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A Global Control Strategy for Urban Vehicles Platooning relying on Nonlinear Decoupling Laws

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Abstract*— To solve problems of traffic saturation in cities, new alternative "Urban Transportation Systems" are based on electric vehicles in free-access. One necessary functionality of such systems is their ability to move in a platoon fashion. Platooning of these automatic guided vehicles, relying on RTK-GPS sensors and inter-vehicles communication, is addressed in this paper. The developed control law is based on a global control strategy; actually, it can take into account all the platoon state, and not only the immediate previous vehicle state. Distance here is understood as difference of curvilinear abscissa along a reference trajectory. Relying on nonlinear control theory, lateral and longitudinal control are fully decoupled, and therefore addressed independently. To ensure passengers comfort, additional monitoring functions supervise our control system. Then, experiment, carried out with urban vehicles, and simulations of long platoon, are presented.

Index Terms— **mobile robots, nonlinear control, platooning, Automatic Guided Vehicles, RTK GPS.**

I. INTRODUCTION

In order to reduce and suppress nuisances, linked to the saturate traffic, new alternative "Urban Transportation Systems" are in developing. Some of these projects, based on urban electric vehicles, have been developped since the mid-90's, e.g. Praxitèle in France [11]-[3], CarLink in the USA [20], Crayon in Japan [6].

To move autonomously with the best efficiency, one of the most interesting functionality appears to be the platooning of vehicles composed of a leader followed by vehicles in a single file. It is this functionality that we are going to develop here. Nevertheless, the automatic guided vehicles need to be localized the more accurate possible in their environment. Different approaches can be envisaged. Some applications, requiring equipped infrastructures, are in developing or developed: automatic vans in suspension over a guideway, thanks to Electro Magnetic forces, are described in [13], a fleet of urban shuttles detecting magnetic track integrated in the road pavement is described in [7]. The majority of Automated Highways Systems needs an equipped road with an adapted architecture as described in PATH project [9]. An alternative consists in relying on direct sensors (as cameras [4], radar [10],...), providing relative information with respect to the preceding vehicle without requiring an equipped structure. Finally, mixed approaches are also investigated: in [19], the authors combine a direct sensor (laser radar) with an inter-vehicles communication integrated in an equipped road infrastructure transmitting data from throttle and brake actuators. Unluckily, all these solutions have drawbacks: respectively the cost and the necessity to equip an area, and/or, a too small field of perception for the considered sensor. To overcome such problems, an interesting solution is the use of RTK GPS (Real Time Kinematic Global Positioning System) sensors, which can provide in realtime vehicle localization with a centimeter accuracy. These sensors, coupled with an inter-vehicles communication, permit to share absolute localization measurements. Some results of vehicles platoon control relying on this technology can be found in the literature: in [2], the authors develop particulary the GPS aspect, while in [16], the communication is studied.

This last approach is here further developed: RTK-GPS sensors and inter-vehicles communication relying on WiFi technology are mounted on urban electric vehicles called Cycabs (Fig. 1), which serve as development products in several French laboratories.

Fig. 1. Our experimental vehicles: Cycabs

One possible objective in platooning is to control vehicles velocity in order to keep either a constant cartesian distance or a constant time (see e.g. [8]) between the cars. Here, our aim is to keep a constant curvilinear distance between vehicles. The main advantage of curvilinear distance is that it agrees with the distance travelled (monotonous behavior) and is perfectly consistent when following reference paths with high curvature (which is not the case with direct distance).

Our platooning control design relies on nonlinear techniques, as in [5], instead of control approaches based on linear approximations (e.g. [14] [16]). These techniques can provide better tracking performances and allow to fully decouple longitudinal and lateral controls. Thanks to this decoupling feature, lateral guidance of each vehicle in the platoon can indeed be achieved independently, from its longitudinal control. In [21], automatic lateral guidance of an isolated vehicle has been addressed. So, the present paper addresses only longitudinal control.

Usually, the standard approach to control a platoon is based on a local strategy, i.e. each vehicle is controlled from the unique data received from the single immediate front vehicle, see [1]. Such a local approach presents drawbacks, like errors accumulation: the regulation errors, introduced by sensors noises, are growing from the first vehicle to the last one leading to unacceptable oscillations. To overcome these problems, inter-vehicles communication has to be considered: in [15], distance, velocity and acceleration with respect to the preceding vehicle are transmitted in order to compute the expected spacing error, and therefore to incorporate prediction in the controller. In [23], information from the immediate preceding and following vehicles are used in order to guarantee stability in tight platoon applications.

In this paper, in order to more widely capture the platoon behavior, information transmitted from the immediate front vehicle and the leader one are used to control each fleet element according to a global strategy. Moreover, to ensure passengers security and comfort, a monitoring approach is set to manage saturations of the nonlinear platooning control law in critical situations.

The paper is organized as follows: first, platoon modeling is addressed. Then, platoon control law design is presented. After, on one hand, full-scale experiments show the performances of a platoon composed of 2 vehicles, and, on the other hand, long platoon (10 cars) simulations are then reported.

II. Platoon modeling

A. Modeling Assumptions

Since Cycabs are devoted to move in urban environments, i.e. at low speed on asphalt, dynamic modeling can be unconsidered. Kinematic model can satisfactorily describe vehicle behavior, as corroborated by extensive tests done in various situations (different masses onboarded, on sloping grounds,...). In this paper, the celebrated tricycle model, validated by numerous laboratories [12] [18] [4] [21], is used to describe Cycab: the two actual front wheels are replaced by a unique virtual wheel located at the mid-distance between the actual wheels. The notations used are detailed and illustrated in Fig. 2:

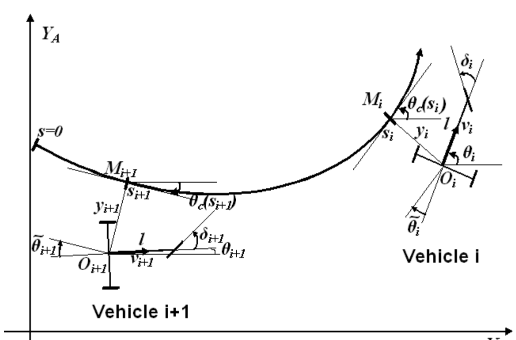

Fig. 2. Model tricycle description

- C is the common reference path, defined in an absolute frame $[A, X_A, Y_A)$.
- O_i is the center of the i^{th} vehicle rear axle.
- M_i is the closest point on C to O_i.
- s_i is the curvilinear coordinate of point M_i along C, it corresponds to the distance covered along C by vehicle i.
- $c(s_i)$ denotes the curvature of path C at M_i, and $\theta_c(s_i)$ stands for the orientation of the tangent to C at M_i, with respect to frame $[A, X_A, Y_A)$.
- θ_i is the heading of i^{th} Cycab at point O_i, with respect to frame $[A, X_A, Y_A)$.
- $\tilde{\theta}_i = \theta_i - \theta_c(s_i)$ denotes the angular deviation of the i^{th} vehicle with respect to C.
- y_i is the lateral deviation of the i^{th} vehicle with respect to C.
- δ_i is the orientation of the i^{th} vehicle front wheel with respect to its centerline.
- L is Cycab wheelbase.
- v_i is the i^{th} vehicle linear velocity at point O_i.
- n is the number of vehicles in the platoon, so $(i < n)$.

B. State Space Model Derivation

The vector $(s_i, y_i, \tilde{\theta}_i)$ describes the state of the i^{th} vehicle. It can be inferred online by comparing vehicle absolute localization (provided e.g. by a RTK-GPS sensor) to the reference path. The celebrated tricycle model is (see [18], [4], [21]):

$$\begin{array}{l} \dot{s}_i = v_i \frac{\cos\tilde{\theta}_i}{1 - y_i c(s_i)} \\ \dot{y}_i = v_i \sin\tilde{\theta}_i \\ \dot{\tilde{\theta}}_i = v_i \left(\frac{\tan\delta_i}{L} - \frac{c(s_i)\ \cos\tilde{\theta}_i}{1 - y_i\ c(s_i)} \right) \end{array} \qquad (1)$$

Control objectives are to bring and maintain y_i and $\tilde{\theta}_i$ to 0, by means of δ_i, and the gap between cars to a fixed value d, by means of v_i. It is considered that: $y_i \neq \frac{1}{c(s_i)}$ (i.e. vehicles are never on the reference path curvature center). In practical situation, if the n vehicles are well initialized, this singularity in model (1) is never met.

III. Control Law Design

First, it is shown that longitudinal and lateral controls can be decoupled. Then longitudinal control law is designed.

A. Decoupling feature

Via invertible state and control transformations, nonlinear model (1) of each Cycab can be converted, in an exact way, into the following so-called chained form, see [18]:

$$\begin{array}{l} \dot{a}_{1i} = m_{1i} \\ \dot{a}_{2i} = a_{3i} m_{1i} \\ \dot{a}_{3i} = m_{2i} \end{array}$$

where $(a_{1i}, a_{2i}, a_{3i}) = (s_i, y_i, (1 - c(s_i)y_i)\tan\tilde{\theta}_i)$ is the chained state vector and $M = (m_{1i}, m_{2i})^T = \Upsilon(v_i, \delta_i)$ is the chained control vector. From this chained form, a large part of linear systems theory can be used (but, since transformations are exact ones, it is not required that vehicle configuration is close to a specific one, contrarily to what is needed with tangent linearization techniques). More precisely, it can be noticed that lateral control of each vehicle (i.e. control of a_{2i} and a_{3i}) can be achieved independently by designing only m_{2i}. Since it can be shown that m_{2i} is related in an invertible way to δ_i (provided that $v_i \neq 0$), lateral control is fully decoupled from longitudinal one: in lateral control, v_i appears as a free parameter, that can now be used to achieve longitudinal control. Details and performances of lateral control, not reported hereafter, can be found in [21].

B. Longitudinal Control

In this part, a longitudinal (or platooning) control law is designed. First, two platooning navigation strategies, respectively a local one and one based on an absolute reference, are studied and compared. Then, a Global Control Strategy (GCS), combining the advantages of each approach, is proposed and control law design is reported. Finally, to ensure safety and improve comfort, control values are supervised by a monitoring unit.

1) Platooning Navigation Strategies: A first possibility to achieve platooning is to rely on a Local Control Strategy (LCS), i.e. control law of each car is only dependant on the previous car, and aims at preserving a constant curvilinear distance d with respect to it. Collision risks are therefore explicitly addressed. This control scheme, investigated in [1] is depicted on Fig. 3. The input of the control law for the $(i+1)^{th}$ vehicle is:

$$e^i_{i+1} = s_i - s_{i+1} - d \qquad (2)$$

LCS has been satisfactorily implemented for a two cars platoon (see Fig. 9). However simulations presented on Fig. 12 demonstrate that LCS is inappropriate in controlling long platoons: due to errors accumulation, oscillatory behaviors are observed when the number of vehicles is increased.

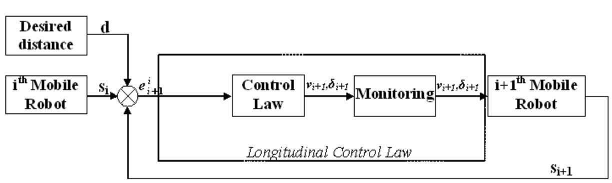

Fig. 3. Longitudinal control law with LCS

To overcome this problem, an alternative is to control each car with the aim to preserve a constant curvilinear distance with respect to a common absolute reference (chosen here as the platoon leader. However, in case of platoon splitting or undesired intermediate vehicle behavior, this reference could be changed for an eventual new leader.). The input of the control law for the $(i+1)^{th}$ vehicle is:

$$e^1_{i+1} = s_1 - s_{i+1} - i.d \qquad (3)$$

Errors accumulation is then eliminated and in theory, the number of vehicles in the platoon is unlimited. Unluckily, the immediate front vehicle is not considered: e.g. if the i^{th} vehicle stops (or slows down), the $(i+1)^{th}$ continues to maintain a constant gap with the leader without taking into account the i^{th} car, the inter-distance is so not respected and, collisions can occur.

2) Global Control Strategy: These two approaches present several advantages, but also some drawbacks ! Therefore a Global Control Strategy (GCS) is proposed here below to retain only the advantages. GCS scheme is illustrated on Fig. 4.

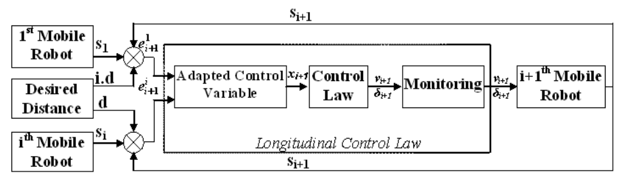

Fig. 4. Longitudinal control law with GCS

The input of the control law is now set up, in a module called "Adapted Control Variable", from (2) and (3):

$$x_{i+1} = \sigma_{i+1} e^1_{i+1} + (1 - \sigma_{i+1}) e^i_{i+1} \qquad (4)$$

with σ_{i+1} giving more or less predominance at each error.

In order to design σ_{i+1}, security distance d_s is introduced as the minimal curvilinear distance that always must be observed between 2 vehicles. When distance between vehicles i and $i+1$ is close to this limit, collision risk is important. Therefore, local approach must prevail over the absolute reference one. σ_{i+1} must then be close to 0 when e^i_{i+1} is close to $-d + d_s$. On the contrary, when inter-vehicles distance is close to d, absolute reference approach can be safely used. σ_{i+1} must then be close to 1 when e^i_{i+1} is close to 0. Such a commutation can be obtained via the sigmoid function (5):

$$\sigma_{i+1}(z_{i+1}) = 0.5 \left(\frac{1 - e^{-a z_{i+1}}}{1 + e^{-a z_{i+1}}} + 1 \right) \qquad (5)$$

driven by variable z_{i+1} defined by:

$$z_{i+1} = e^i_{i+1} + \frac{d - d_s}{2}$$

Parameter $a = 2.5$ is chosen to ensure the shape on Fig. 5.

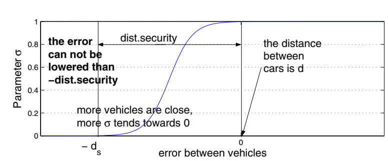

Fig. 5. Function σ_{i+1}

3) Control Law: Differentiating adapted control variable x_{i+1} (equation (4)) leads to:

$$\dot{x}_{i+1} = \sigma_{i+1}\dot{e}^1_{i+1} + (1-\sigma_{i+1})\dot{e}^i_{i+1} + \dot{\sigma}^1_{i+1} - \dot{\sigma}_{i+1}e^i_{i+1} \quad (6)$$

In order to simplify the equations, let us denote:

$$\dot{\sigma}_{i+1} = A(z_{i+1})\dot{e}^i_{i+1} \quad \text{with} \quad A(z_{i+1}) = \frac{ae^{-az_{i+1}}}{(1+e^{-az_{i+1}})^2} \quad (7)$$

From (1), (2), (3), (6) and (7), it can be written:

$$\dot{x}_{i+1} = \sigma_{i+1}\frac{v_1\cos\tilde{\theta}_1}{1-y_1c(s_1)} + (1-\sigma_{i+1})\frac{v_i\cos\tilde{\theta}_i}{1-y_ic(s_i)}$$
$$+A(z_{i+1})\dot{e}^i_{i+1}(s_1 - s_i - (i-1)d) - \frac{v_{i+1}\cos\tilde{\theta}_{i+1}}{1-y_{i+1}c(s_{i+1})} \quad (8)$$

Just as in lateral control design, exact linearization techniques can also be used: actual control variable is the follower velocity v_{i+1}. Let us however introduce fictive control u_{i+1}, related to v_{i+1} according to :

$$v_{i+1} = \frac{1-y_{i+1}\ c(s_{i+1})}{\cos\tilde{\theta}_{i+1}[1+A(z_{i+1})(s_1-s_i-(i-1)d)]}\Big(\sigma_{i+1}\frac{v_1\cos\tilde{\theta}_1}{1-y_1\ c(s_1)}$$
$$+[1-\sigma_{i+1}+A(z_{i+1})(s_1-s_i-(i-1)d)]\frac{v_i\cos\tilde{\theta}_i}{1-y_i\ c(s_i)} - u_{i+1}\Big) \quad (9)$$

Convergence of x_{i+1} to 0 can then be ensured by designing:

$$u_{i+1} = -k\,x_{i+1} \quad \text{with} \quad k > 0 \quad (10)$$

The actual platoon control law is finally obtained by reporting (10) in (9).

Proportional fictive control (10) provides satisfactory results in urban environment, see Fig. 9. However, if perturbations (sliding, sloping ground,...) occur, more elaborated correctors could also be envisaged.

Control (9)-(10) presents one singularity, namely $1 + (s_1 - s_i - (i-1)d)A(z_{i+1}) = 0$. However, it corresponds to a very special configuration of the first, the i^{th} and the $(i+1)^{th}$ vehicles, which is not expected to be met in practical situation. Moreover, if this configuration was met, v_{i+1} would increase to reach very large values that would then be corrected by monitoring.

4) Monitoring: Saturation problems can clearly appear: e.g. if the cars are too far, large accelerations, and so high velocities, can occur. In order to achieve passengers security and comfort, some constraints have to be satisfied. First, vehicles velocities have to be bounded:

$$0 \leq v_{i+1} \leq v_{max} \quad (11)$$

This ensures that vehicles never move back nor exceed a desired velocity. Secondly, if vehicle $i+1$ is far behind vehicle i, or if vehicle i presents an odd behavior (e.g. if it stops abruptly), control law (9)-(10) may then lead to very large accelerations/decelerations, very unpleasant to passengers aboard. Therefore, the monitoring scheme shown on Fig. 6 has been introduced, with the aim to privilege passengers comfort, as far as their security can be guaranteed.

More precisely, the notation a_{comf} on Fig. 6 stands for the maximum acceleration/deceleration comfortable to a passenger aboard. Then, if the acceleration/deceleration of vehicle $i+1$, denoted a_{i+1}, is superior to that value, a security test is performed:

- the case $a_{i+1} > a_{comf} > 0$ occurs when vehicle $i+1$ is far behind vehicle i. In such a situation, a_{i+1} can be limited to a_{comf} without any collision risk.
- the case $a_{i+1} < -a_{comf} < 0$ occurs if vehicle i stops abruptly. In such a situation, collision risks have to be investigated. To this aim, the distance covered by vehicle $i+1$, if it was stopped with a deceleration $-a_{comf}$, is first computed, and its final inter-distance with vehicle i is derived (the worst case, i.e. vehicle i is stopped, is here assumed).
  - if this inter-distance is superior to d_s, then a_{i+1} can safely be limited to $-a_{comf}$.
  - in the other case, the deceleration (denoted $-a_{urg}$) leading to a projected inter-distance equal to d_s is computed, and a_{i+1} is limited to that value. Passengers security is privileged with respect to their comfort.

When computing the final inter-distances with constant decelerations ($-a_{urg}$ or $-a_{comf}$), delays introduced by actuator features and transmission latencies are taken into account.

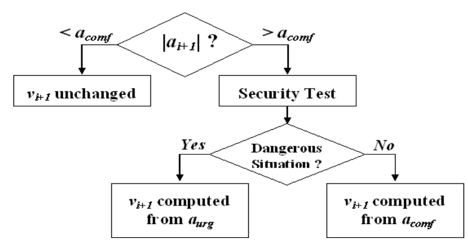

Fig. 6. Monitoring scheme

IV. Experimentation and Simulation Results

This section is divided into two parts: first, experimental results involving two vehicles validate control law (9)-(10) and monitoring. Secondly, simulations with larger platoons compare capabilities of LCS and GCS.

A. Experimentation

Several experiments have been carried out at "Campus des Cézeaux", in Clermont-Ferrand area. These experiments involve only two vehicles, therefore σ_{i+1} has no influence as the immediate front car and the leader are the same. However, experiments with more vehicles are planned, since our lab will soon be equipped with additional vehicles.

1) Experimental Vehicle: Experimental vehicles, named Cycab, are depicted on Fig. 1. Their small dimensions (length $1.90m$, width $1.20m$) are advantages for the urban traffic. The used kinematic configuration is the same as the one of a car-like vehicle. Its maximum speed is $5m/s$. The mounted RTK GPS receiver provides measurements at a $10Hz$ sampling frequency, with a $2cm$ accuracy. The communication between cars is ensured via WiFi.

2) Experiment: The gains of the lateral control law are tuned to impose that lateral deviation converges to 0 within $15m$. Parameters of the longitudinal law are set to $k = 0.6$, $v_{max} = 4m/s$, $a_{comf} = 1m/s^2$ (ensued from studies reported in [22]), $d = 8m$ and $d_s = 6.50m$. In practical situation, we could imagine that the leader is pulling a trailer, and that collision occurs if the inter-distance is inferior to d_s.

The experiment reported on Fig 7 can be divided into three main parts. First, the hooking is tested: at initial time, the space between the cars is close to $20m$. Thanks to the monitoring, the hooking appears smooth and comfortable (acceleration saturated at a_{comf} and $v < v_{max}$, see Fig. 8). In a second phase, the longitudinal standard law performances are scanned. Once the follower is hooked, the gap is equal to d with a satisfactory standard deviation of $4.7cm$ and a mean error inferior to $1cm$ (Fig. 9). Finally, the security of the law, in critical situation is investigated. Preliminary, the leader reaches a higher velocity in order to position the platoon in a critical situation when it stops abruptly. As the security can not be achieved with a deceleration equal to $-a_{comf}$, an urgency deceleration equal to $-1.2m/s^2$ is computed and applied, see Fig. 10 and Fig. 11. This experiment demonstrates satisfactory performances of the control law (9)-(10) and monitoring (comfort mode is tested at the beginning and security mode at the end).

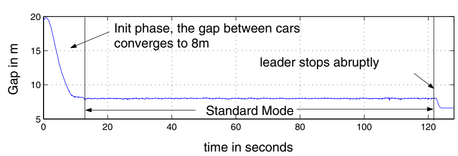

Fig. 7. Curvilinear distance between cars

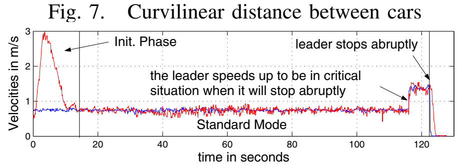

Fig. 8. Velocities measured by GPS

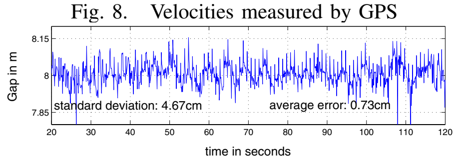

Fig. 9. Zoom on curvilinear distance in standard mode

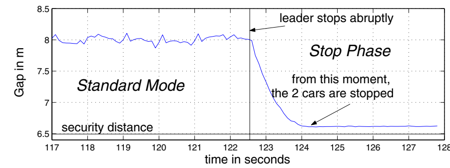

Fig. 10. Curvilinear Distance between cars in stop phase

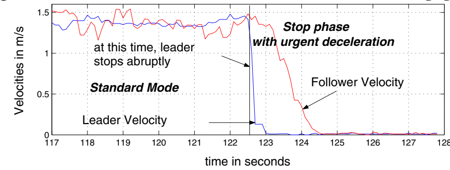

Fig. 11. Velocities evolution during stop phase

B. Simulations

In this part, GCS is compared with a classical LCS. The common scenario is a path following to be achieved, by a 10 vehicles long platoon, at a constant velocity of $2m/s$ (fixed by the leader). In order to simulate LCS, the parameter σ_{i+1} is simply set to 0 in control law (9)-(10). All parameters are identical in LCS and GCS simulations (they are the same as in the experiment). Finally GPS features are introduced via a white noise with a standard deviation of $10cm$ added to position measurements. GPS sensors used in previous experiment have a $2cm$ accuracy, but are quite expensive. When numerous vehicles have to be equipped, decimeter GPS appears more realistic. Moreover, less accurate sensors reveal more clearly the advantages of GCS over LCS.

The first simulation presents LCS. In order to highlight errors accumulation, the gap between each vehicle and a common reference point in the platoon, i.e. the platoon leader, is depicted on Fig. 12. The main drawbacks of LCS appear then clearly: the distance to the leader presents a standard deviation of $9.7cm$ for the first follower, when it is $67.7cm$ for the last one. The situation gets even worse in tight turns: when the last vehicle is in a bend, at $t = 95s$ see Fig. 12, the maximum error recorded is $2.80m$.

In the second simulation, when GCS is used, these drawbacks disappear, see Fig. 13: each follower is subjected to errors of the same order of magnitude. The standard longitudinal deviations of each vehicle are close to $10cm$ ($9.5cm$ for the first follower and $10.9cm$ for the last one, i.e. the error is simply equal to the introduced GPS noise, see Fig. 15). Therefore, these simulations demonstrate that GCS surmounts the limitations of LCS. Moreover, when observing parameter σ_{i+1} in the Init. phase (Fig. 14), it can be seen that the platooning laws commute progressively from LCS (when inter-vehicles distance is small) to a control with respect to an absolute reference (when the gap is close to d). Platoon security is therefore ensured (by LCS) when cars are close to each other, and in standard mode, high regulation performances are obtained (by the absolute reference). The skill to adapt the longitudinal error at the met situation is clearly demonstrated.

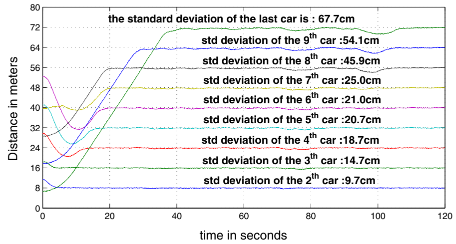

Fig. 12. Distance with the leader (LCS)

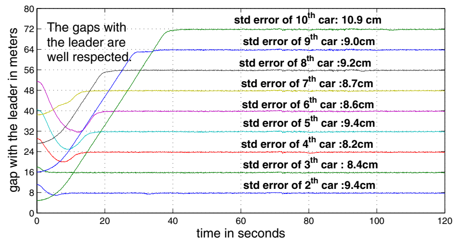

Fig. 13. Distance with the leader (GCS)

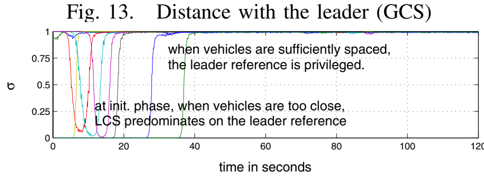

Fig. 14. Evolution of parameter σ_{i+1}

Vehicle	2	3	4	...	8	9	10
LCS	9.7	14.7	18.7	...	45.9	54.1	67.7
GCS	9.5	8.4	8.2	...	9.2	9.0	10.9

Fig. 15. Standard deviation (in cm) according the strategy

V. CONCLUSION

In this paper, a Global Control Strategy (GCS) has been derived to address platooning. It takes into account the immediate front vehicle (as standard Local Control Strategy (LCS)), but also preceding vehicles. Therefore, in safe situation, errors accumulation inherent to LCS is avoided, but immediate front vehicle is taken into account when vehicles are abnormally close to each other. Monitoring has also been sketched in order to guarantee passengers security and comfort. Finally, performances of GCS have been demonstrated via full-scale experiments on urban vehicles and simulations of long platoons.

From a technological point of view, possible losses of GPS signal, due to canyoning effect, are a major concern. To deal with this difficulty, data fusion combining GPS and odometric sensors is investigated. An other solution consists in reconstructing the vehicles state by vision, see [17]. Moreover, online communication from each vehicle to the vehicles ranked behind, appears to be an ambitious challenge in long platoons.

REFERENCES

[1] J. Bom, B. Thuilot, F. Marmoiton, and P. Martinet. Nonlinear control for urban vehicles platooning, relying upon a unique kinematic GPS. In 22^{nd} *Intern. Conf. on Robotics and Automation (ICRA'05)*, Barcelona (Spain), April 2005.

[2] M.E. Cannon, C. Basnayake, S. Crawford, S. Syed, and G. Lachapelle. Precise GPS sensor subsystem for vehicle platoon control. In *Conf. ION GPS/GNSS*, pages 213–224, Portland OR (USA), Sept. 2003.

[3] P. Daviet, S. Abdou, and M. Parent. Platooning for vehicles and automatic parking by scheduling robotic actions. In *Intern. Symposium on Robotics and Manufacturing (WAC'96)*, Montpellier (France), 1996.

[4] P. Daviet and M. Parent. Platooning for small public urban vehicles. In 4^{th} *Intern. Symposium Experimental Robotics (ISER'95)*, pages 345–354, Stanford, CA (USA), July 1995.

[5] A. De Luca, G. Oriolo, and C. Samson. Feedback control of a nonholonomic car-like robot. In *Robot Motion Planning and Control,* J.P. Laumond eds, volume 229 of *Lectures Notes in Control and Information Sciences*, pages 171–253, Springer-Verlag, 1998.

[6] P. Evans. New energy sources for the car : how toyota sees the future. *Energy News (Australian Institute of Energy)*, 18(2), June 2000.

[7] D. Gillet and T. Chevroulet. BURST : Bright urban system for transportation. In 2^{nd} *Intern. Workshop on European Scientific and Industrial Collaboration (WESIC'99)*, Newport (Wales), Sept. 1999.

[8] A. Girault and S. Yovine. Stability analysis of a longitudinal control law for autonomous vehicles. In *IEEE Conf. on Decison and Control (CDC'99)*, volume 4, pages 3728–3733, Phoenix AR (USA), December 1999.

[9] R. Horowitz and P. Varaiya. Control design of an automated highway system. *Proc. IEEE*, 88(7):913–925, July 2000.

[10] H. Kuroda, S. Kuragaki, T. Minowa, and K. Nakamura. An adaptive cruise control system using a milimeter wave radar. In *IEEE Intern. Conf. on Intelligent Vehicles (IV'98)*, volume 1, pages 168–172, Stuttgart (Germany), October 1998.

[11] C. Laugier. Towards autonomous vehicles for future intelligent transportation systems. In *Proc.* 6^{th} *Conf. of Italian Association in Artificial Intelligence*, pages 251–258, Padova (Italy), Sept. 1998.

[12] J.P. Laumond, editor. *La Robotique Mobile*. Hermes Science, Paris, Sept. 2001.

[13] M^3 Team. The M^3 urban transportation system. FTA Project Report MA-26-7077, MagneMotion Inc., Acton, MA (USA), January 2003.

[14] H. Makela, P. Kaarmila, and K. Koskinen. Convoy navigation. In 3^{rd} *IFAC Conf. on Intelligent Autonomous Vehicles (IAV'98)*, pages 31–36, Madrid (Spain), March 1998.

[15] T.S. No, K.-T. Chong, and D.-H. Roh. A Lyapunov function approach to longitudinal control of vehicles in a platoon. *IEEE Trans. on Vehicular Technology*, 50(1):116–124, January 2001.

[16] M. Ohtomo, R. Kimura, S . Fukushima, and N. Fujii. Automatic following system utilizing vehicle-to-vehicle communication. In *IEEE Intern. Conf. on Intelligent Vehicles (IV'98)*, volume 2, pages 381–384, Stuttgart (Germany), October 1998.

[17] E. Royer, M. Lhuillier, M. Dhome, and T. Chateau. Towards an alternative GPS sensor in dense urban environment from visual memory. In *British Machine Vision Conference*, volume 1, pages 197–206, Kingston (England), September 2004.

[18] C. Samson. Control of chained systems: application to path following and time-varying point stabilization of mobile robots. *IEEE Trans. on Automatic Control*, 40(1):64–77, January 1995.

[19] Y. Seto and H. Inoue. Development of platoon driving in AHS. *JSAE Review*, 20(1):93–99.

[20] S. Shaheen, K. Wipyewski, C. Rodier, L. Novick, M.A. Meyn, and J. Wright. Carlink II: a commuter carsharing pilot program final report. PATH Research Report UCB-ITS-PRR-2004-23, Univ. of California, Berkeley (USA), August 2004.

[21] B. Thuilot, J. Bom, F. Marmoiton, and P. Martinet. Accurate automatic guidance of an urban electric vehicle relying on a kinematic GPS sensor. In 5^{th} *IFAC Symposium on Intelligent Autonomous Vehicles (IAV'04)*, Lisboa (Portugal), July 2004.

[22] TranSafety Inc. Simulated on-the-road emergencies used to test stopping sight distance assumptions. *Road Management and Engineering Journal*, July 1997.

[23] Y. Zhang, E.B. Kosmatopoulos, P.A. Ioannou, and C.C. Chien. Autonomous intelligent cruise control using front and back information for tight vehicle following maneuvers. *IEEE Trans. on Vehicular Technology*, 48(1):319–328, January 1999.