19th International Conference on Modeling & Applied Simulation
17th International Multidisciplinary Modeling & Simulation Multiconference

ISSN 2724-0037 ISBN 978-88-85741-48-5
DOI: 10.46354/i3m.2020.mas.011

Longitudinal and Lateral Control using Global Decentralized Strategy with a Comparison of Different Approaches for Autonomous Vehicles Convoy

M-M.Mohamed-Ahmed[1,*] and Aziz Naamane[1]

[1]Aix Marseille University, Université de Toulon, CNRS, LIS, Marseille, France

[*]Corresponding author. Email address: mohamed-mahmoud.mohamed-ahmed@lis-lab.fr

Abstract

In this paper, a longitudinal and lateral control approach is proposed for a convoy of multi vehicles. A global decentralized architecture based on the information from neighbors and the leader vehicle is used, to ensure stability and safety between neighbors. Lateral control based on the longitudinal speed of the i-th vehicle and the characteristic of the reference trajectory of the leader to cancel the lateral deviation of the convoy from this trajectory and also allows coupled longitudinal and lateral motion control. The robustness of the linearization control by inverse dynamics (for longitudinal movement) and the sliding mode control (for lateral movement), concerning the parameters of the dynamic model, will be studied in this paper. To compare different control approaches for the convoy, we add sensor errors between vehicles, to study the accumulation of the errors towards the other cars of the convoy. To validate these approaches, we use the platform of SCANeR^{TM}-Studio to control a convoy of 10 vehicles.

Keywords: Nonlinear Control; Autonomous Vehicles; Convoy; Platoon; Longitudinal and Lateral Control.

1. Introduction

Since the last century, the industrial world of transport specialists has been taking more interest in intelligent vehicles. It is investing in this domain by numerous researchers in different research laboratories intending to find tools that allow vehicles to be more intelligent, autonomous, and consume less energy and also ensure the safety of people as many accidents are caused by negligence or tiredness of the driver. In terms of rentability, a convoy of many trucks transporting goods along the long way, can move based on one driver, driving the first truck and the others following him, or replace the drivers in case of tiredness as in the Chauffeur project. Another example is the AutoNet2030 project – Cooperative Systems in Support of Networked Automated Driving by 2030 – for an aim to have more advanced cooperation and driving assistance for automatized vehicles and study the types of information needed to achieve this objective (De La Fortelle et al., 2014; Chang et al., 1991).

Several models have been proposed in the literature to control the convoy in both directions of movement. The double integral model is the most used model, to simplify the non-linear dynamics of each vehicle, or by an exact linearization using the chain transformation, as proposed in (Ali et al., 2015). This model considered to study the longitudinal movement and inter distance between the vehicles of the convoy. Other models have also been used for the geometric control which are based on the kinematic model (Qian et al., 2016;

Xiang and Bräunl, 2010). Control approaches exist in the literature and based on communication between vehicles, such as the local architecture approach, which is the most widely used approach and is also called the leader-follower approach (Petrov, 2009; Hedrick et al., 1991). Each vehicle in convoy uses information from the preceding vehicle (unidirectional) (Muazu et al., 2017; Sheikholeslam and Desoer, 1993). Other approaches also that are based on information from all vehicles or part of the convoy, the first is called the centralized approach and the second the decentralized approach (Avanzini et al., 2010; Khatir and Davidson, 2005). The choice of a control approach depends on the number of available sensors or an economic question but is always fundamental to ensure the stability and safety of the convoy (Swaroop, 1994; ?). In (Mohamed-Ahmed et al., 2019), we have proposed a control based on the local unidirectional approach, in which we applied a non-linear predictive control for both movements of the convoy.

In this work, we propose a longitudinal and lateral control approach for a convoy of autonomous vehicles in an urban milieu. The longitudinal control of the convoy is based on the decentralized global approach such that the vehicles in convoy receive information from the leader and the preceding vehicle. This approach makes it possible to cancel the accumulation of longitudinal errors towards other vehicles in the case of a sensor error between two neighboring vehicles and also ensures the global stability of the convoy. Lateral control is considered in this work to cancel the lateral deviation of the convoy from the desired trajectory, which is defined for the fleet or leader's trajectory. Longitudinal and lateral control are coupled by the longitudinal speed of the convoy. For the longitudinal movement, we use a linearization control by inverse dynamics, and for the lateral control, we use a sliding mode control. A comparison for the different control approaches such as the local approach (Leader-follower) and the global approach based on the information of the neighbors and the speed of the leader or the speed and position of the leader at the same time, will be studied by adding errors between two neighboring vehicles to see the effect of accumulation of errors towards the other vehicles in the convoy. Dynamic model is considered to take into account the non-linear dynamics movement of the convoy in the differences frame and also to calculate the control laws of each vehicle. The robustness of the control will be studied in the presence of errors on the model parameters. To validate these approaches, we use The driving simulator SCANeR-studio, software developed by OKTAL and Matlab Simulink.

The paper is organized as follows. Section II represents the modeling of the convoy, such as the dynamic and state model of a vehicle and then the movement of the convoy considering the spacing error between the vehicles. Longitudinal and lateral control of the convoy are presented in section III with their stability studies for both movements. Finally, the validation using The driving simulator SCANeR-studio with comparisons of the different control approaches is presented in section IV.

2. Modeling

In order to control the movement of each vehicle in convoy, we will start to present the models that will be used for longitudinal and lateral control.

2.1. Dynamic model

In the case of a convoy traveling on different routes, the coupling between the two controls is necessary to complete the mission in the right condition. This coupling requires taking into account the non-linearity of the system and the coupling between the longitudinal and lateral model for the i-th vehicle. In our case, the two wheels at the rear are considered to be driven by engine torque and the steering angle is assumed to be equal for the two wheels in front. Let G_i be the centre of gravity for the i-th vehicle and (G_i, x_i, y_i) is the vehicle frame and (O_i, X_i, Y_i) is the fixed frame. The description of the i-th vehicle is presented in the Fig.1.

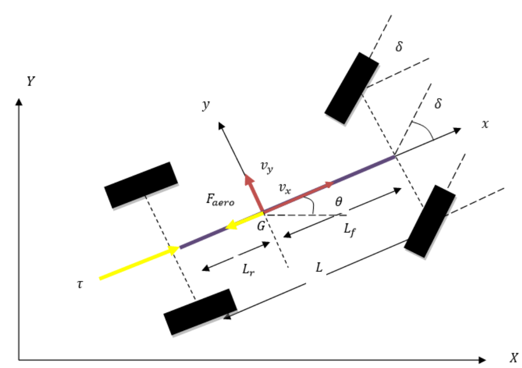

Figure 1. The Vehicle Description

where:

L_f,L_r: distance between G and front and rear wheels.
m,I_z: the mass and Inertia Moment of the vehicles.
m_w, I_w: the mass and the rotational inertia of the wheel.
$\dot{x}, v_x$: longitudinal vehicle velocity along x axis.
$\dot{y}, v_y$: lateral velocity (axis y).
θ: yaw angle and $\dot{\theta}$: yaw rate.
$a_x = \ddot{x} - \dot{y}\dot{\theta}$: longitudinal acceleration.
$a_y = \ddot{y} + \dot{x}\dot{\theta}$: lateral acceleration.
$C_{\alpha f}, C_{\alpha r}$: are respectively the cornering stiffness of the

front and the rear wheels.
τ: driving/braking wheels torque. δ: steering wheel angle.
$F_{aero} = \frac{1}{2}\rho c s \dot{x}^2$: aerodynamic force, where ρ, s and c: are the air density, the vehicle frontal surface and the aerodynamic constant.
R_t: radius of the tire and E: Vehicle's track.
L_3, I_3: the interconnection between the different bodies composing the vehicle.

The dynamic model of the i-th vehicle is represented as follows (Chebly, 2017):

$$\begin{cases} m_e\ddot{x}_i - m\dot{y}_i\dot{\theta}_i + L_3\dot{\theta}_i^2 + \delta_i(2C_{\alpha f}\delta_i - 2C_{\alpha f}\frac{\dot{x}_i(\dot{y}_i+L_f\dot{\theta}_i)}{\dot{x}_i^2-(\dot{\theta}_i E/2)^2})+ \\ F_{aero_i} = \frac{\tau_i}{R_t} \\ m\ddot{y}_i - L_3\ddot{\theta}_i + m\dot{x}_i\dot{\theta}_i + 2C_{\alpha f}\frac{\dot{x}_i(\dot{y}_i+L_f\dot{\theta}_i)}{\dot{x}_i^2-(\dot{\theta}_i E/2)^2} + 2C_{\alpha r}\frac{\dot{x}_i(\dot{y}_i-L_r\dot{\theta}_i)}{\dot{x}_i^2-(\dot{\theta}_i E/2)^2} \\ = (2C_{\alpha f} - 2\frac{I_w}{R_t^2}\ddot{x}_i)\delta_i \\ I_3\ddot{\theta}_i - L_3\ddot{y}_i + 2L_f C_{\alpha f}\frac{\dot{x}_i(\dot{y}_i+L_f\dot{\theta}_i)}{\dot{x}_i^2-(\dot{\theta}_i E/2)^2}) - 2L_r C_{\alpha r}\frac{\dot{x}_i(\dot{y}_i-L_r\dot{\theta}_i)}{\dot{x}_i^2-(\dot{\theta}_i E/2)^2} \\ -L_3\dot{x}_i\dot{\theta}_i = L_f(2C_{\alpha f} - 2\frac{I_w}{R_t^2}\ddot{x}_i)\delta_i - (\frac{E}{2}C_{\alpha f}\frac{E\dot{\theta}_i(\dot{y}_i+L_f\dot{\theta}_i)}{\dot{x}_i^2-(\dot{\theta}_i E/2)^2})\delta_i \end{cases} \tag{1}$$

where: $m_e = m+4\frac{I_w}{R_t^2}$, $L_3 = 2m_w(L_r-L_f)$ and $I_3 = I_z+m_w E^2$.

We have two principal inputs for the i-th vehicle, which will be used to control the longitudinal movement by driving/braking wheels torque ($u_{xi} = \frac{\tau_i}{R_{t_i}}$) and for the lateral movement by steering wheel ($u_{yi} = (2C_{\alpha fi} - 2\frac{I_{wi}}{R_{t_i}^2}\ddot{q}_{1i})\delta_i$) in order to follow the leader's trajectory and to cancel the lateral deviation from this trajectory.

2.2. State Model

Taking them as a vector of positions for the three movements of the i-th vehicle:

$$q_i = [q_{xi}, q_{yi}, q_{\theta i}]^T = [x_i, y_i, \theta_i]^T$$

We have proposed in Mohamed-Ahmed et al. (2020) to write the dynamic model defined in (1) in the following robotic form:

$$M_i(q_i).\ddot{q}_i + H_i(\dot{q}_i, q_i) = U_i \tag{2}$$

where the inertia Matrix $M_i(q_i)$ is:

$$M_i(q_i) = \begin{pmatrix} m_{e_i} & 0 & 0 \\ 0 & m_i & -L_{3i} \\ 0 & -L_{3i} & I_{3i} \end{pmatrix}$$

$H_i(\dot{q}_i, q_i)$:

$$\begin{pmatrix} -m_i\dot{q}_{yi}\dot{q}_{\theta i} + L_{3i}\dot{q}_{\theta i}^2 + \delta_i(2C_{\alpha fi}\delta_i - 2C_{\alpha fi}\frac{\dot{q}_{xi}(\dot{q}_{yi}+L_{fi}\dot{q}_{\theta i})}{\dot{q}_{xi}^2-(\dot{q}_{\theta i}E_i/2)^2}) + F_{aero_i} \\ m_i\dot{q}_{xi}\dot{q}_{\theta i} + 2C_{\alpha fi}\frac{\dot{q}_{xi}(\dot{q}_{yi}+L_{fi}\dot{q}_{\theta i})}{\dot{q}_{xi}^2-(\dot{q}_{\theta i}E_i/2)^2} + 2C_{\alpha ri}\frac{\dot{q}_{xi}(\dot{q}_{yi}-L_{ri}\dot{q}_{\theta i})}{\dot{q}_{xi}^2-(\dot{q}_{\theta i}E_i/2)^2} \\ 2L_{fi}C_{\alpha fi}\frac{\dot{q}_{xi}(\dot{q}_{yi}+L_{fi}\dot{q}_{\theta i})}{\dot{q}_{xi}^2-(\dot{q}_{\theta i}E_i/2)^2}) - 2L_{ri}C_{\alpha ri}\frac{\dot{q}_{xi}(\dot{q}_{yi}-L_{ri}\dot{q}_{\theta i})}{\dot{q}_{xi}^2-(\dot{q}_{\theta i}E_i/2)^2} - L_{3i}\dot{q}_{xi}\dot{q}_{\theta i} \end{pmatrix}$$

and the input vector $U_i = (u_{xi}, u_{yi}, u_{\theta i})^T$:

$$U_i = \begin{pmatrix} \frac{\tau_i}{R_{t_i}} \\ (2C_{\alpha fi} - 2\frac{I_{wi}}{R_{t_i}^2}\ddot{q}_{xi})\delta_i \\ L_{fi}u_{yi} - (\frac{E_i}{2}C_{\alpha fi}\frac{E_i\dot{q}_{\theta i}(\dot{q}_{yi}+L_{fi}\dot{q}_{\theta i})}{\dot{q}_{xi}^2-(\dot{q}_{\theta i}E_i/2)^2})\delta_i \end{pmatrix}$$

To determine the state model of the i-th vehicle, we take as state vector:

$$z_i = (z_{1i}, z_{2i})^T = (q_i, \dot{q}_i)^T$$

with positions: $z_{1i} = q_i = [x_i, y_i, \theta_i]^T$
and velocities: $z_{2i} = \dot{q}_i = [\dot{x}_i, \dot{y}_i, \dot{\theta}_i]^T$

The state model is determined using the equation defined in (2), is given as follows:

$$\begin{cases} \dot{z}_{1i} = z_{2i} \\ \dot{z}_{2i} = f(z_{1i}, z_{2i}) + g(z_{1i})U_i \end{cases} \tag{3}$$

where : $f(z_{1i}, z_{2i}) = -M^{-1}(z_{1i})H_i(z_{1i}, z_{2i})$
and $g(z_{1i}) = M^{-1}(z_{1i})$

This model represents the state model for the i-th vehicle, such that U_i represents the input of the system, to control the longitudinal (u_{x_i}), lateral (u_{y_i}) movement and to determine the yaw movement (u_{θ_i}) based on the steering angle.

2.3. Convoy Motion

The movement of the convoy is represented in Fig.2 and Fig. 3, which shows a set of vehicles following each other. Let G_i be the centre of gravity of the i-th vehicle , S_i, S_{i-1} the curvilinear abscissa of i-th and $(i-1)$-th vehicle, l_d the desired safety distance between each two neighbouring vehicles. The defined curvilinear error (e_{s_i}) between vehicles is given as follows:

$$e_{s_i} = S_i - S_{i-1} + l_{d_i} \tag{4}$$

In our case, the lateral displacement is taken into account even if it seems neglected compared to the longitudinal displacement:

$$e_{s_i} = \int_0^T (\dot{x}_i^2 + \dot{y}_i^2)^{\frac{1}{2}} dt - \int_0^T (\dot{x}_{i-1}^2 + \dot{y}_{i-1}^2)^{\frac{1}{2}} dt + l_{d_i} \qquad (5)$$

A more detailed definition for the longitudinal and lateral movement of the convoy can be found in the control section.

3. Longitudinal and lateral control

3.1. Longitudinal Control

The longitudinal control of the fleet is to keep a desired distance between the vehicles and impose a reference speed of the leader on the convoy, which requires sensors at the border of each vehicle to receive information from the neighbors and the leader in the case of the global decentralized approach. In our case, we assume that the information from the leader and neighbors is available in real-time to calculate the law of longitudinal control Fig.2. To ensure safety and avoid the accumulation of errors to other vehicles, the speed of the leader (x_0) is shared for all cars in the convoy. The curvilinear error between neighboring vehicles is defined as follows:

$$e_{x_i} = S_i - S_{i-1} + l_d \qquad (6)$$

where: l_d : Safety distance. S_i: The curvilinear abscissa for the i-th vehicle.
The error of speed between neighbors (between the i-th and $(i-1)$-th vehicle) :

$$\dot{e}_{x_i} = \dot{x}_i - \dot{x}_{i-1}$$

The speed error between the leader and the i-th vehicle:

$$\dot{e}_{x_{i,0}} = \dot{x}_i - \dot{x}_0$$

where $\dot{x}_0$: the longitudinal speed of the leader and $\dot{x}_i$: the speed of i-th vehicle.

This choice of curvilinear errors is intended to keep a constant distance which is not proportional to the speed of the convoy ($\Delta S_i = S_{i-1} - S_i = l_d$). This proposal makes it possible to avoid abruptly increasing the distance in the event of high longitudinal speed and to avoid decreasing the distance also in the event of decreasing speeds along the trajectory by respecting the minimum safety distance between neighbors.

For the longitudinal control, the linearization control by inverse dynamics is used. This control based on vehicle dynamics and a derivative proportional corrector. The general expression of the linearization control by inverse dynamics for the system defined in (2) :

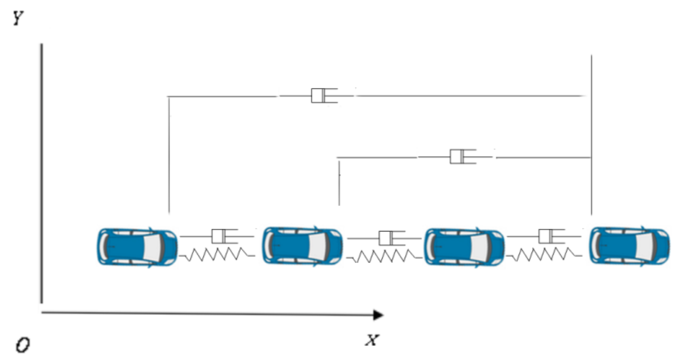

Figure 2. The longitudinal movement of the convoy

$$U_{xi} = \alpha_i v_i + \beta_i$$

where $\alpha_i = M_i$, $\beta_i = H_i$ and v_i represents the corrector. Using this control on the longitudinal movement we have:

$$\begin{cases} \alpha_i = m_{e_i} = M_{1i} \\ \beta_i = H_{1i} = -m\dot{y}_i\dot{\theta}_i + L_3\dot{\theta}_i^2 + \delta_i(2C_{\alpha f}\delta_i - 2C_{\alpha f}\frac{\dot{x}_i(\dot{y}_i + L_f\dot{\theta}_i)}{\dot{x}_i^2 - (\dot{\theta}_i E/2)^2}) + \\ F_{aero_i} \\ v_i = -K_p e_{x_i} - K_v \dot{e}_{x_i} - K_{v_0}\dot{e}_{x_{i,0}} \end{cases} \qquad (7)$$

To study the stability in closed loop, we start writing the dynamics of the error by taking into account the acceleration error between the i-th and $(i-1)$-th vehicle:

$$M_{1i}(\ddot{e}_{x_i} + K_v\dot{e}_{x_i} + K_p e_{x_i} + K_{v_0}\dot{e}_{x_{i,0}}) = \Delta H_{1i}$$

where $\ddot{e}_{x_i} = \ddot{x}_i - \ddot{x}_{i-1}$ and $\Delta H_{1i} = [\hat{H}_{1i} - H_{1i}]$ such as $\hat{H}_{1i}$ represents the estimation on the model parameters (longitudinal equation). K_v, K_p and K_{v_0} are positive defined gains.

To study the stability of the control, the following Lyapunov candidate function is chosen:

$$V_{x_i} = \frac{1}{2}\dot{e}_{x_i}^T\dot{e}_{x_i} + \frac{1}{2}e_{x_i}^T K_p e_{x_i}$$

By calculating the derivative of this function :

$$\dot{V}_{x_i} = \dot{e}_{x_i}^T\ddot{e}_{x_i} + \dot{e}_{x_i}^T K_p e_{x_i}$$

The acceleration error is replaced by its expression :

$$\dot{V}_{x_i} = \dot{e}_{x_i}^T(-K_v\dot{e}_{x_i} - K_p e_{x_i} - K_{v_0}\dot{e}_{x_{i,0}} + M_{1i}^{-1}\Delta H_{1i}) + \dot{e}_{x_i}^T K_p e_{x_i}$$

By developing this equation we have:

$$\dot{V}_{x_i} = \dot{e}_{x_i}^T(-K_v\dot{e}_{x_i} - K_{v_o}\dot{e}_{x_{i,o}} + M_{1i}^{-1}\Delta H_{1i})$$

Let H^+ satisfies the following condition:

$$||\hat{H}_{1i} - H_{1i})|| \leq H^+$$

We choose the gains as follows:

$$H^+ < K_{v_o} < K_v$$

With this condition on the gains of the corrector and the estimation on the model parameters, the derivative of the Lyapunov function is strictly negative:

$$\dot{V}_{x_i} < -\dot{e}_{x_i}^T K_v \dot{e}_{x_i}$$

The stability and safety between neighboring vehicles are ensured by respecting the different conditions on the gains and parameters of the model and also the constraints on the inter-distances between vehicles.

3.2. Lateral Control

The aim of lateral control of the fleet is to cancel the lateral deviation of each vehicle from the desired trajectory, that is to say $e_{y_i} = 0$ Fig. 3.

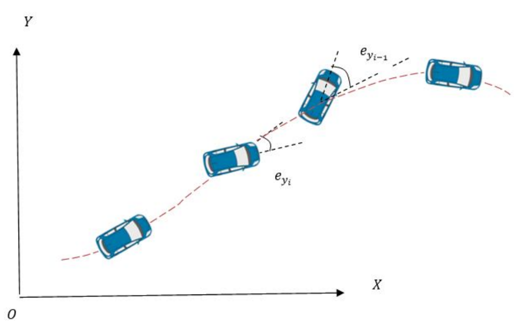

Figure 3. Lateral deviation of the convoy

To control the lateral movement of the convoy, we use a sliding mode control Mohamed-Ahmed et al. (2020). First, we define the sliding surface for the i-th vehicle:

$$s_i = \dot{e}_{yi} + K_2 e_{yi} \tag{8}$$

where s_i: represents the sliding surface for the i-th vehicle. e_{yi}: the lateral position error and $\dot{e}_i$: the lateral velocity error.
The lateral control of the fleet is based on the characteristic of the desired trajectory and the longitudinal speed, i.e. both controls are coupled.

Let $\ddot{e}_{y_i}$ be the lateral acceleration error defined as follows:

$$\ddot{e}_{y_i} = a_{y_i} - a_{y_{i_d}} \tag{9}$$

where a_{y_i}: the lateral acceleration and $a_{y_{i_d}}$: the desired lateral acceleration.

The desired lateral acceleration $a_{y_{i_d}}$ is calculated using the radius of the desired trajectory shown in Fig. 3 and the square longitudinal velocity assuming that both measurements are available in real time:

$$\begin{cases} a_{y_{i_d}} = \dot{x}_i^2/R_i \\ a_{y_i} = \ddot{y}_i + \dot{x}_i\dot{\theta}_i \end{cases} \tag{10}$$

where R_i : the radius curvature of the trajectory desired of the i-th vehicle.
In the following, we write the lateral acceleration error as a function of $\ddot{y}_i$ and $\ddot{y}_d$ to introduce it into the dynamic model and calculate the equivalent control. We replace $a_{y_{i_d}}$ and a_{y_i} by their expression defined in the equation (10):

$$\ddot{e}_{y_i} = \ddot{y}_i + \dot{x}_i\dot{\theta}_i - \dot{x}_i^2/R_i \tag{11}$$

Take it $\ddot{y}_{i_d} = -(\dot{x}_i\dot{\theta}_i - \dot{x}_i^2/R_i)$, we can write the error equation in the following form:

$$\ddot{e}_{y_i} = \ddot{y}_i - \ddot{y}_{i_d}$$

The sliding mode control composed of two subcommands, the first one is based on the super-twisting function which represents the robust control (U_{rob}), the second command is the equivalent control (U_{eq}) based on the dynamics of the model. It is used to get to the sliding surface and also to decrease the spike by the twisting function. The robust control defined as a following:

$$U_{rob} = -K_1 sign(s_i)$$

The second term of the control (U_{eq}) calculated by deriving the sliding surface defined in the equation (8) :

$$\dot{s}_i = \ddot{e}_{y_i} + K_2\dot{e}_{y_i}$$

Replacing $\ddot{e}_{y_i}$ by its expression and take $\dot{s}_i = 0$, we find the equating control based on the state model defined in (3):

$$u_{eq_i} = g_{2_i}(z_{1_i})^{-1}(\dot{z}_{2_{y_d}} - k_2(z_{2_{y_i}} - z_{2_{y_d}}) - f_{2_i}(\hat{z}_{1_i}, \hat{z}_{2_i}))$$

The sum of two controls represents the lateral control applied to the convoy :

$$U_{y_i} = U_{eq_i} + U_{rob_i}$$

Replacing the two controls by their expressions is the global lateral control:

$$U_{y_i} = g_{2_i}(z_{1_i})^{-1}(z_{2_{y_d}} - k_2(z_{2_{y_i}} - z_{2_{y_d}}) \\ \ldots - f_{2_i}(\hat{z}_{1_i}, \hat{z}_{2i})) - K_1 sign(s_i) \quad (12)$$

The study of the convergence of the lateral control based on a Lyapunov function; this function is defined positive and has been chosen according to the sliding surface :

$$V_{y_i} = \frac{1}{2} s_i^T s_i$$

The stability of the lateral movement of the convoy is based on the attractiveness of the sliding surface defined in (8).
To study the attractiveness we derive the function V_{y_i} and we replace $\dot{s}$ with its expression:

$$\dot{V}_{y_i} = s_i^T \dot{s}_i = s_i^T[\ddot{e}_{y_i} + K_2\dot{e}_{y_i}] = s_i^T[\dot{z}_{2_{y_i}} - \dot{z}_{2_{y_d}} + K_2\dot{e}_{y_i}]$$

We replace $\ddot{e}_{y_i}$ by its expression:

$$\dot{V}_{y_i} = s_i^T[f_{2_i}(z_{1_i}, z_{2_i}) + g_{2_i}(z_{1_i})U_{y_i} - \dot{z}_{2_{y_d}} + K_2\dot{e}_{y_i}]$$

We replace the expression of the control (12) in the previous equation:

$$\dot{V}_{y_i} = s_i^T[f_{2_i}(z_{1_i}, z_{2_i}) - g_{2_i}(z_{1_i})K_1 sign(s_i) + \dot{z}_{2_{y_d}} - \\ K_2(z_{2_{y_i}} - z_{2_{y_d}}) - f(\hat{z}_{1_i}, \hat{z}_{2_i}) - \dot{z}_{2_{y_d}} + K_2\dot{e}_{y_i}] \quad (13)$$

Developing this equation, we have:

$$\dot{V}_{y_i} = s_i^T[-\Delta f_{2_i} - g_{2_i}K_1 sign(s_i)] \quad (14)$$

We have that g_{2_i} represents the inverse of the second line (equation of lateral movement) of the matrix M_i, which is defined positive (the inverse of the vehicle mass).
We choose the gain K_1 such as : $K_1 > ||\Delta f_i||$ and K_2 a positive defined gain. With these conditions, it is possible to write the function $\dot{V}_i$:

$$\dot{V}_{y_i} < -\eta_i|s_i| < 0$$

where η_i : positive constants.
The lateral stability of the convoy is proven if the conditions of convergence to the sliding surface are respected. This attractiveness of the chosen sliding surface for the lateral movement of the convoy allows to stay on the reference trajectory and to cancel the lateral deviation of the convoy from this trajectory as shown in Fig. 3.

4. Simulation

To validate the law of longitudinal and lateral control, we controlled a convoy of 10 vehicles in order to follow the desired trajectory shown in Fig.5. The reference speed, which also represents the speed of the leader, is shown in Fig.6. The road curvature is shown in Fig.7, which will allow us to validate the law of lateral control of the convoy and to follow the desired trajectory presented in Fig.5. The simulation was done using The driving simulator SCANeR-studio, software developed by OKTAL and Matlab Simulink.

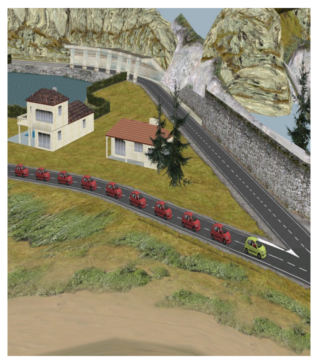

Figure 4. Convoy 10-vehicles SCANeR Studio

Figure 5. Reference Trajectory of the convoy in SCANeR-Studio

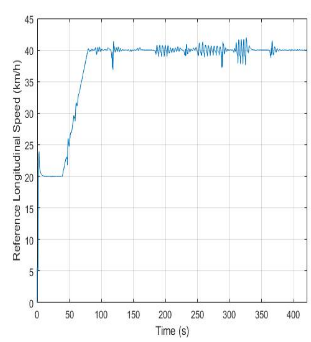

Figure 6. Reference Speed

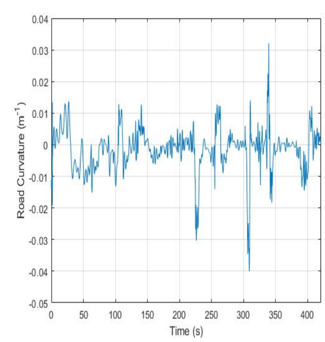

Figure 7. Road Curvature

As presented in the law of longitudinal control, we shared the leader's speed for all vehicles in convoy. Each vehicle uses the information from the preceding vehicle and the leader. The desired safety distance has been chosen 3 m between every two vehicles in the convoy. The lateral control aims to follow the trajectory defined in Fig.5 and cancel the lateral deviation from that trajectory.

The results show in Fig.8 the movement of the fleet in the desired trajectory with an almost negligible lateral error if we assume that the model parameters are known as present in Fig.9, which shows that the lateral deviation with the reference trajectory is almost neglected ($e_{y_i} \in [-0.01, 0.015m]$) with the proposed lateral control law.

The longitudinal speeds of the convoy are shown in Fig.10, where they converge rapidly towards the speed of the leader vehicle. This speed is around 40 km/h from t=75s. As presented in the section of the control on the conditions of the inter distance between the vehicles, which must be constant (3 m) which is proved according to Fig.11 which represents the inter distance which is around 3 m with a small variation between [-0.005m and 0.03m] caused by the variation of the longitudinal speed. Fig.11 also shows that the longitudinal error does not accumulate at other vehicles along the trajectory, which is a very important condition for the overall stability of the convoy if we assume that we do not have errors on the sensors to exchange information between the vehicles. The inter distance always remains constant when the longitudinal speed of the convoy reaches 40 km/h. Longitudinal and lateral errors can be improved by adjusting the control gains.

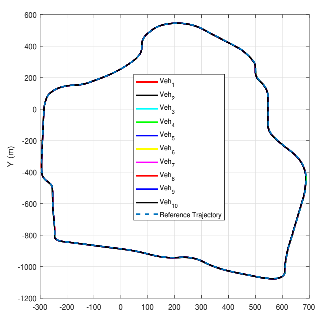

Figure 8. Trajectory of the Convoy

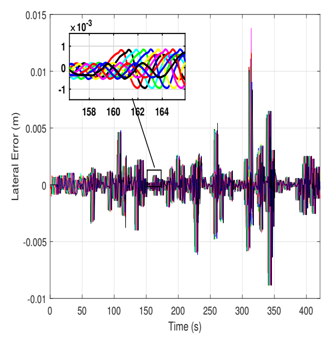

Figure 9. Lateral Error of the convoy

Fig.12 shows the steering angles of the convoy, which describes the behavior of the lateral movement and which is proportional to the road curvature of the desired trajectory. The lateral movement of the convoy reaches a lateral acceleration value ($a_{yi} = \ddot{y}_i + \dot{x}_i\dot{\theta}_i$) around $4m/s^2$ Fig.13, which means an important turn with a longitudinal speed around of 40km/h, the convoy always stays on the leader's desired trajectory. As explained in the control section, the two controls (longitudinal and lateral) are coupled and the desired lateral acceleration is calculated according to the road curvature (radius of the trajectory) and the longitudinal speed. The lateral speed ($\dot{y}_i$) of the convoy is shown in

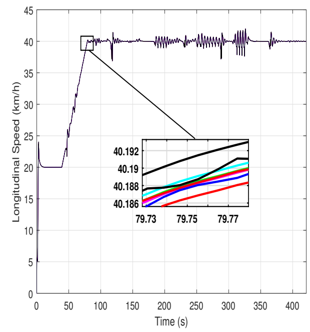

Figure 10. Longitidinal Speed of the convoy

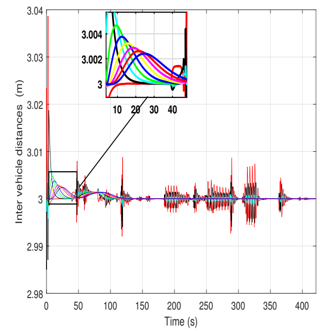

Figure 11. Inter Distance between the neighbours Vehicles

Fig.14 and is proportional to the radius of the desired trajectory. The yaw speed is shown in Fig.15.

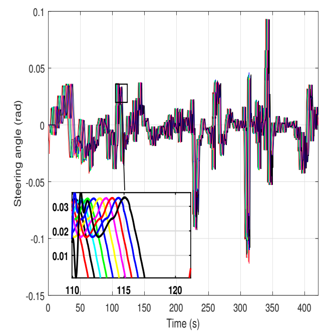

Figure 12. Steering angle of the convoy

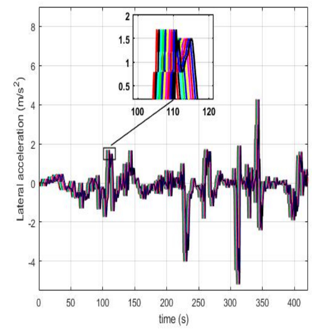

Figure 13. Lateral acceleration a_{yi}

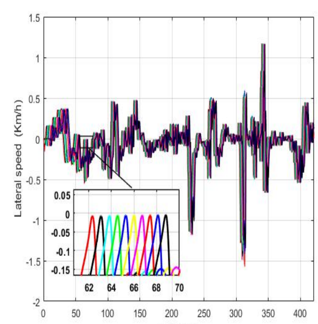

Figure 14. Lateral Speed

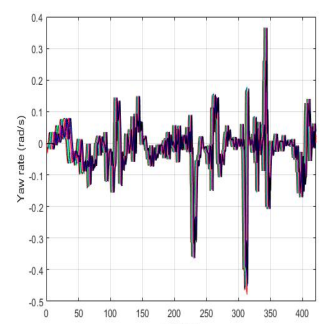

Figure 15. Yaw rate

These results show the performance of the law of longitudinal and lateral control proposed in this paper to control the movement of the convoy in both directions. The convoy always remains in the reference trajectory of the leader and the inter-vehicle distance quickly converges towards the value of the desired distance (3m) between the vehicles. The lateral deviation is almost neglected which means that errors are not accumulated towards the other vehicles along the trajectory.

4.1. Robustness of the Longitudinal and Lateral Control

To test the robustness of the longitudinal and lateral control against errors on the parameters of the convoy model, we will consider two possible cases:
Case 1: we assume we have a 20% error on the function f_i and $g_i \Rightarrow \Delta f_i = f_i - \hat{f}_i = 20\% f_i$ and $\Delta g_i = g_i - \hat{g}_i = 20\% g_i$.
-Case 2: for the second case, the errors are increased to attain an estimation error of 50% $\Rightarrow \Delta f_i = f_i - \hat{f}_i = 50\% f_i$ and $\Delta g_i = g_i - \hat{g}_i = 50\% g_i$.

The robustness results show us an increase in the lateral deviation of the convoy , according to Fig. 16 for an estimation error of 20% to be between $e_{y_i} \in [-0.04, 0.03m]$, while in the case where the parameters are known, the lateral deviation from the desired trajectory was around $e_{y_i} \in [-0.01, 0.015m]$ Fig. 9. In the case of a 50% error, we also find that the lateral position error increases to be bounded between $e_{y_i} \in [-0.12, 0.06m]$ but it's still acceptable for the lateral movement. On the other hand, the variation in the distance between neighbouring vehicles (Fig.17 and Fig19) remains negligible if the error on the estimation of model parameters is increased. This robustness on the longitudinal motion over the inter distance does not prove the robustness of the linearization control by the inverse dynamics, but rather by the decentralization approach we have used for the longitudinal movement. The lateral deviation remains acceptable which proves the robustness of the sliding mode control with high lateral acceleration, and can be improved by increasing the gains, respecting the saturation on the control, and avoiding the chattering problem.

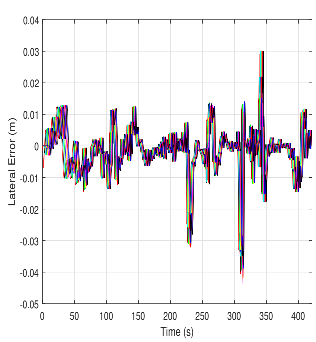

Figure 16. Lateral Error with 20% Error

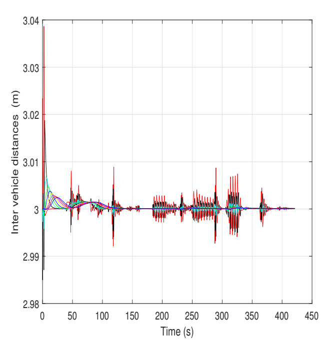

Figure 17. Inter Distance with 20% Error

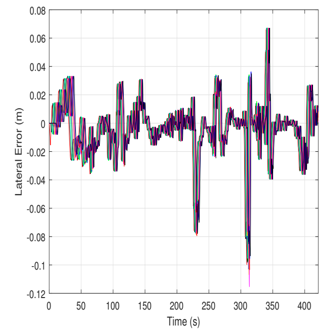

Figure 18. Lateral Error with 50% Error

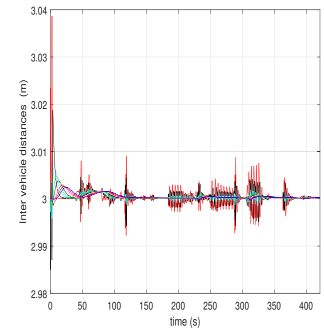

Figure 19. Inter Distance with 50% Error

4.2. Comparison of approaches

To compare different control approaches based on the information from the convoy, we added sensor errors between the 2-th and the 3-th vehicle, to study the propagation or accumulation of errors to the other vehicles. For comparison, we considered the following three control approaches:
Approach 1: we consider that we have the information from neighbors' vehicles to calculate the control law. This approach is known as Leader-follower or local approach Fig. 20.
Approach 2: we have the information from the neighbors' vehicles and the speed of the leader. This approach is part of the decentralised global family Fig. 25.
Approach 3: we assume we have the information from neighbors with speed and the position of the leader Fig. 30.
To validate these approaches, we recalculate in each case the longitudinal control (linearization control by inverse dynamics) and lateral control (sliding mode control) based on the information available for the different approaches.

The results show us for the local approach Fig. 20, an accumulation of errors between leader and i-th vehicle to other vehicles Fig.21. At the presence of the error between the 2-th and the 3-th vehicle Fig. 22, we have an increase of the inter distance between the two vehicles to reach a value of 3.5 m. When we changed the control strategy to test the global approach based on the leader's speed Fig. 25 which is shared for all vehicles, we found that the accumulation of errors between the leader and the i-th vehicle is present, but is decreasing along the convoy. So at any given moment, the error will cancel Fig. 26. The Fig 27 shows us a variation of the inter distance between neighboring vehicles to compensate the errors of the accumulations between leader and the i-th vehicle, respecting the critical inter-distance between neighbors, which we have chosen $\Delta S_{min} = 2m$. By changing the control strategy to the global approach based on the speed and position of the leader Fig. 30, we have observed that the accumulation of errors between the leader and the other vehicles is practically negligible Fig. 26. The Fig. 23, Fig. 28 and Fig. 33 show us the lateral deviations for the different approaches. When we use the different approaches; we can see that the lateral movement has not been affected by the presence of the errors for the longitudinal movement on the inter-distance between the neighbours. This is because the lateral control makes it possible to stay on the desired trajectory with the different inter-distance between the vehicles in the convoy.

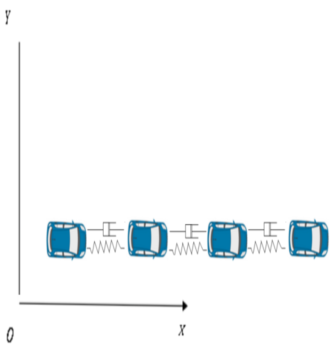

Figure 20. Local Approach - Leader Follower

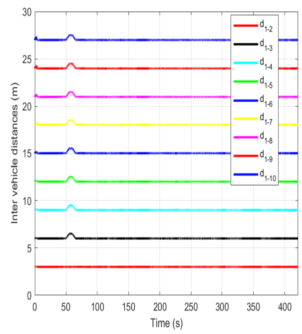

Figure 21. Inter Vehicle Distance between Leader and i-th vehicle

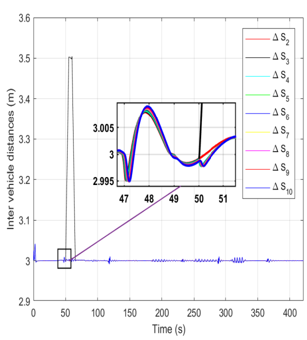

Figure 22. Inter Vehicle Distance between neighbors

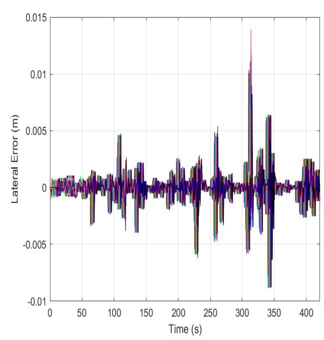

Figure 23. Lateral Error using the local approach for the convoy

Figure 24. Local Approach

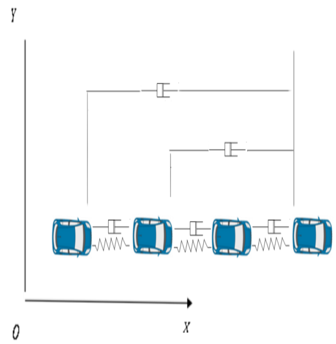

Figure 25. Global approach using the speed of the leader

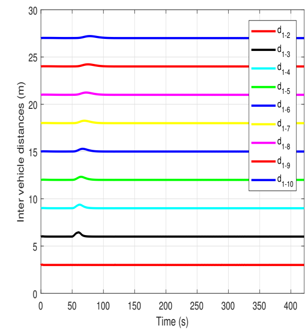

Figure 26. Inter Vehicle Distance between Leader and i-th vehicle

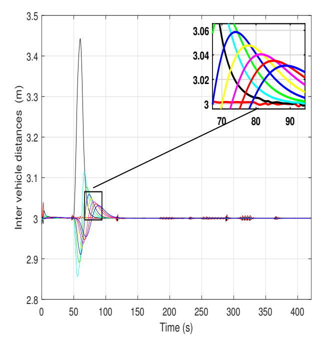

Figure 27. Inter Vehicle Distance between neighbors

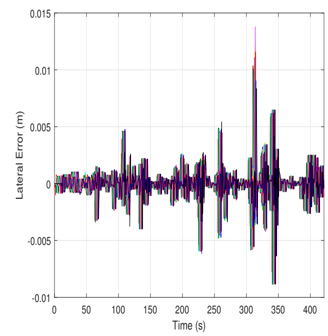

Figure 28. Lateral Error using the global approach for the convoy

Figure 29. Global approach using the speed of the leader

5. Conclusion

In this paper, we have proposed a longitudinal and lateral control based on the inverse dynamic linearization control for the longitudinal motion and the sliding mode control for the lateral movement. A control approach that uses neighbor and leader information has been developed to compute the law of longitudinal control with a safe distance between vehicles to avoid collisions and ensure convoy stability. The results show a good performance of the controller and the lateral deviation of the convoy from the desired trajectory is almost negligible and the inter distance remains around the desired distance with a small variation due to the variation of the speed of the convoy. In the case where the model parameters are not well estimated, the controller shows robustness against errors on the model parameters for both motions. A very important comparison based on different approaches to convoy control has been proposed to check whether errors will accumulate or propagate to other vehicles. In the case, we have a sensor error or communications error between two neighbors' vehicles. The results show an accumulation of errors to other vehicles when we use the local or leader-follower approach. On the other hand, when using the global approach in which neighbor and leader information are used, the accumulation of errors is directly canceled by always respecting constraints on the critical inter-distance between the neighbors' vehicles.
In the next work, and as a perspective, we will use a non-linear observer to calculate the inverse dynamics of the convoy, and also we will control the vehicles in the presence of obstacles.

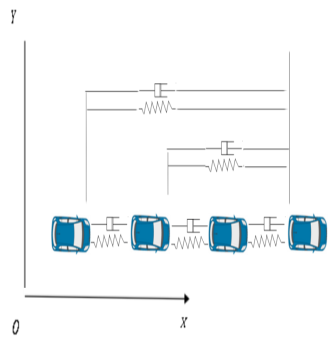

Figure 30. Global approach using the speed and position of the leader

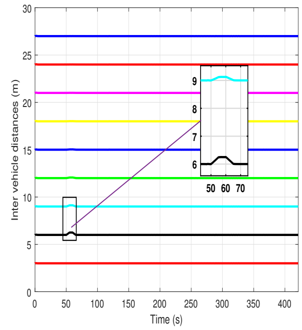

Figure 31. Inter Vehicle Distance between Leader and i-th vehicle

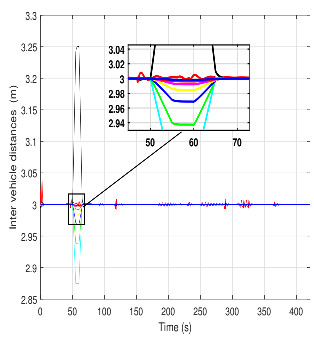

Figure 32. Inter Vehicle Distance between neighbors

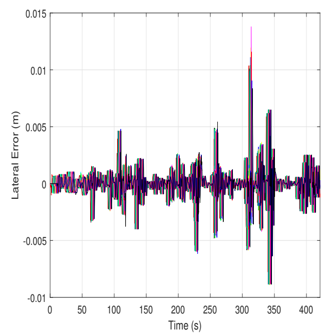

Figure 33. Lateral Error using the global approach for the convoy

Figure 34. Global approach using the speed and position of the leader

References

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.

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.

Chang, K. S., Li, W., Devlin, P., Shaikhbahai, A., Varaiya, P., Hedrick, J. K., McMahon, D., Narendran, V., Swaroop, D., and Olds, J. (1991). Experimentation with a vehicle platoon control system. In *Vehicle Navigation and Information Systems Conference, 1991*, volume 2, pages 1117–1124.

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

Cox, D. R. (1972). Regression models and life tables (with Discussion). *J. R. Statist. Soc.* B, 34:187–220.

De La Fortelle, A., Qian, X., Diemer, S., Grégoire, J., Moutarde, F., Bonnabel, S., Marjovi, A., Martinoli, A., Llatser, I., Festag, A., et al. (2014). Network of automated vehicles: the autonet 2030 vision.

Fan, J. and Peng, H. (2004). Nonconcave penalized likelihood with a diverging number of parameters. *Ann. Statist.*, 32:928–61.

Heard, N. A., Holmes, C. C., and Stephens, D. A. (2006). A quantitative study of gene regulation involved in the immune response of Anopheline mosquitoes: An application of Bayesian hierarchical clustering of curves. *J. Am. Statist. Assoc.*, 101:18–29.

Hedrick, J. K., McMahon, D., Narendran, V., and Swaroop, D. (1991). Longitudinal vehicle controller design for ivhs systems. In *1991 American Control Conference*, pages 3107–3112.

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.

Mohamed-Ahmed, M., M'sirdi, N., and Naamane, A. (2020). Non-linear control based on state estimation for the convoy of autonomous vehicles. In *ICCARV 2020: 14-th International Conference on Control Automation Robotics and Vision*.

Mohamed-Ahmed, M., Naamane, A., and M'sirdi, N. (2019). Path tracking for the convoy of autonomous vehicles based on a non-linear predictive control. In *The 12-th International Conference on Integrated Modeling and Analysis in Applied Control and Automation (IMAACA)*.

Muazu, 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.

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

Qian, X., Altch, F., de La Fortelle, 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*.

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.

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

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