Overview on Modeling for Control of Autonomous Road Vehicles Platoon

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Abstract: This is an overview on the models used to control fleets of road vehicles. In general, simplified vehicle models are used and their coupling features are introduced through the (individual) controllers. The robustness and precision of motion control needs geometric, kinematic and dynamic descriptions. We propose a modeling methodology for robots platooning to introduce specific features in the platoon behavior. This overview proposes reference models to link the fleet vehicles and assign a character to the group independent from control.

1 INTRODUCTION

1.1 Context and Objectives

To increase the capacity of the infrastructures while improving the safety and the comfort, vehicle platooning is of interest. Several solutions are considered, in the urban environment and on the highway, by automating vehicles driving and autonomous fleet control (Nouveliere et al., 2002; Alcala et al., 2018; Allou and Zennir, 2018). This can be a very efficient means of transportation for passengers and freight and for increasing traffic capacity. For example, a convoy of trucks carries goods, with only one driver (Bauer and Tomizuka, 1996; M'Sirdi, 2018). Other benefits, such as reducing fuel consumption and minimizing labor, may exist in piggybacking or truck-mounted cars. The convoy consists of a leading vehicle and trailing trucks. The leader can be autonomous or manually driven, other vehicles follow him with a safety distance to avoid collisions between vehicles.

Depending on the application purpose, a lot of vehicle models have been considered in the literature (Nouveliere et al., 2002; Alcala et al., 2018; Allou and Zennir, 2018). The representation is, in general, simplified and the fleet control is at a level higher than the one of the embedded feedback (local level of the DoF or actuators). Robust control laws, can avoid the use of precise models, but this means that all efforts are done in control (Menhour et al., 2015).

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The nonlinear robust control approaches give the fleet a better controlled and more robust behavior against uncertainties (Szanto et al., 2020; Lenain, 2005; Guillet et al., 2014). In this type of approach, the disadvantages are the availability of information on the vehicles of the chain, the need for sensors, the communication of the data, and the observability. There is still a lack of inter vehicles relations,environment interactions and global strategy.

There is no general modelling methodology. The main focus of this paper is the fleet modeling and information contained in the models. It is well known that there exists also robust control approaches, avoiding models or considering only integrators in the process (Menhour et al., 2015). Indeed, the entire vehicle dynamic controllability must be mobilized to perform safe driving and emergency maneuvers like an obstacle or slipping avoidance and urgent controlled braking (Ali et al., 2015; M'Sirdi, 2018). The models used for fleets control focus on the representation of relative trajectories of the vehicles. Some of them consider only longitudinal motion (1D) and few of them are 2D. Each modeling approach suggests or more appropriate control approaches (M'Sirdi, 2020).

The organization of this paper is as follows. After this introduction, the section 2 presents the convoy models used in fleets control. This is followed by a general overview of the most often used control architectures (local and global). In section 3, inspired from the nature, we propose a new modeling approach to represent a fleet of vehicles. This will allow to assign a special character to the group and application of sev-

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eral non linear control approaches for the autonomous fleet driving. Then we conclude and give some perspectives on our work on observation and control of robots platooning.

2 CONVOY MODELS USED IN CONTROL

Table 1: Table of state variables and Acronyms.

L	distance between the vehicle axles
G_i	The gravity center of vehicle i
l_f	distance from the front axle to G
l_r	distance from the rear axle to G
m_i	mass of vehicle i plus 2 wheels
X_i	Longitudinal position of vehicle i in R_0
Y_i	Lateral position of vehicle i in R_0
ψ_i	Angular position of vehicle i in R_0
ψ_Γ	Orientation at M of ref Trajectory in R_0
x_v	Longitudinal vehicle position in R_v
y_v	Lateral vehicle position in R_v
δ_i	Front Steering angle (input vehicle i)
δ_r	rear Steering angle ($d_r = 0$ in general)
$e_{i,i-1}$	longit distance inter vehicles i and i-1
$\varepsilon_{i,j}$	lateral distance between vehicles i and j
u_i	input of the vehicle i
$d_{i,j}$	desired distance between vehicles
d_i	IVD: Inter Vehicles Distance
h	IVSD Inter Vehicle Safety Distance
s_i	Curvilinear abcissa of the vehicle i
LDI	Londitudinal Double Integrator
LUM	Longitudinal Unidirectional Model
LBM	Longitudinal Bidirectional Model
ACM	Anti-Collision Margin
L	distance between the vehicle axles
G_i	The gravity center of vehicle i
l_f	distance from the front axle to G
l_r	distance from the rear axle to G
$c(s)$	Curvature tangent to Γ at M
B_f,K_f	Damping and Stifness of RM-IVDR
f,r,l,d	Indices for front, rear, left and right sides
RM-IVDR	Reference Model Inter Vehicles Dynamic Relations

2.1 Longitudinal Control Models (1D)

In general, a set of simplified and individual 1D models are considered. The only interest of 1D models is the study of the IVSD (Inter-Vehicle Safety Distance). This type of model and its controls ignore the lateral movement and curvatures of the trajectory. Note that there is no relation between the vehicles equations except by the relative distance variables e_i, which is used in the control only.

2.1.1 Longitudinal Unidirectional Models (LUM)

The most used model, for the longitudinal control of the convoy is the double Integrator (Swaroop, 1994). The input u_i is the force applied to the vehicle i.

$$\ddot{x}_i = u_i \tag{1}$$

For the Longitudinal Unidirectional Model, some authors add a mass and a damper (Avanzini, 2010). m is the vehicle mass and b a damper. Many parameters are neglected. The vehicles are considered independent and linked only by the control.

$$m\ddot{x}_i + b\dot{x} + k(x - d_r) = u_i \tag{2}$$

The desired relative Inter-Vehicle Distance IVD (see figure 1) d_r is considered in the control with the error or relative distance to the preceding vehicle $e_{i,i-1}$.

$$e_{i,j} = x_j - x_i - (i-j)d \tag{3}$$

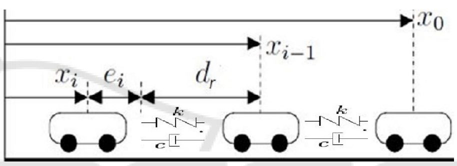

Figure 1: LDI and LUM Mass-Spring-Damper.

2.1.2 Longitudinal Bidirectional Models (LBM)

The LBM is a second-order system and the distances to the neighbors (preceding $e_{i,i-1}$ and following $e_{i,i+1}$) are fed back through the control (Avanzini, 2010). In this scheme, the individual vehicle models are coupled with the control interaction forces. Figure 1 shows a bidirectional longitudinal (mass, spring and damper) model which link each vehicle to its neighbors (previous and follower one).

2.1.3 LBM-VISD with Inter Vehicles Safety Distance (IVSD)

The model dynamic equations, for a fleet of n vehicles, may be written as follows:

$$\begin{cases} m\ddot{x}_1 = & k(x_1 - x_2 - d_{1,2}) - c(\dot{x}_1 - \dot{x}_2) - h\dot{x}_1 + u_1 \\ m\ddot{x}_i = & k(x_{i-1} - x_i - d_{i-1,i}) - k(x_i - x_{i+1} - d_{i,i+1}) + \\ & +c(\dot{x}_{i-1} - 2\dot{x}_i + \dot{x}_{i+1}) - h\dot{x}_i + u_i \\ \dots & \dots \\ m\ddot{x}_n = & k(x_{n-1} - x_n - d_{n-1,n}) - c(\dot{x}_{n-1} - \dot{x}_n) - h\dot{x}_n + u_n \end{cases} \tag{4}$$

where k is the coefficient of stiffness, c the damping coefficient and d the length of the spring (inter-vehicle distance). The leading vehicle is driven by force input control u_1. It receives the forces of constraints transmitted by the links springs - dampers, on the chain of the vehicles of the convoy. The inputs $u_2, ...u_n$ (not used in the literature) may be zero or some complementary control inputs that we have added to enhance the controllability.

- with either $d_{i-1,i} = d = constant$ and $h = 0\ \forall i$. This imposes an IVD. To ensure the stability of the fleet, according to the authors (Yanakiev and Kanellakopoulos, 1996) (Avanzini, 2010), the ratio c^2/km must be greater than constants that increase proportionally to the vehicle index i in the convoy.
- or $d_{i-1,i}$ chosen for each vehicle i and $h = 0\ \forall i$. Another IVD has been proposed, to improve the stability (Contet et al., 2009). It consists of choosing, for each vehicle, a distance command $d_{i-1,i}$ between the vehicles of the convoy, according to the state of the fleet and stability constraints
- or $d_{i-1,i} = d = constant$ and $h \neq 0$. The Anti-Collision Margin (ACM) h is added as a time distance margin to avoid collisions between vehicles (Mu'azu et al., 2017).

The study of stability in (Contet et al., 2009), shows that the bidirectional control architecture gives good theoretical results when the number of vehicles of the convoy is limited. In general, these models are used for convoys that move at low speeds, do not take into account the risk of failures, or the effects of errors and noise measurement (Avanzini, 2010). Adding a dynamics in the model has benefits.

2.2 2D Convoy Models for Control

2.2.1 Unicycle Model (UCM)

A unicycle uses a minimal kinematic representation. v_i is the linear velocity of the vehicle i and ψ_i is the orientation angle of the vehicle wheel i (Samson and Ait-Abderrahim, 1990; Xiang and Braunl, 2010; Ricardo et al., 2008).

$$\begin{cases} \dot{X}_i = & v_{x_{vi}}.cos(\psi_i) \\ \dot{Y}_i = & v_{x_{vi}}sin(\psi_i) \\ \dot{\psi}_i = & w_i K_\gamma \gamma_i \end{cases} \quad (5)$$

A study of chain transformation for a convoy is proposed, to determine the Inter-Vehicle Distances (d_v) and the relative caps (γ) between the neighboring vehicles. The control applied to the convoy vehicles is based on a tangential linearization; The overall stability has been proven for the linearized model.

2.2.2 Use of the Kinematic Models (KM)

Several applications use only a kinematic model, in a 2D space with limited speeds in the urban frame.

This is not advisable for a truck convoy on the highway. Using a bidirectional control can alleviate the problem (Avanzini et al., 2010). The model equations are presented in equation (6). One can see a demo of this model in open loop, by M Compere, in https://ch.mathworks.com/matlabcentral/fileexchange/67034-simple-animation-for-n-vehicles?focused=9173618&tab=function

$$\begin{cases} \dot{X}_i = v_{x_{vi}}.cos(\psi_i) - \frac{L}{2}.\dot{\psi}_i.\sin\psi_i \\ \dot{Y}_i = v_{x_{vi}}.\sin(\psi_i) + \frac{L}{2}.\dot{\psi}_i.\cos\psi_i \\ \dot{\psi}_i = \frac{v_{x_{vi}}.\delta_i}{L_i} \end{cases} \quad (6)$$

2.2.3 Kinematics Bicycle Model (KBM)

Geometric Convoy Model. Now we need to localize the vehicle with regard to the reference trajectory to be followed. The road reference path is noted Γ. Figure 2 shows the geometric scheme of the vehicles with regard to the path Γ in the absolute frame R_0. The vehicle is modeled with respect to the reference path Γ (Lenain, 2005; Cartade et al., 2005). The geometric model defines the relations between vehicle variables (in the vehicle frame R_v) to Cartesian ones and to the reference trajectory.

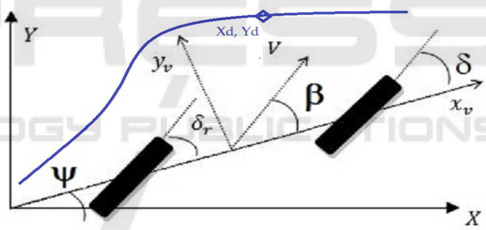

Figure 2: Bicycle Model.

Let us recall that ψ_i is the orientation in the absolute reference R_0 and l_{d_i} denotes the desired IVSD distance between 2 vehicles. Let s_i be the curvilinear abscissa of the vehicle i. This abscissa is at a distance d_i from the reference (desired) trajectory Γ (at point M).

$c(s)$: the curvature of the trajectory Γ at the point M

$\psi_\Gamma(s)$: Orientation of the tangent at M, in the absolute frame R_0 (desired vehicle orientation)

$\tilde{\psi}_i = \psi_i - \psi_\Gamma(s)$ is the angular deviation of the vehicle i relative to Γ.

$e_{s_i} = s_{i-1} - s_i - l_{d_i}$ is the curvilinear spacing error, or difference between 2 vehicles with a kinematic model expressed as follows (see fig 2).

$$\begin{cases} \dot{X} = v.cos(\psi_i + \beta) \\ \dot{Y} = v.sin(\psi_i + \beta) \end{cases} \quad (7)$$

β denotes the side slip Angle

δ_i and δ_{r_i} are the front and rear steering

$\delta_v = \Psi_i + \beta$ is the vehicle motion angle

$$\begin{cases} \beta = \tan^{-1}(\frac{l_r.\tan(\delta)+l_f.\tan(\delta_r)}{l_f+l_r}) \\ \dot{\Psi} = \frac{v.cos(\beta)}{l_f+l_r}.(\tan(\delta)-\tan(\delta_r)) \end{cases} \tag{8}$$

Assuming that $\delta_r = 0$ and $\beta = 0$, the Kinematics of the system can be written as in equation (6)

Now, to be able to follow a trajectory (Γ) let us define the desired position (Fig2) for the vehicle as (X_d, Y_d). We get ψ_d

$$\psi_d = \tan^{-1}(\frac{(Y_d - Y)}{(X_d - X)}) \tag{9}$$

For the control, that there are two control inputs (steering and velocity), we then define the curvilinear trajectory errors (for the distance and the angle):

$$\begin{cases} e_d = \sqrt{(X_d-X)^2+(Y_d-Y)^2} \\ e_\psi = \psi_d - \psi \end{cases} \tag{10}$$

For the longitudinal and lateral control (in Cartesian space R_0) of a train of two vehicles following a leader, in (Allou and Zennir, 2018), the authors use multi-PID controllers (Optimized by PSO and Fuzzy Logic) to compute the orientation and velocity of the vehicle:

$$\begin{array}{l} \Psi_c = PID(e_\Psi) = (K_{p_1} + \frac{K_{i_1}}{s} + K_{d_1}.s)e_\psi \\ v_c = PID(e_d) = (K_{p_2} + \frac{K_{i_2}}{s} + K_{d_2}.s)e_d \end{array} \tag{11}$$

The two PID control parameters (K_{x_i}) are optimized by Particle Swarm (PSO) technique and by a fuzzy approach. The parameter optimization is based on a fitness weight function Time Square Error (ITSE). The drawback of this approach is the lack of dynamics and that precise measurements of the absolute position variables is needed.

2.2.4 Dynamics Bicycle Model (DBM)

Also known as the Ackermann model, the DBM is a Longitudinal and lateral model describing dynamic and kinematic vehicle motions (Martinez et al., 2004; Sprinkle et al., 2008). Its formulation varies from one author to others (Daviet and Parent, 1996; Khatir and Davidson, 2005; Bascetta et al., 2016; Zin et al., 2004; Song et al., 2017; Huang et al., 2016).

DBM Decentralized Control. The simplified dynamic model (as presented in (Khatir and Davison, 2004)) is written in a three DoF system where v_{x_i} denote the linear velocity of the vehicle i and θ_i its wheel orientation angle and β_i the vehicle's steering angle i.

$$\begin{cases} m\dot{v}_{xi} = f_{xi}\cos(\beta)_i + f_{yi}\sin(\beta_i) \\ \dot{\beta}_i = -\frac{1}{mv_i}f_{xi}\sin(\beta_i) + \frac{1}{mv_i}f_{yi}\cos\beta_i - \psi_i \\ \dot{\psi}_i = \frac{1}{I}f_\tau \end{cases} \tag{12}$$

The bicycle Kinematics model is:

$$\begin{cases} \dot{X}_i = v_{x_i}\cos(\theta_i + \beta_i) \\ \dot{Y}_i = v_{x_i}\sin(\theta_i + \beta_i) \\ \dot{\theta}_i^a = \psi_i \end{cases} \tag{13}$$

Platoon of Autonomous Buses. In (Stanley and Katupitiya, 2013b; Stanley and Katupitiya, 2013a), the authors use the DBM with a different formulation for each bus of a platoon dynamics. Their work is focused on the multi-agent systems to demonstrate the ability for platoons to cooperatively maneuver around each other. The kinematic equations are the same as in eq 6:

$$\begin{cases} \dot{X}_i = v_{x_i}\cos\psi - \frac{L}{2}\dot{\psi}_i\cos\psi_i \\ \dot{Y}_i = v_{x_i}\sin\psi + \frac{L}{2}\dot{\psi}_i\sin\psi_i \end{cases} \tag{14}$$

with r=L/2 is the distance between the effective center of rotation in the vehicle and the definite origin of the vehicle, ψ as the vehicle orientation in a reference coordinate system, and $\omega = \dot{y}$ as the vehicle body turning rate. The dynamic equations, for each vehicle, are

$$\begin{cases} m(\ddot{X} - \dot{Y}\dot{\psi}) = R_r - \sin\delta F_f - \cos\delta(T_f - R_f) - T_r \\ m(\ddot{Y} + \dot{X}\dot{\psi}) = -\cos\delta.F_f + F_r + \sin\delta.(T_f - R_f) \\ J\ddot{\psi} = -l_f.\cos\delta.F_f + l_r.F_r + l_f.\sin\delta.(T_f - R_f) \end{cases} \tag{15}$$

T represents traction or propulsion, R the rolling resistance and F the lateral forces on the wheels. The slip angles are shown as the β_s.

2.2.5 Robotics Models

The longitudinal and lateral positions and orientation (X, Y, θ) of each vehicle i (with mass m_i and inertia I_i) of the convoy are represented in a Cartesian frame R_0. G_i is the gravity center of the vehicle, (v_{xi}, v_{yi}) are its longitudinal and lateral velocities.

Robotic Models are composed of Dynamic equations (eq 16, Kinematic transformation (see equation 6, and a geometric representation. This is why they are more precise and advisable.

Dynamic Equations. The Lagrange method leads to a set of dynamic equations (2.2.5) to describe the motion of one vehicle (see the left scheme of figure 3), in the vehicle reference frame $R_v = (G_i, x_{vi}, y_{vi})$ (Rabhi, 2005; DeSantis, 1995; Chebly, 2017). δ_i is the steering front wheel angle and ψ: the yaw angle.

The input force is $F_{xr_i} = F_{mot_i}$ and F_{res_i} gathers the resistance forces from the slope gravity and aerodynamics. The rolling resistance is ρ_{vi} and the road slope is ζ.

$$F_{res_i} = mg\sin\zeta + \frac{\rho AC_d}{I}\dot{v}_{x_v}^2 sgn(\dot{v}_{x_v}) - \rho_{vi}$$

The longitudinal and lateral wheel forces are noted $F_{xf_i}, F_{xr_i}, F_{yf_i}, F_{yr_i}$. They can be got either trough the wheel-road contact modeling or considering simply longitudinal and lateral cornering stiffness for each wheel (Rabhi, 2005) ($I_i = I_z + 2I_w + m_w(l_f^2 + l_r^2)$).

$$\begin{aligned} & m_i.\dot{v}_{x_{vi}} = F_{xf_i}.\cos\delta_i - F_{yf_i}.\sin\delta_i + F_{xr_i} - F_{res_i} \\ & m_i.\dot{v}_{y_{vi}} + a.m_w\ddot{\psi} = F_{xf_i}.\sin\delta_i + F_{yf_i}.\cos\delta_i + F_{yr_i} \\ & I_i.\ddot{\psi}_i + a.m_w\dot{v}_y = l_f(F_{xf_i}\sin\delta_i + F_{yf_i}\cos\delta_i - F_{yf_i}) - F_{yr_i}.l_r \end{aligned} \tag{16}$$

l_f and l_r are distances to G_i from the front wheel and from the rear wheel (respectively); $a = l_f - l_r$.

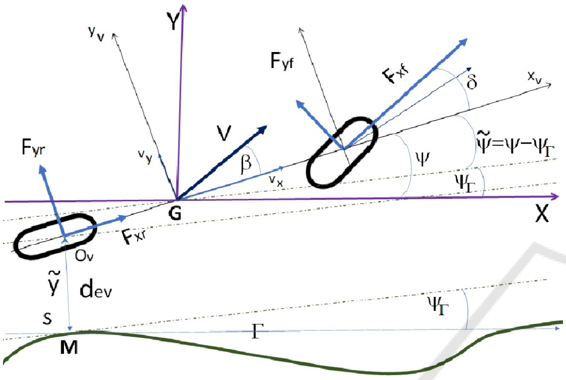

Figure 3: Bicycle Model and trajectory Γ.

The actuation dynamics when considered can be written as follows, where J_x, r_x, T_x are the wheels inertia, rays, and motor torques. For a rear traction vehicle $T_{m_f}i = 0$ and $T_{m_r}i \neq 0$.

$$\begin{cases} J_f.\dot{\omega}_{fi} = (T_{m_f}i - r_{fi}.F_{xf}) \\ J_r.\dot{\omega}_{ri} = (T_{m_r}i - r_{ri}.F_{xr}) \end{cases} \tag{17}$$

Let us recall that the process has only 2 inputs (the torque and the steering).

Geometric Model. The figure 3 shows the geometric scheme of the vehicles with the reference path γ in the absolute frame $R(0xy)$.

Let us note s_i, the curvilinear abscissa (position M) of vehicle i. The abscissa s_i is located with respect to a desired trajectory or trajectory Γ and we note d the Side linear deviation of the vehicle i with respect to the desired trajectory Γ.
O_i is the center of the rear axle of the ith vehicle and s_i is the distance traveled (curvilinear abscissa) by the closest point to O_i on the path Γ. $c(s_i)$ is the curvature of the Γ path in s_i.
Recall that d_i is the desired curvilinear distance between vehicles and $c(S)$ is the curvature of the trajectory C at the point M. The Curvilinear spacing between 2 vehicles is then: $e_{s_i} = s_{i-1} - s_i - d_i$

$\tilde{\psi}_i = \psi - \psi_\Gamma$ is the angular deviation of the vehicle i relative to reference trajectory Γ.

The Kinematic equations are needed to get the Curvilinear velocities ($\dot{s}_i$) to follow the motion of the vehicle i and determine its orientation. The curvilinear kinematic model can be written:

$$\begin{cases} \dot{s}_i = \frac{\cos(\tilde{\psi}_i)}{1-\tilde{y}_i.c(s)} v_{x_{v_i}} \\ \dot{\tilde{y}}_i = \sin(\tilde{\psi}_i).v_{x_{v_i}} \\ \dot{\tilde{\psi}}_i = (\frac{\tan\delta_i}{L} - \frac{c(s)\cos(\tilde{\psi}_i)}{1-\tilde{y}_i.c(s)})v_{x_{v_i}} \end{cases} \tag{18}$$

The kinematic modeling of vehicles, describes the velocities based on the geometry of these vehicles. The kinematic model alone does not completely represent the physical reality (Cordesses, 2000). The half vehicle model, known as the bicycle, is an acceptable representation for the dynamics of the convoy and is most often used (Nadji, 2007; Nouveliere et al., 2002; Lenain, 2005; Cartade et al., 2005).

These equations represent a non-holonomic system, the state vector has three dimensions and two dimensional control. The mathematical singularity ($d_c(s) = 1$) will never appear because the point O_v is not at the center of the curve of the desired trajectory. O_i is the center of the rear axle of the ith vehicle. $c(s_i)$ is the curvature of the Γ path in s_i (Cordesses, 2000) (see figures 3).

Some authors, to be complete, add to this model a representation of wheel slip and drift angles (Lenain, 2005; Cartade et al., 2005; Petrov, 2009). If we consider β_i^F and β_i^R the drift angles (front and back) of the robot. The kinematics becomes then

$$\begin{cases} \dot{s}_i = v_i \frac{\cos(\tilde{\psi}_i+\beta_i^R)}{1-c(s_i)\tilde{y}_i} \\ \dot{\tilde{y}}_i = v_i \sin(\tilde{\psi}_i + \beta_i^R) \\ \dot{\tilde{\psi}}_i = \cos(\beta_i^R)\frac{tan(\delta_i+\beta_i^F)-tan(\beta_i^R)}{L} - \frac{c(s_i)\cos(\tilde{\psi}_i+\beta_i^R)}{1-c(s_i)\tilde{y}_i} \end{cases} \tag{19}$$

2.2.6 Conclusion on Vehicles Models

We have presented the models used for the control of vehicle fleets ranging from the simplest to the most complete one. Several architectures have been used, but there is still a lack of clear strategies non dependent of the control laws used. For control of the vehicle chain, the robotics models are the most appropriate for the good motion control of the vehicles while taking into account their dynamics and kinematic relations. They involve correctly the transformations from the vehicles operational variables to the Cartesian space representation.

Note that up to now, only the individual model of one vehicle of the fleet are considered and there is no criteria on the global behaviour or the fleet shape.

In section 3, we will propose a more complete model, by adding to the robotics equations, a clear description of the links and couplings of the vehicles within the fleet and with their environment.

2.3 Control Architectures for Fleets

The existing control architectures can be classified into several categories: Kinematic / Dynamic, Local / Global, Uni or Bi-directional. This is related to the information used to control each vehicle. They are local or global depending on sensor information they use to control (Global: from all the vehicles, or Local only neighbors). The two approaches can be unidirectional (preceding neighbors) or bidirectional (neighbors in front and behind).

2.3.1 Global Fleet Control Architecture

For the global or centralized architecture (GUC, GBC), the control law applied to each vehicle of the fleet is based on the data (positions, velocities, ...) of all the vehicles of the convoy (Yazbeck, 2014). Sometimes it can be partial, with data limited to the leader and some of the neighboring vehicles, if the convoy chain is too long. For example, in partial GBC, one uses the states variables of the **leader** and the 4 (front and rear plus left and right if any) or only 2 neighboring vehicles. This approach has been used in (Caicedo et al., 2003), for a convoy moving in a straight line. This makes global approaches more expensive(Ali et al., 2015).

2.3.2 Local or Decentralized Control Architecture

In general, the most of vehicle pilots use only the information of the previous vehicle and possibly (only partially) that of the following one (LUC, LBC). This decentralized control (LUC) approach requires fewer sensors and and very little information exchange between vehicles of the convoy, than the centralized approach. It also requires less computations and information. The control is based on the data restricted to neighbours in the convoy, to minimize the numbers of the sensors used. (Qian et al., 2016; Nouveliere et al., 2002; Sheikholeslam and Desoer, 1993).

2.3.3 Local Bidirectional Control Architecture (LBC)

In bidirectional architecture, we are interested in information about the two neighbors,the previous vehicle and the follower one. Each vehicle is controlled targeting the previous one with regard to its followers and leaders.

In this case, the disadvantages are the availability of information on the vehicles of the chain, the need for sensors, the communication of the data, and the observability.

2.3.4 Local Unidirectional Control (LUC)

Each vehicle is controlled targeting the previous one regardless to its follower. The driven vehicle in LUC is slaved to follow its predecessor (Avanzini et al., 2010). Tracking errors, introduced by sensors, actuators, and delays accumulate from the leader vehicle to the last one, in the convoy chain and affect the stability of the convoy motion. This causes oscillations due to accumulated errors (Ali et al., 2015). This also causes unacceptable disturbances if the string is long (Avanzini, 2010). These problems are only partially avoided in the global architecture.

3 NEW MODELING APPROACH PROPOSED FOR PLATOONING

The robotic modeling approach seems more suitable for driving fleets of vehicles, robots or mobile devices. Let us first, discuss some observations of the nature groups and then, we will use a more complete architecture with a strategy that will consider models including the group characteristics which is inspired by the behavior of animals.

3.1 Modeling for Platooning

Two examples of fleets of 5 vehicles will be used to illustrate our modeling approach. They are represented in figure (4). We will define the geometric model of each vehicle and for the global fleet. Using the five gravity centers of the 5 vehicles we will define the geometric form of the fleet. Then, each vehicle is localized regard to the gravity center or the red vehicle chosen as being the leader. Therefore the kinematics and finally the dynamic equations for each vehicle will be considered.

Geometric Models in R_v. If the red vehicle is the leader of the fleet 1 of the figure 4, its position is $q_0 = [x_{v_0}, y_{v_0}, \psi_0]^T$, the preceding vehicle is at $q_1 = q_0 + [d, 0, 0]^T$ the rear one at $q_2 = q_0 + [-d, 0, 0]^T$, the left one at $q_3 = q_0 + [0, d_y, 0]^T$ and the right one at $q_4 = q_0 + [0, -d_y, 0]^T$, where d and d_y are the longitudinal and lateral IVSD. The geometric transformationis

$$T_i^{kin} = \begin{pmatrix} \cos\psi_i & -\sin\psi_i & 0 \\ \sin\psi_i & \cos\psi_i & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{20}$$

Kinematics Models. The Kinematic transformation matrix, for each vehicle, is the same as previously given (eq 6). We then get here:

$$\dot{X}_0 = T_0^{kin}.\dot{q}_0 \;\;,\;\; \dot{X}_1 = T_1^{kin}.\dot{q}_1$$
$$\dot{X}_2 = T_2^{kin}.\dot{q}_2 \;\;,\;\; \dot{X}_3 = T_3^{kin}.\dot{q}_3 \;\;,\;\; \dot{X}_4 = T_4^{kin}.\dot{q}_4$$

Dynamic Models. The Lagrange method can be used to get the (Inverse or Direct) Dynamic Model equations, in the vehicle frame R_v, (M'Sirdi et al., 2007) for each vehicle, knowing it is related to its neighbours (by τ_{r_j}).

$$\begin{array}{lll} InverseDM & U_i = & M_i(q_i).\ddot{q}_i + H_i(\dot{q}_i, q_i) \\ DirectDM & \ddot{q}_i = & M_i(q_i)^{-1}(-H_i(\dot{q}_i, q_i) + U_i) \\ where & U_i = & u_i - \tau_{f_{i+1}} - \tau_{r_{i-1}} - \tau_{l_i} - \tau_{d_i} \cdots \end{array} \tag{21}$$

with the operational variables $q_i = [x_{v_i}, y_{v_i}, \psi_i]^T$ as the position vector for vehicle i, and $\dot{q}_i, \ddot{q}_i$ the velocity and acceleration vectors. To this model we can add the actuators (equation 17) and wheel ground contact models (ignored here for the sake of simplicity and considered in another control step).

Inter Vehicles Dynamic Relations (IVDR)

We introduce here the IVDR as a Reference Model to include the constraints defining the vehicles interaction dynamics (instead of only an intervehicle distance (constant or not); $(\tau_{r_{i-1}}, \tau_{f_{i+1}})$ are rear and front constraints and (τ_{l_i}, τ_{d_i}) are from the left and right vehicles in the fleet 1 of the figure (4). We can have four Reference Models (RM) for one vehicle and more RM if we need. We can also relate all the vehicles to the leader. We can also share a percentage of leading.

The forces τ_{x_j}, represents the constraints (attraction/repulsion) from the nearby vehicles (front, rear, left and right). This is the description of the relation of the vehicle i to the other ones in the group (or platoon). As an example, the relation with the preceding vehicle could be, with a simple mass-spring-damper model (for simplicity):

$$\tau_{f_{i+1}} = \quad M_i.\ddot{e}_{i,i+1} + B_f i.\dot{e}_{i,i+1} + K_f i.e_{i,i+1} + w_{f_{i+1}} \tag{22}$$

where $e_{i,j}$ is the distance between two vehicles.

A virtual control input $w_{f_{i+1}}$ is introduced to keep control of any variation which can be done on the fly on the reference model character. It is also worthwhile to note that this virtual input will probably enhance the platoon controllability. It can be used by a high control level to manage the character of the fleet and change its features depending the operational state, the environment and the road conditions.

The constraints torques are linked by pairs through the desired Reference Models for the Inter Vehicles Dynamic Relations (RM-IVDR). In the figure (4) we see that these torques are generated by damping and springs reference models.

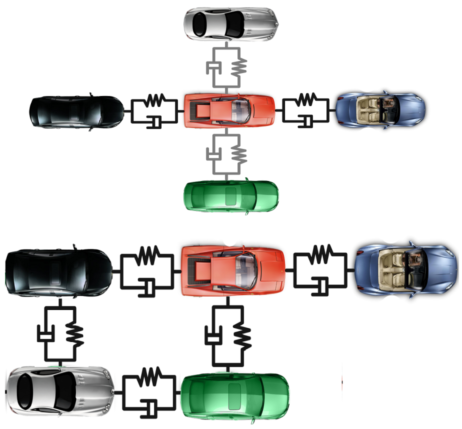

Figure 4: Fleets of 5 Vehicles.

Please note that for the first fleet (of figure (4)) we need Four reference models (2 longitudinal and 2 lateral) and for the second one 5 RM-IVDR are needed. We can also consider that all the vehicles are also linked to the leader. Why not adding, for all the vehicles a link to the blue one (first) or the last one.

In addition, note that the RM-IVDR models (mass-spring-damper) are considered here for simplicity. We can choose more complex models and use nonlinear stiffness (rigidity for the front and flexible for the rear). The parameters are not obligatorily linear, nor constant and bidirectional. A vehicle, (interesting or not) for the fleet, may be attached to the platoon or left if it goes too far. We can consider also holonomic or non-holonomic constraints (with equalities or inequalities $C(X) \geq c_0$).

This is the main difference with the previous approaches where vehicles are related only through the controllers. We include specific reference models to define the character of the dynamic relations between vehicles.

The proposed Dynamic Model for the Platoon

The model can be expressed in the operational frame or in the Cartesian frame by geometric and kinematic transformations. Let us note ε_r and ε_l the distance between the vehicle and the right or the left one. The parameters indexed f, r, l, d, corresponds to the Reference model with regard to the front, rear, left and right vehicle (respectively).

The proposed dynamic model for the platoon is then

$$\begin{array}{ll} For & i = 1, \ldots N, \\ U_i = & M\ddot{X}_i + H(\dot{X}_i, X_i) \\ \tau_{f_{i+1}} = & M_i.\ddot{e}_{i,i+1} + B_{f_i}.\dot{e}_{i,i+1} + K_{f_i}.e_{i,i+1} + w_{f_{i+1}} \\ \tau_{r_{i-1}} = & M_i.\ddot{e}_{i,i-1} + B_{r_i}.\dot{e}_{i,i-1} + K_{r_i}.e_{i,i-1} + w_{r_{i-1}} \\ \tau_{l_i} = & M_i.\ddot{\varepsilon}_{i,i_l} + B_{l_i}.\dot{\varepsilon}_{i,i_l} + K_{l_i}.\varepsilon_{i,i_l} + w_{l_i} \\ \tau_{d_i} = & M_i.\ddot{\varepsilon}_{i,i_r} + B_{d_i}.\dot{\varepsilon}_{i,i_r} + K_{d_i}.\varepsilon_{i,i_r} + w_{d_i} \end{array} \tag{23}$$

In fact the reference models (RM-IVDR), add to the system degrees of freedom (DoF) corresponding to the relative motions. This will make the control more admissible and more realistic. Those DoF are added, in our model, with the corresponding virtual control inputs to enhance the process observability controllability. The system can be considered in a triangular form to assign to the system mechanical impedance features to the different DoF.

4 CONCLUSIONS

There is no general theory for modeling platoons of vehicles, drones or robots. This paper has considered the fleets or groups modeling as an open problem for autonomous global driving.

An overview of the modeling approaches used for platooning control is presented. The reported applications in literature consider separate and simple vehicle models and link their behaviour only through the control laws. This means that there is no a priory defined relation between the group elements (except the inter vehicles distance) and then there is no optimal strategy through the control. To much efforts are left to the control.

The proposed model gives more clearly the global description of the fleet and separate definitions of the control objective and the behaviour (Reference Model) for Inter Vehicles Dynamic Relations. It allows more flexibility for the control laws and respect the constraints using an appropriate Reference Model for the behaviour (which copes with the control admissibility). In our ongoing research, we will show that the Platoon observability and controllability is enhanced when using the new proposed model.

In perspectives the platoon Observability and controllability will be analysed and non linear control techniques will be applied to control the global platoon behavior.

REFERENCES

Alcala, E., Puig, V., Quevedo, J., and Escobet, T. (2018). Gain-scheduling lpv control for autonomous vehicles including friction force estimation and compensation mechanism. *IET Control Theory Applications*, 12(12):1683–1693.

Ali, A., Garcia, G., and Martinet, P. (2015). Urban platooning using a flatbed tow truck model. In *Intelligent Vehicles Symposium (IV), 2015 IEEE*, pages 374–379. IEEE.

Allou, S. and Zennir, Y. (2018). A comparative study of pid-pso and fuzzy controller for path tracking control of autonomous ground vehicles. In *Proceedings of the 15th International Conference on Informatics in Control, Automation and Robotics - Volume 1: ICINCO,*, pages 306–314. INSTICC, SciTePress.

Avanzini, P. (2010). *Modélisation et commande d'un convoi de véhicules urbains par vision*. PhD thesis, Université Blaise Pascal-Clermont-Ferrand II.

Avanzini, P., Thuilot, B., and Martinet, P. (2010). Accurate platoon control of urban vehicles, based solely on monocular vision. In *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*, pages 6077–6082. IEEE.

Bascetta, L., Cucci, D. A., and Matteucci, M. (2016). Kinematic trajectory tracking controller for an all-terrain ackermann steering vehicle. *IFAC-PapersOnLine*, 49(15):13 – 18. 9th IFAC Symposium on Intelligent Autonomous Vehicles IAV 2016.

Bauer, M. and Tomizuka, M. (1996). Fuzzy logic traction controllers and their effect on longitudinal vehicle platoon systems. *Vehicle System Dynamics*, 25(4):277–303.

Caicedo, R. E., Valasek, J., and Junkins, J. L. (2003). Preliminary results of one-dimensional vehicle formation control using a structural analogy. In *American Control Conference, 2003. Proceedings of the 2003*, volume 6, pages 4687–4692. IEEE.

Cartade, P., Lenain, R., Thuilot, B., and Berducat, M. (2005). Algorithmes pour la commande d'une formation de robots mobiles. In *Conférence Internationale Francophone d'Automatique (CIFA2012) Grenoble, France. 4-6 Juillet 2012*, pages 2159–2165. IEEE.

Chebly, A. (2017). *Trajectory planning and tracking for autonomous vehicles navigation*. PhD thesis, Université de Technologie de Compiègne.

Contet, J.-M., Gechter, F., Gruer, P., and Koukam, A. (2009). Bending virtual spring-damper: a solution to improve local platoon control. In *International Conference on Computational Science*, pages 601–610. Springer.

Cordesses, L. (2000). *Commande de robots holonomes et non holonomes. Application au guidage d'engins agricoles par GPS*. PhD thesis, Université Blaise Pascal - Clermont II.

Daviet, P. and Parent, M. (1996). Longitudinal and lateral servoing of vehicles in a platoon. In *Intelligent Vehicles Symposium, 1996., Proceedings of the 1996 IEEE*, pages 41–46. IEEE.

DeSantis, R. (1995). Path-tracking for car-like robots with single and double steering. *IEEE Transactions on vehicular technology*, 44(2):366–377.

Guillet, A., Lenain, R., Thuilot, B., and Martinet, P. (2014). Adaptable robot formation control: Adaptive and predictive formation control of autonomous vehicles. *IEEE Robotics Automation Magazine*, 21(1):28–39.

Huang, C., Naghdy, F., and Du, H. (2016). Model predictive control based lane change control system for an autonomous vehicle. In *Region 10 Conference (TENCON) 2016 IEEE*, pages 3349–3354. IEEE.

Khatir, M. E. and Davidson, E. (2005). Decentralized control of a large platoon of vehicles operating on a plane with steering dynamics. In *Proceedings of the American Control Conference, 2005*, pages 2159–2165. IEEE.

Khatir, M. E. and Davison, E. J. (2004). Decentralized control of a large platoon of vehicles using non-identical controllers. In *American Control Conference, 2004. Proceedings of the 2004*, volume 3, pages 2769–2776. IEEE.

Lenain, R. (2005). *Contribution à la modélisation et à la commande de robots mobiles en présence de glissement: application au suivi de trajectoire pour les engins agricoles*. PhD thesis, Université Blaise Pascal-Clermont-Ferrand II.

Martinez, J.-J., Avila, J.-C., and de Wit], C. C. (2004). A new bicycle vehicle model with dynamic contact friction. *IFAC Proceedings Volumes*, 37(22):625 – 630. IFAC Symposium on Advances in Automotive Control 2004, Salerno, Italy, 19-23 April 2004.

Menhour, L., D'Andréa-Novel, B., Fliess, M., Gruyer, D., and Mounier, H. (2015). A new model-free design for vehicle control and its validation through an advanced simulation platform. In *14th annual European Control Conference - ECC 2015*, Linz, Austria.

M'Sirdi, N. K. (2018). Vehicle platooning: an overview on modelling and control approaches. In *International Conference on Applied Smart Systems (ICASS'18)*. Medea University.

M'Sirdi, N. K. (2020). Autonomous vehicle platooning and motioncontrol: Overview on models and control approaches; features and characters. In springer, P. I., editor, *International Conference on Electronic Engineering and Renewable Energy (ICEERE'2020)*, volume 1, Oujda, Morocco.

M'Sirdi, N. K., Rabhi, A., and Naamane, A. (2007). Vehicle models and estimation of contact forces and tire road friction. In *ICINCO 2007, Proceedings of the Fourth International Conference on Informatics in Control, Automation and Robotics, Robotics and Automation 1, Angers, France, May 9-12, 2007*, pages 351–358.

Mu'azu, J. M., Sudin, S., Mohamed, Z., Yusuf, A., Usman, A. D., and Hassan, A. U. (2017). An improved topology model for two-vehicle look-ahead and rear-vehicle convoy control. *IEEE 3rd International Conference on Electro-Technology for National Development (NIGERCON)*, 6:0.

Nadji, M. (2007). *Adéquation de la dynamique de véhicule à la géométrie des virages routiers: apport à la sécurité routière*. PhD thesis, Villeurbanne, INSA.

Nouveliere, L., Marie, J. S., and an N K M'Sirdi, S. M. (2002). Controle longitudinal de véhicules parcommande sous optimale. In *CIFA 2002*, pages 906–911. Nantes Juillet.

Petrov, P. (2009). Nonlinear adaptive control of a two-vehicle convoy. *Open Cybernetics & Systemics Journal*, 3:70–78.

Qian, X., de La Fortelle, F. A. A., and Moutarde, F. (2016). A distributed model predictive control framework for road-following formation control of car-like vehicles. In *arXiv:1605.00026v1 [cs.RO] 29 Apr 2016*.

Rabhi, A. (2005). *Estimation de la dynamique du véhicule en interaction avec son environnement*. PhD thesis, Versailles-St Quentin en Yvelines.

Ricardo, C., Aguiar, A. P., and Gaspar, J. (2008). Control of unicycle type robots tracking, path following and point stabilization. In *Proc. of IV Jornadas de Engenharia Electrónica e Telecomunicações e de Computadores*, pages 180–185. Lisbon Portugal.

Samson, C. and Ait-Abderrahim, K. (1990). Mobile robot control. Part 1 : Feedback control of nonholonomic wheeled cart in cartesian space. Research Report RR-1288, INRIA.

Sheikholeslam, S. and Desoer, C. A. (1993). Longitudinal control of a platoon of vehicles with no communication of lead vehicle information: A system level study. *IEEE Transactions on vehicular technology*, 42(4):546–554.

Song, L., Guo, H., Wang, F., Liu, J., and Chen, H. (2017). Model predictive control oriented shared steering control for intelligent vehicles. In *Control And Decision Conference (CCDC), 2017 29th Chinese*, pages 7568–7573. IEEE.

Sprinkle, J., Eklund, J. M., Gonzalez, H., Grotli, E., Sanketi, P., and Moser, M. (2008). Recovering models of a four-wheel vehicle using vehicular system data. Technical Report UCB/EECS-2008-92, EECS Department, University of California, Berkeley.

Stanley, J. L. and Katupitiya, J. (2013a). Cooperative autonomous platoon maneuvers on highways. In *IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, Wollongong, Australia.

Stanley, J. L. and Katupitiya, J. (2013b). Modeling and control of a platoon of autonomous buses; project: Autonomous vehicle transportation. In IVS, editor, *Conference: Intelligent Vehicles Symposium (IV), 2013 IEEE*.

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

Szanto, A., Hajdu, S., and Deak, K. (2020). Survey of the application fields and modeling methods of automotive vehicle dynamics models. *International Journal of Engineering and Management Sciences (IJEMS) Vol. 5. (2020). No. 2*, 5(2):196–209.

Xiang, J. and Braunl, T. (2010). String formations of multiple vehicles via pursuit strategy. *IET control theory and applications*, 4(6):1027–1038.

Yanakiev, D. and Kanellakopoulos, I. (1996). A simplified framework for string stability analysis in ahs1. *IFAC Proceedings Volumes*, 29(1):7873–7878.

Yazbeck, J. (2014). *Accrochage immatériel sûr et précis de véhicules automatiques*. PhD thesis, Université de Lorraine.

Zin, A., Sename, O., and Dugard, L. (2004). Active comfort and handling improvement with a 3d bicycle model. *IFAC Proceedings Volumes*, 37(22):619 – 624. IFAC Symposium on Advances in Automotive Control 2004, Salerno, Italy, 19-23 April 2004.