Decentralized local approach for lateral control of platoons

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Abstract— **This paper deals with the platooning problem: we aim to steer a train of vehicles along an unknown path followed by the first vehicle. Many techniques have been developed in this field, but they presented several drawbacks. On one side, a centralised control requires communication between vehicles: any data loss may prevent the correct behaviour of the platoon. On the other side, a decentralised control is more robust as each vehicle is autonomous, but path tracking is less precise (the followers may deviate and cut corners).**

This paper studies the lateral control and proposes a decentralised local approach, to improve the platooning performance especially along corners. Each robot uses its perceptions to compute the position of its preceding vehicle, and memorises it to form a path. It then tends to follow this path instead of trying to reach the preceding vehicle's position. In other terms, the lateral controller will have as input a position on this path which is closer than the preceding vehicle's position. This reduces the lateral error in the platoon motion.

I. INTRODUCTION

Nowadays, many studies and projects aim to improve the cities of the future. Putting stations of electrical vehicles in town centers should both allow individual transportation and reduce the problems of traffic jams and parking places. In this context, platooning techniques are used to rebalance these vehicle stations' load.

Platooning aims at steering a train of vehicles along a path by avoiding collisions between vehicles and minimising the lateral deviation from this path. This technique should improve the public transportation and allow 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, which covers also the topic of the work presented in this paper.

Considering a platoon moving at low speed, longitudinal and lateral controls can be 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 Alexis Scheuer, Olivier Simonin and François Charpillet [7]. (Scheuer et al. [7] ? Scheuer, Simonin and Charpillet [7] ?)

Lateral controllers for near to near approaches which can be found in the literature still are far from perfect as robots usually cut corners. This paper presents a ROBUST (à vérifier plus tard dans la partie experiments) lateral controller where the path of the platoon's leader is unknown. The followers need to reconstruct and follow this path with a minimum of lateral deviation while minimizing communications (as communication problems may induce data loss and time delays). The conception of this lateral controller relies on the transformation of the preceding robots' positions into a global reference (each robot only stores the successive positions of its predecessor and does not send them to the rest of the platoon), all these points forming the path to follow. Each robot follows the path stored in its global reference, the control is therefore decentralised.

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 decentralized local approach developped in his work allows us to have easily reconfigurable platoons : we can add or remove robots without affecting the platooning. This paper also studies the interaction between longitudinal and lateral controls showing how the movement of the platoon's leader affects the perfomances of the platooning.

The paper is organised as follows. Section II introduces the framework of the approach. Section III presents the works done by Bom (at the LASMEA[1] laboratory) and Daviet & Parent. Section IV explains the proposed approach for the lateral control. Then, Section V study this proposed approach and experimental results. Finally, Section VI concludes.

II. CONSIDERED MODELS

Before we present the existing approaches, Subsection II-A defines the unicycle model, showing the influence of this kinematic model on the performances of the robot and therefore, on the platooning. Then, Subsection II-B recalls the definitions of centralised and decentralised controls while Subsection II-C presents the differences between global and local approaches.

A. Unicycle kinematic model

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].

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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 :

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

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

B. *Centralised and decentralised controls*

A robot moves according to its commanding speeds v and ω. The computation of these commands can be either centralised or decentralised.

A centralised control is obtained when a controller, common to all robots, computes and sends the commands to each one. So, the communication is a must and robots risk loosing data. The robots are not autonomous as they depend on a central controller to generate their commands. On the contrary, in a decentralised control, each robot is autonomous as it computes its own commands using the acquired data. The decentralized control is more robust and easier to configurate : with no need of communication, a robot can be added or removed without making changes to the state of the platoon.

In this paper, we focus on the design of a decentralised lateral controller.

C. *Global and local approaches*

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

In a global approach, each robot knows its own state and the states of all the others and acts according to this information. The communication between the robots is a must.

In a local approach, each robot can only get data about its neighbourhood and act according to this information. Communication between robots is not necessary since each robot can acquire the needed information using its own perceptions.

III. EXISTING APPROACHES

Several works can be found in the litterature dealing with global decentralized approaches (ex Bom) or local decentralized approaches (ex DP). These approaches were implemented on unicycle (ex Simonin+Dragus) or tricycle (ex Bom, DP,..) vehicles with taking into consideration just their kinematic model (ex DP,..) or also their dynamic model (ex...). Physics inspired multiagent system (ex..), and physics inspired impedance system (ex spring-chain model, ..) were also proposed for vehicle platooning. Here, we present the two approaches (Bom et DP) that we used to developp our approach.

A. *Bom's approach*

Bom developed a decentralised global approach based on path following: the robots have to follow a reference path transmitted by the leader of the platoon. The leading robot communicates with its followers and gives them its actual position and motion, used to rebuild its path. Depending on its mechanical capabilities, each follower will tend to reach this path after covering a certain distance called the look-ahead 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 path at $s_i + d_m$ (see Figure 1).

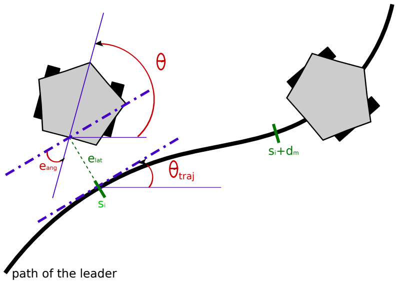

Fig. 1. The global approach developed by LASMEA.

B. *Daviet & Parent's approach*

Daviet & Parent developed a decentralized local approach based on tracking the preceding robot in a low speed platoon without using communication [4], [6]. Each robot acquires the data (position and velocity) of the preceding robot 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. A first lateral control law (denoted as DP_1) leads to a follower which cuts remarkably the corners, as it moves towards the preceding robot. Daviet & Parent developed another lateral control law DP_2 derived from a third degree polynomial, which reduces the cut of the corners [5].

C. *Discussion*

The two approaches developed by Daviet & Parent and Bom have some drawbacks, which lead us to develop another approach to improve the platooning.

In the local approach of Daviet & Parent, the lateral control laws are simple but not efficient: with both control laws, following robot tends to cut the corners. In the global approach of Bom, 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 cities: data are noisy and the coverage of the GPS is weak.

By comparing the platooning results of these two approaches, Bom's approach shows less cuts of corners. This is due to the memorization and the tracking of the leader's path.

IV. THE PROPOSED APPROACH

To discard the drawbacks mentioned in section III, we propose a decentralized local approach based on the memorization and tracking of the preceding robot's path of each following robot. Having the robots initially distant induce a spatial delay making the memorization of the preceding robot's positions necessary to reduce lateral deviations. At each time step, the robot acquires and memorizes the position and velociy of its predecessor, and its own position, orientation and velocity. These data are essential to compute a velocity for the longitudinal control of the follower that aims its preceding robot while avoiding collision. They are also used to compute an angular velocity for the lateral control where the robot chooses to aim, not its predecessor, but a closest position from the memorized ones. Then, the robot applies these commands to track its preceding robot's path smoothly and without oscillating or making harsh turning (see Figure 2).

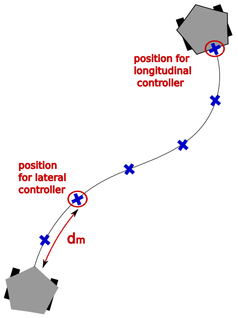

Fig. 2. Aimed positions for the longitudinal and lateral controls.

To avoid the problem of memory's saturation, each robot remove from its FIFO list the exceeded positions of its preceding robot.
PROBLEM DE DERIVE DE L'ODOMETRIE

A. Longitudinal control

A collision-free control, called SSC [7] is used as a longitudinal control. This controller ensures a safe behavior of the platoon even in critical cases where the robot moves with a maximum acceleration and its predecessor moves with a maximum decceleration. This gives us a very close platoon respecting a critical distance d_{crit} between each couple of robots. In other terms, each robot computes an acceleration a that allows it to reach a closer position from its preceding robot while keeping an interdistance equal or greater than d_{crit}. This acceleration is used to compute the new velocity command as follow :

$$v = a * \Delta T + v_{previous} \tag{2}$$

where :

- ΔT is the time step.
- $v_{previous}$ is the previous velocity of the robot.

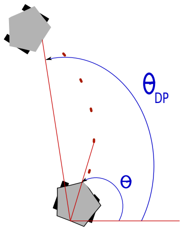

Fig. 3. Aimed direction in Daviet & Parent and proposed approaches.

B. Lateral control

As we mentioned before, each robot stores the positions of its predecessor. Then, instead of aiming the precedimg robot as in subsection III-B , it chooses a closer position among the non exceeded saved ones, situated at a lookahead distance d_m. This leads to a drastic reduction of the corners' cuts. A good lookahead distance should depend on the speed of the vehicle and the curvature of the path : the faster the robot moves, the farther away from the robot the aimed point is; and the higher the trajectory curvature is, the closest to the robot the aimed point is. In a first step, in the sake of simplicity, we consider a constant lookahead distance.

As it is shown in Figure 3, 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 notably less cut the corner.

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. 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 aimed.
Thus, the angular velocity is defined as :

$$\omega = \frac{\arctan(\Delta Y / \Delta X)}{\Delta T} \tag{3}$$

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.

C. Discussion

On one side, the main difference between our approach and the approach of Daviet & Parent is the memorization and tracking of its preceding robot's path, instead of tracking its preceding robot. On the other side, two points differenciate our approach from the approch of Bom : First, the leader of the platoon doesn't transmit its path to all the followers, on the contrary, each robot acquires and reconstruct locally the path of its preceding robot. Second, the lateral control law used in our approach is more simple and needs less cost of calculations than the control law of Bom's approach.

V. EXPERIMENTS WITH MOBILE ROBOTS

A. *Experimental device*

Experiments of the model are performed with Khepera III mobile robots (KTeam compagny), two wheels autonomous robots embedded with a Linux OS. Robots are placed on an experimental device, called interactive table, allowing us to study multi-robot behaviors and to perform perception between robots (see Fig. 4). The table is able to track robots' positions (using infrared cameras) and communicate them (a Wifi board is embedded on robots). The precision of the measures is about $2mm$.

Fig. 4. Circular trajectory : snapshot of the movie www.loria.fr/XXXXX

B. *A four robots experiment*

We performed different platoons, from two to four robots. The leader aims at performing a spiral path. Its speed is $15cm.s^{-1}$. Note that the platoon starts from the center of the spiral et turns outward.

C. *Analysis of trajectories deviation*

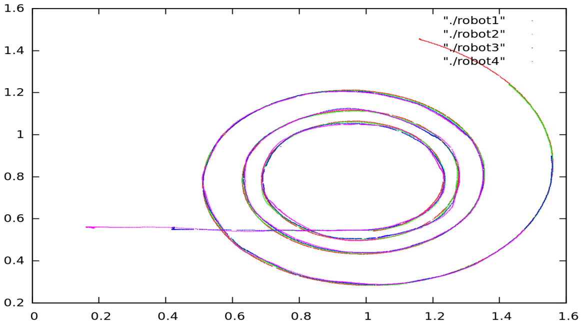

Fig. 5. Plot of paths followed by the 4 robots

Figure 5 plots the recorded positions, showing the paths followed by the robots, and how they evolve during the spiral path. The main interest of this path is that the curvature varies during the time allowing us to study the lateral control.

To evalute the platooning accuracy, we computed the lateral deviation between recorded paths (frequency of record is 45 Hz). Figure 6 presents the lateral deviation between the leader and each follower (y-axis). X-axis is the time interval [5 s, 45 s] of the reference (leader) path. One can see that the maximum deviation between the leader and an other robot is 1.6 cm (0.75 cm in the mean), and the maximum deviation between two consecutive robots is 0.6 cm. It appears also that deviation is cumulative, a drawback well known in the local platooning approach. However, we can see that the lateral deviation stays very small.

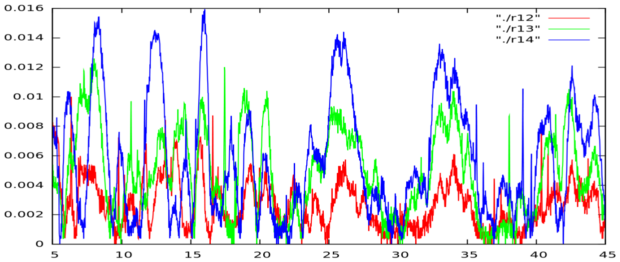

Fig. 6. Robots' lateral deviation to the leader, during the spiral path

D. *Influence of the leader's velocity on the platooning*

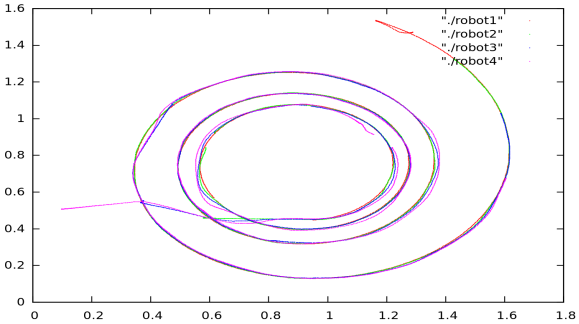

Fig. 7. Plot of paths followed by the 4 robots, leader's velocity=18 cm/sec

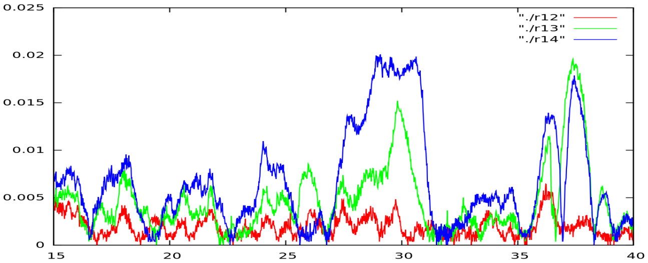

Fig. 8. Robots' lateral deviation to the leader during the spiral path, leader's velocity=18 cm/sec

As we can see in Figure 7, increasing the leading robot's velocity decreases the platooning accuracy. The quality of the path reconstruction process is dependant of the leader's speed. As the position acquisition frenquency obviously stays the same, the distance between two successive data points increases and thus reduces the precision of the trajectory approximation. Because of this loss of precision, robots tend to cut the curves a bit. In Figure 8, we can see that the lateral deviation has increased in comparison with Figure 6 : The maximum lateral deviation between the leading robot and its followers has increased from $0.6cm$ when the leader was travelling at $0.15cm/sec$ (see Figure 6) to $2cm$ when the leading robot was travelling at $0.18cm/sec$.

E. Influence of the leader's dynamic movement

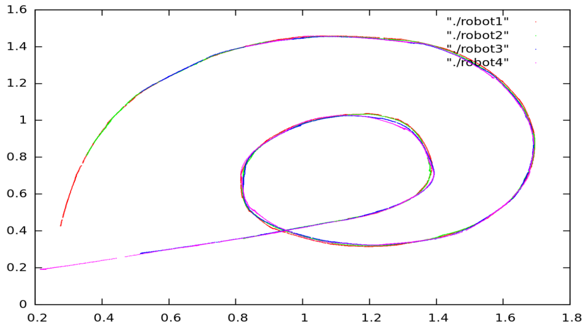

Fig. 9. Plot of paths followed by the 4 robots, leader's velocity is variable

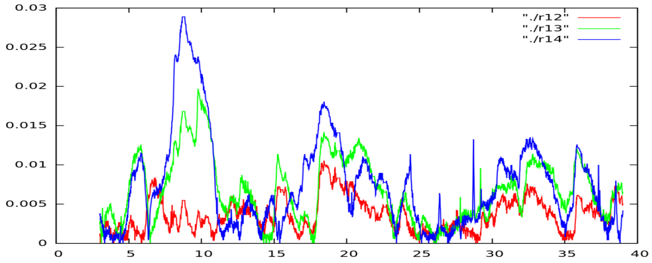

Fig. 10. Robots' lateral deviation to the leader during the spiral path, leader's velocity is variable

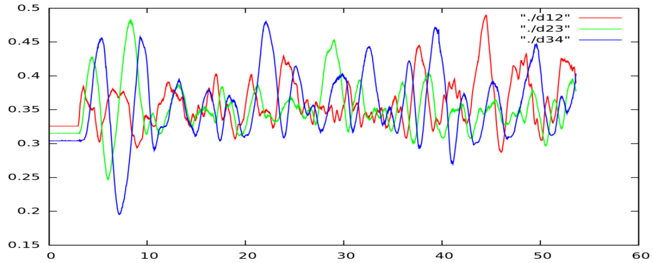

Fig. 11. Robots' interdistance between each others during the spiral path, leader's velocity is variable

We performed a platooning with a leading robot travelling at a variable velocity. The goal is to see how the longitudinal control described in Subsection **??** may affect the behavior of the followers. Figure 9 shows how the following robots react along the spiral path. Lateral deviations are evaluated and presented in Figure 10, where the maximum lateral deviation between the leader and the last robot of the platoon is about $2.8cm$. Figure 11 describes the longitudinal behavior of the platoon. As we can see, the avoidance of collisions between robots is garanteed as the interdistance is always higher than zero. We can also see, on one side, the delay between the robots, trying to catch their respective predecessors when the leader accelerates, and on the other side how they respectively deccelerate when the velocity of the leading robot decreases.

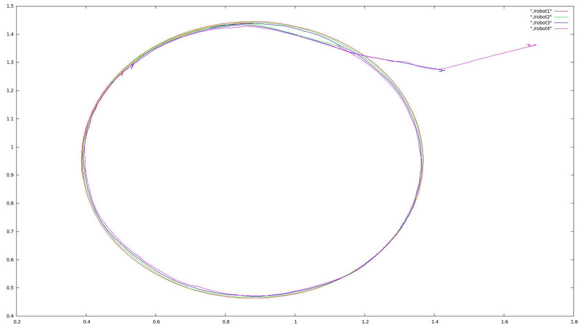

Fig. 12. Platooning with a small lookahead distance $d_m = 1cm$

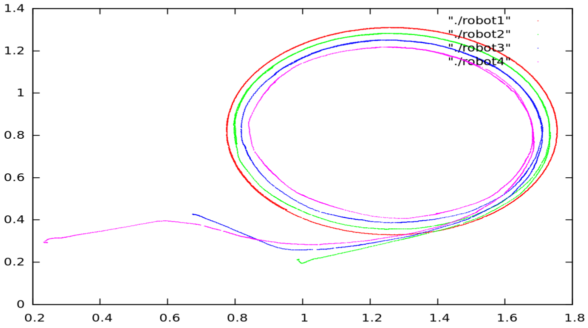

Fig. 13. Platooning with a high lookahead distance $d_m = 10cm$

F. Influence of the lookahead distance on the platooning

As described before, 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 cut of corners are all the more remarkable when the lookahead distance is higher: the lateral deviation increases with the lookahead distance. Figures 12 and 13 show two platoonings done with two different lookahead distances : in Figure 12, d_m is equal to $1cm$, and in Figure 13, d_m is equal to $10cm$. In both cases, the followers are initially not located on a line but arbitrary shifted as presented in Figure 14. The figures show first the straight paths followed by robots, then how robots follow the circular trajectory of the leader.

Figures 15 and 16 show the lateral deviations in the two cases mentioned above. As we can see, the lateral deviation is much more important when the lookahead distance is higher.

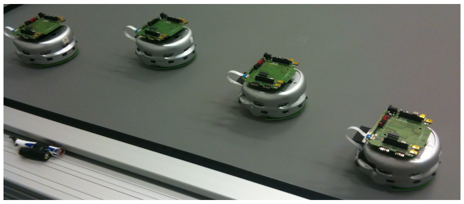

Fig. 14. Initial configuration

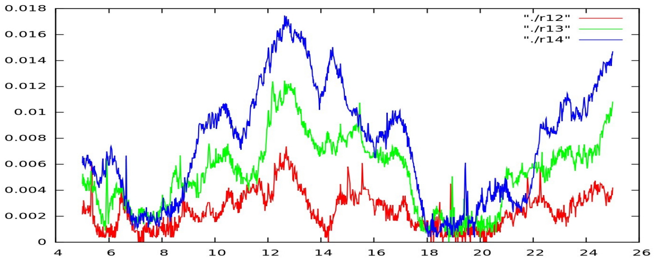

Fig. 15. Robots' lateral deviation to the leader, during the circular trajectory for $d_m = 1cm$

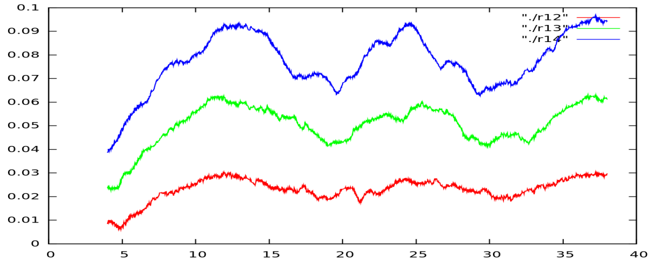

Fig. 16. Robots' lateral deviation to the leader, during the circular trajectory for $d_m = 10cm$

VI. CONCLUSION

This paper has studied the lateral control of a platoon. It has presented two approaches developed in this field: the global approach of Bom 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 find a formal expression 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 while considerating the forces that can affect the movement of the robot. Finally, as we saw in Section **??**, increasing the leader's velocity affect the accuracy of the platooning by increasing the lateral deviation. This lateral deviation is due to the fact that the robot acquires positions more distant of its predecessor. To resolve this problem, we are intending on interpolating the positions of the reconstructed path.

ACKNOWLEDGEMENT

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