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A simulation study of a bi-directional load-exchangeable automated guided vehicle system ☆

Che-Fu Hsueh

Department of Marketing and Distribution Management, Ching Yun University, Taoyuan 32097, Taiwan

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ABSTRACT

This paper proposes a new design for a bi-directional automated guided vehicle (AGV) system, in which two AGVs can exchange their loads, their scheduled transportation tasks, and even their vehicle numbers when they move in opposite directions. With this load-exchangeable AGV (EX-AGV) system, common problems such as conflicts and deadlocks will not occur; therefore, the load of an AGV is always on its shortest path, resulting in higher system performance and avoiding unnecessary waiting times and detours. An off-line mathematical model and on-line control rules are proposed for the EX-AGV system. A series of simulation experiments is carried out; the results show that the EX-AGV system performs efficiently and robustly.

1. Introduction

Automated guided vehicles (AGVs) are advanced material handling devices used to transport goods and materials between workstations and storehouses of an automated manufacturing system. AGVs involve at least one driverless automated guided vehicle. Each vehicle travels on pre-determined guidepaths, and its routings can be altered arbitrarily according to transportation requests. Thus, an AGV system possesses more flexibility and capacity then other conventional material-handing systems and plays an important role in the flexible manufacturing systems (FMS).

If the AGVs can move in only one direction, the system is *unidirectional*. In contrast, if the AGVs are authorized to traverse a lane in two opposite directions, the system is *bi-directional*. A bi-directional AGV system can considerably improve the performance of a manufacturing system. However, these advantages are accompanied by increased risk of potential conflicts.

Several vehicle management problems (such as conflicts, deadlocks, collisions, blockings, etc.) may arise in the AGV system. For example, if the AGVs moving in opposite directions are forced to stop in front of each other, vehicle blocking occurs, and no further transport is possible. Without manual intervention, a deadlock situation is created. Deadlocks can also occur at buffer areas of pick-up and delivery points. If a load is available for transport at a pick-up and delivery point and a loaded AGV is in line before an empty AGV, then the loaded AGV cannot be unloaded, and the new load cannot be transported. Once these problems occur, the material and vehicle flows may be blocked, and work will stall until a recovery procedure can be performed; this results in low throughput, loss of control, and shut-down of the overall system. Therefore, these vehicle management problems must be carefully considered in the operation and construction of an AGV system.

Readers can refer to a thorough survey conducted by Vis (2006) for more information about research in AGV systems. Generally speaking, there are three methods in the literature to avoid conflicts and deadlocks: design the layout of guidepaths in such a way that conflicts and deadlocks are avoided; divide the traffic area into several non-overlapping control zones; or develop routing strategies to prevent conflicts and deadlocks. We briefly introduce each of these methods.

In the design of guidepath, three types of layouts can avoid conflicts and deadlocks: *single loop*, *tandem configurations*, and *segmented flow configurations*. First, in a single loop layout, several vehicles travel in a unidirectional loop. The disadvantages include lower throughput; moreover, once an AGV breaks down, the loop is unusable. Second, a tandem configuration design consists of non-overlapping single vehicle loops with transfer stations in between. This layout is proposed by Bozer and Srinivasan (1989) and Bozer and Srinivasan (1991, 1992). Building on this, Hsieh and Shah (1996) present a model to design tandem AGV systems while minimizing the number of loops. Similarly, Kim and Chung (2007) present an analytical model to design a tandem AGV system with two-load AGVs. Third, Sinriech and Tanchoco (1995) introduce the segmented flowpath layout, which consists of one or more mutually independent zones. Each zone is separated into

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E-mail address: cfhsueh@cyu.edu.tw

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non-overlapping segments, and each segment is served by a single AGV. Between the ends of two segments, stations are located where loads can be transferred from one AGV to another. Methods to design this kind of layout have been described by Barad and Sinriech (1998) and Sinriech and Tanchoco (1997). Asef-Vaziri and Goetschalckx (2008) develop integer programming models for the simultaneous design of guidepath tracks and locations of pick-up and dropoff stations. Two alternative bi-directional topologies are compared: a dual track loop and a single track loop partitioned into non-overlapping segments.

Lee and Lin (1995) propose an algorithm to avoid deadlocks in unidirectional control zone networks. Petri Nets are used to represent the current state and generate future states of the system to analyze deadlocks. The algorithm, which includes deadlock prediction and traveling decisions, should be executed each time that an AGV tries to travel from one zone to another. Yeh and Yeh (1998) also address deadlock problems of unidirectional control zone AGV systems and propose an algorithm to deal with it. The current states of the system are represented in a directed graph, which can also be used to generate future states of the system. The algorithm should be applied each time that a vehicle travels to a new zone and looks ahead to all future zones that have to be traveled by the vehicle. Different from fixed-zone strategies, Ho (2000) develop a strategy for vehicle-collision prevention and load balancing in an AGV system with a single-loop guidepath. With this dynamic zone strategy, zones are redesigned during operation to avoid significant differences in workload. In addition, Moorthy, Wee, Ng, and Teo (2003) study the prediction and avoidance of deadlocks for a zone-controlled AGV system at a container terminal and propose a new cyclic detection algorithm that dynamically projects the position of each vehicle after one zone step and detects chains of vehicles requesting zones in cyclic form. Most papers discussing deadlocks prediction and avoidance for zone-controlled AGV systems are based on unidirectional guidepath design.

For conflict-free routing of bi-directional AGV systems, Kim and Tanchoco (1991) develop an efficient algorithm for finding the shortest time routes. They introduce the concept of the time window graph, in which the node set represents free time windows and the arc set represents reachability between the free time windows. Nevertheless, the algorithm has a major drawback: it is not robust, and conflicts may occur if the scheduled arrival or departure times are not fulfilled because of the unpredictable disturbances. To avoid this situation, Maza and Castagna (2005) propose a two-stage robust control for conflict-free routing of bi-directional AGV systems. In the first stage, a pre-planning method (Kim & Tanchoco, 1991) to establish the fastest conflict-free routes for AGVs is adopted; in the second stage, conflicts are avoided in a real-time manner when needed. Similarly, Nishi, Ando, and Konishi (2006) present a local rescheduling procedure for the distributed routing system of multiple AGVs in dynamic environments where requests for transportation are given in real time. Nishi, Morinaka, and Konishi (2007) also propose a distributed routing method under motion delay disturbance for multiple AGVs. In this method, each AGV derives its optimal route to minimize the sum of the transportation time and the penalties with respect to collision probability with other AGVs.

Most of these methods require additional waiting time or moving along a longer route; as a result, system performance decreases. In this paper, we intend to develop a new AGV system, in which every AGV can always move along the shortest path and does not have to wait at the zone boundary or detour to a longer route. To achieve this objective, we propose a load-exchangeable AGV (EX-AGV) system that allows two AGVs to exchange their loads, their scheduled tasks, and even their vehicle numbers when they move in opposite directions and stop in front of each other. The remainder of the paper is organized as follows. Section 2 provides descriptions of the EX-AGV system. A mathematical model and a solution algorithm framework for off-line control of EX-AGV are proposed in Section 3. In Section 4, on-line control rules of EX-AGV are discussed. Simulation studies are performed in Section 5, and the paper concludes in Section 6.

2. Descriptions of the EX-AGV system

The EX-AGV system is designed as an advanced material handling system for a flexible manufacturing system. The unique feature of an EX-AGV is the ability to exchange loads. Once the AGVs can exchange their loads, conflicts and deadlocks will not occur; therefore, the load of an AGV is always on its shortest path, resulting in higher system performance. For successful deployment of the EX-AGV system, the AGVs should be designed with the following requirements: (1) on-board microprocessors; (2) obstacle sensors and wireless communication; and (3) mechanical operation to exchange loads on two adjacent AGVs. The technology required for making an EX-AGV is attainable today, such as obstacle sensors, radio frequency identification (RFID), wireless communication, traditional AGVs, and so on.

An on-board microprocessor can store information such as transportation tasks and initiate actions according to the environment after performing computations. With attached sensors, an AGV can tell whether an obstacle or another AGV is in front and how far it is. A workstation/storehouse can assign transportation tasks to an AGV through wireless communication. An AGV can also exchange information with other AGVs through wireless communication. Since mechanical operation to exchange loads on two AGVs has not been presented in the literature, we illustrate a feasible design of such an EX-AGV in Fig. 1.

At most times, the EX-AGV is in normal mode. When two loaded EX-AGVs are approaching each other, they automatically switch to stretching mode. That is, the EX-AGVs extend to twice their width in order to accommodate two loads simultaneously and to exchange loads. When exchange operation is complete, the EX-AGV returns to normal mode. Other kinds of EX-AGV may be designed; the above-mentioned EX-AGV is just one possible form. When two EX-AGVs are approaching, they can exchange their transportation tasks and/or loads. Three situations of EX-AGV exchange

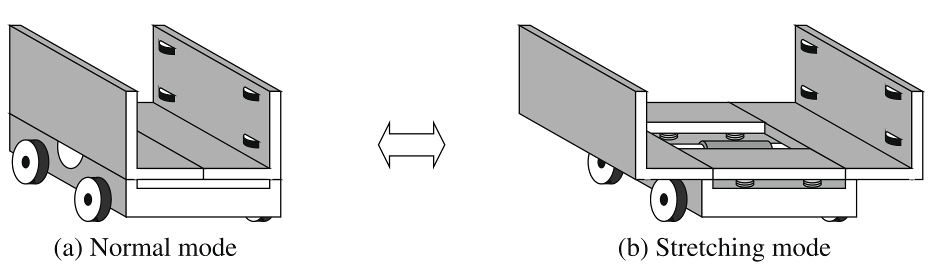

Fig. 1. Design of EX-AGV. (a) Normal mode. (b) Stretching mode.