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Model based tracking control using Jerky behavior in platoon of vehicles

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***Abstract*— In this work, a reconstruction of the sensor-based tracking control in a platoon of autonomous vehicles is developed. This control is reproduced with accuracy in the absence of data from the laser rangefinder. Only the velocity of each involved vehicle in the platoon is considered, as well as the inter-vehicle communication. This reconstruction occurs when the laser rangefinder is disturbed or failed. It helps maintaining a fault tolerant control when the measurement is unavailable. The control strategy is validated on a real-time simulator of vehicles dynamic, based on experimental measurements, acquired from autonomous vehicles.**

I. Introduction

Laser measurement technology devices can be used for wide outdoor applications, including anti-collision, detection, classification, or position evaluation in navigation. These devices pilot the data information of the surrounding environment, representing the multidimensional data of the contour in 2D or 3D.

In the field of intelligent transportation system, the laser rangefinder is used for self-detection of obstacles or navigation assistance. Like all intelligent sensors, they can be sensitive to external disturbances according to their level. The presence of rain, snow and fog can affect the acquired data and generate false alarms.

In the case of a convoy of automated vehicles, configured as platoon, the disruption or the loss of tracking information of the inter-distance can affect the normal functioning of internal traffic and operations.

In this paper, a model-based control strategy for a platoon of autonomous vehicles is presented. This allows the reconstruction of the sensor-based tracking control when the laser rangefinder is failed or disturbed. The aim is to maintain the high level control of the platoon of autonomous vehicles when the tracking information is unavailable.

In the literature, two class of vehicle platoon control are distinguishable. This depends on the type of model used for the control. A qualitative approach, based on a Fuzzy control is developed in [1] for longitudinal control of platoon of vehicles. Based on rule-decision principle, this approach remains soft for the implementation compared to some quantitative approaches. In the same class of control, a multi-agent approach is used in [5], for local control of vehicle platoon is proposed. Each follower vehicle has information about its heading angle and the distance and azimuth of the leader vehicle. The position of the follower is determined by the odometry. Also in [6], a local control appraoach to linear platoon is described based on multi-agent approach. In [7], a global decentralized platoon control strategy is proposed by taking advantage of inter-vehicle communication for platooning navigation in urban environment.

In parallel, a lot of contributions are done this last decade on quantitative model-based control of platoon of vehicles. Among them, an impedance control applied to a vehicle platoon system is developed in [8]. It is a model-based control of a succession of spring-damper systems. In [9], [10], a variable structure control applied to platoon of vehicles is proposed, where a stability of the whole system is proofed and demonstrated through a numerical example.

Lateral and longitudinal controls for cooperative driving of automated vehicles have been proposed in [11]. The longitudinal control algorithm is based on PD control in presence of the measurement of the inter-distance between vehicles. In [12], longitudinal and lateral controls of platoon are described based on vision with a camera.

Another approach of platoon control has been developed in [14]. It concerns a switching strategy for longitudinal control of vehicles, based on successions of throttle and brake movements.

In [16], a collision avoidance of a convoy of autonomous vehicle is studied based on quantitative model

A control of a platoon of nonholonomic robotic vehicles inspired from the control of redundant manipulator is presented in [13].

A kinematic model-based control of a platoon of autonomous vehicles is given in [3], [4] and [2]. The first is based a choice of suitable tasks for robust tracking under singularities, and the second is assisted by the navigation information outcome from the Global Positioning System.

Finally, this reconstruction is based on the following steps:

1) Modeling of the jerky movement in a platoon of vehicles;
2) Tracking control using an adaptive compensation strategy of the inter-distance.

The organization of the paper is scheduled as follows: the second section concerns the platoon dynamic based on the behavior of the Jerky movement, the third section focuses on the adaptive tracking control and finally the fourth section regroups the simulation and experimental results. The paper ends with a conclusion and presentation of the future work.

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II. Dynamic Model of the Jerky movement in Platoon of Vehicles

The Intelligent Autonomous Vehicles (IAVs) are considered as the logical extension of the mobile robots at the scale of conventional vehicles or to specific handling vehicles operating in confined space (see Figure (1)). In this context, InTraDE project [18] was launched in the North West Europe region. It aims to improve the traffic management and the space optimization in the port terminal using an intelligent transport system. This is based on omnidirectional autonomous vehicles which should adapt to different environments, inversely to the existing transport solution of the Automated Guided Vehicle (AGV). Each IAV is used for handling and routing containers between identified targets in the environment of the port terminal with an appropriate low and safe velocity.

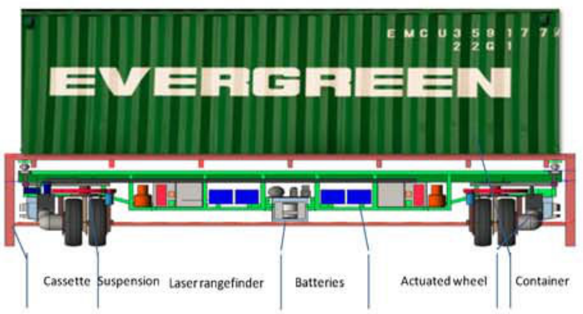

Fig. 1. Intelligent Autonomous Vehicle.

The *Jerky* dynamic, also known as the *Stick-Slip* motion is often described by mechanisms that perform relative slow movements. This phenomenon is found mainly on the relative motion issued from the contact between different rigid mechanisms. The presence of a certain flexibility in this contact can generate the phenomenon of the Jerky, represented by a succession of jumps and stops. From a tribological aspect, this phenomenon occurs when the value of the static friction coefficient is greater than its dynamic value [17].

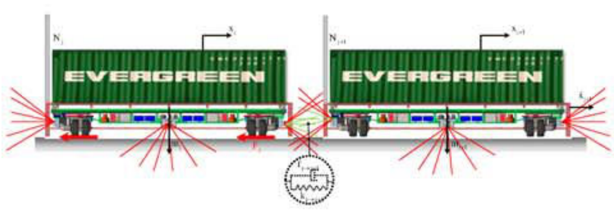

Fig. 2. Platoon of two IAVs.

In the given case study, the considered transport system is composed of a platoon of autonomous vehicles (see Figure (2)). These IAVs are designed in the framework of InTraDE project and structured in leader-followers. They are characterized by full decentralized traction and steering systems. This macroscopic train mechanism can be schematically described by a tracking of two vehicles $(j, j+1)$, which are virtually interconnected via a spring-dashpot system with the couple $\left(k_{j\to j+1}, f_{j\to j+1}\right)$ of elasticity and damping coefficients. This virtual interconnection system represents in reality the state information of the inter-distance variable, collected from the laser range finder and analytically it describes the necessary efforts calculated by the j^{th} vehicle in order to maintain the safe inter-distance with the $(j+1)^{th}$ vehicle.

Let's consider the longitudinal dynamic of the j^{th} vehicle according to the displacement x_j. At the macroscopic modeling level, the normal force N_j generates a viscous friction force F_j of the whole vehicle. This dynamic friction force varies linearly with the j^{th} slip velocity $\dot{S}_j$ during the rolling stage, as follows:

$$\begin{cases} F_j = -\alpha_{2_j}\left|\dot{S}_j\right| sign(\dot{S}_j) \\ \dot{S}_j = \dot{x}_j - R\dot{\theta}_{s_j} \end{cases} \tag{1}$$

where: R is the assumed static radius of the wheel, α_{2_j} is the viscous friction coefficient and $\dot{\theta}_{s_j}$ is the j^{th} angular velocity of the wheel.

When the leader vehicle $(j+1)$ moves longitudinally with a quantity of x_{j+1}, the follower (j) starts its track in the head or forward directions, depending to the sign of $\dot{x}_{j+1}$ and to the identified safe inter-distance.

Physically, this behavior can be emulated at a low velocity displacement by a virtual force of $k_{j\to j+1}x_{j+1} + f_{j\to j+1}\dot{x}_{j+1}$, stretching the follower vehicle through a virtual spring of Figure (2), necessary to hit the static friction force $\alpha_{0_j}N_j$, where α_{0_j} is the static friction coefficient. The vehicle of mass m_j will start moving and the friction coefficient will reach its dynamic value α_{d_j}, generally less than the static friction [17]. Then, the dynamic of the generalized longitudinal motion of the mass m_j between the stop period and the slip period is given by the following equation (2):

$$\left(\alpha_{0_j} - \alpha_{d_j}\right) N_j = m_j \ddot{x}_j \tag{2}$$

After this short transient dynamic, the virtual spring effect is now appearing, where the vehicle (j) moves in a front bound before it stops, describing the *Stick-Slip* motion. The physical meaning of this phenomenon is that the static contact friction is greater than its dynamic value. By applying a uniform velocity $\dot{x}_{j+1}$ on the vehicle $(j+1)$ (see Figure (2)) at the initial conditions: $t = 0$, $x_j = 0$ and $x_{j+1} = x_{0_j}$, then the virtual spring applies the following traction force F_{T_j}:

$$F_{T_j} = \alpha_{0_j}N_j + k_{j\to j+1}(\dot{x}_{j+1}.t - x_j) + f_{j\to j+1}(\dot{x}_{j+1} - \dot{x}_j) \tag{3}$$

The dynamic of the vehicle mass m_j, is now described by equation (4):

$$
\begin{aligned}
& m_j\ddot{x}_j+f_{j\to j+1}\dot{x}_j+k_{j\to j+1}x_j \qquad (4)\\
= \;& \alpha_{0_j}N_j-\alpha_{d_j}N_j sign(\dot{S}_j)+k_{j\to j+1}\dot{x}_{j+1}t+f_{j\to j+1}\dot{x}_{j+1}
\end{aligned}
$$

When the dynamic friction coefficient α_{d_j} varies linearly with the slip velocity where: $\alpha_{d_j}=\alpha_{1_j}+\alpha_{2_j}\left|\dot{S}_j\right|$, where α_{1_j} represent the stiction coefficient, then the following differential equation will be obtained for vehicle (j) motion:

$$
\begin{aligned}
& m_j\ddot{x}_j+f_{j\to j+1}(\dot{x}_j-\dot{x}_{j+1})+k_{j\to j+1}(x_j-\dot{x}_{j+1}.t) \qquad (5)\\
= \;& \alpha_{0_j}N_j-(\alpha_{1_j}+\alpha_{2_j}.\left|\dot{S}_j\right|)N_j sign(\dot{S}_j)
\end{aligned}
$$

The two states of the vehicle (j), namely the position x_j and the velocity $\dot{x}_j$ can be illustrated by Figure (3) in the case of uniform motion of the vehicle $(j+1)$. We can notice that x_{j+1} starts from an initial value of $x_{0_j}=\frac{\alpha_{0_j}N_j}{k_{j\to j+1}}$ and the vehicle (j) is tracking by a succession of stick and slip motions.

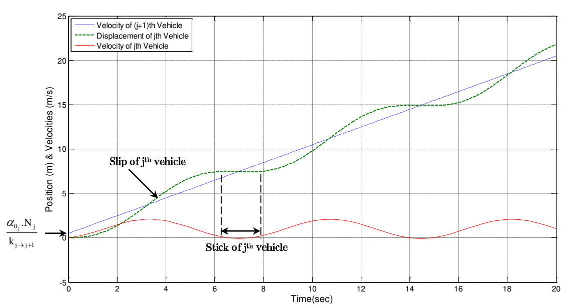

Fig. 3. Jerky behavior in a platoon of two IAVs.

III. Adaptive Tracking Control

The applied longitudinal and adaptive tracking control of the dynamic model (5) is given by the following differential equation:

$$
m_j\ddot{x}_j+f_{j\to j+1}(\dot{x}_j-\dot{x}_{j+1})+k_{j\to j+1}(x_j-x_{j+1})=U_j-F_j \qquad (6)
$$

Where, $F_j=(\alpha_{1_j}+\alpha_{2_j}\left|\dot{S}_j\right|)N_j sign(\dot{S}_j)$ and U_j is the longitudinal control of the j^{th} vehicle expressed as follows:

$$
U_j=m_j\ddot{x}_{j+1}-m_j\ddot{d}_{s_j}-f_{j\to j+1}\dot{d}_{s_j}-k_{j\to j+1}d_{s_j}-\alpha_{0_j}N_j \qquad (7)
$$

$\ddot{x}_{j+1}$ is the linear acceleration of the $(j+1)^{th}$ vehicle, d_{s_j}, $\dot{d}_{s_j}$ and $\ddot{d}_{s_j}$ are respectively the desired and safe inter-distance between two successive vehicles and its first and second derivatives. The inter-distance d_j is supposed measured by the laser rangefinder system and it can be calculated from equation (5) in the case of unavailable information data, based on the identification of the virtual spring elongation [15]. It is given by:

$$
d_j=\frac{\alpha_{0_j}N_j}{k_{j\to j+1}}+x_{j+1}-x_j \qquad (8)
$$

and its first and second derivatives are:

$$
\begin{cases} \dot{d}_j=\dot{x}_{j+1}-\dot{x}_j \\ \ddot{d}_j=\ddot{x}_{j+1}-\ddot{x}_j \end{cases} \qquad (9)
$$

By replacing equations (7), (8) and (9) in (6), we obtain the following equation:

$$
m_j\ddot{e}_j+f_{j\to j+1}\dot{e}_j+k_{j\to j+1}e_j=-\alpha_{2_j}N_j\dot{S}_j \qquad (10)
$$

where: $e_j=d_j-d_{s_j}$.

The equation (10) describes a relation between the inter-distance error and the slip velocity of equation (1), which describes itself the error between the linear velocity of the vehicle (j) and the linear velocity of the wheel. Thus, the aim of the applied control in (7) is to find the best parameters of $f_{j\to j+1}$ and $k_{j\to j+1}$, allowing e_j to converge to 0 with a low slip velocity. This means that the vehicle (j) is in a perfect rolling with a minimum slippage.

The equation (10) can be written with a state representation as follows:

$$
Q(s)=\frac{S_j(s)}{e_j(s)}=\frac{-\alpha_{2_j}N_j s}{m_j s^2+f_{j\to j+1}s+k_{j\to j+1}} \qquad (11)
$$

The function $Q(s)$ is strictly positive reel and it can be written in a state representation as follows:

$$
\begin{cases} \dot{\varepsilon}=A\varepsilon+BS_j \\ e_j=C\varepsilon \end{cases} \qquad (12)
$$

where: $\varepsilon=\begin{pmatrix} x_1 & x_2 \end{pmatrix}^T$ the state vector and intermediate variable between the input system S_j and the output system e_j, $A=\begin{pmatrix} 0 & \frac{-k_{j\to j+1}}{m_j} \\ 1 & \frac{-f_{j\to j+1}}{m_j} \end{pmatrix}$, $B=\begin{pmatrix} 0 \\ \frac{-\alpha_{2_j}N_j}{m_j} \end{pmatrix}$, $C=\begin{pmatrix} 0 & 1 \end{pmatrix}$.

Regardless $Q(s)$ is strictly positive reel and according the $Kalman-Yakubovic$ lemma, it exists two matrices $P=P^T>0$ and $M=M^T>0$ that:

$$
\begin{cases} A^TP+PA=-M \\ PB=C^T \end{cases} \qquad (13)
$$

Let us consider the positive *Lyapunov* time function expressed as follows:

$$
v=\varepsilon^TP\varepsilon-\int(e_j+S_j)^2dt>0 \qquad (14)
$$

The time derivation of this energy function allows writing:

$$
\begin{aligned}
\dot{v} &= \dot{\varepsilon}^TP\varepsilon+\varepsilon^TP\dot{\varepsilon}-(e_j+S_j)^2 \qquad (15)\\
&= \varepsilon^T\left(A^TP+PA\right)\varepsilon+2\varepsilon^TPBS_j-e_j^2-S_j^2-2e_jS_j\\
&= -\varepsilon^TM\varepsilon+2e_jS_j-e_j^2-S_j^2-2e_jS_j\\
&= -\varepsilon^TM\varepsilon-e_j^2-S_j^2\leq 0
\end{aligned}
$$

For such condition, the controlled system is asymptotically stable, where the error e_j converges to zero at the equilibrium state $\varepsilon = 0$ and $S_j = 0$.

IV. SIMULATION AND EXPERIMENTAL RESULTS

SCANeR ^{TM} [19] is a professional software dedicated for engineering and research applications. It is a modular and real-time based configuration. Using an Application Programming Interface (API) of the Figure (4), it is useful to integrate the developed tracking control algorithm, applied on a platoon of IAVs. The management of the real-time traffic flow is done through the association of the 3D road mapping given in XML-format and the vehicle dynamic (see Figure (4)). The main feature of such simulation tool in the framework of the InTraDE project is the prior approval of the control algorithm before implementation in the real IAV system.

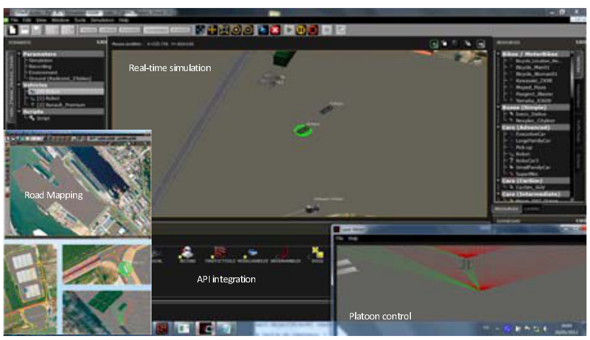

Fig. 4. Real-time simulation of platton of IAVs.

For the following results, a platoon of 4 IAVs is involved with: $d_{s_j} = 15m$; $m_j = 3500Kg$; $f_{j\rightarrow j+1} = 25Ns/m$; $k_{j\rightarrow j+1} = 0,1N/m$; $\alpha_{2_j} = 2.5$; It is assumed that the communication vehicle-to-vehicle is available when the data information of the tracking of the laser rangefinder is absent or perturbed. In this case, the follower vehicle receives continuously the data of positioning and velocity of its leader in order to estimate the relative inter-distance d_j. Thus, the tracking control operates until reaching then maintaining the desired inter-distance. Two scenarios are considered for this simulation, the first concerns a linear path tracking of the Figure (5), where the traveled path of each vehicle is shown with the respect of a uniform inter-distance after applying the tracking control at $2,5s$. The profile of the linear velocity for each vehicle in the Figure (6) is divided in two periods; transient period with a variable damping behavior, started from the follower 1 until the follower 4. This is due to the propagation of the Jerky phenomenon on the platoon length. In the steady period, it is shown the uniformization of the tracking velocity. The variation of the inter-distance for each IAV (see Figure (7)), with an apparent stick and slip behavior during the transient period.

The second scenario shows a planar path of the Figure (8), where the longitudinal velocities and inter-distances for

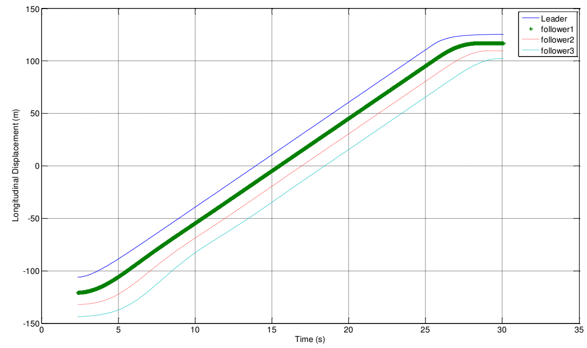

Fig. 5. Longitudinal tracking on a linear path.

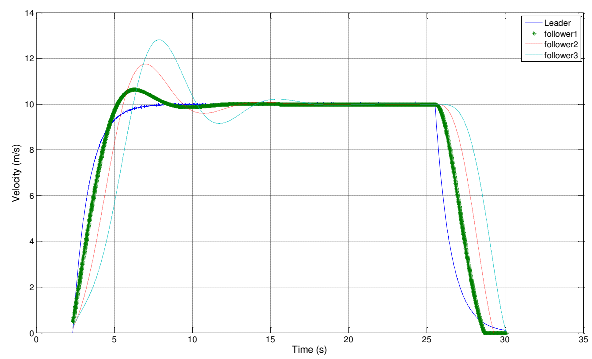

Fig. 6. The linear velocities of the IAVs.

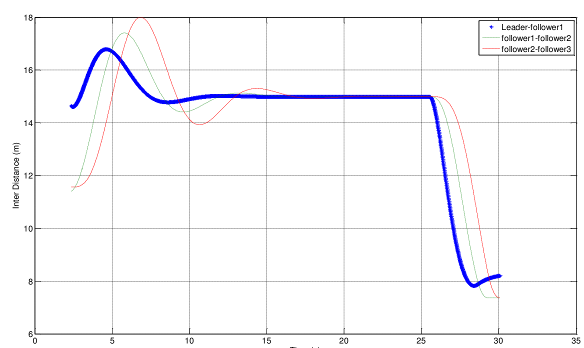

Fig. 7. The inter-distance profile between the platoon of vehicles.

the involved IAVs are presented in the Figures (9) (10), mentioning the transient and steady periods for each change of the path orientation.

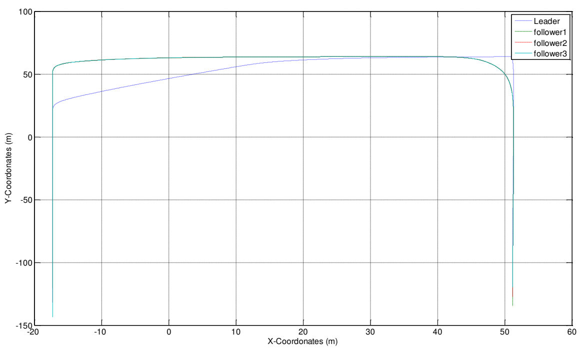

Fig. 8. The longitudinal tracking for a planar path.

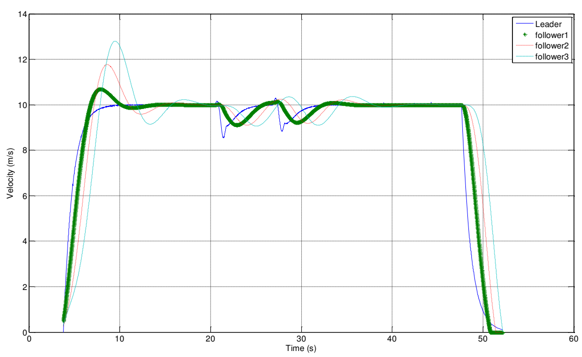

Fig. 9. The linear velocities of the IAVs.

Finally, we experimented through an experimental platform, the feasibility of emulating the functioning of the platooning, based on the laser rangefinder by the adaptive tracking control, using the Jerky movement. This platform Figure (11) represents a platoon of two IAVs, one a heavy vehicle of $3000kg$ of mass and the follower is a light vehicle with a mass of $400kg$. The communication between the vehicles are performed using a wireless connection with a central computer. The real IAVs of the port are actually under design and they will be operational at the end of the year 2012. Knowing that the proposed adaptive tracking control does not depends on the type of IAV, this was helpful to integrate it in this available platoon. For three minutes of data recording, a time-instant profile (see Figure (12)) of the ′SICK′ laser rangefinder [20] of the follower vehicle is given in the case of free fault and perturbation. The targeted tracking angle is varying for the two and half circles of path (Figure (13)). Finally, the inter-distance between the leader and the follower is described in Figure (14). It is noticed that in the interval $[125s, 132s]$, the platoon is stopped and the inter-distance with the tracking angle are kept constants.

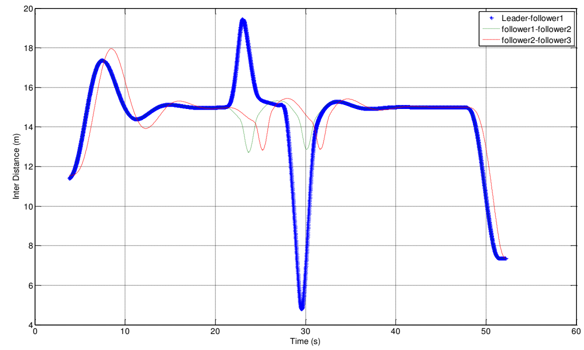

Fig. 10. The inter-distance profile between the platoon of vehicles.

In Figure (15a), the black line curve represents the switch on/off of the laser rangefinder. When the laser is switch on in the interval $[0s,\ 31s]$ the red line curve shows the real inter-distance between the vehicles measured from the laser rangefinder. But, when the laser is switch off after $31s$ the proposed jerky model is used to estimate the inter-distance and it is represented by the blue line curve. If the laser rangefinder is not stopped after $31s$ during the switch off, the error between the inter-distance measured by the laser and estimated by the model can be observed in Figure (15b). This error may be because of the odometry precision and slip of the vehicles.

Fig. 11. Platoon of IAVs.

V. Conclusion

In this paper, a reconstruction of the Jerky movement for platoon of intelligent autonomous vehicles is developed. This movement is based on the dynamic of the stick and the slip motion. The reconstruction of this model can emulate the real behavior of the tracking for a platoon. The aim is to be able to recover the faulted or perturbed tracking information in presence of technological device such as the

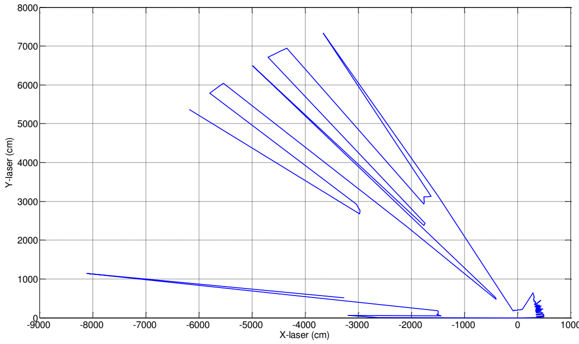

Fig. 12. Profile of the Laser rangefinder for the follower vehicle.

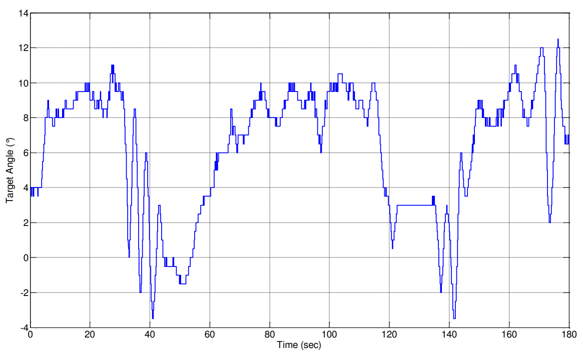

Fig. 13. The target tracking angle.

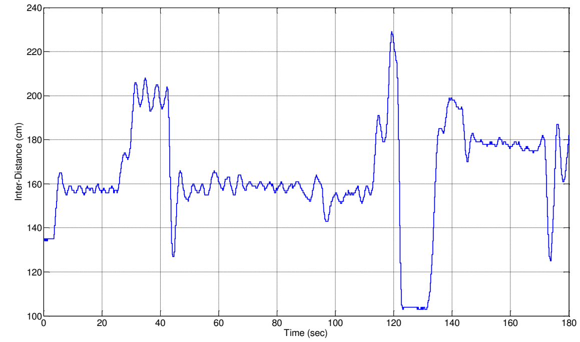

Fig. 14. The inter-distance between the leader and the follower vehicles.

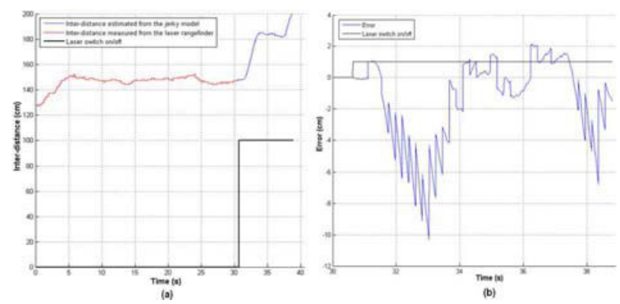

Fig. 15. (a) The inter-distance calculated by the laser rangefinder and the proposed model (b) The error in inter-distance.

laser rangefinder. An adaptive tracking control of the inter-distance are used to compensate the advanced or delayed positioning of the follower. Finally, it is important for a future work to consider the lateral tracking and the presence of perturbations in the communication vehicle-to-vehicle to perform the global control of the platoon.

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