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AGVS Mechanism

Suhua Hsieh and Kuei-Huang Max Lin

Department of Mechanical Engineering, National Taiwan University, No. 1 Roosevelt Road Sec. 4, Taipei, Taiwan 10764, Republic of China

This paper presents a new terminology, "the AGVS mechanism" , and a three-stage design concept for achieving a robust AGVS mechanism. The definition of the AGVS mechanism will be given first. The three-stage design concept, which includes the composite-floor-path system, the cell control system and the collision-free zone control system, will also be described in this paper.

Keywords: AGVS; Cell control; Collision free, Floor path; Travel mechanism

1. Introduction

The definition of a flexible manufacturing system (FMS), according to Groover [1] is that it is capable of processing a variety of different types of parts simultaneously under NC program control at various workstations. The material flow in such a system may change from time to time depending on the manufacturing process of the product which is being produced. Therefore, the material handling system should be able to perform random transportations of workparts between workstations.

An automated guided vehicle system (AGVS) is thought to be the most suitable material handling system for the FMS owing to its potential flexibility. The desired flexibility of the AGVS has to be determined and designed before the system is built. The material handling system physically integrates the manufacturing cells and the storage/retrieval system. Therefore, any activities in the manufacturing system may directly or indirectly affect the performance of the AGVS. The achievement of the desired flexibility of the AGVS does not have a trivial solution, and should be determined by considering many different aspects. Once the desired flexibility is determined, the transportation system must be able to move parts as required within the system. The designer has to embed this flexibility somewhere in the system. Should the "somewhere" be a device, a control algorithm, or the result of a combination of hardware and software?

Two similar machines may have totally different ways of operating. One may be convenient, and the other may not. This is because different machine structures are the result of different design concepts. The daily on-line control algorithm of the AGVS is dependent on the existing flow path and path guidance control system. An AGVS with simple flow path patterns may need a complex on-line control algorithm to enhance its capabilities. A complex flow pattern system may need an even more complex control algorithm to achieve full system capability. Complex operation methods lead to inefficient system performance and high operating cost. The capability is what users expect, and the inefficiency and high cost are what they would like to prevent. How can the AGVS users have a system with one "F" (flexible) capability and two "E" (efficient and economic) requirements?

To answer the above questions, we propose a new concept, which is "the AGVS mechanism". In an AGVS, those, as long as they are built-in and dealing with the transferring of workparts from one station to any other station, belong to the AGVS mechanism. Generally speaking, the AGVS mechanism has two important parts. One is to load (unload) workparts from a station (vehicle) to a vehicle (station), which is the transfer mechanism; the other is to transport workparts from one station to any other station, which is the travel mechanism. A city with a well-designed transportation network system can reduce its traffic problems. An AGVS with a well-designed transportation network system may also decrease those conflicts which arise from the interactions of manufacturing system activities. The transportation network is the main structure of the travel mechanism. A robust travel mechanism is the answer to the above questions.

The machine mechanism has been studied by the application of physical laws governing the motion of parts and the forces transmitted by these parts, but the concept of the AGVS mechanism is new. The system environmental effects on the machine have also been extensively studied. The work emphasised the development of the AGVS components; little effort has been put into the integration of the AGVS components. A successful integration means a good combination of the system components. A good combination of the AGVS components leads to a robust AGVS mechanism.

Correspondence and offprint requests to: Dr Suhua Hsieh, Department of Mechanical Engineering, National Taiwan University, No. 1 Roosevelt Road Sec. 4, Taipei, Taiwan 10764, Republic of China.

The purpose of this paper is, first, to define what the AGVS mechanism is, and, secondly, to propose a three-stage design concept to achieve a robust AGVS mechanism. Because the AGVS environment is usually an FMS, a variety of material flows have to be included. A composite floor path system, which consists of several different flow path patterns, is suggested for use in the first stage, so that the system can choose the desired flow path pattern at any moment. A hierarchically distributed control system is then used to divide the system workload evenly among several cell controllers in the second stage. The original complicated system is divided into many simple subsystems. The last question is how to control a small AGV cell. A method of constructing a collision-free system is suggested in the third stage. By the use of this three-stage design concept, a robust AGVS travel mechanism can be achieved step by step.

2. Definition of AGVS Mechanism

A machine can be viewed as a combination of parts, which have a known motion relative to each other, and are arranged to do a desired form of work. The AGVS, which accomplishes the task of material handling without human operators, can be regarded as a large machine. It consists of three basic physical components (the vehicle, the flow path, and the load transferring system) and two basic information components (the vehicle control and the traffic control systems) [2]. These components have a known action relative to each other, and are so interrelated to do the work of material handling.

The study of the machine mechanism uses the laws governing the motion of the parts of a machine and the forces transmitted by these parts. Since the nature of the motion does not depend upon the physical dimensions (strength, mass, volume) of the moving parts, the study can be divided into two parts:

1. Kinematics is the study of the relative motion of machine parts.
2. Dynamics deals with the forces acting on the parts of a machine.

The object of an AGVS is to transport workparts to the right place at the right time by the correct route. The movements of workparts are realised through the motion of individual vehicles. Since the vehicle motion does not depend on the vehicle dimensions, the study of the AGVS mechanism deals only with the rules governing the motion of individual vehicles, and the quantity of workparts carried by these vehicles. The study of the AGVS mechanism will be divided into two parts. One is the relative motion between three physical components, which are vehicles relative to flow paths, vehicles relative to other vehicles and vehicles relative to load transferrring equipment; the other is the quantity of workparts carried by vehicles.

The movements of workparts within an AGVS can be divided into two types:

1. Workparts are loaded from workstations onto vehicles, and unloaded from vehicles onto workstations, i.e. load transferring
2. Workparts are transported between workstations, i.e. vehicle travelling

Hence, the AGVS mechanism includes the transfer mechanism and the travel mechanism. The transfer mechanism consists of the load handling equipments on the vehicles and workstations; the travel mechanism consists of the flow path and the path guidance control system. The AGVS mechanism is defined as a combination of five basic components, which regulate the motion of individual vehicles travelling within the path network.

In the design of a machine, it is necessary to decide on the boundary between the machine system and its environment. In an AGVS, environmental factors may include the number, the location and the type of workstations, available spaces, the plant layout, operators, production schedules, management policies, etc. In general, the design of a machine has two phases. Phase one is the selection of the mechanism to produce the required motions, and phase two is the design of elements of the machine. A similar situation arises in the design of an AGVS. The selection of the mechanism to produce the required movements of workparts is the first phase, and the design of the physical dimensions of its components is the second phase.

Unlike the design of a machine, little experience is available for the selection of the AGVS mechanism, especially the travel mechanism. This is because it is not easy to specify fully the design objective of an AGVS. For example, flexibility of an AGVS is usually required but difficult to achieve. The desired degree of flexibility of an AGVS has to be determined and designed into the mechanism before construction. The flexibility of the mechanism will depend on the degrees of freedom of vehicle motions. The floor path network and the number of vehicles are the two major factors affecting the degrees of freedom of vehicle motions. Therefore, the design of the AGVS travel mechanism should first take these two factors into consideration.

The performance of a machine depends not only on its built-in mechanism but also on its method of operation which is constrained by the built-in mechanism. The performance of an AGVS also depends on its built-in mechanism as well as on its operation, which is normally executed by an on-line control program. The choice of the algorithm for the on-line control program is restricted by the mechanism.

Clearly, a successful AGVS mechanism leads to the success of the AGVS. How can a "good" AGVS mechanism be designed? The solution has a lot to do with the floor path network and the number of vehicles.

3. Mechanism Design Stage I – Composite Floor Path System

For large-scale manufacture, a large variety of products needs to be produced. The material flow may be very complex, or changed from time to time. For example, an automobile maker produces a number of different cars. For each type of car, there are a large number of different components or parts involved. The machining processes may not be similar.

If the car maker produces these components or parts in a FMS, the CNC machine tools in the plant could possibly produce "A" parts at this moment and "B" parts at next moment. This is unlike the transfer line, where the workparts are transported from the first machine in the line through to the last, instead the workparts are moved from one workstation to any other workstation. Therefore, the material flow is very complex. Here, one should notice that the CNC machine tool can produce only "A" parts or "B" parts at a time. Another relevant example relates to food manufacture. The food manufacture produces food from apples, such as apple cider, apple sauce, etc. during the autumn and food from grapes, such as raisins, grape soda, etc. during the summer. Other seasonal fruits are used during their season. The processes of making apple sauce are different from those of making raisins. Hence, the material flow is changed by the seasons.

To choose a material handling system from those systems mentioned above, flexibility is usually the first concern. Unfortunately, building a flexible system may easily bring complexity to the system too. How can one construct a flexible but uncomplex system? We observe that a CNC machining centre can machine many different parts at different times by loading the appropriate part programs. A robot can handle parts with different geometric shapes at different times according to the robot task program. This gives us the idea of developing a versatile mechanism system for the AGVS, which can present different floor path pattern at different times by loading the corresponding program. We name it "the composite floor path system".

In an AGVS, the vehicle is guided by the floor path guidance. The vehicle reads commands from the controller through the guide wire and electrical devices (such as relays, switches, etc.) embedded in the floor, and reports the current status through the floor wire and/or devices to the controller. Usually, a programmable logic controller (PLC) is used as the floor controller, and a ladder diagram residing in the PLC directs the flow path direction and executes the zone control functions [3]. As mentioned in the previous section, a floor path pattern, guide wires and relays, switches and sensors, and a ladder diagram may determine a travel mechanism. If there is another different set of those components and program, another travel mechanism can be implemented in the same floor at a different time. Therefore, the system may exhibit different material flow patterns at different times if more than one kind of travel mechanism exists. Several kinds of travel mechanisms in a system can, therefore, make a composite floor path system.

Family parts can be categorised according to group technology (GT). The material flows of the family of parts are similar owing to the similar manufacturing processes. The required flow path pattern of one family of parts should be much simpler than that of all parts. As long as different families of parts will never be fabricated at the same time, on the same machine, it is not necessary for the AGVS to use all the flow paths all the time. Whenever family A parts are ready to be produced, the floor controller may load the corresponding "part travel mechanism program" which is a ladder diagram to enable the guide wire and electric devices of the desired floor path pattern and disable the others in undesired paths. Hence, the travel mechanism exhibited at that time can match the manufacturing process of the part perfectly, and the AGVS can have flexibility without complexity.

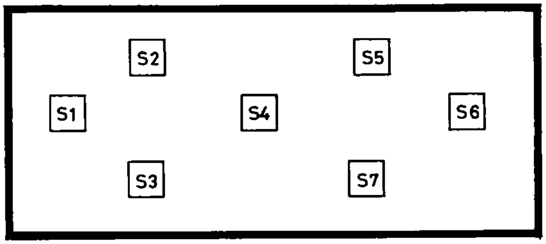

Fig. 1. The factory layout.

Table 1. The production process of products A, B, C and D.

Product	Production processes
A	S1 → S2 → S4 → S3 → S1
B	S1 → S2 → S6 → S7 → S1
C	S1 → S3 → S4 → S2 → S1
D	S1 → S3 → S6 → S5 → S1

3.1 Case Study

A simple example is now used to demonstrate the composite floor path system. It is supposed that a factory produces four different types of product, A, B, C and D. There are seven workstations, S1, S2, S3, S4, S5, S6 and S7, used to produce these products. The plant layout is shown in Fig. 1. The production process of each part is shown in Table 1. Because it is a batch type shop, the factory produces one kind of part at a time. Therefore, it is not necessary to have the travel mechanism suitable for all the production processes of all the products simultaneously. It is thus suggested that the composite floor path system be used. According to the production processes of all the products, a diagram of the AGVS' track and stopping points is illustrated in Fig. 2. Four different flow path patterns are suggested and shown in Fig. 3. When product A is produced, the vehicle need never pass by S5, S6 and S7. Thus there is no need to enable the guide wire of paths to S5, S6 and S7. Therefore, a simple uni-directional

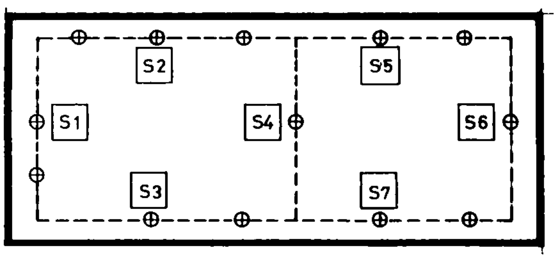

Fig. 2. The AGVS' channel cut (---) and stop point (⊕) diagram.

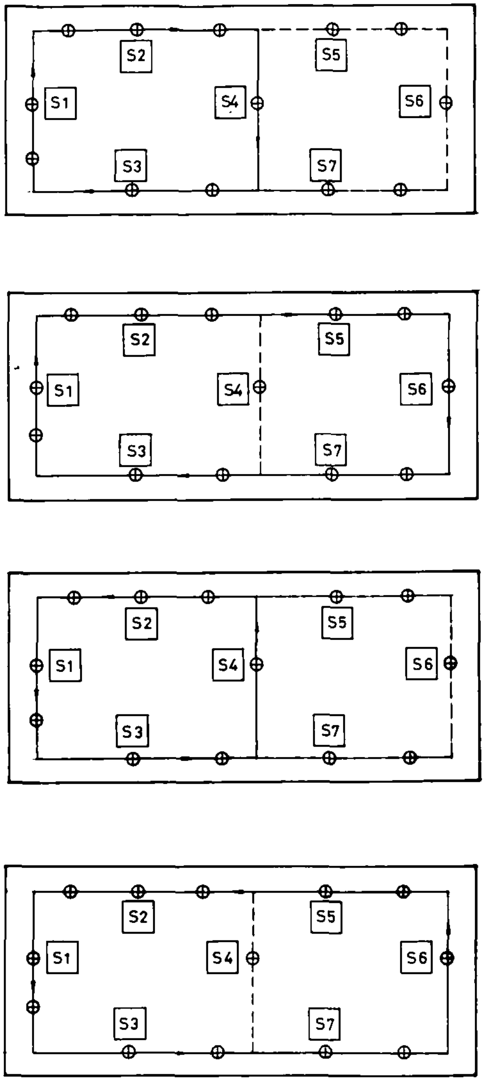

Fig. 3. Floor path patterns. (*a*) For part A. (*b*) For part B. (*c*) For part C. (*d*) For part D.

loop in the floor path (see Fig. 3*a*) is adequate. When producing product B, the vehicle need never pass through the path where S4 is located. Therefore, another longer but still simple uni-directional loop (see Fig. 3*b*) is suggested. Based on these two floor patterns, two travel mechanisms can be built by sharing the guide wire and floor devices in the overlapped portions, and controlled by the corresponding part travel mechanism program. The floor path patterns are so simple that there are no merge or intersection points. If the two mechanisms are combined and become one, when a vehicle at S7 is moving toward S3, the on-line traffic control program has to monitor whether there is another vehicle at S4 and also moving toward S3. Because of the possibility of that "what if" occurrence, the system response will be slower, and the construction cost will be higher (by having to add more electrical devices at the merge point). Fig. 3*c* is the floor path pattern for product C. The direction of the traffic flow is opposite to that of product A. If products A and C flows are combined, the traffic mechanism has to allow vehicles to travel in both directions safely. There are two possibly ways to implement a bi-directional system [3] – having parallel wire tracks with a reverse orientation on each aisle, or a single switchable wire-track on each aisle. The two methods may require sophisticated control hardware and/or software to deal with the merge and intersection problems. In the case when products A and C are never produced at the same time, it is not necessary to have bi-directional paths existing at the same time. A system switch to reverse the direction of the flow paths can solve the problem. The system switch can be triggered automatically by the execution of the part travel mechanism program. Fig. 3*d* is the product D flow path pattern which is very similar to the product B pattern. As long as the four products are never fabricated at the same time, a four-travel-mechanism system is much better than a single travel-mechanism from both cost and efficiency view points, if both provide the same flexibilities.

3.2 Advantages

The advantages of the composite floor path system are:

1. Reduces many traffic control problems such as merge and intersection
2. Speeds system responses because of the simplicity of the system
3. Has high degree of flexibility because more than one travel mechanism exists in a system
4. Has low construction and daily operation cost
5. Can be easily changed or expanded in the future because the structure of the system is modularised and the implementation of the system is dependent on the software more than the hardware.

4. Mechanism Design Stage II – Cell Control System

When there is only one vehicle in the system, collision, blocking and deadlocking can never happen. The system needs no traffic control. The system can run as long as the vehicle can move. When more than one vehicle is in the system, traffic problems may occur and traffic control becomes essential. How to dispatch jobs and determine vehicle routings are also very important in the AGVS. Traffic control, job dispatches and vehicle routings, are system management problems. If vehicles are the feet of the AGVS, the system management is the wisdom of the AGVS. The more vehicles in the system, the wiser the system management must be. Because the number of vehicles required in the system is usually determined by the ratio of the average of total travel distances per shift and the working hours per shift, the total number of vehicles required cannot be changed arbitrarily. If a large number of vehicles is required in the system, how can one decrease the difficulty of the system management problem without reducing the number of vehicles? The concept of the cell control system could be the solution.

What is the cell control system? For any large and complex system, if it is divided into several subsystems, each subsystem has a local controller to distribute the commands from the system controller to floor device controllers and report the subsystem status to the system controller. The subsystem is called a "cell", and the distributed control system is called "cell control". In the AGVS, according to the workpart transportation flows, the workstation locations, and the size and geometric shape of the factory, the whole system could be divided into several cells. Normally, a vehicle can take commands only from its home cell controller, and cannot leave its home by itself. Hence, all the vehicles can never go too far from home to take job commands. The cell control structure contains Bozer's tandem structure [5]. Unlike the tandem structure, the cell control system allows overlaps among cells, more than one loop in a cell, and may not have a transit area between cells. Vehicles in a cell can be transferred to another cell manually.

4.1 Example

Fig 4 is an example of the AGVS adopting a cell control system. As shown in the figure, the factory has four production lines, a heat treatment room, a quality control (QC) room and an automated storage retrieval system (AS/RS). The material flow is indicated by arrows in the figures. Besides loading and unloading stations for the AS/RS, the heat treatment room and the QC room, there are two loading/unloading stations for each of the production lines. The raw material, components and finished products are stored in the AS/RS. Every product has to be processed by production lines 1, 2, 3 and 4, and be heat treated. The flow of the production processes is indicated by arrows in the figure. When the product is finished it will be sent to the QC room for final inspection before being sent back to the AS/RS.

As Fig. 4 shows the flow paths have been divided into two parts, cell 1 and cell 2. Vehicles in cell 1 can travel among stations S1–S7 and P1, P3, P5 and P7, are not allowed to go to cell 2. These stations are on the left-hand side of the factory. Vehicles in cell 2 can travel within the right-hand side of the factory, including the six stations, S1, S2, P2, P4, P6 and P8. Most of the floor paths are uni-directional except for those paths in cell 2, P2, P4, P6 and P8 segments, where not more than one vehicle is allowed. Fig. 5 shows that only a very limited area is overlapped by the two cells (the circled area in Fig. 5). This means that the only part in which cell 1 vehicles have interactions with cell 2 vehicles is in the overlapped area. Each cell controller has to consider only those vehicles in its cell. When approaching the overlapped area, the cell controller has to ask the system controller for permission to go into the area. Therefore, the number of vehicles under each controller is cut to half (assuming that the workloads of the two cells are well balanced). The system management is not as complex as before. For instance, when assigning jobs to vehicles, if both vehicles 1 and 2 were close to job 1, and only vehicle 1 was close to job 2, the system management has to consider two jobs at the same time, and should assign job 1 to vehicle 2 and job 2 to vehicle 1. If there are more than two jobs waiting to be done, then the system management has to consider several jobs at the same time. However, if the cell control system is used, vehicles are allowed to travel only in a limited area, any vehicle in the cell, as long as it is available, can be assigned to any waiting job. Therefore, the system management problems are less difficult. Another reason is that, because the number of vehicles in a cell is always fixed, the distribution of vehicles in the system is widespread, hence, blocking, deadlocking, etc. problems are less likely to happen. This results in a robust travel mechanism.

Before concluding this section, some possible objections have to be dealt with. One may complain that the travel from points A to B is too long, and there is no station between the two points and that without the cell control, vehicles on the right-hand side may take routes through the heat treatment station to reduce the travel distance, and may share work with vehicles on the left-hand side. In fact, because there are no stations between points A and B, vehicles can use the highest speed to travel between the two points to cut down the travel time. The travel distance may be longer, but the

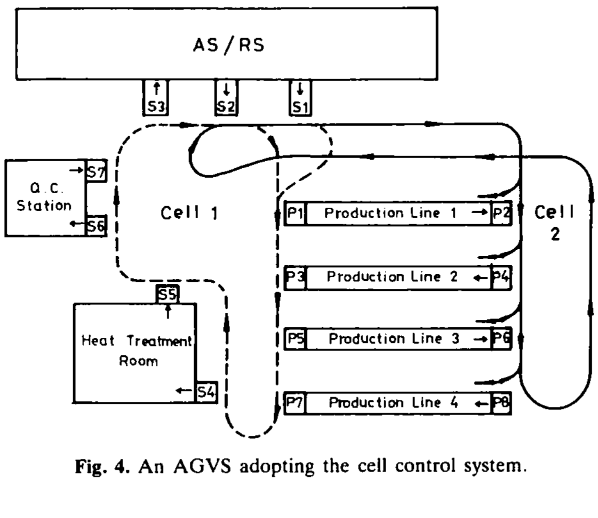

Fig. 4. An AGVS adopting the cell control system.

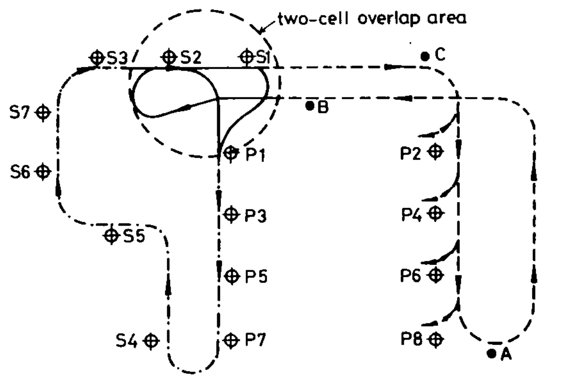

Fig. 5. The overlap area of the two cells, ⊕, vehicle loading and unloading point. ●, vehicle standing point.

travel time is not necessarily increased. Vehicle travel between S1 and C can also be at high speed.

4.2 Advantages

The cell control system limits the number of vehicles in the cell and the vehicle travel range. Therefore, the cell control system can simplify the job dispatch and vehicle routing and other traffic problems.

5. Mechanism Design Stage III – Collision Free Zone Control System

For the AGVS of a large-scale and high-variety manufacture, through composite floor path system design, several different floor path patterns have been identified and embedded in the system. By executing the particular part travel mechanism program, the nature of the desired material flow is thus revealed. Through the cell control system design, the number of vehicles under a controller has been reduced, and the vehicle travel distance has been limited to a small range. Therefore, the originally complex AGVS is decomposed into several simple AGVS. After design stage I and II, the majority of the required mechanism functions are established and embedded in the system. The only mechanism function which needs to be established in the last stage is the collision-free function. As for other traffic problems such as deadlocking, blocking, etc., there is no way to prevent this at the design stage. This is because those problems have to incorporate the time factor and be prevented at the on-line traffic control stage by adopting a robust vehicle-routing algorithm [6]. However, the likelihood of the traffic problem occurring has been reduced in mechanism design stage I and II.

As mentioned above, "collision free" is the only function which needs to be designed at the third stage. How can a collision-free function be built into the mechanism? Is there any quicker way besides simulation? Hsieh & Lin [6] established by Petri nets some basic traffic control nodes such as single loop, merge and intersection nodes for both uni-, mixed, or bi-directional systems, respectively [7]. By the union of those basic control nodes, an AGVS can be modelled. Because of the 1-bound characteristic of those nodes, the established model is guaranteed free from collision. Hsieh & Lin's method is worth adopting for the development of the collision-free travel mechanism. Those basic control nodes will be modified and redefined in a more concise way by Petri nets as follows. Because, at this moment, the identification of vehicles is not necessary, plain Petri nets are used instead of coloured Petri nets.

Generally speaking, there are four basic path substructures – line, divide, merge and intersection (see Fig. 6). The travel structure can be composed by the union of the four basic path substructures.

5.1 Line Substructure

The line substructure can connect one zone with another. The Petri-net model for a three-zone line is shown in Fig. 7

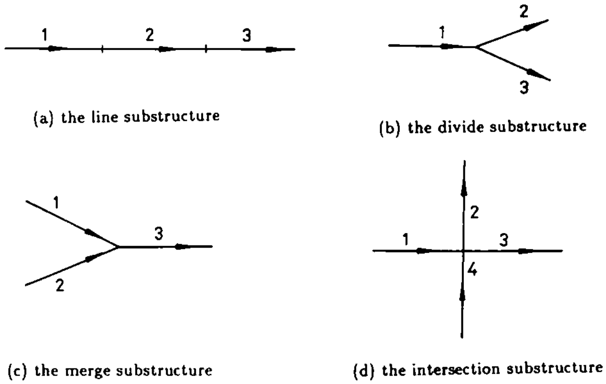

Fig. 6. The basic path substructures. (*a*) The line substructure. (*b*) The divide substructure. (*c*) The merge substructure. (*d*) The intersection substructure.

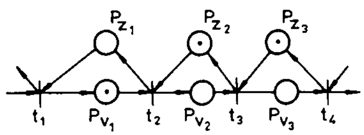

Fig. 7. The traffic control node of the line substructure.

where there are zones 1, 2 and 3, and place P_{z_i} (i = 1, 2, 3) represents the availability of the zone i. When there is a token in the place P_{z_i}, it indicates that the zone is available for vehicles to travel through. Another three places in the figure, P_{v_1}, P_{v_2}, and P_{v_3}, represent the possible states of vehicles. When a token is in P_{v_i}, (i = 1, 2, 3), it indicates a vehicle is currently at zone i. The transitions, t_1, ..., t_4 represent the execution of the vehicle move command. To fire the transition, input places of the transition have to contain a token. For example, if a given command is that the vehicle in zone 1 has to move to zone 2, t_2 needs to be fired. Since a vehicle is now at zone 1 (P_{v_1} contains a token) and zone 2 is available (P_{z_2} also contains a token), t_2 can be fired. Hence the command can be executed. The N-zone line can be established in a similar way.

5.2 Divide Substructure

The divide substructure can connect one zone with another two zones. The Petri-net model for the divide structure is shown in Fig. 8. A very similar description as for the line structure is given here. Place P_{z_i} (i = 1, 2, 3) represents the

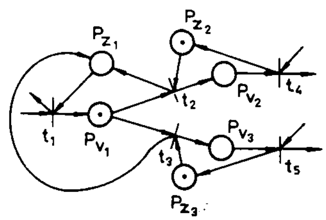

Fig. 8. The traffic control node of the divide substructure.

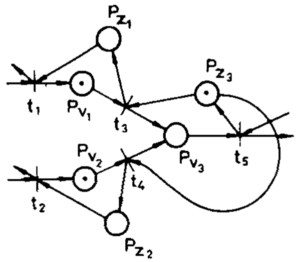

Fig. 9. The traffic control node of the merge substructure.

availability of zone i. When there is a token in the place P_{z_i}, it indicates that zone i is available for vehicles to pass through. Three more places in the figure, P_{v_1}, P_{v_2} and P_{v_3} represent the possible states of vehicles. When a token is in P_{v_i}, (i = 1, 2, 3), it indicates that a vehicle is currently at zone i. The transitions, t_1, ..., t_5 represent the execution of the vehicle move command. The description of the transition firing rules are the same as those for the line structure. One zone to three or more zones divide substructures, can be built by the similar way.

5.3 Merge Substructure

The merge substructure can merge two zones into one. Similar steps are used to build the merge Petri-net model (see Fig. 9). Unlike the line and divide substructures, as long as the transition is able to be fired, the collision problem can never happen. In Fig. 9, a vehicle is at zone 1 and another vehicle is at zone 2. t_3 and t_4 share one common input (P_{v_3}). Therefore, if t_3 is fired, then t_4 cannot be fired; or if t_4 is fired, then t_3 cannot be fired. The collision problem is thus avoided. The only problem left is who has the right to go first. This does not belong to functions of the travel mechanism, and should be discussed in the system management. Three or more zones, to a single zone, merge structure can be built in a similar way.

5.4 Intersection Substructure

The intersection substructure is not as straightforward as the other three. It is supposed that there are two independent line structures as shown in Fig. 10. A vehicle is at zone 1 and

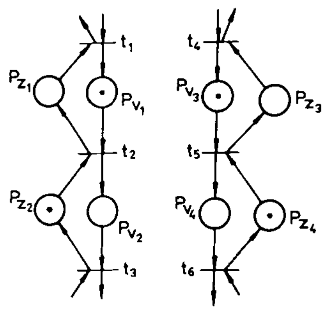

Fig. 10. Two independent line structures.

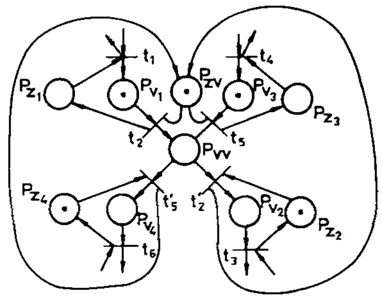

Fig. 11. The traffic control node of the line substructure.

another vehicle is at zone 3. If the two lines have no connection, the vehicle at zone 1 can move to zone 2 as long as zone 2 is available (t_2 can be fired); the vehicle at zone 3 can move to zone 4 as long as zone 4 is available (t_5 can be fired). However, if the two lines intersect each other at the middle as shown in Fig. 11, the transitions t_2 and t_5 can never be fired at the same time in order to prevent from collision. Therefore, two virtual places P_{vv} (to represent a virtual state for vehicles at the intersection) and P_{zv} (to represent the availability of the intersection) are added to the model to control the traffic. More information regarding this can be found in [6].

Four concise basic-traffic-control-nodes have been redefined above. After the union of the four basic control nodes, a collision-free zone control system model can be obtained.

6. Conclusions

This paper presents a conceptual design for the AGVS. The AGVS mechanism is first presented, which includes the transfer and travel mechanism. The transfer mechanism has been discussed by many researchers. The concept of the robust travel mechanism is dealt with in this paper and a design method proposed. There are three design stages. The first one is to emphasise the simplification in time, which is the composite floor path system; the second one is in space, which is the cell control system; the last one is to guarantee collision-free operation, which is the collision-free zone control system. How to achieve the three systems, depends on many external and internal factors, and may follow general rules. Work on this matter will be the subject of future research.

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