Obstacle avoidance for industrial AGVs

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***Abstract*—The paper deals with the obstacle avoidance problem for Automated Guided Vehicles (AGVs). We propose an automatic algorithm to build new obstacle-free trajectories that leave the original roadmap. The new path has to also comply with the dynamic and kinematic constraints of the AGV. The new paths are generated by means of polar spline curves, lane-change maneuver curves and line segments. The proposed method is validated by means of simulations.**

I. Introduction

This paper describes a methodology for solving the obstacle avoidance problem for Automated Guided Vehicles (AGVs) moving in an industrial environment.

When dealing with mobile robots, collision avoidance is a fundamental issue and for this reason, it has been extensively studied in the past. Without aiming completeness, we will hereafter briefly describe some of the main approaches that can be found in the literature, with the purpose of highlighting the motivation for the proposed methodology.

Generally speaking, mobile robots are controlled to move from one location to another one. When moving in real environments, unforeseen events may happen: for instance, other non-cooperative mobile entities might share the same environment. Therefore, vehicles need to be equipped with appropriate sensors [1], [2], and opportune countermeasures have to be taken for avoiding collisions.

Typically, this objective is fulfilled introducing an appropriately defined control action, that makes the robot *deviate* from its originally defined behavior. For instance, artificial potential fields are a very well know technique for collision avoidance (see e.g. [3]–[11]). With this methodology, robots are driven to perform the gradient descent of an opportunely designed artificial potential field, whose gradient produces a repulsive force that drives each robot to move away from obstacles or other robots. However, the main drawback of artificial potential fields is in the well known local minima problem [12]: interacting with the primary task of the mobile robots, collision avoidance artificial potential fields can create undesired asymptotically stable configurations, that prevent the robots from reaching the desired configuration. This is clearly unacceptable for industrial applications, as it would prevent jobs to be executed.

Another popular method consist in defining the obstacle avoidance action as a gyroscopic force [13]–[18]. Roughly speaking, a gyroscopic force is always perpendicular to the velocity of the robot: this implies that these forces do not do any work, and does not modify the convergence characteristics of typical desired control laws. A similar approach is the null space based behavioral approach [19], [20]. This methodology consists in combining different behaviors in a hierarchical manner. In fact, with this technique, the highest priority behavior is completely fulfilled, while the lowest priority behavior is only partially fulfilled, when a conflict arises with the highest priority behavior. Specifically, the lowest priority behavior is projected onto the null space of the highest priority behavior. Considering the collision avoidance as the highest priority behavior, then all the other tasks are executed by the AGV only as long as they do not interfere with the collision avoidance itself.

While these methodologies are effective for general purpose mobile vehicles moving in arbitrary environment, they do not appear to be suitable for industrial applications. In particular, the operative environment considered in this paper consists in a fleet of AGVs used for logistics operations in industrial environments [21], [22]. As described in [23], in the vast majority of modern automatic warehouses, AGVs are constrained to move along a set of (virtual) paths and this set is usually called roadmap. An algorithm for automatically building a roadmap was introduced in [24]. Up to sixty AGVs can travel in an automatic warehouse and the way the roadmap is designed tremendously affects the way traffic can be managed and, consequently, the efficiency of the overall system. The fleet of AGVs is then generally coordinated by a centralized supervisor, which coordinated the AGVs along the roadmap in order to minimize traffic congestion, thus maximizing the productivity of the plant. A partially decentralized method for coordinating the fleet of AGVs was presented in [25], [26].

A probabilistic Bayesian approach is exploited in [27] for replanning the path on the roadmap based on the presence of obstacles. Clearly, this approach assumes that each segment of the roadmap is bi-directional, which is not always verified.

Conversely, in this paper we derive a methodology for computing local deviations from the roadmap. These deviations are computed locally by each AGV, relying on information acquired by means of on-board sensors, and from a global knowledge of the environment, gathered by the centralized control center. Local deviations from the roadmap are exploited by the AGVs for avoiding collision with obstacles, while still moving towards their goal.

The paper is organized as follows. Section II introduces the problem under analysis. The local deviation algorithm is described in detail in Section III. Section IV shows some simulation results that validate the proposed local deviation algorithm. Finally, Section V contains concluding remarks.

II. Description of the System and Problem Statement

In this paper we consider a fleet of AGVs used in an industrial environment for performing logistics operations. In particular, AGVs are used for moving goods among the different parts of the industrial environment. Specifically, typical tasks to be performed consist of picking a pallet of goods from an automated production line, and delivering it to the shipping area, where usually empty trucks are parked. Sometimes the pallets cannot be shipped directly, but need to be stored in a warehouse. The AGV fleet is generally managed by a centralized controller, usually referred to as Warehouse Management System (WMS), that is in charge of assigning the tasks to the AGVs, and of coordinating their motion.

The motion of the AGVs is typically constrained on a roadmap. The *roadmap* is the set of paths along which the AGVs can travel to fulfill their tasks. The roadmap is defined in such a way that a path exists to connect each pair of operation positions. Moreover, each path is defined in order to avoid collisions with the infrastructure. An example of roadmap defined in a portion of a plant is represented in Fig. 1.

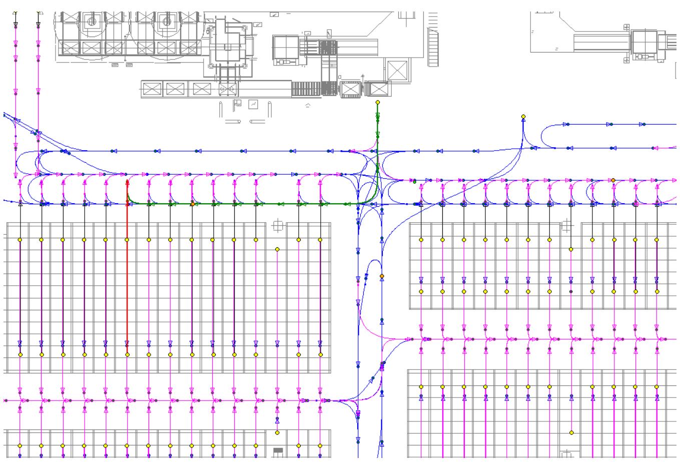


Fig. 1: Portion of the roadmap of an industrial plant

Each segment of the roadmap is geometrically defined as a specific portion of curve. For the sake of simplicity, a limited number of types of curves is generally utilized in a single plant. On these lines, we will hereafter consider the following assumption, without loss of generality.

Assumption 1 *Each segment of the roadmap is defined either by a segment of straight line or by a portion of polar spline curve [28].*

As described in [28], a *polar spline* curve is a fifth order polynomial curve with continuous curvature radius r defined as follows:

$$r(\phi) = a_0 + a_1\phi + a_2\phi^2 + a_3\phi^3 + a_4\phi^4 + a_5\phi^5 \qquad (1)$$

where ϕ is the polar angle. Furthermore a polar spline curve has to respect additional kinematic and dynamic constraints (i.e. minimum break radius, maximum curvature and maximum centrifugal acceleration) in order to generate the desired smooth path. The parameters are given by the following expressions:

$$\begin{cases} a_0 = R_1 \\ a_1 = 0 \\ a_2 = \dfrac{R_1}{2} \\ a_3 = \dfrac{-20R_1 + 20R_2 - 3R_1\Phi^2 + R_2\Phi^2}{2\Phi^3} \\ a_4 = \dfrac{30R_1 - 30R_2 + 3R_1\Phi^2 - 2R_2\Phi^2}{2\Phi^4} \\ a_5 = \dfrac{-120R_1 + 120R_2 - R_1\Phi^2 + R_2\Phi^2}{2\Phi^5} \end{cases} \qquad (2)$$

where R_1 and R_2 are the initial and final radius and Φ is the angle between the two line segments to be connected by the curve.

Roadmaps are exploited for reducing the complexity of the problem of coordinating multiple vehicles. While this approach is effective in terms of required computational resources, constraining the motion of the AGVs on a finite set of roads severely reduces the flexibility of the system. In particular, this reduced flexibility clearly affects the performance of the system in the presence of unforeseen obstacles. In fact, if an obstacle suddenly appears in front of an AGV, it is necessary to re-plan the AGV's path, in order to avoid collisions with the obstacle. If AGVs are constrained on the roadmap, re-planning means finding an alternative path on the roadmap, which is not always feasible: consider, for instance, the frequent case of mono-directional roads. In this case, if an alternative path can not be found on the roadmap, the AGV gets stuck, until the obstacle is removed. A simple example is depicted in Fig. 2.

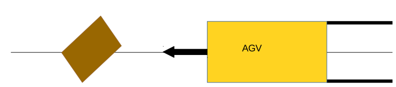


Fig. 2: The AGV remains stopped until the obstacle is removed

In order to avoid this problem, in this paper we introduce a methodology for computing local deviations from the roadmap, to be exploited by the AGVs for obstacle avoidance purposes.

In particular, in the presence of obstacles on the roadmap, the AGV has to compute a local path that:

- allows the AGV to pass the obstacle without colliding with the obstacle itself,
- does not cause collisions with the infrastructure,
- does not cause collisions with other AGVs or other moving entities.

Subsequently, an appropriate sensing system has to be exploited by each AGV for measuring the position, dimension, and velocity of obstacles. In particular, we make the following assumption.

Assumption 2 *Each AGV is able to localize itself in the environment, and is equipped with a set of on board sensors that provide measurements of the relative position of the obstacles, as well as of their dimension.*

We also assume the presence of an infrastructural sensing system, that is exploited for monitoring intersections, corners and black spots. A communication infrastructure is then exploited for gathering sensor data into a global representation of the environment, that will be hereafter referred to as *global live view*.

Assumption 3 *A constantly updated representation of the environment, the* global live view, *gathers sensing data from the infrastructural sensors and from the on board sensors. Information on the position, orientation, velocity and class of acquired obstacles is then available to the AGVs.*

Details on the data fusion methodology exploited for the global live view can be found in [29].

Data acquired by the on board sensors, and global data gathered in the global live view, can then be exploited for obstacle avoidance purposes. The problem under consideration can be stated as follows.

Problem 1 *Consider an AGV moving along a roadmap, and consider the presence of an obstacle on the AGV's path. Given sensor measurements of the position, orientation, velocity and class of the obstacle, as well as of the infrastructure elements, compute an admissible path that locally deviates from the roadmap, that can be used by the AGV for avoiding the obstacle.*

III. Local deviation algorithm

In this section we introduce an algorithm used for computing a local deviation from the roadmap, exploited for obstacle avoidance.

The algorithm has the following objectives:

- Computing a path that, given the shape of the AGV, guarantees avoidance of collisions with the obstacles, and with any infrastructural element.
- Defining a path that is admissible with respect to the kinematic constraints of the AGVs. In particular, the curvature radius has to be limited.
- Guaranteeing that, once the obstacle has been passed, the AGV returns on the roadmap, carrying on the original path plan and fulfilling its objective.

The proposed algorithm is defined as the following sequence of steps:

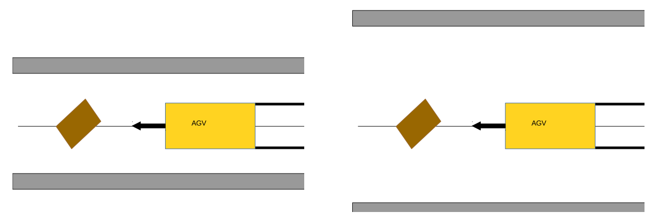
A. Safety check
B. Leaving the roadmap
C. Overtaking the obstacle
D. Return on the roadmap

The details of each step of the algorithm are given in the following subsections.

A. Safety check

It is worth noting that, for safety purposes, a deviation from the roadmap is admissible only if a sufficient amount of free space is available for the AGV to complete the maneuver, without colliding with any obstacle or infrastructural element.

Therefore, based on the measurements performed by the on board sensors, integrated with the data available in the global live view, the size of the free space can be computed. The free space is then compared with the size of the AGV: an acknowledgement is then produced if the free space is sufficiently wide. Conversely, if the amount of free space is not sufficient to guarantee safe maneuvers, the AGV is not allowed to leave the roadmap, and the algorithm is terminated. An example is represented in Fig. 3.



(a) No space for the overtaking maneuver

(b) The overtaking of the obstacle is possible

Fig. 3: Safety check

B. Leaving the roadmap

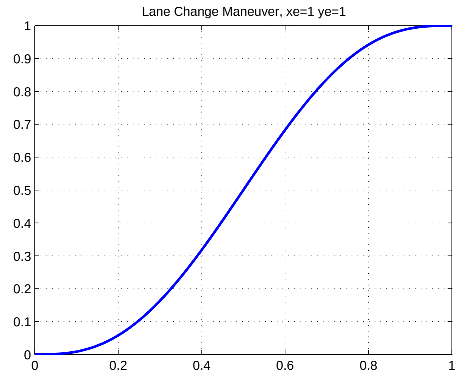
This step aims at building a new segment which leaves the original roadmap. A *lane-change maneuver curve* is exploited in order to produce a transition between parallel lanes in the same direction. The curve has a typical "S" shape. The lane-change maneuver is a cartesian-polynomial portion of curve that provides a continuous curvature transition. It was defined in [28] as follows:

$$y(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5 \qquad (3)$$

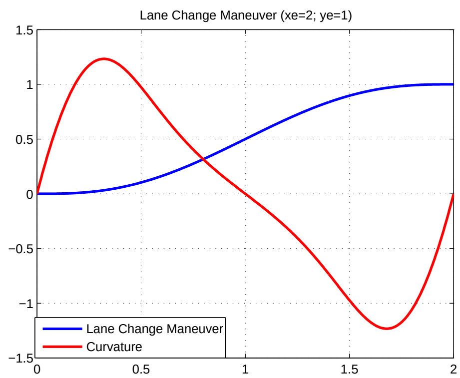
The parameters can be easily derived imposing continuity and differentiability of the curve, while considering the constraints about the maximum curvature and the steering-rate. In particular, the parameters of the lane-change curve are defined in order to minimize the deviation from the roadmap, while still guaranteeing the safety distance from the obstacle. In order to guarantee collision avoidance, a bounding box of the obstacle is computed, define as a rectangle with one pair of sides parallel to the roadmap.

C. Overtaking the obstacle

This step implements the actual overtaking of the obstacle. In particular, a path is defined that lets the AGV pass the obstacle, without increasing the distance from the original roadmap. For this purpose, based on the *length* of the obstacle, the path is defined as a portion of curve that is parallel to the original roadmap. Based on Assumption 1, the following two cases are considered:



(a) A lane-change curve



(b) Lange change curve and its curvature

Fig. 4: lane-change maneuver

1) *Obstacle on a straight line segment*: in this case, the overtaking path is defined as a straight line segment, parallel to the roadmap, whose length is equal to the obstacle length, Fig. 5a.
2) *Obstacle on a polar spline curve*: in this case, the overtaking path is defined as a polar spline curve parametrized with respect to the radius and angle of the original curve, Fig. 5b.

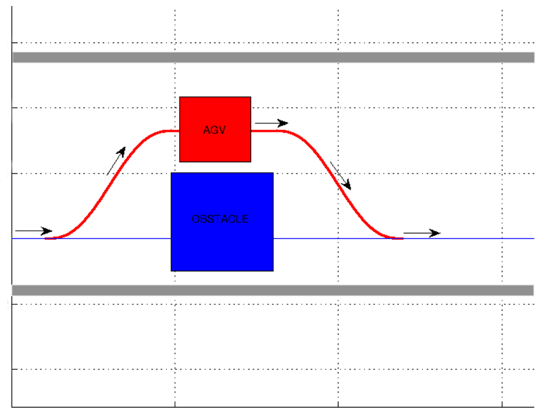
It is worth noting that the new portion of the path starts and ends on a line segment. Therefore the new curve may require much more space in case of obstacle on a polar spline curve. The obstacle is overtaken by the shortest possible path with respect to the obstacle's dimension and position on the roadmap. Fig. 5c shows this situation.

D. Return on the roadmap

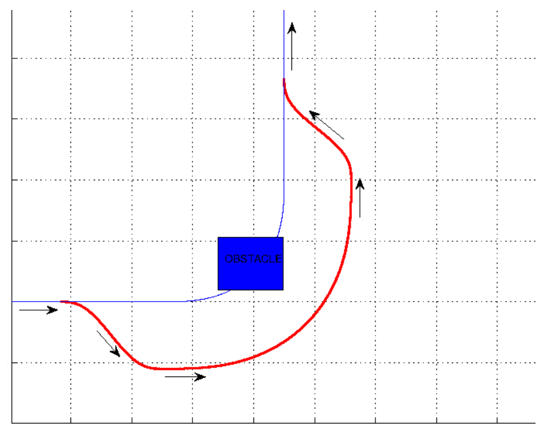
Once the obstacle has been overtaken, the AGV has to return on the roadmap, in order to fulfill its original objectives. A *lane-change curve* is then defined to join the previously computed deviation with the closest admissible point on the roadmap.

IV. Simulations

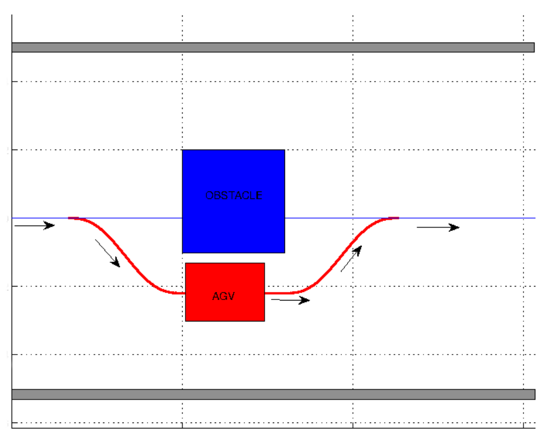
Several simulations were implemented to evaluate the performance of the proposed algorithm in different operative



(a) Obstacle on a straight line segment



(b) Obstacle on a polar spline curve



(c) Overtaking the obstacle by the shortest path

Fig. 5: Overtaking the obstacle

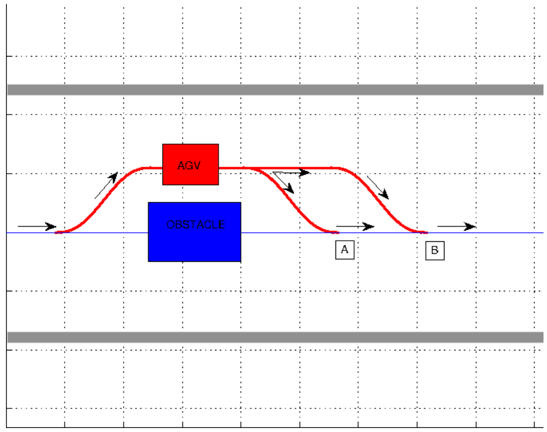
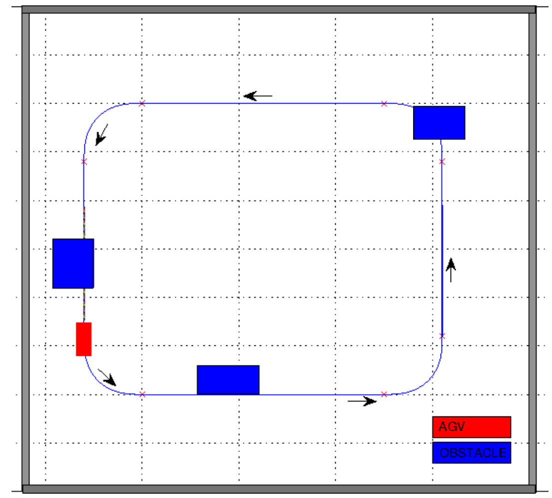
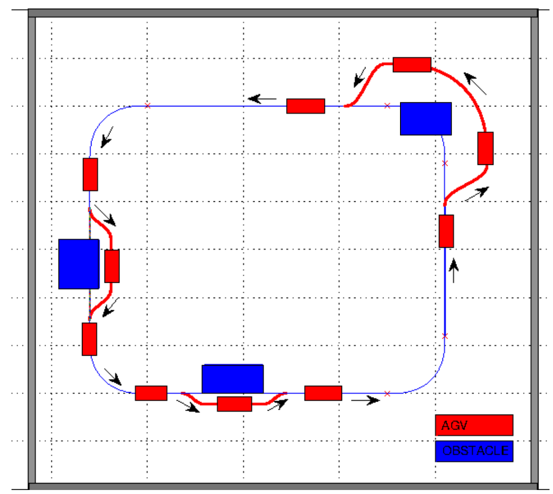


Fig. 6: Return on the roadmap: the overtaking can end in different parts of the roadmap depending on the actual space. Points A and B are two possible points of attachment to the roadmap.



(a) Original roadmap



(b) Roadmap (in blue) with deviations from the original paths (in red)

Fig. 7: Roadmap with several obstacles: red rectangles are the AGV's positions and blue rectangles are the obstacles on the roadmap.

scenarios. In particular, we considered generically defined roadmaps, with segments defined both as straight line portions and as polar splines. Obstacles with different size and shape were placed in different positions of the roadmap, and the local deviation paths were derived.

A simple but insightful example is represented in Fig. 7. In particular, Fig. 7a represents a ring-like portion of roadmap, where some obstacles (blue rectangles in the picture) are placed to interfere with the motion of the AGVs (an AGV is represented in the picture with a red rectangle).

Based on the obstacles' positions, and on the characteristics of the roadmap, opportune deviations are computed, based on the proposed algorithm. Fig. 7b shows the results obtained in the proposed example: red lines represent the local deviation paths. As expected, feasible paths are computed, since a sufficient amount of free space is always available.

It is worth remarking that an AGV might be blocked by an obstacle that does not lie on the roadmap, but is sufficiently close to the roadmap itself. As expected, the algorithm correctly deals with this case as well. An example is depicted in Fig. 8, where the local deviation (in red) from the original roadmap (in blue) is computed to guarantee the safety distance between the AGV and the obstacle.

V. Conclusions

The paper describes an algorithm for the automatic generation of new paths to avoid obstacles on a roadmap in automatic AGV systems. The new trajectories are built in order to keep the AGV safe (a minimum distance from the obstacles has to be guaranteed), while minimizing the deviation from the originally planned path (i.e. the roadmap).

Furthermore the new paths are built taking into account the constraints generated by the dynamic and kinematic structure of the AGVs, i.e. maximum acceleration, maximum centrifugal acceleration etc.

The proposed method was validate by means of extensive simulations in various scenarios. Next step will regard the implementation of the proposed methodology on a real AGV moving in a real industrial environment.

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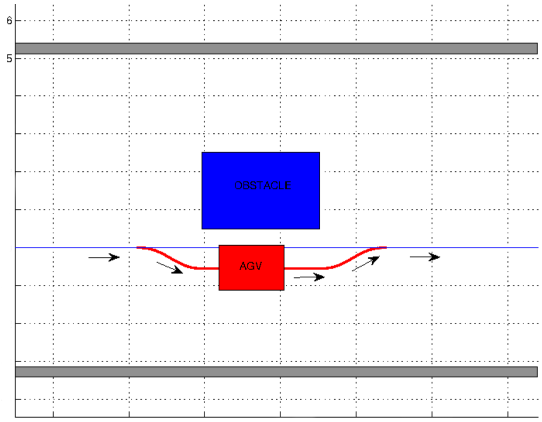

Fig. 8: Overtaking of an obstacle which is not on the roadmap, but too close to it

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