Decentralized local approach for lateral control of platoons

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Abstract— **This paper deals with platooning problem that aims to steer a train of vehicles along a trajectory. Many techniques were developed in this field, but they presented several inconveniences. On one side, a centralized control requires communication between vehicles: any data loss may prevent the correct behavior of the vehicles. On the other side, a decentralized control is more robust as each vehicle is autonomous, but trajectory tracking is less precise (the followers may deviate and cut the corners).**

This paper studies the lateral control and proposes a decentralized local approach, that improves the platooning performance specially along corners. It memorizes the positions describing the trajectory of a vehicle. Then, the follower tends to follow this trajectory, not the preceding vehicle itself. In other terms, the lateral controller will have as input the suitable position of the trajectory that is closest to the follower.

I. INTRODUCTION

Nowadays, many studies and projects aim to improve the cities of the future by replacing current vehicles by intelligent electrical ones. The hypercenters will be equipped by these vehicles and platooning technique will be used to rebalance the stations' load.

Platooning aims to steer a train of vehicles along a trajectory by avoiding collisions between vehicles and minimizing the lateral deviation from this trajectory. This technique should improve the public transportation and allows the conception of automated highways that can reduce fuel consumption and therefore, decrease pollution.

Platooning can also be used in freight ports where transport vehicles can travel closely yet safely to carry containers from ships to docks. This is one of the goals of the INTRADE project, that covers also the topic of the work presented in this paper.

Considering a platoon moving at a low speed, longitudinal and lateral controls can be, in this case, considered independently. The work presented below aims to design a lateral controller for a platoon of robots. Thus, we will be using a longitudinal controller developed by Daviet & Parent [4].

Many lateral controllers for near to near approaches can be found in the literature but robots usually cut the corners. The goal of this paper is to present an improved lateral controller that reduces the corner cuts.

We consider here a decentralized local approach where robots only perceive their preceding ones. There is no need for communication between them, avoiding the risk of data loss.

The conception of this lateral controller relies on memorizing the positions where the preceding robot had passed. Then, each robot computes its own commands, the control is therefore decentralized. Considering the low speed hypothesis, we can disregard the drifting problem. Thus we can use the kinematic unicycle model to represent the robots movement.

The paper is organized as follows. Section II recalls the two main approaches developed in platooning: the global and local approaches. It also presents the works done by the LASMEA[1] laboratory and Daviet & Parent. Section III explains the proposed approach for the lateral control. Then, Section IV gives experimental results and shows simulations on Matlab for the proposed approach. Finally, Section VI concludes.

II. EXISTING APPROACHES

Before we present the existing approaches, Subsection II-A defines the unicycle and tricycle models showing the influence of the kinematic model on the performances of the vehicle and therefore, on the platooning. Then, Subsection II-B explains the centralized and decentralized controls while Subsection II-C describes the global and local approaches. Finally, subsections II-D and II-E focus on presenting the approaches of the LASMEA laboratory and Daviet & Parent respectively.

A. Unicycle and tricycle models

In general, modeling a robot comprises studying its kinematics and dynamics. In this paper, we only consider kinematic aspects of the motion. Thus, we do not take into account its dynamic model [3].

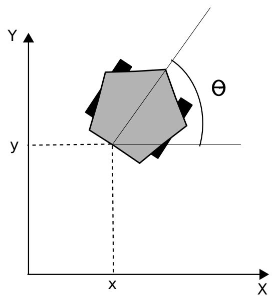

Fig. 1. The unicycle model of a robot

The state of a unicycle robot is given by its position and orientation (x, y, θ) in a world reference frame [2].

Its motion verifies the following equations (see Figure 1):

$$\begin{cases} \dot{x} = v\cos\theta \\ \dot{y} = v\sin\theta \\ \dot{\theta} = \omega \end{cases} \tag{1}$$

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where v and ω are respectively the linear and angular velocities. A unicycle model does not restrict the angular velocity. The vehicle can turn on the spot without any constraint, taking any orientation it wants.

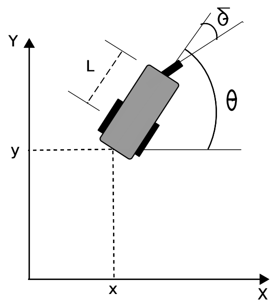

Fig. 2. The tricycle model of a robot

The state of a tricycle robot is also given by (x, y, θ) [1]. However, its motion verifies (see Figure 2):

$$\begin{cases} \dot{x} = v\cos\theta \\ \dot{y} = v\sin\theta \\ w = \dot{\theta} = v\dfrac{\tan\delta}{L} \end{cases} \tag{2}$$

where:

- L is the distance between front and rear wheels' axles.
- δ is the orientation of the leading wheel of the vehicle.

In this model, δ is generally mechanically bounded, preventing the robot from turning on the spot. The angular velocity w is function of the robot length L and its linear velocity v.

B. Centralized and decentralized controls

A robot moves according to its commanding speeds. The computation of these commands can be either centralized or decentralized.

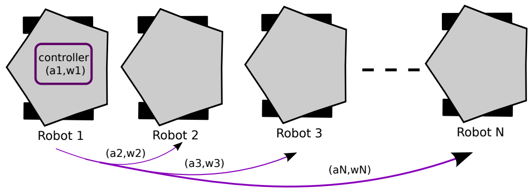

Fig. 3. The centralised control

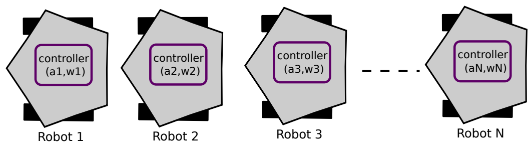

Fig. 4. The decentralized control

A centralized control is obtained when a controller, common to all robots, computes and sends the commands to each one. In Figure 3, the lateral controller is located on the first robot of the platoon.

However, Figure 4 shows a decentralized control where each robot computes its own commands using the acquired data. In a centralized control, the robots are not autonomous. The communication between them is a must. So, they risk to loose data. On the contrary, the decentralized control is more robust. Each robot is autonomous as it does not depend on a central controller to generate its commands. The decentralized control is also simple for connexion of robots. With no need of communication, a robot can be added without making changes to the state of the platoon. In this paper, we focus on the design of a decentralized lateral controller.

C. Global and local approaches

Platooning can either be realized in a global approach or in a local one.

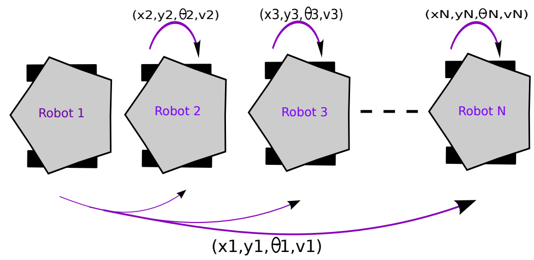

Fig. 5. The global approach

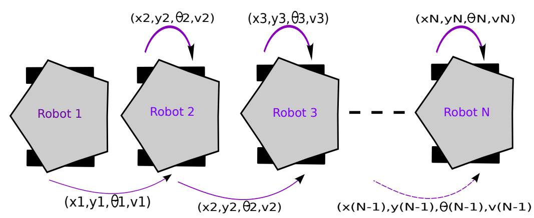

Fig. 6. The local approach

In a global approach, each robot knows its own state and the states of all the others and acts according to these information (see Figure 5). The communication between the robots is a must. Thus, all the robots are situated in the same frame.

In a local approach, each robot can only get data about its neighborhood and acts according to this state (see Figure 6). Communication between robots is not necessary since each robot can acquire the needed information using its own perceptions.

A global approach can be centralized (the leading vehicle of the platoon computes the commands and sends them to each follower) or decentralized (each vehicle computes its own commands using the information received from the leader).

Now, we proceed to present the local approach developed by Daviet & Parent [5], and the global approach of the LASMEA [1].

D. The LASMEA approach

The LASMEA laboratory developed a decentralized global approach based on the path following, where the robots have to follow a referenced trajectory drawn by the leader of the platoon.

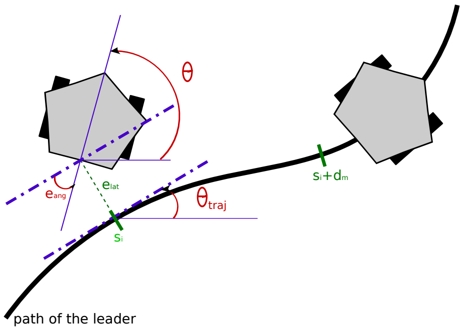

Fig. 7. The global approach developed by LASMEA

The leading robot communicates with its followers and gives them its actual position and motion needed to rebuild its trajectory. Depending on its mechanical capacities, each follower will tend to reach this trajectory once covered a certain distance called the lookahead distance d_m. Thus, the controller of each following robot tends to reduce the lateral and angular errors and maintain them as close as possible to zero [1]. Staring with a curvilinear distance s_i, the follower tends to reduce these errors and reach the trajectory at s_i+d_m (see Figure 7).

E. Daviet & Parent approach

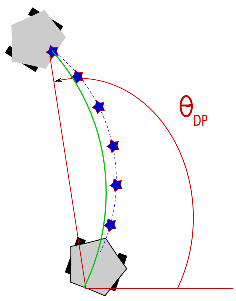

Fig. 8. The local approach developed by Daviet & Parent

Daviet & Parent developed an approach based on tracking the preceding robot in a low speed platoon without using communication ([4], [6]). Each robot acquires the data relative to its preceding (position and velocity) by using its own perceptions. The longitudinal control computes a linear acceleration for the robot to avoid collisions with others, and the lateral control finds an angular velocity to reach a given state. However, this lateral control law (mentioned by DP_1) leads to a follower which cuts remarkably the corners because its wheel angle is equal to the direction of its preceding robot (see Figure 8). Daviet & Parent developed another lateral control law DP_2 derived from a third degree polynomial which reduces the cut of the corners [5]. The

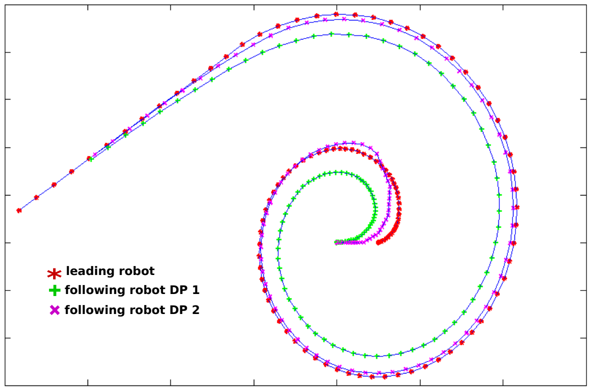

Fig. 9. Comparison between the two lateral control laws of Daviet & Parent

improvement of the lateral control provided by this second law can be seen in the simulation represented by Figure 9. The green (+) curve represents the trajectory of the follower obtained by applying DP_1, and the magenta (x) one is the trajectory obtained by applying DP_2. As we can see, the cut of corners is reduced by using DP_2.

F. Discussion

The two approaches developed by Daviet & Parent and the LASMEA laboratory have some drawbacks that made us think to develop another approach improving the platooning.

In the local approach of Daviet & Parent, the lateral control law is simple but not efficient. Steering the robot along the direction of its preceding leads to a remarkable cut of corners. In the global approach of the LASMEA, the robots risk to loose some data that concern the state of the platoon because of the communication. Also, the use of the GPS to obtain the positions of the robots is not efficient in the cities: data are noisy and the coverage of the GPS is weak.

By comparing the platooning results of these two approaches, simulations on Matlab show a less cut of corners in the LASMEA's approach. This is due to the memorizing of the leader's trajectory.

III. The Proposed Approach

The controllers developed above do not present high performances. However, the simplicity of the control law DP_1 used by Daviet & Parent and the memorizing of the leader's trajectory in the LASMEA approach have been used to develop our approach.

The main idea is that each robot acquires and memorizes the positions of its preceding robot. Then, for the lateral control, it selects a position among the saved ones located at a lookahead distance d_m. After choosing the point to aim, and considering the platoon moving at low speed, the robot applies the control laws in order to reach this position smoothly and without oscillating or making harsh turning (see Figure 10). The lookahead distance depends on the speed of the vehicle and the curvature of the trajectory. The more the robot moves quickly, the more the aimed point is far away from the robot; and the more the trajectory curvature

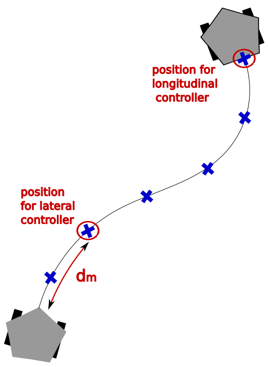

Fig. 10. Selection of suitable positions by the proposed approach for the longitudinal and lateral controls

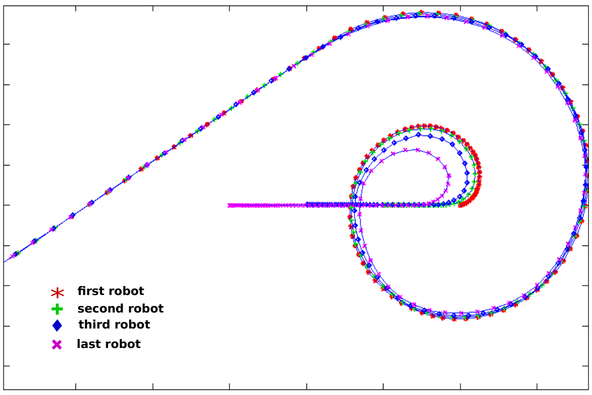

Fig. 11. Platooning realized by the proposed approach applied on a train of four robots

is high, the more the aimed point is closer to the robot. In a first step, in the sake of simplicity, we took a constant lookahead distance.

This idea was evoked without much details in [7], where the lateral control approach, applied on a two-vehicles platoon, is based on memorizing the positions of the leader and the motion parameters of the follower over time.

Applying this approach on a train of 4 robots gives the platooning represented by Figure 11: the red (*) curve is the trajectory of the first robot, while the blue (⧫), green (+) and magenta (x) curves represent the trajectories of the followers. The lateral deviations between the trajectory of each robot and the trajectory of the first robot in the train is represented in Figure 12. The last vehicle in the platoon has a significant lateral deviation at the beginning of the platooning. This is due to the fact that the curvature of its predecessor trajectory is high and also to the accumulation of the lateral gaps illustrated in Figure 13. But as we can see in Figure 12, this deviation decreases quickly, wich is not the case with the original law (see Figure 16).

A. *Importance of memorizing in the lateral control*

The main idea that differentiate our approach from the approach of Daviet & Parent in the lateral control is memorizing the positions of the preceding robot of each one. Thus, each robot does not aim its preceding robot as in the approach of Daviet & Parent, but, it aims a closer position. This leads to a drastic reduction of the corners cut.

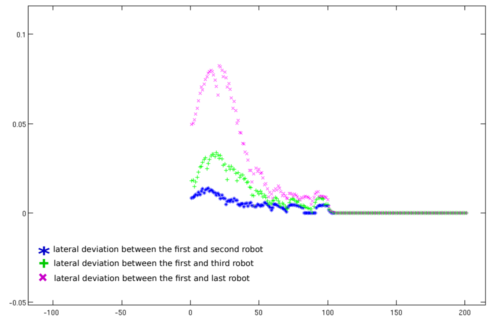

Fig. 12. Lateral deviations between each follower and the leader of the platoon

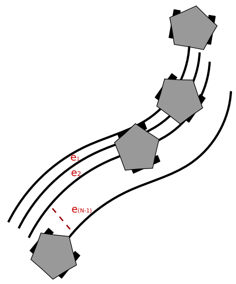

Fig. 13. Accumulation of the lateral gap in a near-to-near approach

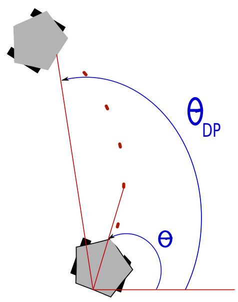

Fig. 14. Comparison between the approach of Daviet & Parent and the proposed approach to show the improvement in the lateral control

As it is shown in Figure 14, by applying the lateral control of Daviet & Parent, the robot will turn through an angle equal to θ_{DP}; by applying the proposed approach, the robot will turn through a smaller angle equal to θ, and it will senseably less cut the corner.

B. *The longitudinal and lateral controls*

As mentioned before, the platoon moves at a low speed allowing us to consider the longitudinal and lateral controls independently. We are interested in studying the lateral control, so we will use the longitudinal control of Daviet & Parent.

1) Longitudinal control: The main goal of the longitudinal control is to guarantee a movement of the platoon without collision [4]. Beeing in a near-to-near approach, each robot will perceive its preceding robot and acts so that it respects, along its travel, a minimal distance between them. The longitudinal controller of the follower uses its velocity, the interdistance and the interspeed between the two successive robots to compute its new acceleration, and then deduce its velocity:

$$a = \frac{1}{h}[\Delta V + K_p(\Delta D - hV_f - d_{min})] \tag{3}$$

where:

- ΔV is the interspeed between the two successive robots.
- ΔD is the interdistance between the two successive robots.
- V_f is the velocity of the following robot.
- d_{min} is the minimal distance to guarantee between the two successive robots.
- h is a constant.
- K_p is min($\frac{1}{h}$ and $\frac{A_{max}}{V_f}$), A_{max} is the maximum acceleration of the robot.

2) Lateral control: The lateral deviation of a robot along the tracking of a curvilinear trajectory is reduced by the lateral controller. The purpose of this controller is to compute an angular velocity that allows the robot to turn along a corner with a minimum lateral deflection. As mentioned above in Section III, the robot chooses, among the non exceeded saved positions of its preceding robot, the suitable one located at the lookahead distance, to aim. Then, the easiest control law is to steer the wheel angle of the robot along the direction of the selected position. The information needed to calculate the angular velocity, in this case, is the interdistance and the interangle between the robot and the position to aim.
Thus, the angular velocity is defined as:

$$\omega = \frac{\arctan(\Delta Y/\Delta X)}{\Delta T} \tag{4}$$

where:

- ΔT is the time step.
- ΔX and ΔY are the coordinates of the aimed position in the referential of the follower. They are obtained using the interdistance and the interangle between the robot and the specified position.

We choosed the control law DP_1 because it emphasizes the improvement of the lateral control specially along the corners provided by our proposed approach to the platoon. As simulations had shown, the approach of Daviet & Parent using the same lateral control law gave us a significant cut of corners. Using the same control law, this lateral deviation is extremely reduced (Subsection IV-A) by applying the proposed approach.

C. Kinematic model

As we mentioned before in Subsection II-A, we consider a unicycle model of robots. The simulated movement of the robot evolves according to the linear acceleration and the angular velocity computed by the controllers above. The function called "move" allows us to obtain the new position of the robot. This function takes as parameters the actual position, orientation and velocity of the robot, the linear acceleration and angular velocity to apply as commands during the step time ΔT. Then, it calculates the new position, orientation and velocity [8]:
$(x_{prev}, y_{prev}, \theta_{prev}, v_{prev}, a, w, \Delta T) \rightarrow (x_{new}, y_{new}, \theta_{new}, v_{new})$

Besides, the velocity v of the robot is limited between v_{max} and v_{min}. So, move(x_{prev}, y_{prev}, θ_{prev}, v_{prev},a,w,ΔT) gives us:

- if($v_{min} < v_{new} < v_{max}$)

$$\begin{cases} x_{new} = x_{prev} + \left(v_{prev} + \frac{a}{2}\Delta T\right)\cos\theta_{new}\Delta T \\ y_{new} = y_{prev} + \left(v_{prev} + \frac{a}{2}\Delta T\right)\sin\theta_{new}\Delta T \end{cases}$$

- if($v_{new} < v_{min}$)

$$\begin{cases} x_{new} = x_{prev} + \left(v_{min}\Delta T - \frac{\Delta V_{min}^2}{2a}\right)\cos\theta_{new} \\ y_{new} = y_{prev} + \left(v_{min}\Delta T - \frac{\Delta V_{min}^2}{2a}\right)\sin\theta_{new} \end{cases}$$

- if($v_{new} > v_{max}$)

$$\begin{cases} x_{new} = x_{prev} + \left(v_{max}\Delta T - \frac{\Delta V_{max}^2}{2a}\right)\cos\theta_{new} \\ y_{new} = y_{prev} + \left(v_{max}\Delta T - \frac{\Delta V_{max}^2}{2a}\right)\sin\theta_{new} \end{cases}$$

where:

$$\begin{aligned} v_{new} &= a\Delta T + v_{prev} \\ \theta_{new} &= \omega\Delta T + \theta_{prev} \\ \Delta V_{max} &= v_{max} - v_{prev} \\ \Delta V_{min} &= v_{prev} - v_{min} \end{aligned}$$

IV. STUDY OF THE PROPOSED APPROACH

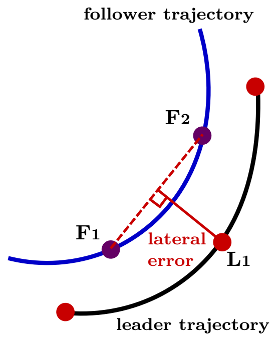

Fig. 15. The lateral error between the trajectories of the robot and its follower

One of the criteria usually used to evaluate the efficiency of the proposed approach is the lateral deviation between the trajectory of each follower and the referenced trajectory: we compute the instantaneous gap between these two trajectories represented by Figure 15. Being in a discret case, this deviation is calculated as follows: for each position of the leader, we pick the two closer positions of its follower and we calculate the distance between the position of the leader and the segment obtained by the two selected positions of the follower.

To study the proposed approach, several simulations on a platoon are done; the platoon is considered moving along a predefined trajectory.

A. Comparison between the approach of Daviet & Parent and the proposed approach

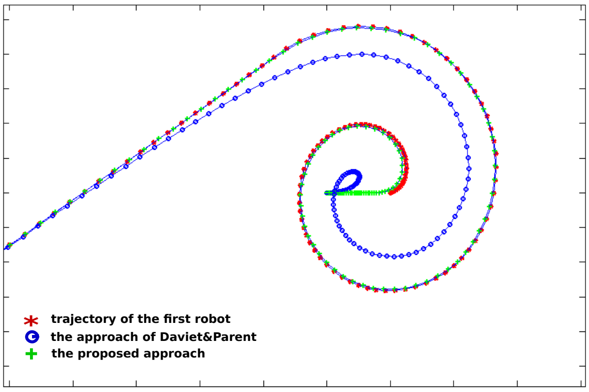

Fig. 16. Comparison of a platooning realized by the approach of Daviet & Parent and the proposed approach

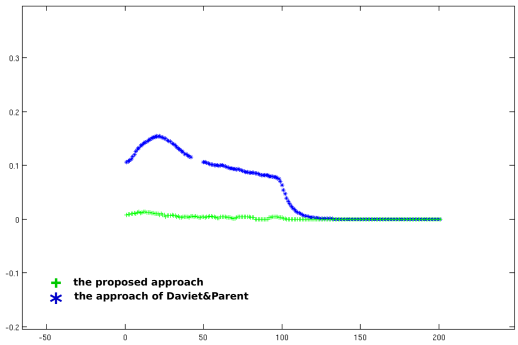

Fig. 17. Lateral errors between the trajectories of the leader and the follower

We consider two successive robots moving in this platoon. The follower is supposed tracking its preceding robot along the trajectory. First, we apply the control of Daviet & Parent on the robots. Then, we apply the control of the proposed approach. The results of these platoonings are shown in Figure 16; the red (*) curve is the trajectory of the leader. The blue (o) one is the trajectory of the follower according to the algorithm of Daviet & Parent. Finally, the green (+) curve represents the platooning obtained by the proposed approach.

As we can see, the robot using Daviet & Parent approach remains far from the leader for a long time. This is due to the fact that the follower goes in the direction of its robot, but does not try to follow its path. On the contrary, the path of the robot preceding using the proposed approach reaches the leader's path, and remains close to it. This is explained by the fact that the follower memorizes the positions where its preceding robot had passed and tries to track them. Initially, we can notice that the robot moves towards the first position of the leader although this leader is not at this position anymore. The figure 17 shows the lateral error between the trajectories of the follower and its preceding robot in the two cases, Daviet& Parent approach, and the proposed one.

B. Influence of the lookahead distance on the lateral deviation

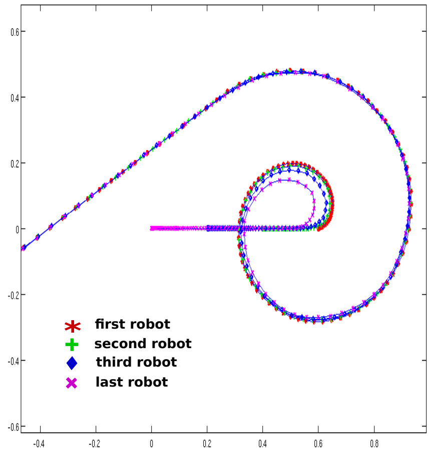

Fig. 18. Platooning realized with a small lookahead distance d_m=$\frac{1}{5}$ d_{min}, d_{min} is the initial interdistance between two successive robots.

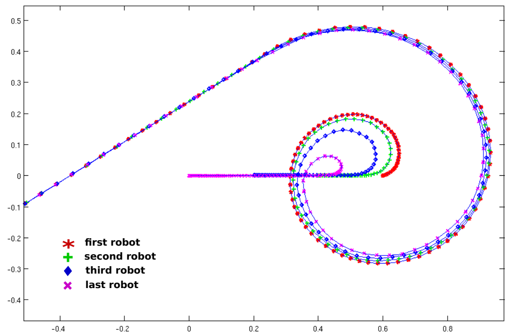

Fig. 19. Platooning realized with a high lookahead distance $d_m = \frac{1}{2} d_{min}$

The lookahead distance is a fundamental parameter in this approach. It defines the minimal distance that the robot looks at to choose the position to aim. It also influences on the lateral deviation specially when the robot is moving along a corner. The more this lookahead distance is high, the more the cut of corners is remarkable and thus the lateral deviation is significant. This is illustrated by the figures 18 and 19,

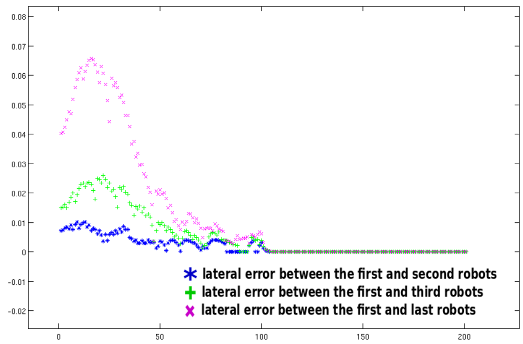

Fig. 20. Lateral errors between the curves of the first robot and each of the followers in a platooning realized with a small lookahead distance

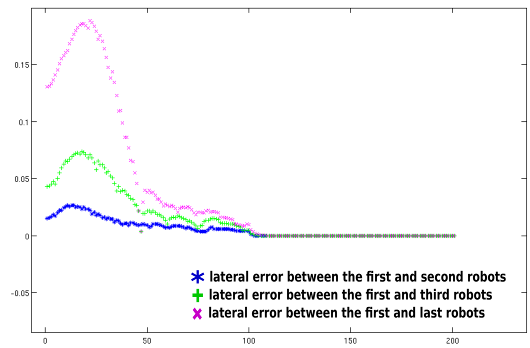

Fig. 21. Lateral errors between the curves of the first robot and each of the followers in a platooning realized with a high lookahead distance

where we realize a platooning of four robots and we represent the lateral errors in figures 20 and 21.

C. Influence of the maximum values of the angular velocity

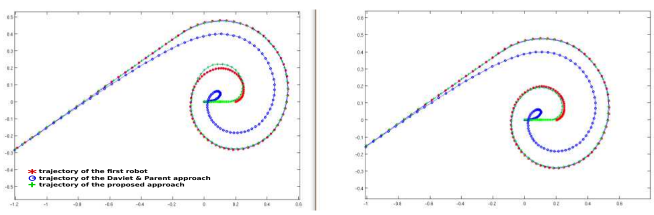

Fig. 22. Influence of the variation of the maximum angular velocity on the platooning

The limitations of the maximum value of the angular velocity of the robot influence on its performance and thus on the platooning. By increasing the angular velocity, we see that the cut of the corners is reduced: the robot can turn through a bigger angle to reach the aimed positions. This is illustrated by the evolution of the green (+) curve in Figure 22 where the maximum angular velocity in the graph located on the right side is bigger than the maximum angular velocity of the left side graph.

D. Influence of an initial lateral deviation of the robot on its performances in tracking

In this case of study, we modify the initial positions of the robots to see the influence of the deviation along

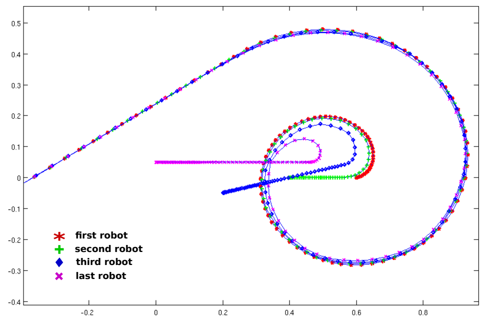

Fig. 23. A platooning realized by a nonaligned train of robots

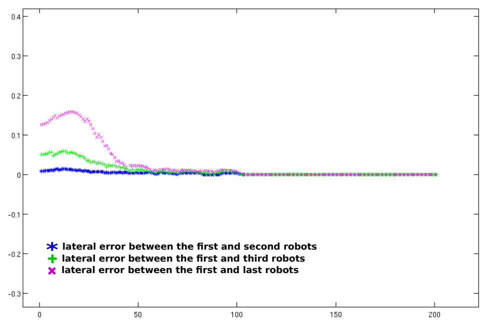

Fig. 24. Lateral errors between the curves of the first robot and each of the followers in a platooning realized on a monaligned train of robots

y-axis on the platooning. We examine if the robots can follow each others starting from unaligned positions. The Figure 23 shows an example of such a situation, the robots had successed to decrease the initial y-axis deviation and they reached the trajectory of the platoon leader. The lateral error is illustrated in Figure 24.

However, would the initial lateral deviation be important, the robots may reach a position in wich the lateral control law gives an inconsistent command.

V. Implementation of the proposed approach on robots

A. with or without communication?

To implement the proposed approach on robots, we should choose between considering communication between them or not. As the proposed approach is local, communication between robots is not needed.

If we choose to consider communication between the robots, each one will acquire its own information using the GPS and send them to its follower. These information will be relative to a world reference frame. Then, each robot having its own information and the information of its preceding robot, a simple computation gives the interdistance, intervelocity and interangle needed as entries to compute the commands. The inconveniences in this case are the risk of loosing data while communicating, and the possibility of not acquiring new information from the GPS specially if we are

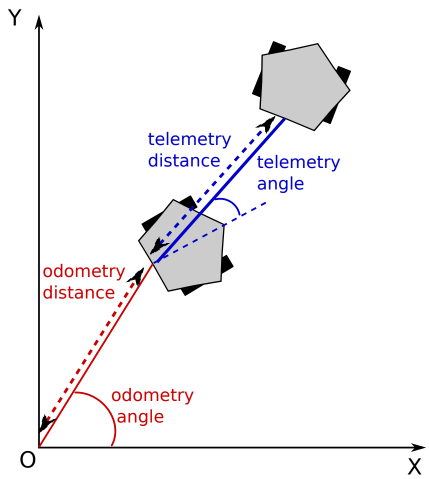

Fig. 25. Acquiring data from the onboard sensors

in cities where the GPS coverage is too weak and the data are too noisy.

For all these reasons, we choose to consider a platooning without communication. Each robot uses its perceptions to get the information that it needs. In one side, the telemetry gives the interdistance and the interangle between two successive robots (the interangle is the orientation of the preceding robot compared to the follower). In other terms, it gives the position of the robot in the referential of its follower. These acquired data will not be relative to the same referential because the robot is moving. In the other side, to get its own position, the follower can use the GPS (not recommended because of the inconveniences mentioned before) or the odometry that gives its position and orientation in a fixed referential, the odometry referential whose its origin corresponds to the starting position of the robot. Thus, at an instant t, each robot will have its own data (relative to the referentiel of the odometry) and the data corresponding to its preceding robot (relative to its actual referential). A transformation of these information is made so that they correspond to the odometry referential. This transformation is simply a change of reference (Figure 25).

B. limitation of the memory size of robots

Another point to consider is the limited memory size of the robot that can not memorize all the positions of the preceding robot. So, a sliding buffer, with fixed size, allows the robot to save the most recent positions of its preceding robot and gets rid of the oldest and already exceeded ones.

VI. Conclusion

This paper had studied the lateral control of a platoon. It presented two approaches developed in this field: the global approach of the LASMEA laboratory and the local approach of Daviet & Parent, and showed the inconveniences of these approaches. Then, it proposed a local decentralized approach where the robots are autonomous. This approach is based on memorizing the positions of the preceding robot of each one and aiming to reach the positions situated at a certain distance called the lookahead distance d_m. By studying this approach, we noticed that the cut of corners is remarkably reduced, specially when the lookahead distance is small.

But, as we mentioned before, the lookahead distance is currently constant while it should depend on several parameters (like the velocity of the robot and the curvature of the trajectory). We intend to try and find a formula of d_m wich reduces the lateral deviation. We also applied our approach on a unicycle model without considering the dynamical model of a robot. We still have to apply this approach on a tricycle model by taking into consideration the forces that can affect the movement of the vehicle. Finally, we are intending to simulate this approach on the Scanner Studio software on one side, and on the other side, we are planning to implement and test it on real robots.

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