A control strategy taking advantage of inter-vehicle communication for platooning navigation in urban environment

P. Avanzini[1,3], B. Thuilot[1,3] and P. Martinet[2,3]

[1] Clermont Université, Université Blaise Pascal, LASMEA, BP 10448, 63000 Clermont-Ferrand, France
[2] Clermont Université, IFMA, LASMEA, BP 10448, 63000 Clermont-Ferrand, France
[3] CNRS, UMR 6602, LASMEA, 63177 Aubière, France
Pierre.AVANZINI@lasmea.univ-bpclermont.fr

***Abstract*— This paper deals with platooning navigation in the context of innovative solutions for urban transportation systems. More precisely, a sustainable approach centered on automated electric vehicles in free-access is considered. To tackle the major problem of congestions in dense areas, cooperative navigation according to a platoon formation is investigated. With the aim to ensure the formation stability, i.e. longitudinal disturbances within the platoon do not grow when progressing down the chain, a global decentralized platoon control strategy is here proposed. It is supported by inter-vehicle communications and relies on nonlinear control techniques. A wide range of experiments, carried out with up to four urban vehicles, demonstrates the capabilities of the proposed approach: two localization devices have been tested (RTK-GPS and monocular vision) along with two guidance modes (the path to be followed is either predefined or inferred on-line from the motion of the manually driven first vehicle).**

***Index Terms*— mobile robots, automatic guided vehicles, platooning, nonlinear control, path following.**

I. INTRODUCTION

Urban mobility is currently being developed under a new conceptual framework induced by the significant traffic increase in metropolitan areas and growing sustainable considerations. Reducing congestion appears to be a critical goal which can be achieved by adopting a balanced and diversified mobility approach. As a consequence, the use of autonomous electric vehicles in free-access is a promising and environment-friendly alternative, especially when the public demand is properly structured, e.g. commutations within inner-cities or large industrial estates. The large flexibility that can be obtained with such a transport system (commutation at any time and along any route) is definitely its main attractive feature and should meet user expectations.

One functionality of special interest that can enhance this transport system is automated platooning, i.e. several autonomous vehicles following the trajectory of a first one, with pre-specified inter-distances. Such a functionality, on the one hand allows to easily adapt the transport offer to the actual need (via platoon length), and on the other hand eases maintenance operations, since only one person (driving the first vehicle) can then move several vehicles at a time (e.g. to bring vehicles back to some station). Moreover, since cooperative navigation can ensure more coherent motions, an increase in traffic as well as an enhancement in safety can be expected. Platooning is therefore considered in this paper.

Since a main objective is to manage the traffic flow, the performances of the whole formation must be guaranteed and therefore the concept of string stability [21] has to be considered when designing the control strategy. Namely, the stability of a platoon formation requires that the effects of disturbances are reducing when propagating from the leading vehicle to the follower ones, thus ensuring that unacceptable oscillations within the platoon can not be induced by sensor noises and/or actuator delay.

Fig. 1. Experimental vehicles: a Cycab leading three Cycab/RobuCab

The paper is organized as follows: the control architecture for vehicle platooning is first discussed in Section II. A global decentralized control strategy is then sketched in Section III and the integration of navigation functionalites is presented in Section IV. Finally, in Section V, experiments involving up to four electric vehicles demonstrate the capabilities of the proposed approach with different set-up and guidance modes.

II. CONTROL ARCHITECTURE DISCUSSION

As introduced in [20], string stability mainly depends on the information used for vehicle control. The different approaches proposed in the literature can then be classified into two categories: local and global strategies. The most common approaches rely on ***local strategies***, i.e. each vehicle is controlled exclusively from the information it can acquire, relative only to the neighboring vehicles. The well-known *leader-follower approach* belongs to this category and considers only the preceding vehicle. Unfortunately, it has been proven [17] that an infinite string can not be stabilized by a linear controller even when the vehicle model is simplified as a double integrator. String stability can be achieved by considering either a non-identical approach [11] or a variable spacing policy [8], [12]. In the first case, a communication is required between adjacent vehicles to adapt the control gains. However the gains are increasing with the vehicle index, so that from a practical point of view platoon length is limited. In the second case, the spacing policy depends on vehicle velocity and consequently affects the platoon tightness at the expense of the traffic flow. A related alternative, relying on a cyclic topology, ensures string stability by controlling the lead vehicle with respect to the last one [14]. Nevertheless, such a scheme lacks of flexibility and demands for the platoon to be supervised. As a result, more complex topologies have been investigated, using information from several nearby vehicles to achieve string stability. For instance, since spring-damper systems present intrinsic robustness to model error and measurement signal noise, such an analogy has been introduced, regarding vehicles as a serial chain of mass particles [23], [24], [7]. A control law is then derived from the combined front and rear information relying on the analogy with virtual mechanical forces. Unfortunately, in that case, string stability is only satisfied in realistic conditions for finite strings of autonomous vehicles (see [23]).

Such a problem can be overcome by considering ***global strategies***, i.e. each vehicle is now controlled from data shared between all the vehicles. This category requires a communication network and a balanced management of information flows is essential. For instance, if a centralized architecture is adopted, all interactions between subsystems can be taken into account. Platooning can then be formulated as an optimization problem [13] and/or can use the formalism of generalized coordinates [6], where the formation is characterized by its geometry and its position with respect to some reference point. In both cases, the string stability is ensured, since the control input for each vehicle depends on the spacing errors of the entire formation. However, this poses a burdensome data handling problem, especially when the vehicle string is long. To circumvent this technological limitation, our research is focused on distributed control approaches. The emphasis is put on ensuring a stable formation while minimizing the communication cost between agents. From this point of view, a stable guidance approach is proposed in [19], [18], where the velocity and accelerations information of the lead vehicle are transmitted to all the following vehicles. Nevertheless, in practical situations, collision risks between adjacent vehicles can occur when using such a minimal communication scheme. The control of more general formations is considered in [9], [10], relying on virtual rigid structures whose dynamics is dictated with respect to some reference vehicle. Nevertheless, these techniques aim at imposing some pre-specified geometric pattern, and not that each vehicle accurately reproduces the trajectory of the first one. Instead, in this paper, a trajectory-based strategy is proposed, as illustrated in Fig. 2. The strategy relies on nonlinear control techniques: lateral and longitudinal controls are decoupled, so that lateral guidance of each vehicle with respect to the same reference path can be achieved independently from longitudinal control, designed to maintain a pre-specified curvilinear vehicle inter-distance. In order to ensure string stability as well as passengers security and comfort, the platoon behavior is imposed using data from the immediate front vehicle and from the leader one.

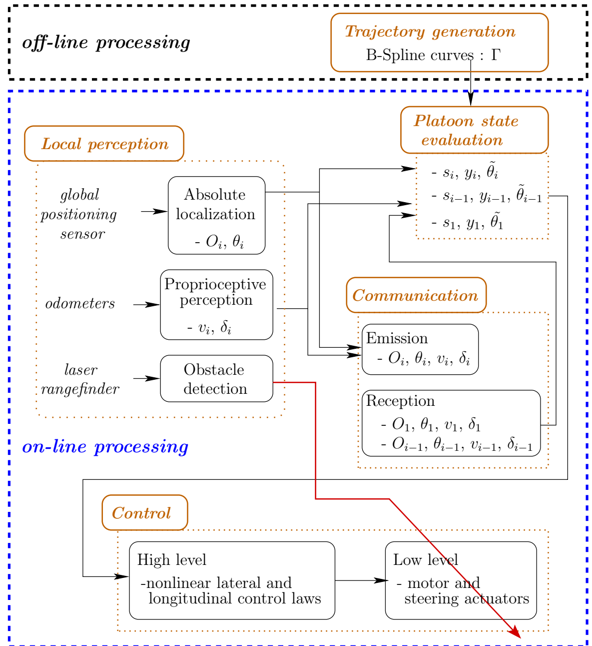


Fig. 2. Platoon architecture

III. Global decentralized control strategy

A. Modeling assumptions

The scope of this study concerns small-sized vehicles acting in urban areas. As a result, several simplifying assumptions can be made. It is assumed that vehicles are rigid bodies, symmetrical with respect to their main axis and moving at quite low speed. It is thus possible to neglect the dynamic components (suspension . . .) and the tire deflection. In addition, dedicated navigation areas are asphalt roads and the contact between the wheels and the ground can be assumed without slipping. Given these assumptions, the control laws can be designed from a kinematic model and the most suitable one is the bicycle model (also called Ackermann model): the vehicle is then schematized by a rear driving wheel and a front steering wheel. To represent the system, the following notation, illustrated in Fig. 3 and 4, are introduced:

Notation:

- Γ is the common reference path for any vehicle (specified in advance or to be inferred from the trajectory of the first one), 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 to O_i on Γ.

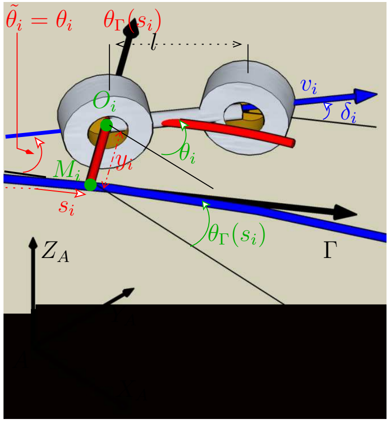


Fig. 3. Vehicle model

- s_i is the arc-length coordinate of M_i along Γ and $k(s_i)$ is the curvature of path Γ at this point.
- $\theta_\Gamma(s_i)$ is the orientation of the tangent to Γ at M_i with respect to $[A, X_A, Y_A)$.
- θ_i is the heading of i^{th} vehicle with respect to $[A, X_A, Y_A)$.
- $\tilde{\theta}_i = \theta_i - \theta_\Gamma(s_i)$ is the angular deviation of the i^{th} vehicle with respect to Γ.
- y_i is the lateral deviation of the i^{th} vehicle with respect to Γ.
- δ_i is the i^{th} vehicle front wheel steering angle.
- l is the vehicle wheelbase.
- v_i is the i^{th} vehicle linear velocity at point O_i.

Finally, Fig. 4 introduces the quantity $d_{i,j} = s_i - s_j$ that denotes the longitudinal distance between vehicles i and j in the platoon, evaluated as an arc-length distance along path Γ.

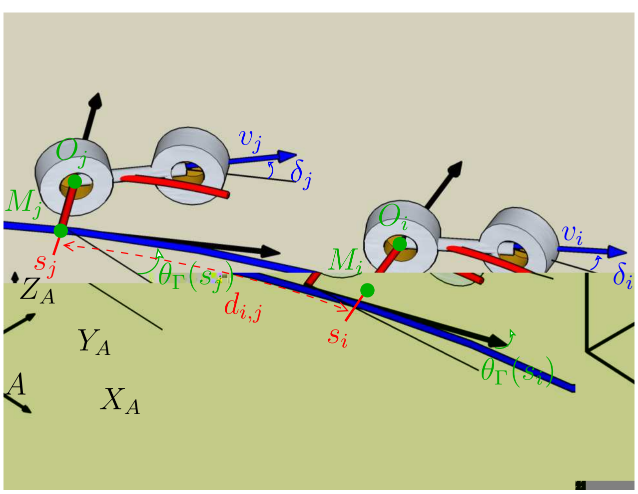


Fig. 4. Longitudinal distance $d_{i,j}$

State Space Model Derivation: The state of the i^{th} vehicle can be described in the Frenet frame along the reference trajectory Γ by the triplet $\left[s_i, y_i, \tilde{\theta}_i\right]$ and the state space equation of the bicycle model can be written as follows (see [5]):

$$\begin{cases} \dot{s}_i = \dfrac{v_i.\cos\tilde{\theta}_i}{1 - y_i.k(s_i)} \\ \dot{y}_i = v_i.\sin\tilde{\theta}_i \\ \dot{\tilde{\theta}}_i = \dfrac{v_i.\tan\delta_i}{l} - \dfrac{v_i.k(s_i).\cos\tilde{\theta}_i}{1 - y_i.k(s_i)} \end{cases} \quad (1)$$

The model (1) is clearly singular if $y_i = \dfrac{1}{k(s_i)}$, i.e. if O_i is superposed with the path Γ curvature center at abscissa s_i. However, this singularity is never encountered in practical situations, firstly because the curvature along the reference trajectory Γ is generally quite small, and secondly because the vehicle is expected to remain close to Γ.

B. Chained form of the state space model

Vehicle model (1) is nonlinear. However, it has been established in [16] that kinematic models of non-holonomic mobile robots can be converted via invertible state and control transformations into so-called *chained forms*, more convenient to address vehicle control. In the case of model (1), the state and control transformations are respectively given by (2) and (3):

$$\begin{aligned} \Phi([\, s_i \quad y_i \quad \tilde{\theta}_i \,]) &= [\, a_{1i} \quad a_{2i} \quad a_{3i} \,] \\ &\triangleq [\, s_i \quad y_i \quad (1 - y_i.k(s_i)).\tan\tilde{\theta}_i \,] \end{aligned} \quad (2)$$

$$(m_{1i}, m_{2i}) = \Xi(v_i, \delta_i) \quad (3)$$

with:

$$m_{1i} \triangleq v_i \frac{\cos\tilde{\theta}_i}{1 - y_i.k(s_i)} \quad (4)$$

$$m_{2i} \triangleq \frac{d}{dt}((1 - y_i.k(s_i)).\tan\tilde{\theta}_i) \quad (5)$$

Transformations Φ and Ξ are invertible under the conditions $y \neq \dfrac{1}{k(s_i)}$ (model singularity discussed above), $v_i \neq 0$ and also $\tilde{\theta}_i \neq \frac{\pi}{2}[\pi]$, unexpected configurations if the platoon has been properly initialized. Substituting (2), (4) and (5) into (1), the nonlinear bicycle model can be rewritten without approximation as the following chained form:

$$\begin{cases} \dot{a}_{1i} = m_{1i} \\ \dot{a}_{2i} = a_{3i}\, m_{1i} \\ \dot{a}_{3i} = m_{2i} \end{cases} \quad (6)$$

Model (6) depends on two control variables: m_{1i} is consistent with the vehicle curvilinear velocity $\dot{s}_i$ along Γ and m_{2i} is related to its angular velocity $\omega_i = \frac{v_i.\tan\delta_i}{l}$. Control laws are now designed, relying on model (6). It is shown that vehicle guidance along a path can be achieved with performances independent of the longitudinal velocity, so that lateral and longitudinal control can be decoupled (described respectively in Sections III-C and III-D).

C. Lateral control

To this aim, chained system (6) is rewritten by differentiating with respect to the curvilinear abscissa rather than to the time. Denoting $a'_{ji} = \frac{da_{ji}}{da_{1i}} = \frac{da_{ji}}{ds_i}$, the chained form (6) is then:

$$\begin{cases} a'_{1i} = 1 \\ a'_{2i} = a_{3i} \\ a'_{3i} = \frac{m_{2i}}{m_{1i}} = m_{3i} \end{cases} \tag{7}$$

Path following consists in regulating to zero lateral and angular deviations. According to (2), it is equivalent to impose the convergence of variables a_{2i} and a_{3i} to zero. Given the structure of system (7) (a double integrator), a proportional derivative controller for variable m_{3i} is then chosen:

$$m_{3i} = -K_d a_{3i} - K_p a_{2i}, \quad (K_p,\ K_d) \in \mathbb{R}^{+*} \times \mathbb{R}^{+*} \tag{8}$$

where K_d and K_p are positive scalars specifying the convergence rate. By reporting (8) into (7), this controller indeed leads to the following differential equation:

$$a''_{2i} + K_d a'_{2i} + K_p a_{2i} = 0. \tag{9}$$

As equation (9) is differentiated with respect to the variable $a_{1i} = s_i$, a settling distance is specified by gains K_p and K_d instead of a settling time. Therefore, for a given initial positioning error of the i^{th} vehicle, its lateral behavior is imposed regardless of the vehicle linear velocity v_i, assumed non-zero, even if that velocity is time-varying [22]. By inverting chained transformations (2-4-5), the nonlinear control law is expressed as follows:

$$\delta_i(y_i, \tilde{\theta}_i) = \arctan\Bigg(l\left[\frac{\cos^3\tilde{\theta}_i}{(1-k(s_i).y_i)^2}\left(\frac{dk(s_i)}{ds_i}.y_i.\tan\tilde{\theta}_i - K_d(1-k(s_i).y_i)\tan\tilde{\theta}_i - K_p y_i + k(s_i)(1-k(s_i).y_i)\tan^2\tilde{\theta}_i\right) + \frac{k(s_i).\cos\tilde{\theta}_i}{1-k(s_i).y_i}\right]\Bigg) \tag{10}$$

It is well defined under the three conditions above mentioned ($v_i \neq 0$, $y_i \neq \frac{1}{k(s_i)}$ and $\tilde{\theta}_i \neq \frac{\pi}{2}[\pi]$).

D. Longitudinal Control

A local longitudinal error and a global one are here considered. First, the local error between the i^{th} and the $i+1^{th}$ vehicles is defined as:

$$e^i_{i+1} = d_{i,i+1} - d^\star = s_i - s_{i+1} - d^\star \tag{11}$$

Regulating e^i_{i+1} to zero would impose a constant curvilinear distance $d^\star$ between any pair of vehicles. Collision risks would then be explicitly addressed. However, as discussed in Section II, the main disadvantage of this local strategy is that the string stability can not be ensured. To overcome this problem, a global error e^1_{i+1} is also considered:

$$e^1_{i+1} = d_{1,i+1} - i.d^\star = s_1 - s_{i+1} - i.d^\star \tag{12}$$

Regulating e^1_{i+1} to zero would impose a constant curvilinear distance with respect to a common absolute reference, chosen here as the abscissa of the platoon leader. Nevertheless, for obvious safety reasons, longitudinal control law cannot completely ignore the local error e^i_{i+1} because of the collision risk: for instance, if the i^{th} vehicle stops or slows down, it will abnormally be approached by the $i+1^{th}$ one since this latter continues to maintain a constant gap with the lead vehicle.

In view of these remarks, a new hybrid error variable c_{i+1} is built from (11) and (12):

$$c_{i+1} = \sigma_{i+1}(z_{i+1}).e^1_{i+1} + (1-\sigma_{i+1}(z_{i+1})).e^i_{i+1} \tag{13}$$

$$\text{with } z_{i+1} = e^i_{i+1} + \frac{d^\star - d_s}{2}, \tag{14}$$

and d_s denotes a security distance, defined as the minimal curvilinear distance that always must be observed between two vehicles. The function σ_{i+1}, defined in the interval $[0, 1]$, is defined as:

$$\sigma_{i+1}(z_{i+1}) = 0.5\left(\frac{1-e^{-az_{i+1}}}{1+e^{-az_{i+1}}} + 1\right) = \frac{1}{1+e^{-az_{i+1}}},\ a > 0 \tag{15}$$

The behavior of function σ_{i+1} is illustrated in Fig. 5 with $a = 2.5$, $d^\star = 5m$ and $d_s = 2,\ 3$ and $4m$. As evidenced by the "S" shape of the curve, function σ_{i+1} is used to give the predominance to either the global error or to the local one:

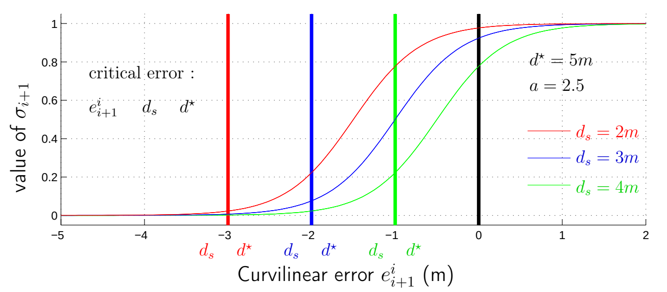


Fig. 5. Function σ_{i+1}

- when there is no imminent collision risk, i.e. $e^i_{i+1} \geq d_s$, the global approach relying on a common reference can be safely used ($\sigma_{i+1} = 1$ and therefore $c_{i+1} = e^1_{i+1}$).
- on the contrary, when the collision risk is important, i.e. e^i_{i+1} becomes less than $d_s - d^\star$, the local approach must prevail over the global one ($\sigma_{i+1} = 0$ and therefore $c_{i+1} = e^i_{i+1}$).

The scheme of the longitudinal control is depicted in Fig. 6.

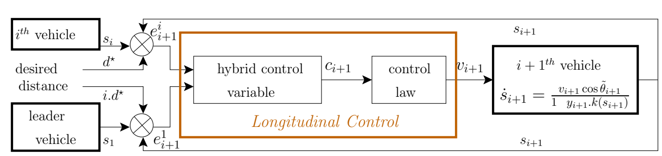


Fig. 6. Longitudinal control with a global strategy

Control law design: Differentiating the hybrid control variable c_{i+1} leads to:

$$\dot{c}_{i+1} = \sigma_{i+1}\dot{e}^1_{i+1} + (1-\sigma_{i+1})\dot{e}^i_{i+1} + \dot{\sigma}_{i+1}e^1_{i+1} - \dot{\sigma}_{i+1}e^i_{i+1} \tag{16}$$

In order to simplify the equations, let us denote:

$$A(z_{i+1}) = \frac{a e^{-a z_{i+1}}}{(1+e^{-a z_{i+1}})^2} \tag{17}$$

Therefore $\dot{\sigma}_{i+1}$ can be written as:

$$\dot{\sigma}_{i+1} = A(z_{i+1})\dot{e}^i_{i+1} \tag{18}$$

Just as in lateral control design, exact linearization techniques can also be used: nonlinear equation (16) can be converted without approximation into the linear one:

$$\dot{c}_{i+1} = m_{4(i+1)} \tag{19}$$

by introducing the virtual control variable $m_{4(i+1)}$ related to v_{i+1} according to (just inject the expressions of $\dot{e}^1_{i+1}$, $\dot{e}^i_{i+1}$ and $\dot{\sigma}_{i+1}$ in (16):

$$v_{i+1} = \frac{1-y_{i+1}.k(s_{i+1})}{\cos\tilde{\theta}_{i+1}\left[1+A(z_{i+1})e^1_i\right]}\left(\sigma_i \frac{v_1\cos\tilde{\theta}_1}{1-y_1.k(s_1)} + \left[1 \quad \sigma_{i+1}+A(z_{i+1})e^1_i\right]\frac{v_i\cos\tilde{\theta}_i}{1-y_i.k(s_i)} \quad m_{4(i+1)}\right) \tag{20}$$

Convergence of c_{i+1} to zero can then be ensured by choosing a proportional controller for the variable $m_{4(i+1)}$:

$$m_{4(i+1)} = \quad K.c_{i+1}, \text{ avec } K \text{ 2 R}^{+*} \tag{21}$$

The actual nonlinear longitudinal control law is finally obtained by reporting (21) into (20). It presents one singularity, namely $1 + A(z_{i+1})e^1_i = 0$. However, this corresponds to a very special configuration of the first, the i^{ith} and the $(i+1)^{th}$ vehicles, which is not expected to be encountered in practical situations. Moreover, if this configuration was met, v_{i+1} would increase to reach very large values, that would then be corrected by monitoring (not presented here).

IV. NAVIGATION FUNCTIONALITIES

The potentialities of this control strategy have first been demonstrated with the experimental vehicles shown in Fig.1, when their absolute localization is supplied by accurate RTK GPS receivers: completely automated platooning, with respect to some given reference trajectory specified beforehand, has been investigated in [4]. In order to increase the flexibility of this transportation system and enable the guidance in realistic urban conditions, new functionalities have been developed in a second step.

Manual guidance mode

A manual convoying functionality has been proposed in [1]. The lead vehicle is no longer in an autonomous mode, but manually driven and defining on-line the trajectory to be followed by the other vehicles. The architecture of the lead vehicle is then modified as shown in Fig. 7. Such a manual guidance mode is very attractive, for public transportation as well as for maintenance operations, since vehicles can then instantaneously be driven along any route, without requiring a previously recorded reference trajectory. The challenge consists in creating on-line a C^2 reference path (as required in control laws) as close as possible to the trajectory of the leader, although its raw localization data are noisy. Uniform B-Spline curves, extended on-line according to an iterative optimization process, have been proposed to represent the reference path. A sliding window, only containing the latest localization data of the lead vehicle, enables to bound the computation time and adjust only the extremity of the reference trajectory, without impacting the part of this trajectory that the other vehicles are already tracking. Optimization parameters, namely the size of the sliding window, the number of control points to be adjusted and the degree of the B-Spline curves, are specified according to the vehicle velocity (see [1]).

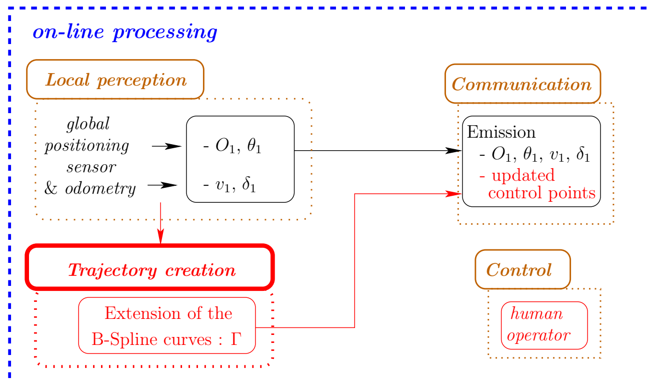


Fig. 7. Architecture of the lead vehicle

Localization by monocular vision

RTK GPS receivers are not realistic sensors in the context of urban transportation systems: they are not reliable since the satellite signals can be masked by tall buildings. Cameras appear more appropriate, since the buildings offer a rich environment from an image processing point of view (and in addition, they are definitely cheaper).

Vehicle localization relying on monocular vision has been investigated in [15]. The difficulty lies in the fact that absolute localization is expressed in a virtual vision world, slightly distorted with respect to the actual metric one. Such deformations, that mainly occur in the curved parts (i.e. when the points of interest used to localize the vehicle are changing), alter noticeably the estimation of inter-vehicle distances, and therefore impair longitudinal control performances. When completely automated platooning is addressed, two strategies have been proposed to estimate on-line local scale factors between the two worlds, along the specified reference trajectory (see Fig. 10). These local scale factors can then be used to correct raw localization data, enabling accurate distance evaluation.

Two vehicles are involved in the first approach [3], whose architecture is depicted in Fig. 8 for the second vehicle: its laser rangefinder is used to evaluate the direct distance to the leading vehicle, and an iterative optimization relying on these telemetric data is run to obtain the local scale factors. The second approach [2] is easier to implement since it relies only on the odometric data of the leading vehicle, as shown in Fig. 9: the local scale factors are then derived according to a nonlinear observer.

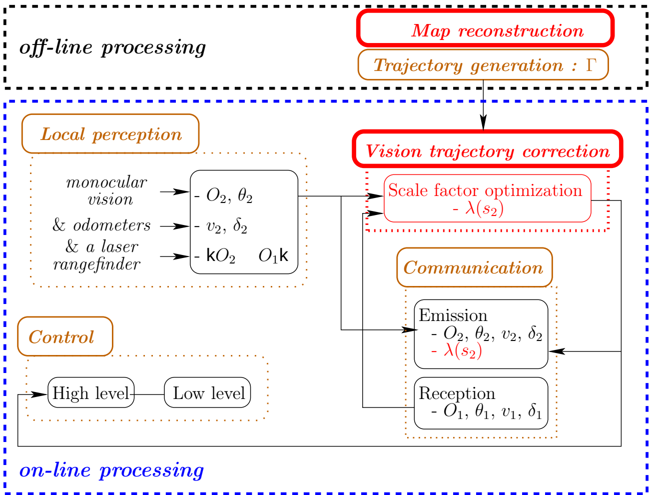


Fig. 8. Architecture of the second vehicle: first approach

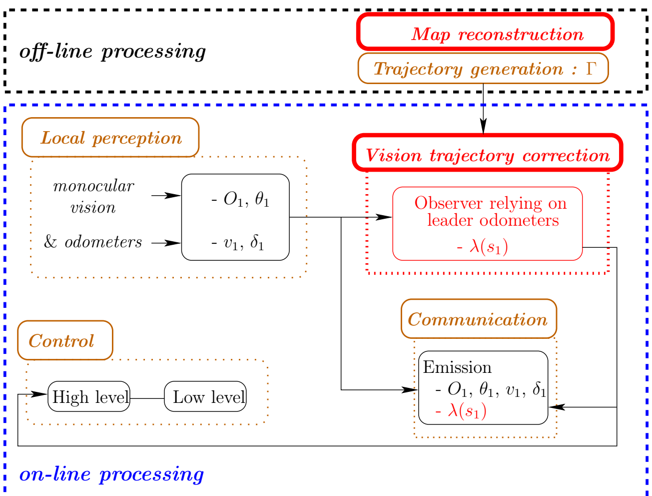


Fig. 9. Architecture of the lead vehicle: second approach

The relevance of these two strategies is illustrated in Fig. 10: it can be noticed that both scale factors sets computed on-line are very close to the actual ones evaluated off-line from RTK-GPS measurements. The scale factor peak, visible around $52m$, is due to the sudden appearance and disappearance of a tree in the field of perception of the camera.

V. EXPERIMENTAL RESULTS

In order to investigate the capabilities of the proposed control laws, several experiments have been carried out in Clermont-Ferrand on "PAVIN Site", an open platform devoted to urban transportation system evaluation.

A. *Experimental set-up*

The experimental vehicles are shown in Fig. 1. They are electric vehicles, powered by lead-acid batteries providing 2 hours autonomy. Two *(resp. four)* passengers can travel

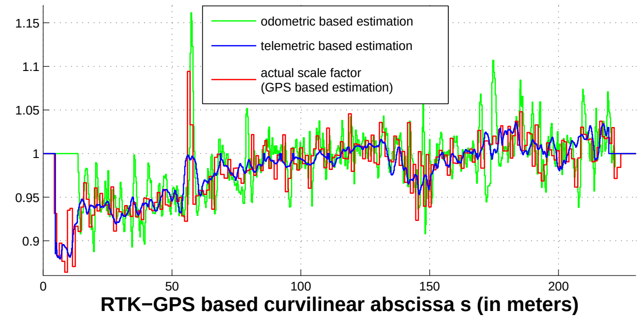


Fig. 10. On-line scale factor estimation

aboard the Cycab *(resp. the RobuCab)*. Their small dimensions (length 1.90m, width 1.20m) and their maximum speed (5m.s^{-1}) are appropriate to urban environments. Vision-based localization and platoon control laws are implemented in C++ language on Pentium based computers using RTAI-Linux OS. Laser rangefinders provide telemetric data at a 60*Hz* sampling frequency, with a standard deviation within 2cm. The cameras supply visual data at a sampling frequency between 8 and 15*Hz*, according to the luminosity. Each vehicle is also equipped with an RTK-GPS receiver, running at a 10*Hz* sampling frequency, either used for vehicle control (manual guidance mode) or exclusively devoted to performance analysis (vision-based localization). Finally, inter-vehicle communication is ensured via WiFi technology. Since the data of each vehicle are transmitted as soon as the localization step is completed, the communication frequency is similar to the frequency of the localization device.

B. *Experimental results*

The experiments reported below consist in platoon control with a constant leader velocity $v1 = 1m.s^{-1}$. Several scenarios have been investigated.

1) Manual guidance mode: Three vehicles follow the path generated on-line by a manually driven one along a 240m-long path. The lateral deviation of of the three followers remains mainly within 10cm from the leader trajectory and does not exceed 14cm, see Fig. 11. Lateral guidance is therefore as satisfactory as in previous work, when vehicles were guided with respect to a pre-specified reference trajectory (see [4]).

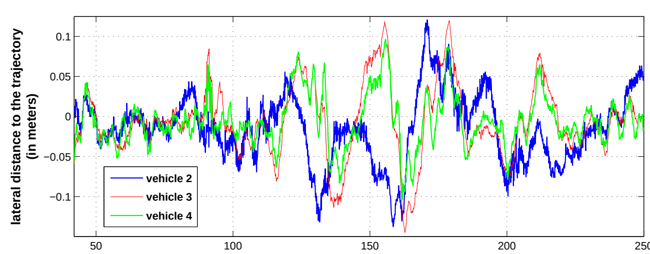
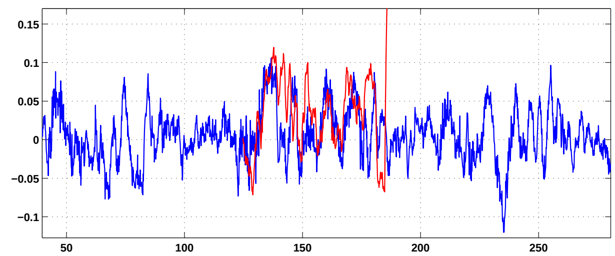


Fig. 11. Vehicle lateral deviations: manual guidance mode

The accuracy of the longitudinal control law is investigated in Fig. 12. Once the platoon is in nominal mode (i.e. all vehicles have reached their desired inter-distances), the behavior is identical to what was observed in previous work [4], namely a 10cm accuracy: the on-line reference trajectory generation does not disturb the longitudinal performances.



[13] W. Levine and M. Athans. On the optimal error regulation of a string of moving vehicles. *IEEE Transactions on Automatic Control*, 11(3):355–361, 1966.

[14] J.A. Rogge and D. Aeyels. Vehicle platoons through ring coupling. *IEEE Transactions on Automatic Control*, 53(6):1370–1377, 2008.

[15] E. Royer, J. Bom, M. Dhome, B. Thuilot, M. Lhuillier, and F. Marmoiton. Outdoor autonomous navigation using monocular vision. In *IEEE Intern. Conf. on Intelligent Robots and Systems (IROS)*, pages 3395–3400, Edmonton (Canada), 2005.

[16] 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, 1995.

[17] P. Seiler, A. Pant, and K. Hedrick. Disturbance propagation in vehicle strings. *IEEE Transactions on automatic control*, 49(10):1835–1841, 2004.

[18] S. Sheikholeslam and C. A. Desoer. Longitudinal control of a platoon of vehicles. i, ii and iii. Institute of transportation studies, research reports, Institute of Transportation Studies, UC Berkeley, 1990.

[19] S.E. Shladover. Operation of automated guideway transit vehicles in dynamically reconfigured trains and platoons. Technical report, U.S. Department of Transportation, Urban Mass Transportation Administration, Washington, D.C., july 1979.

[20] D. Swaroop. *String Stability of Interconnected Systems: An application to platooning in AHS*. PhD thesis, University of California at Berkeley, December 1994.

[21] D. Swaroop and J.K. Hedrick. String stability of interconnected systems. *IEEE Transactions on Automatic Control*, 41(3):349–357, 1996.

[22] B. Thuilot, J. Bom, F. Marmoiton, and P. Martinet. Accurate automatic guidance of an urban electric vehicle relying on a kinematic GPS sensor. In *IFAC Symp. on Intelligent Autonomous Vehicles (IAV)*, Lisbon (Portugal), 2004.

[23] D. Yanakiev and I. Kanellakopoulos. A simplified framework for string stability analysis in AHS. In *IFAC World Congress*, pages 177–182, San Francisco (USA), 1996.

[24] S.Y. Yi and K.T. Chong. Impedance control for a vehicle platoon system. *Mechatronics*, 15(5):627–638, 2005.