Towards Decentralized Coordination of Multi Robot Systems in Industrial Environments: a Hierarchical Traffic Control Strategy

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***Abstract*—This paper describes an innovative approach to manage multiple Automated Guided Vehicles (AGVs) in an industrial environment. The proposed approach is based on a two layer architecture for path planning. This architecture consists of a topological layer, composed by macro-cells, and of a route map layer in which the AGVs have to move along fixed paths. The traffic is managed in a decentralized manner. Each AGV computes autonomously its own path both at topological layer and at route map layer. The coordination among the AGVs is based on the negotiation of shared resources. An early phase of validation is provided by the simulation in a structured environment.**

I. Introduction

This paper deals with the path planning and coordination of multiple Automated Guided Vehicles (AGVs) in an automated warehouse.

Nowadays the AGV solutions for automated warehouses are becoming more and more the standard in addressing the problems of production efficiency and flexibility [1]. Then the number of AGVs is growing more and more and the need to coordinate them in an intelligent way is increasingly at the center of discussions [2]. The standard approach to coordinate a fleet of AGVs lies in a centralized supervisor (the control center) which manages all the information coming form the Warehouse Management System (WMS) and from the environment. The control center handles the coordination of the fleet and the AGVs are managed in order to minimize, or to avoid, the traffic congestion [3]: the optimal path which minimizes a global cost function is searched for each AGV.

This paper deals with the research in progress about the navigation of multiple vehicles (AGVs). The paper presents the idea on which the navigation objective of the PAN-Robots project is based. We propose a different approach with respect to the centralized coordination of multiple AGVs currently used in the state of the art [3] [4]. Our idea is based on a hierarchical control architecture [5]. In detail, two layers are used in order to reduce the total complexity and to simplify the control. The first layer is a topological graph of the plant. The global map of the plant is divided into several macro-areas, called sectors. Each sector corresponds to a node of the graph. Its main purpose is to permit a dynamic re-planning of the paths in case of dynamic events. The second layer is the real route map on which the AGVs move. The coordination on the route map is limited only to a single sector of the first layer. In other words, in each sector, the traffic is managed in a decentralized manner on a local route map.

The rest of the paper is organized as follows. Section II discusses and provides an overview about the problem of the path planning and coordination for AGVs. Section III describes deeply the addressed problem and the objective. Section IV explains the developed algorithm considering both theoretical and implementation aspects. Finally Section V shows the results of the early phase of validation through virtual simulations and Section VI deals with the conclusions and the next steps of development.

II. Related Works

The topic discussed in the paper is related to the path planning of multiple AGVs. First of all, it is important to define the multi-robot path planning problem.
This problem is often categorized as centralized or decentralized according to the information handling structure among robots (see [6]). The centralized approach is configured to determine the entire path plan for all the robots by a single decision maker. These approaches can theoretically find optimal solutions for multi-robot path planning problems [7], but they are restrictive in the number of robots for which they can plan, as the complexity of planning grows exponentially with the number of robots. Thus, while they provide the highest-quality solutions overall, they are generally intractable for large teams.
On the other hand, with a decentralized approach, each robot autonomously determines the routes, dissolving the conflicts and collecting information from other robots. Decentralized techniques are generally faster than centralized ones, however they are not complete and may fail to return valid paths for all robots due to deadlocks [5], [8].

Extending the problem still further, centralized approach for generating complete multi-robot path solutions is the work of many researchers. In [7] the path planning algorithm is derived from the principle of optimality. Here the problem of coordinating a multi-robot system is resolved using a coordination space representation of the robot motions. A

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similar technique to coordinate a fleet of robots can be seen in [9]. The coordination diagram is introduced in order to manage the motion coordination of several robots moving along fixed independent paths. In order to reduce the size of the problem (exponential with the number of robots involved), a path decomposition is applied which decomposes it into its elementary pieces consisting of either straight line segments or arcs of a circle. In this way the algorithm efficiently solves problems involving more than 100 robots.

Because of the high dimension of the multi-robot configuration space, centralized approaches that treat the multi-robot team as a single composite robot tend to be computationally impractical if the full search space is used. Instead, techniques that reduce the size of the search space have been shown to be practical for small-sized problems. One way to reduce the search space is to weakly constrain the allowable paths that robots can follow by limiting the motion of the robots to lie on route maps in the environment. Intuitively, route maps are akin to automotive highways, where robots move from their starting position to a route map, move along the route map to the proximity of the goal, and then move off the route map to the specific goal location. Fixed paths are used in [10] with navigation functions in order to coordinate several robots approaching an intersection. Potential fields are used also in [11]. Other methods consist in using traffic rules [12] in order to build specific autonomous policies.

Another way to reduce the dimension of multi-robot space is to make use of a multi-layer structure representing the world. As explained in [13] and [14], the approach is to construct a hierarchical route map which can abstract the traversable areas using the adequate number of nodes and edges of a graph. The path is searched using the graphs of the several layers.

The AGV navigation is related to the coordination of multiple vehicles on a predefined route map of segments [2]. This route map is usually built in a manual manner by technicians. As a common practice adopted by the AGV system providers, each time that a path is assigned to a vehicle (e.g. for reaching a delivery point), the AGV has to track it until the destination is reached and there is no possibility to re-plan the path. Thus, the traffic control problem is actually a coordination (e.g. tracking velocity control) problem. The standard approach adopted by AGV system providers to coordinate the motion of the vehicles is based on a set of traffic rules manually defined during the installation of the system. This requires a lot of personnel working when an AGV system has to be deployed or modified since several exceptions have to be manually handled both for production and safety reasons. There are already solutions to improve these limitations. In [15] a decentralized coordination of multiple AGVs is provided and the motion of the vehicles is not constrained to a fixed route map. The work shown in [16] and [17] concerns with the development of a traffic manager able to coordinate the AGVs limiting the use of manual traffic rules. Therefore previous works on decentralized robot transportation in an industrial environment mainly include:

- Resource allocation approach: resource allocation normally needs to define certain geographic resources for traffic control, such as cells or segments [18]. Since these resources cannot be shared simultaneously by robots this approach may cause inefficient use of the resources or high complexity in route networks topology.
- Coordination through negotiation [19]: This approach is good for dealing with complex coordination scenarios, but it involves extensive information exchange among negotiating robots increasing the communication load.
- Rule based approaches: the rules can be manually tuned [2] or built in such a way that the coordination is directly reached [12].

III. Problem Statement

The paper deals with the problem of coordinating a fleet of vehicles (AGVs) in order to reduce the amount of computation and complexity currently needed for the centralized solution.

The path planning problem for multi robot systems is a part of the general coordination problem. Typically, the traffic management (or the coordination) for AGVs is characterized by the fact that the definition of the route map and the optimization of the path are treated as separate problems. In the current approaches, the route map is built without any optimization process, and the paths are further optimized according to a specific cost function. Therefore the final path assigned to an AGV, although it has been chosen with an optimization path planning, is actually not optimal due to the fact that the route map is not optimized.

Indeed the path optimization strongly depends on the specific route map, and the route map has to be built according to the optimization process. In other words, the route map has to be defined in order to optimize a specific cost function, which is also the cost function of the path planning process. This cost function depends on the application, and it may concern with the optimization of several parameters as: the travel distance, the crossing time, the priority queue, etc.

Therefore our intent is to define a new approach in which the problem is the whole coordination. The optimization and the path definition are managed simultaneously in order to optimize a global cost function. A centralized approach can lead to an optimal solution but it requires a lot of computational capacity due to the high complexity. For this reason, our idea makes use of a decentralized approach even though only global sub-optimal solutions are provided. Therefore the optimal is guaranteed for the local solutions and not for the global ones.

Going more into detail, the problem is to plan a route for each AGV so that conflicts and deadlocks are avoided. Each AGV starts its path in a initial position, and has to reach its own pick/drop position. Furthermore the path initially defined has to change in case of unforeseen events. In other words, a path re-planning or a dynamic planning is needed. The task assignment (that is, the goal given to the AGV) is assumed to be done in a random way starting from a task list. Our aim is to plan a feasible sub-optimal and dynamic path for multiple AGVs and to coordinate them along a route map without colliding with each others.

We assume that:

- The layout is a 2D static representation of the plant in which free areas and occupied ones are shown
- Each AGV can communicate with the others in its neighborhood
- Each AGV has access to shared data stored in a centralized layer
- The maximum velocity and acceleration are the same for all the AGVs. In other words, the typology of the AGVs is the same
- Each AGV is modeled as a triangle (position and orientation) in order to simplify the early phase of the development
- No dynamic obstacles (manual forklift, people, etc.) are currently contemplated in the content of the paper

IV. Two Layer Control Architecture

In this section, the main idea of the paper is explained. The problem of coordinating a elevated number of AGVs is faced splitting the control through a multi-layer architecture. In our idea two layers are used. The top-layer, or *Topological Layer*, is a topological map representing the global map, with different macro-cells called sectors. The layer below, or second layer, is the geometric map of each sector of the first layer, and will be hereafter referred to as *Route Map Layer*.

Therefore the path planning is done on two levels. Topology path planning searches for the best path to the final goal (actually to the final sector where the real goal is) from the current sector. Route map planning computes the path on the route map and makes the coordination inside the sector.

A. Topological layer

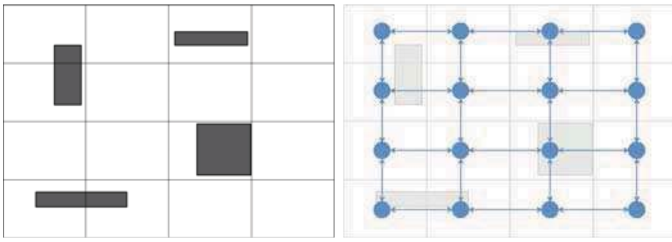
The first layer is the most abstract layer, it is generated by a subdivision of the geometric layout in several sectors.

1) Sector division: A sector is an area, or a region, which can be distinguished from the other ones based on topological aspects, material flow, logistical aspects and geometrical ones. The layer gives a topological representation of the real map. For instance, it shows where a specific room is in relationship to the links with the other rooms in the neighborhood without showing the presence of obstacles or other geometric information. Figure 1 shows a simple division in sectors as a grid-based map.

The enhancement of this topological division lies in the properties owned by the sectors. The entity *sectors* is defined with respect to:

- Geometric space
- Topological information
- Constraints

The constraints can be different based on the needs of the warehouse. Examples are the maximum number of AGVs contained in a single sector and the maximum number of operations of loading/unloading. This kind of information is owned by the sectors and is stored in a centralized manner. In this way, the information is visible to all the AGVs and is shared among them from the centralized storage.



(a) Grid-based sector division (b) Topological graph

Fig. 1: The topological sector division: in 1a the geometric map is divided into regular sectors; in 1b the graph representation generated by the sector division is shown

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2) Path planning on the topological layer: The information owned by the sectors are used to plan the sub-optimal route for an AGV. Each vehicle has to reach its destination minimizing several cost functions, for instance they can be the crossing time, average velocity, travel distance, etc.

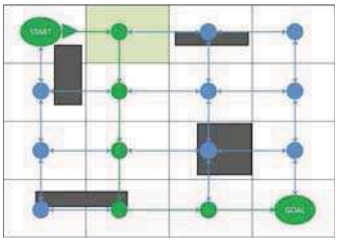
The map of sectors, that is, the first layer, can be simplified through a graph representation. Each sector is a node of a directed graph and the links among neighboring sectors are modeled by the edges of the graph.

The path from the start sector to the goal one is searched by means of the D* algorithm [20]. D* algorithm is an incremental search algorithm which solves the path planning problems where a robot has to navigate to given goal coordinates in unknown terrain. It makes assumptions about the unknown part of the terrain and finds a shortest path from its current coordinates to the goal coordinates under these assumptions. During the path following, the new information (such as previously unknown obstacles) is added to the map, and, if necessary, the algorithm re-plans a new shortest path from its current coordinates to the given goal coordinates.
The choice of this search algorithm is due to the need of re-planning the path in a dynamic way. The simple A* algorithm needs to re-plan all the path if it is requested. Conversely, the D* is able to re-plan only the portion of the path interested by a change. In this way it is possible to obtain a re-plan of a route. Incremental search algorithms speed up searches for sequences of similar search problems by using experience with the previous problems to speed up the search for the current one. Assuming the goal coordinates do not change, the D* algorithm is more efficient than repeated A* searches.

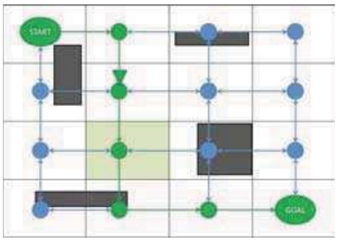
Furthermore a MPC (model predictive control [21], [22]) mechanism has been added. That is, at each step, the AGV checks if the previously assigned path is still feasible. Actually the MPC approach lies in the fact that only a portion of the path is checked and the horizon can be extended or reduced. This approach provides an optimal local solution but a sub-optimal global one, because only the part of the path inside the horizon is interested by the optimization.

Therefore each AGV computes autonomously the own path through the grid of sectors without paying attention to the other AGVs' planned routes. The relationship among them is provided only by the shared data about the state of the sectors. In particular, the data used are the quantity of AGVs contained

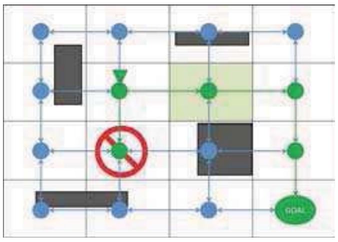
in a sector and, based on it, an AGV can autonomously decide to re-plan its path in order to avoid a congested area.
In order to implement the MPC mechanism, the receding horizon corresponds just to one sector. Therefore, if necessary, each AGV re-plans its own global path keeping checked the next sector.



(a) Global path planning



(b) Checking inside the receding horizon



(c) Re-planing of the path

Fig. 2: The path planning on the topological layer: in 2a the path is searched by means the D* algorithm; in 2b the AGV moves along its path and checks the next sectors; in 2c a re-planning of the path is needed due to the new condition of the next sector

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The steps of the procedure are the following:

1) Each AGV computes its path to the sector of destination
2) At each step, it verifies if the next sector is still navigable (i.e. the number of AGVs contained into it is less then the maximum number)
3) If the approached sector is not navigable, a new path is re-planned avoiding that sector

B. Route Map layer

The route map layer contains the geometric information of the environment and the route map itself. The route map is a set of routes as a highway, and it is composed by distinguished elements called segments. The AGVs are constrained to follow the route map and its segments.

Inside each sector the coordination among AGVs is needed. The second layer manages the real path following of the route map and the avoidance of deadlocks and conflicts among AGVs or among AGVs and obstacles. The coordination is managed locally (in each sector) in a decentralized manner. With this hierarchical architecture it is possible to simplify the whole control in order to focus the coordination of the AGVs only inside each sector in a local way.

Two main contributions appear in this layer. The first deals with the fact that the route map is built according to specific constraints, and the second is the real coordination algorithm.

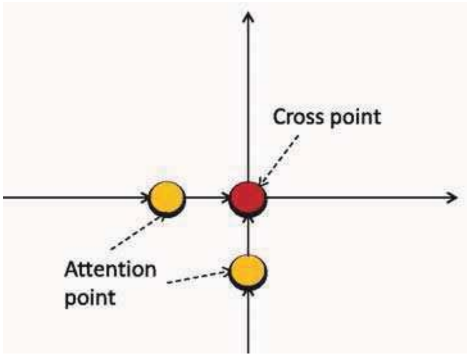
1) Route map properties: The route map is defined in such a way that coordination and path planning are a single entity that should not be treated separately. That is, the coordination is built for a specific type of route map and the route map itself is developed according to the needs of a specific coordination mechanism. Therefore a route map is developed in each sector with the following features:

- The route map is a directed graph: each edge is unidirectional in order to avoid the situation in which two or more AGVs are on the same road but with opposite directions
- There are at least two exits, two entries and one intersection in a sector
- AGVs on different segments can't collide. The minimum distance between two segments has to be sufficient to ensure the passage of the AGVs without collision. If this condition is not possible, then the two segments will be intersected with an intersection
- An *intersection* (node shared by several segments) is a resource to be allocated to a single AGV and it can be free or occupied
- The intersection is defined with a *cross point* and some *attention points* (see figure 3a)
    - Cross points: it is the real intersection due to the collision of two or more segments
    - Attention points: points linked with the cross point. They are the extremes of the colliding segments

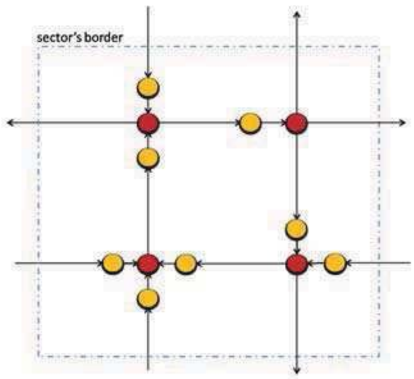
2) Coordination on the route map layer: First of all, each AGV has to search the path on the route map in order to go in the next sector. The path planning inside the sector is actually an allocation of the segments in which the searched path is divided. The algorithm used to find the path is the simple A*. The choice is due to the fact that the route map is fixed, and local dynamic changes aren't expected. When a path is assigned to every AGV, a coordination to avoid conflicts in the intersection among the paths are requested.

The coordination is fulfilled as a hybrid approach exploiting the resource allocation and negotiation mechanisms in order to obtain the advantages of both. It is managed locally because it takes place exclusively inside the sector. Here the AGVs can share information among them without the participation of a centralized supervisor. The data exchange among AGVs concerns:

- AGV priority: each AGV can have different tasks with different levels of priority
- Intersection request: an AGV which is approaching an intersection has to communicate this intention to the others
- Intersection allocation: an AGV allowed to go through an intersection has to communicate this to the others



(a) A Route map intersection



(b) General route map in a sector

Fig. 3: Route map properties

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Conversely the geometric data and the presence of obstacles are accessed by each AGV through the reading of the state of the sector. In the decentralized coordination, each AGV knows the route map and the sector's information and it has to establish a negotiation protocol to the other vehicles in order to avoid conflicts in the intersections. Therefore there is a combination of negotiation and resource allocation. The resource (intersection) is allocated only to a single AGV in order to avoid conflicts and the negotiation permits to avoid deadlocks.

Going deeply into the procedure, the steps for a single AGV are:

1) When the AGV is approaching the intersection and it is still far from the attention point, it has to:
   - share its intention to get the intersection
   - figure out how many other AGVs are approaching to the same intersection
   - share its priority among the negotiating AGVs
   - establish the winner
2) When the AGV is in the attention point and the intersection is free, it has to:
   - go through the intersection if it is the winner
   - stop if it has lost the arbitration
3) When the AGV is leaving the cross point, it has to:
   - free the intersection
   - withdraw the request for access to the previous intersection

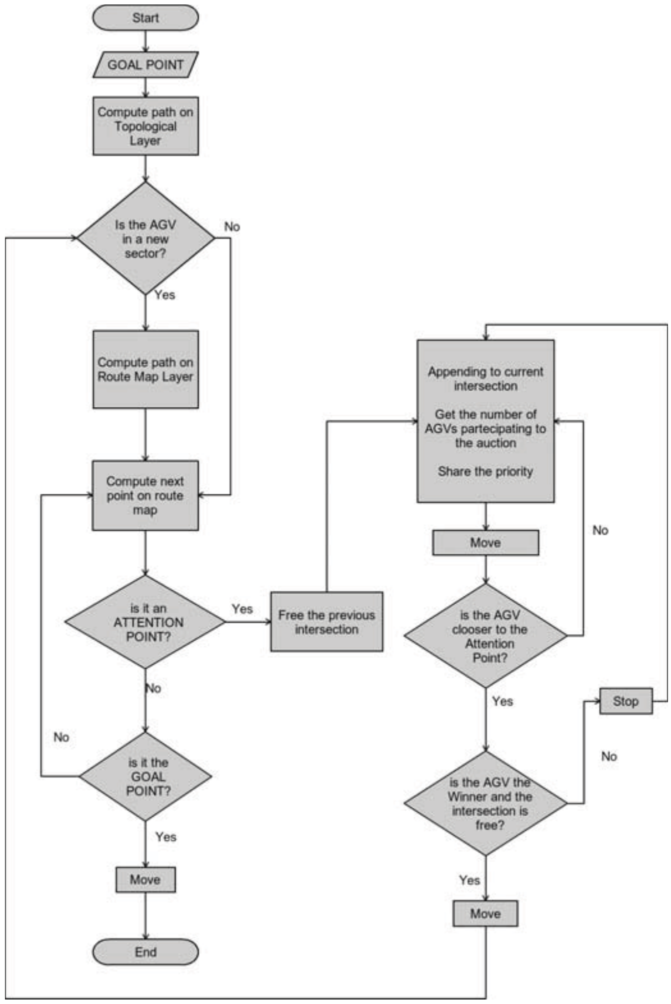


Fig. 4: Flowchart diagram of the path planning and coordination procedures.

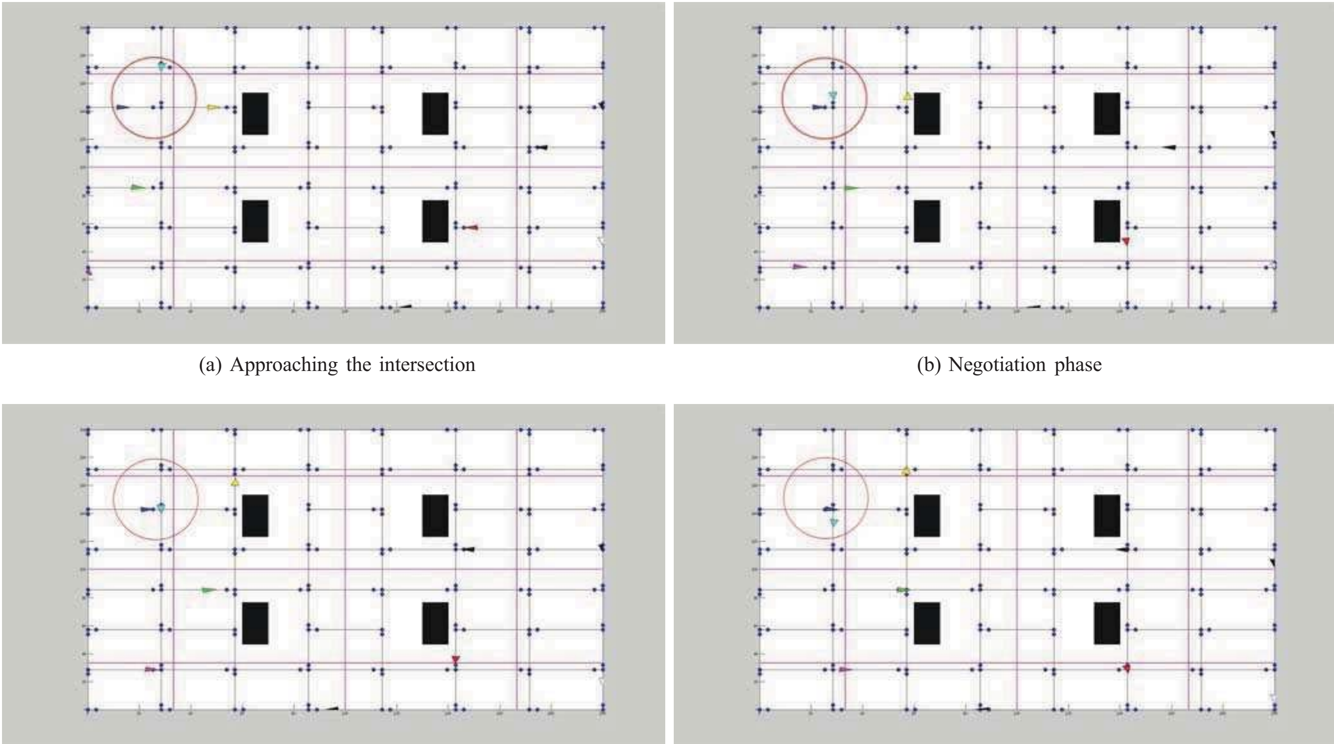
To sum up, the global flowchart diagram is shown in figure 4.

V. Simulation

In order to evaluate the idea, the algorithm is implemented using Matlab and a simple simulation environment is fulfilled. The tests are conducted under the same conditions, in particular, the scenario consists in:

- simple map with four rectangular obstacles
- 16 sectors
- each sector has four intersections
- maximum limit of 4 AGVs allowed in each sector
- start positions of the AGVs are different
- the simulation stops when all the AGVs reach their goals
- the priority is generated randomly for each AGV

In order to simulate a fleet of decentralized AGVs, the algorithm is executed in a parallel manner by implementing



(a) Approaching the intersection

(b) Negotiation phase

(c) The winner goes on

(d) The looser can go

Fig. 5: The screen-shots show the coordination at intersection. In these pictures, the red lines are the segment's borders and the dots are the nodes of the route map

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one single dedicated process per AGV. Figure 5 shows the sequence of events and actions of several AGVs. In particular two AGVS are approaching an intersection and, based on the priority, one AGV goes on and the other one has to stop temporarily.

Although the development of the idea is in an early phase, a statistical analysis is made in order to figure out the computational needs of the algorithm. Several tests are executed changing the number of AGVs, in particular the tests concern 5,10,15 and 20 AGVs. In all of them the elapsed time is monitored. The results (see figure 6) show a linear behavior of the elapsed time in function of the number of AGVs. The higher is the number of AGVs, the higher is the time for the computation. It is worth noting that with the increase of the number of AGVs, also the variance of results increases. This is due to the high number of negotiations which, depending on the random priority of the AGVs, can provide different results on tests performed in similar conditions.

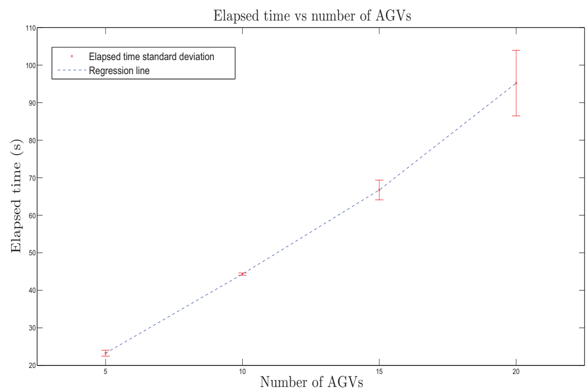

Fig. 6: Elapsed time versus number of AGVs

VI. Conclusion

The paper has dealt with the coordination of a fleet of AGVs through an architecture based on a two-layer approach. The presented idea tries to treat the planning and the path optimization as a common entity. The coordination and the traffic management are treated as global functions. In order to achieve this, a hybrid path planning and coordination is achieved. The path planning is split on the two layers in order to simplify the problem. The path planning executed by each AGV is totally decentralized, but the information about the occupation of the sectors is managed in a centralized way. The local coordination is also totally decentralized. In this case, the AGVs share the information among them in order to negotiate the access to the shared resources (i.e. the intersections).

The simulations have shown that it is easily possible to manage a high number of AGVs with this approach avoiding conflicts among them. The studied scenario is actually a strong simplification of a real plant. Therefore in the next steps, it will be necessary to validate the algorithm on a realistic scenario using the route map of a real plant both through virtual simulation and implementation in a real industrial environment.

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