performance and utilization.

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