Development of an AGV-based intelligent material distribution system

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Material distribution is a special case of the more general requirement for material transfer in a manufacturing environment, and as such it permits simpler solutions. The present article describes an implemented solution for the material distribution problem in the machining shop of an automotive factory using automated guided vehicles (AGVs). We briefly describe the AGV and its associated material handling system, and then describe the intelligent components and their underlying algorithms, which, when put together, create an intelligent distribution system that autonomously assesses demands for materials and accordingly plans, prioritizes and executes deliveries. The system has been tested extensively in a mock environment in our laboratory, the results for which have been reported here.

Keywords: Automated guided vehicle, AGV scheduling, intelligent system, path tracking.

MANUFACTURING requires continuous movement of materials. In the past, these movements were performed manually. The idea of using automated guided vehicles (AGVs) along with programmable material transfer mechanisms for this purpose is gaining in popularity because they have the potential of making all movements of materials in the manufacturing unit completely autonomous, safe and extremely efficient, leading to higher productivity and automatic storage management eventually at a lower cost.

The need for an automated material transfer system is felt by all segments of industries; more so by those whose processes are well structured to take advantage of automation, or those who are keen to avoid manual handling of hazardous (e.g. radioactive or explosive) materials. It is in view of the second requirement in a nuclear establishment such as ours, that we have taken interest in this technology. However, to make a beginning, we chose to work on the problem of automated distribution of materials on the machine shop of an automotive factory.

The most general requirement in an AGV application is the transfer of materials from a set of source units to a set of destination units. In our case, various kinds of semi-finished parts are delivered by vendors to the truck-dock. They are fed from the same station – we call it a loading point (LP). The materials have to be distributed to a number of machining units, which serve as the delivery points (DPs; Figure 1). A given part type can be delivered to only a specific set of DPs. The AGV loads materials in the form of a stack of bins for transportation. Each machining unit (DP) has a specified consumption rate of materials that it receives and processes. It also has a specified capacity for storage of bins on its conveyor. All the information is used for autonomous scheduling of material transfers by AGVs.

Our intelligent material distribution system (IMDS) broadly consists of the following sub-systems:

- AGV along with the requisite support sub-systems;
- Supervisory control system;
- System configuration tools.

Figure 2 shows an overview of the control architecture of IMDS[1]. The vehicle is controlled by a vehicle control program (VCP) running on a programmable logic controller (PLC) under the guidance of a plan executor (PE)

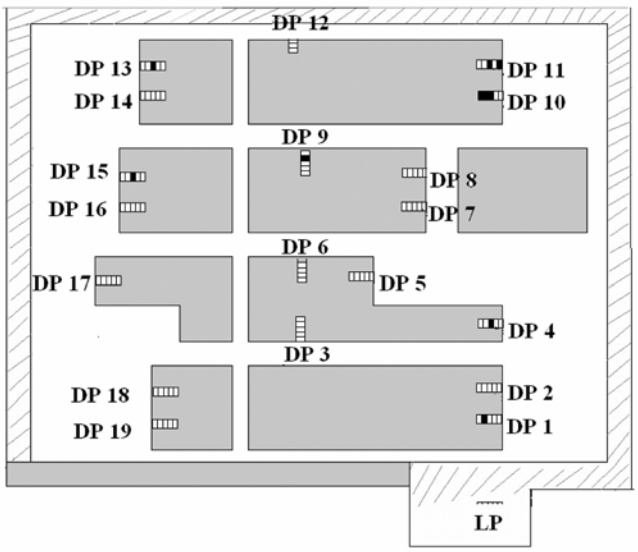

Figure 1. Layout of a machine shop floor. There is a single loading point (LP) and 19 delivery points (DP). The grey areas are to be avoided by the automated guided vehicle (AGV). The hatched area indicates the main corridor available for AGV movement.

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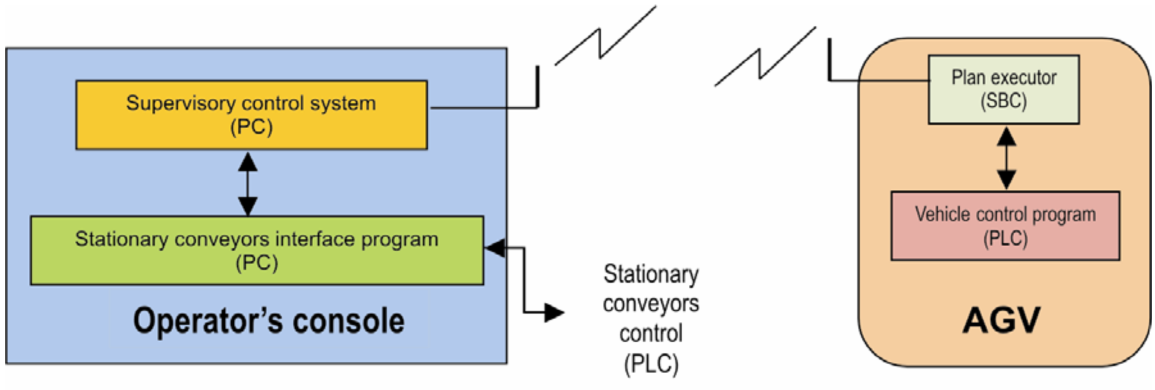

Figure 2. Intelligent material distribution system control architecture.

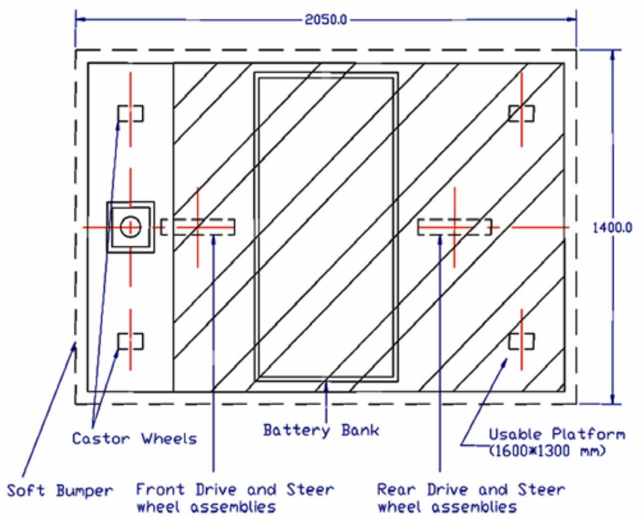

Figure 3. AGV wheel configuration.

program running on an on-board computer. PE executes transfer plans (TPs) prepared and assigned by the supervisory control program to AGV. The supervisory control system runs on a stationary PC located conveniently in the control room or shop floor. This also serves as the operator's console, displaying current status of AGV and loading/unloading stations. A stationary conveyors control program running on a PLC in the shop floor controls all the conveyors in the loading/unloading stations in coordination with the supervisory control system through a stationary conveyors interface program running on the same PC. These are described in more detail in the following sections.

Automated guided vehicle

The AGV is a battery-powered mobile platform with the ability to execute commanded motions and transfers. This is achieved through appropriate design and control of the vehicle as detailed below.

Mechanical design

The AGV has two steer and drive wheels mounted along its length and four support castors on the four corners (Figure 3). This configuration has the advantage of low actuator count for high degrees of freedom, thus making the controls relatively simple. The AGV is about 2 m long and 1.4 m wide, with three rows of conveyors on-board for loading/unloading bins on either side. Its own weight, including the battery is about 700 kg. It has an additional payload capacity of 700 kg. Its maximum speed is about 1.3 m/s.

The drive wheels of AGV are spring-loaded to ensure contact with the ground. Contact is also ensured by the weight of the battery bank, which pulls the chassis down at the centre. On the tiled flooring in our laboratory, no errors in trajectory control arising out of loss of contact of drive wheels have been observed during experimentation.

Vehicle control

All the four actuators of AGV are driven by AC induction motors. A PLC-based VCP controls the motion of AGV. It also controls operation of the on-board material-handling system, monitors sensors, compiles AGV status data and executes operational interlocks.

The AGV can move in three different modes – tangential, crab and differential. The tangential mode allows tangential motion of AGV along straight lines and curves. The crab mode allows movement in any direction parallel to itself. While doing so, it additionally allows a small specified correction in the orientation of the vehicle. In the differential mode, the AGV wheels are oriented perpendicular to its length, and all motions like straight, turn-in-place and motion along a curve may be executed by appropriate control of magnitude and sense of rotation of the two wheels. In the programmed mode of operation of AGV, we use only tangential and crab motions. Tangential motion is used at the turns to keep the vehicle oriented along the trajectory, and crab motion is used for approaching a conveyor laterally within a short distance, maintaining the vehicle orientation parallel to the edge of the conveyor. Straight segments can be traversed in either of the modes. Differential motion is used mainly for turn-in-place during interactive control of AGV from a touch pendant.

Material handling

The AGV as well as the loading and delivery stations are provided with motorized roller conveyors for automated transfer of materials to and from AGV. The AGV conveyors are controlled by the on-board PLC system. The field conveyors have a separate PLC-based control system, and the operation of the conveyor sets gets synchronized through the supervisory control system. Figure 4 shows the actual AGV with various sub-systems.

Safety

The AGV has a set of bump sensors to be able to stop on contact. Additionally, we are in the process of installing a non-contact laser-based obstacle detection system, which provides for slowing down or stopping of AGV depending on the distance of the obstacle much before any contact is established. Apart from physical safety, the integrity of communication channels between various levels of software is also monitored continuously. The AGV is stopped if any breach of safety is detected and the fault is indicated to the operator.

Figure 4. The automated guided vehicle.

Navigation

AGV navigation can be either fixed-path or free-ranging. In fixed-path navigation, the AGV paths are rigidly defined on the shop floor using path markers such as magnetic tape, photo-reflective tape on the floor or burying of wire below the floor. This however leads to a rigid system. We use the free-ranging technique, as it provides flexibility of modifying AGV trajectories at will. In this approach, AGV detects predefined cylindrical reflectors installed within the work area using an on-board laser ranging device. The laser navigator system so formed, returns the (x, y) coordinates and orientation (θ) of the laser ranging device in the global coordinate system to the AGV controller[2] at the rate of 8 Hz. The instantaneous position and orientation of AGV is easily computed from these data. With the knowledge of its location, AGV is able to track the specified trajectory.

The navigator system allows definition of a number of convex-shaped overlapping areas of operation of AGV, comprising various subsets of reflectors to ensure accurate localization in large or poorly connected areas. Each such area is called a layer[2]. The AGV refers to only the most appropriate layer at any instant for its localization.

Trajectory editor

Systems, which use free-ranging techniques, provide high flexibility with respect to definition and modification of the work area and AGV trajectories. This is done using a system configuration tool called trajectory editor. This is a CAD-based software, with the provision to import a layout drawing of the workshop, with outlines of structures, machines and various other entities depicted on it as a background. The trajectory editor facilitates the creation of trajectories and positioning of loading and delivery stations for AGV. The AGV trajectories are made of motion segments, each of which has certain attributes like motion mode (tangential/crab), maximum permissible speed, etc. The motion segments are joined through nodes. Some of them are branching nodes, which give an option of following one of the several motion segments. Figure 5 shows a trajectory editor screen with the designed trajectories in a mock environment.

Plan executor

The PE program, running on the on-board computer, carries out execution of a TP placed on AGV by the supervisory control system. A TP specifies the source from which materials are to be picked up (in our case, the source is always LP) and destinations at which they need to be delivered in a single trip of AGV. On the basis of this plan and using the trajectory database, PE computes the detailed path to be traversed. Accordingly, under the control of a path-tracking algorithm (e.g. pure pursuit algorithm, as explained below), it keeps issuing motion and activity commands to the VCP running on the on-board PLC, until the entire plan gets executed.

Path tracking

The AGV is likely to deviate from its reference path due to inaccuracies in motion control. To correct for these deviations, AGV uses a pure pursuit algorithm[3]. This algorithm continuously monitors the position error of AGV with respect to its reference path and adjusts the radius of curvature of its path r in such a way as to converge to the reference path at some distance L (Figure 6). This distance, called the look-ahead distance, is the most important parameter in this algorithm. If it is too short, the vehicle tends to take sharp turns for correction, inducing oscillations, and if it is too long, the corrective motion becomes weak and the vehicle may drift away from the reference trajectory. The look-ahead distance L also needs to be adjusted for different speeds of the vehicle. As the speed increases, the look-ahead distance has to be increased correspondingly to maintain tracking stability. Optimal values for look-ahead distance, being sensitive to the control and inertial parameters of the vehicle, are determined experimentally at various speed ranges. A look-up-table of these values is used at run-time for deciding the look-ahead distance. We do not try to take care of any variation of look-ahead distance because of variation in vehicle loading.

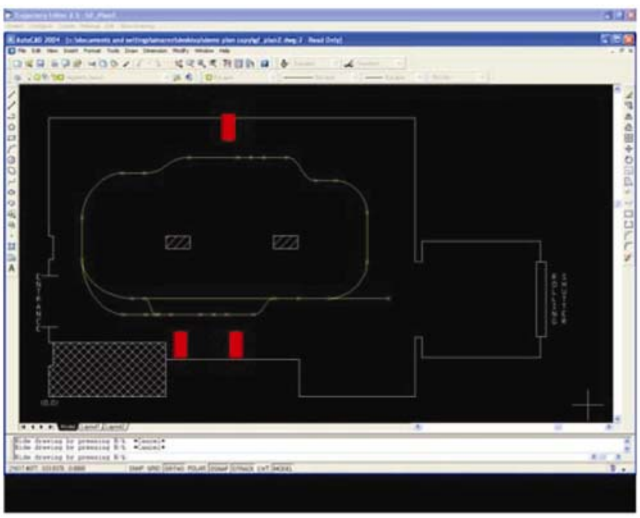

Figure 5. Trajectory editor screen.

Test results

In order to test the path-tracking ability of AGV while it moves as well as when it stops for a transfer, we created a mock environment (Figure 5) in a hall measuring approximately 15 m × 12 m. We installed one LP and two DPs on a closed trajectory. Under the test program, the AGV keeps looping around the hall and keeps transferring in and out stacked bins carrying materials. The AGV was driven at a maximum speed of 500 mm/s, as higher speed of travel appeared unsafe within the limited distance of straight travel possible.

Figure 7 shows the desired and actual path followed by AGV during execution of a TP. There are small deviations of the actual trajectory from the reference trajectory at several points, particularly noticeable at the turns and at places where the motion mode undergoes change (from tangential to crab and vice versa), as this

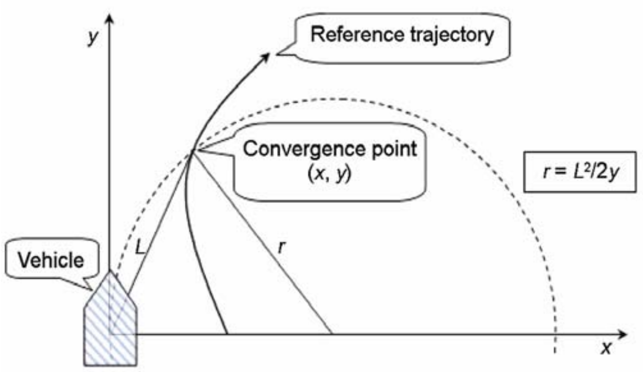

Figure 6. Pure pursuit algorithm determines the radius of curvature r with which the vehicle should move to converge to the reference trajectory at a distance L (look-ahead distance).

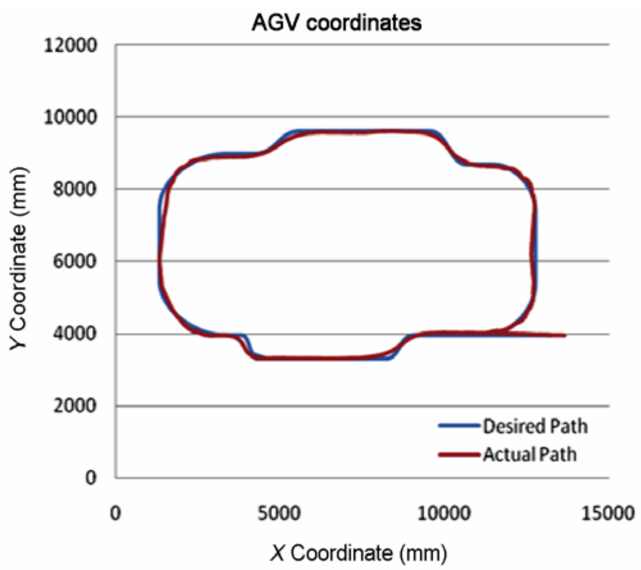

Figure 7. Path actually followed by AGV against the reference path.

creates discontinuity in motion. What matters most, of course, are the errors in position and orientation of AGV when it stops for a transfer, as this affects the safety (no hit) and reliability of material transfer. These errors have been systematically recorded for many test runs and found to be within acceptable limits.

Supervisory control program

The supervisory control program runs on a standard desktop computer, located either in the operation area or in the control room, as convenient. It carries out a range of tasks, namely monitor and display status of AGV and field devices, planning and scheduling material transfers, assigning TPs to the available AGVs, and ensuring that collisions or deadlock conditions are avoided as AGVs go about completing their assigned jobs.

The supervisory controller needs inputs regarding material stock at each DP. This is accomplished by using proximity sensors to sense the presence or absence of bins on the delivery conveyors, or by explicit inputs from the operator at each DP. The system also needs to know the material consumption rates of each DP. This can be input initially from available data and can be estimated on-line subsequently from stock data of each DP.

Typical operational, planning and control problems that need to be addressed to design the supervisory controller are:

(i) Estimate the number of AGVs required for meeting specified consumptions rates of DPs[4].
(ii) Select an appropriate dispatch rule to decide which DPs may be served on the basis of current stock positions[5].
(iii) Routing of AGVs to ensure that they are utilized in an efficient manner[6,7]. Once the DPs are selected, routing decides in which sequence the selected DPs may be visited[8].
(iv) If there are a number of AGVs, they must obey certain protocols for travelling over shared track segments to avoid getting into deadlock situations.

These issues have been addressed in great detail by Singh *et al.*[9,10] with respect to our application environment. Some of the important analyses and results are reproduced below.

Estimation of the number of AGVs: We assume that a single AGV can carry at most w unit loads (bins) at a time. If it takes a total trip-time of t_i to travel to the ith DP, deliver its entire load and return to LP, it can in principle continuously keep feeding the ith DP at the rate of w/t_i unit loads per unit time.

If the ith DP consumes x_i unit loads per unit time, the AGV demand factor of the ith DP is given by

$$d_i = x_i/(w/t_i) = x_i \times t_i/w.$$

The transfer load f_i of the ith DP is $x_i \times t_i$. It is indicative of the effort that AGV has to put in to keep the DP well fed.

The AGV demand factor d_i of the ith DP can now be rewritten as

$$d_i = x_i \times t_i/w = f_i/w,$$

i.e. transfer load divided by AGV capacity. Thus the AGV demand factor of a DP can be reduced by reducing its transfer load or by increasing the AGV capacity. Transfer load can be reduced by reducing the consumption rate of DP or by reducing AGV trip time for that DP, which requires a speed-up of AGV.

The sum of this demand factor d_i over all DPs gives the aggregate demand D_a on AGV by all the DPs

$$D_a = \sum_i d_i.$$

If $D_a < 1$, a single AGV can satisfy the total material transfer requirement. On the other hand, if $D_a > 1$, it implies that a single AGV will not be adequate to satisfy the total material transfer requirement. For our application, D_a turns out to be 1.88, and so two AGVs are required.

Transfer plans

Generation of a TP is the single most important decision process in an AGV system. A TP comprises a chain of nodes to be visited sequentially by AGV. At some of these nodes, AGV has to stop to load or unload materials. The generation of TPs is complicated by the fact that the controller must aim at making efficient use of the load-carrying capacity of AGV, and at the same time respond to requests for materials from any station within a reasonable time. In a semi-autonomous mode, the supervisory system is configured to select a pre-defined TP based on the prevailing pattern of stock position on the DPs. In the autonomous mode, the supervisory controller keeps monitoring the material stock status of each DP continuously. When the material stock at a DP falls below a pre-specified value, it becomes eligible to receive materials. The supervisor maintains a list of such eligible DPs along with their current stock positions, and as soon as an AGV becomes available for service, it decides which DPs should be served based on the prevailing dispatch rule. It also determines the sequence in which the chosen DPs may be visited to minimize travel time. Accordingly, it generates a TP for AGV to execute. Armed with TP, the AGV reaches the LP, where it loads the required materials for delivery to the selected DPs. After reaching a DP, it unloads the appropriate loaded bins and loads empty bins. After all loaded bins are delivered and empty bins picked up, the latter are unloaded to an empty-bin unloading station close to LP. This completes one AGV trip.

Dispatch rules

Transfer plans are obtained by the application of dispatch rules[5,11]. The dispatch rules decide which DPs may be served by AGV as it starts its next trip. They strongly influence the throughput and evenness of material distribution.

Time stock of a DP indicates the time it will take for its stock to vanish if no further supply comes meanwhile. Time stock can be both positive and negative. A negative time stock indicates the time elapsed since the stock fell to zero.

Priority of a DP is the negative of its time stock. We set a minimum value for the priority of a DP above which it becomes eligible to receive materials. It is then considered by the dispatch rule while deciding on which DPs may be served by AGV as it starts its next trip. It is set such that the conveyor capacity is not exceeded in case the AGV delivers to this DP at its current stock level.

The single destination travel, in short SD travel, of a DP is the distance covered by AGV to complete a trip from LP to DP and back to LP. In the context of multiple destination (MD) dispatch rules, we shall also talk about MD travel – the distance an AGV would cover to visit the selected DPs in the desired order and return to LP.

Two different kinds of dispatching are considered:

(i) *Single destination*: Feed the entire capacity of AGV to DP that has the highest priority for service by AGV. All the stacks of plastic bins on-board the AGV now carry the same material and are deliverable at that single DP.

(ii) *Multiple destinations:* The AGV will service more than one DP (this number is equal to the number of conveyor bays on-board the AGV, which is three in our case) in a trip. Four rules are considered here:

- MD1, where AGV selects three DPs in order of their priority and services them in the same trip splitting its capacity w into three parts – one for each DP. The DPs are visited in an order in which MD travel is minimized.

- MD2, where the AGV selects three DPs such that the first DP is the one with the highest priority, while the second and the third are chosen among eligible contenders to minimize the MD travel.

- MD3, which is the same as MD2, but with an added constraint that only the top six eligible contenders (in order of priority) are considered by AGV.

- MD4, where AGV selects an ordering of three DPs from the top six eligible contenders (there are $^6P_3$ such orderings) such that $\sum_i (p_i \times l_i)$ divided by MD travel is maximized. Here p_i is the priority and l_i the SD travel of the ith selected DP. By weighting the priorities with SD travel, this dispatch rule tries to remove the bias of MD2 and MD3 in favour of nearby DPs.

The above dispatch rules were tested for their efficacy in simulation for our material distribution problem in the machine shop. Predictably, SD dispatch rule turns out to be the most efficient in terms of the quantity of material distributed per unit time, although it results in high disparity in satisfaction of the DPs. The satisfaction of a DP is the measure of how much it gets as a fraction of what it asks for. A disparity in satisfaction implies that all DPs are not being treated uniformly, i.e. some DPs are less satisfied than others. In this respect, the multiple destination rules fare significantly better. Performances of MD2, MD3 or MD4 are quite close, though case-specific. In practice, what matters is high material throughput and uniformity of distribution over the DPs. With respect to our material distribution problem, MD4 fares a shade better than MD2 and MD3 in meeting both these demands. More details about the choice of performance metrics for dispatch rules and results of simulation runs are reported in Singh *et al.*[10].

Deadlock avoidance

Computation of aggregate AGV demand for our application shows that for an average AGV speed of 0.5 m/s, at least two AGVs are required to satisfy the total material transfer requirement in the machine shop. The main problem with multiple AGVs is to work out a scheme that maximizes system throughput while avoiding complexity and constraints of a centralized control, and possibility of deadlock of a distributed control system[12]. The following approach has been conceived for this purpose:

- Divide the whole layout into zones such that the aggregate demand of DPs in each zone is comparable in magnitude and is less than unity[13].
- Assign one AGV exclusively for material distribution in one zone. We need as many AGVs as there are zones.
- Select zones in such a way that the length of track segments to be shared by two or more AGVs is minimal.
- Design protocols for travelling through shared segments to rule out deadlock.

In our case, the machine shop is split into two zones for two AGVs such that zone 1 has eleven DPs ($D_a = 0.84$), whereas zone 2 has eight ($D_a = 1.04$; Figure 8). Since each zone must connect to the LP, the approach to LP is typically shared by the two AGVs. We divide the shared segments into two parts – s-way 1 connects LP to the parking place (P), and s-way 2 connects P to zone 2 running through zone 1. The parking, one for each AGV, between the two s-ways (shown as dark squares in Figure 8), allows AGVs to cross each other, if needed. This Parking is also the place for an idle AGV to wait[14]. Here s-way 2 is also the main segment joining all the DPs of zone 1. That makes it difficult for AGV1 to serve its DPs in zone 1, always taking care not to run into AGV2 while it moves from one DP to another in zone 1.

TPs generated by the supervisory controller for both the AGVs are fixed, which means that AGVs never change their routes on the fly. To avoid any deadlock, each AGV must acquire an s-way before proceeding to travel on that. Once on s-way 2, AGV2 relinquishes it only after it has covered the entire length of s-way 2, whereas AGV1 relinquishes it as soon as it leaves s-way 2 to approach a DP of zone 1. In fact, each time AGV1 wants to move from one DP to another in zone 1, it has to check for availability of s-way 2 and wait, if necessary. The parking between s-way 1 and s-way 2 allows one AGV to wait for the next s-way to be released by the other AGV, without blocking the way. The sharing of s-ways, as explained above, allows the two AGVs to execute their TPs in an asynchronous manner, so that each AGV can go around doing its job in its own pace.

Simulation with two AGVs following the above scheme shows marked improvement over the case of a single AGV. However, at a speed of 0.5 m/s of AGV, the system just falls short of providing total satisfaction to all the DPs, although practically it may function reasonably well over a long period of operation. Expectedly, the two-AGV system with SD fares best for both the zones.

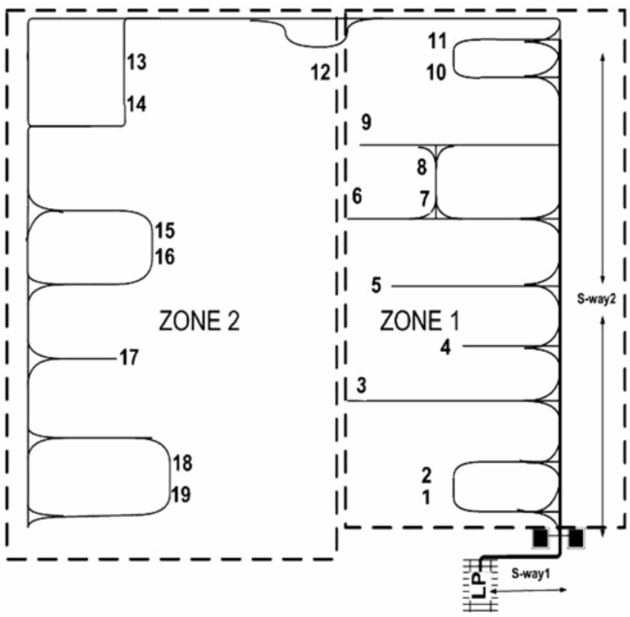

Figure 8. Shared AGV tracks, s-way 1 and s-way 2, shown with dark lines.

As we shift to MD dispatch rules, MD3 fares better in zone 1. In zone 2, all the MD rules perform almost at the same level. MD4, however, fares a little better than the others. The results of the simulation are yet to be verified on the machine shop floor. Actual performance will depend on the speed of AGV, as well as the time taken by AGV for positioning and transfer.

The division of total area of AGV operation into zone 1 and zone 2 has been done in a way that each zone is separate and compact. We had experimented with the alternative of putting DP-12 into zone 1 instead of zone 2 as at present; however, the results were not encouraging in terms of throughput. The reason why a relatively high value of aggregate demand for zone 2 (1.04) compared to that for zone 1 (0.88) works is that the theoretical estimation of aggregate demand does not take into account the frequent waiting periods the AGV-1 serving zone 1 has to bear with before it gets its way in s-way 2, as the same is shared with AGV-2 serving zone 2. AGV-2 however is unobstructed once it enters zone 2. This also reflects in the higher waiting time (3–4%) of AGV-1 compared to that (around 1%) of AGV2 under various dispatch rules[10].

In principle, s-way 2 can be further split into smaller s-ways, each covering one by-lane of zone 1 and allocated to either AGV on demand. This is expected to reduce the average waiting time for AGVs. However, frequent stops and runs also lower the average speed of traversal of AGVs and ultimately it may not be as gainful. However, this aspect has not been explored in the present work because of added complexity of allocation of such segments.

Display and user interface

The supervisory controller continuously displays the status of various sub-systems on the control console. The display includes update of the locations of AGVs in the system, the status of operation of the AGV load-handling equipment, AGV battery charge status, field conveyors status and any warnings and faults generated on any of the sub-systems. The controller also provides user interface for manual intervention. This includes facilities for emergency stopping of AGV, conveyors, etc. in case any fault develops in the system. The interface also allows generation and transmission of a manually generated TP to an AGV. The system keeps logging in all the status, warning and fault messages, which can be used for generating statistical data for the system as well as for fault debugging.

Conclusion

We have described the components of an IMDS, designed and developed for use in a manufacturing environment. A specific application in the automotive sector, viz. the distribution of semi-finished components from truck-dock to the machining shops, was picked up for design of AGV and its control software. However, it is felt that the solutions so generated may be used with modifications or enhancements in many other application areas as well. Because of the need for customization, the technology is inherently expensive. However, as the control architecture is modular, a wide range of sensors, navigation and localization systems can be interchangeably interfaced to the system depending on availability and requirement.

We have tested path tracking and material transfer capability of AGV in a mock environment in our laboratory. We have assessed performance of the material distribution system in the target environment only in simulation. We are yet to check the actual performance of the system in the target environment, as it requires taking many precautionary steps to ensure that production is not affected adversely under any circumstances. However, that is the real challenge we are working towards.

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ACKNOWLEDGEMENTS. We thank the anonymous reviewer for his insightful remarks on various aspects of this work and his contribution in enriching the contents of this manuscript.

Received 18 March 2011; revised accepted 13 September 2011