Control algorithm for echelon platoon based on a 2-spring virtual link

Madeleine EL ZAHER, Jean-Michel CONTET,
Franck GECHTER, and Pablo GRUER

IRTES-SeT, UTBM
13 Rue Thierry Mieg, 90000 Belfort, France.
{firstname.lastname}@utbm.fr

Abstract. This paper presents a reactive multi-agent system for echelon platoon organization. Platoon systems are sets of vehicles that move together while keeping a predefined geometrical configuration without any material coupling. Each vehicle represents an autonomous agent that behaves based only on its own perceptions. The vehicle platoon organization problem consists in defining the algorithms to be executed by each vehicle embedded software, in order to maintain the desired platoon configuration during displacements. Platoon systems found in literature deal generally with column formations adapted to urban or highway transportation systems. Other formations such as line, echelon,... can be encountered in fields like agriculture and the military. In this paper, we focus on the platoon echelon formation.
An approach based on a virtual vehicle-to-vehicle interaction model composed of two springs is proposed. Five different geometries of attachment of the considered model are proposed then compared in order to conclude about the more suitable one.
Keywords : Platoon system, multi-configurations, multi-agent system.

1 Introduction

A platoon system is a set of vehicles that move together while keeping a precise geometrical configuration without any material coupling. Different platoon formations can be used in different fields. The most known formation is the column, where vehicles are placed one behind the other, this configuration is studied in projects like PATH [8], CRISTAL[1], [4]... It is well adapted to urban and highway transportation. Other configurations like line, echelon, ... have other application fields such as military and agriculture. In echelon formations, vehicles form one side of a "V". For harvesting, a platoon in echelon configuration can significantly reduce the duration of plowing. Independently of the platoon formation, controlling the platoon consists in determining the algorithm to be executed by each vehicle embedded control, in order to: first maintain the desired platoon configuration during displacements and second, to follow the desired trajectory.

---

[1] http://projet-cristal.net/

In [7], a control approach dedicated for column platoon formation based on reactive multi-agent systems is proposed. In this approach each vehicle is considered as an agent that behaves based only on the perceptions of its predecessor. To compute its references (speed and orientation), each agent uses a virtual physics inspired interaction model composed of two springs that link the follower vehicle to its predecessor. This paper suggests to use the same 2-springs interaction model in order to deal with the echelon platoon control. To guarantee an echelon formation the points of attachment of the two springs should be different from the points considered in column formation. For this reason, we decided to consider five different geometries of the virtual link attachment.

The main advantage behind the use of the 2-springs model in the echelon platoon formation, is that this facilitates the transition between formations (passing from a platoon formation to other) during platoon operations, a task to be studied in our next works. In fact, if the 2-springs approach is adapted by echelon platoon formations, the transition from echelon formation to column can be made by simply changing the point of attachment of the two springs.

This paper is structured as follow, in section 2 a state of the art about the different platoon configuration and the approach to control these configuration is dressed. Section 3 mentions the coherence between the proposed approach of platoon and the reactive multi-agent system. In section 4, we describe the physical model used in column platoon formation and we dress five different possible installations of the physical model in the echelon formation. In Section 5, the five proposed attachment geometries are tested and simulated, then a comparison of these results is dressed in order to conclude with the most suitable connection for the echelon platoon.

2 State of the art

A platoon is a set of vehicles (generally autonomous) that displace within an environment (rural, urban,...) while maintaining a predefined geometric configuration. This article concentrates on the echelon formation vehicles are placed as one side of a "V". The first vehicle in the platoon, called the leader, can be autonomous or human driven, other vehicles are called follower they follows the leader vehicle.

Figure 1 shows a platoon in an echelon formation. The distances d_1 and d_2 presented in this figure are called respectively lateral and longitudinal distances. In an echelon formation these distances are always not null.

The problem of platoon formation control can be approached to the problem of robots formation control, where three main strategies has been proposed :

- Behavior based ([11]) : in this strategy for each robot is associated a behavior (static obstacle avoidance, avoidance of collision with other robots...) with an importance degree. Each behavior produces a different response (orientation, speed ...). The global behavior is deduced by adding the behaviors weighted by there degree, and normalizing the result. The main disadvan-

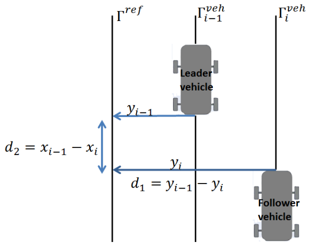


Fig. 1. Platoon in an echelon formation

tage of this strategies, is the difficulty to prove the stability of the system, and the maintenance of the formation.

- Virtual structure ([5], [2]) : in this strategy robots move together as a single rigid body. Each robot try to maintain a fixed position in this virtual body. The virtual body evaluates as only one entity with its orientation and speed. The main disadvantage of such strategy is that it requires a lot of communication between the different components of the system.
- Leader-follower ([3], [12]) : in this strategy, an entity (robot) is considered as a leader and follows a predefined trajectory. Other robots, follows this leader and try to maintain the desired distance and orientation. The main disadvantage of this strategy, is that it depends heavily on the leader vehicle.

Most of the works done on platoon deals with column configurations. Two main approaches were proposed to control the column platoon configuration: global and local approaches. Global approaches ([1], [13]) are centralized, i.e. there exist an entity that determines some reference information. Global approaches shows precise trajectory matching, however they required sophisticated technologies (GPS RTK), and reliable connection network.

Local approaches ([10], [9]) are decentralized approaches, where each vehicle computes its own references based on its perceptions. They require less technologies, generally distance measurement devices are sufficient. However, since only a local view is accessible, the results obtained in trajectory matching are not as good as in global approaches.

The goal of this paper is to propose a local approach of platooning in echelon configuration, were for each vehicle is associated a leader (the vehicle placed in front of). This strategy allows us to avoid the constraint of a unique leader vehicle, and the communication requirement in global approaches. The follower vehicle perceives its leader and try to follow it while maintaining the desired lateral and longitudinal parameters in order to conserve the desired echelon formation.

3 Multi-agent system for vehicle platoons

In local approaches to platoon systems, each vehicle computes its own references autonomously based only on its perceptions. Consequently an adequate embodiment for the local platoon is a reactive multi-agent system, where each vehicle

represents an autonomous agent. The platoon system is then the result of a self-organization of a reactive multi-agent system (RMAS). The global behavior of the platoon systems emerges as a result of the individual behavior of each vehicle agent. Two behaviors can be distinguished in a platoon system : the leader behavior, concerns the vehicle (agent) in the first position of the platoon. This agent is either autonomous or human driven, it interacts directly with the road. The follower behavior: concerns the follower agents. These agents perceive their predecessors and act based on their perceptions.
The behavior of each follower agent can be described as a combination of the two following sub-behaviors (cf.figure2) :

- *Perception* : the follower agent, perceives its predecessor and measures the inter-vehicle distances required in the control behavior, using sensors like laser range finder.
- *Decision* : computes the references of the vehicle (acceleration and orientation) using an interaction model.

The control behavior consists in dealing with three main issues : formation maintaining, collision avoidance and speed regulation.

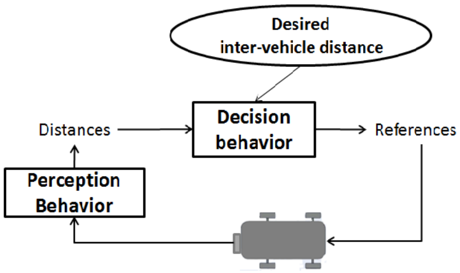


Fig. 2. Sub-behaviors of each follower vehicle

4 Interaction model

Vehicle agents are interconnected by means a virtual physics-inspired model. This model is composed of two springs and a damper, that attach the follower vehicle to its leader. The point of attachment differs depending on the platoon configuration. Figure 3 shows the 2-spring model used in an echelon platoon formation.

Parameters involved in this physical interaction model are :

- m, the mass of the vehicle.
- $width$ and $length$, respectively the width and the length of the vehicle.
- l_1 and l_2, the both springs resting length.

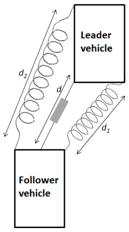


Fig. 3. Physical model installed in an echelon platoon formation

- k_1 and k_2, the stiffness of each one of the two springs. We consider also the existence of a stiffness K equal to the sum of k_1 and k_2.
- h, the damping coefficient.
- v and γ, the speed and the acceleration of the vehicle.
- μ, the friction coefficient.

Laser range finders are used to measure the three distances d_1, d_2 the length of each one of the springs, and d the length of the damper. Four forces intervenes in this model :

- Force of first spring: $\boldsymbol{f_{s1}} = k_1\ \boldsymbol{X_1}$, with $\boldsymbol{X_1}$ the elongation of the first spring, $\|\boldsymbol{X_1}\| = (d_1 - l_1)$.
- Force of the second spring $\boldsymbol{f_{s2}} = k_2\ \boldsymbol{X_2}$, with $\boldsymbol{X_2}$ the elongation of the second spring and $\|\boldsymbol{X_2}\| = (d_2 - l_2)$.
- Damping force : $\boldsymbol{f_d} = h\ \boldsymbol{v}$.
- Friction force : $\boldsymbol{f_f} = -\ \mu\ m\ \boldsymbol{g}$, g represents the gravity of earth.

Each follower vehicle computes its references (speed and orientation) according to Newton's second law of motion [2]:

$$\boldsymbol{F} = m\ \boldsymbol{\gamma}\ = \boldsymbol{f_{s1}}\ +\ \boldsymbol{f_{s2}}\ +\ +\ \boldsymbol{f_h}\ +\ \boldsymbol{f_f} \tag{1}$$

4.1 Model parameters

Before starting the platoon operations, the four parameters K, k_1, k_2 and h have to be determined. In this section, we will describe briefly how we compute this parameters in a platoon column formation.
K is constant during the platoon operations. In case of linear circulation $\|\boldsymbol{X_1}\|$ $= \|\boldsymbol{X_2}\|$ and $k_1 = k_2 = \frac{K}{2}$. To facilitate the computation, we will replace the two springs by one having K as stiffness and $\|\boldsymbol{X}\|$ as elongation. The speed of the vehicle is written $\dot{\boldsymbol{X}}$, and the acceleration will be written as $\ddot{\boldsymbol{X}}$. So equation 1 could be written like :

$$m\ \ddot{\boldsymbol{X}} = -K\ \boldsymbol{X} - h\ \dot{\boldsymbol{X}} + \mu\ m\ \boldsymbol{g} \tag{2}$$

---

[2] The acceleration $\boldsymbol{\gamma}$ of a body is parallel and directly proportional to the sum of forces $\boldsymbol{F}$ and inversely proportional to the mass m, i.e., $\boldsymbol{F} = m\ \boldsymbol{\gamma}$.

Before the vehicle startup we have : $\mathbf{0} = -K\ \boldsymbol{X} - h\ \dot{\boldsymbol{X}} + \mu\ m\ \boldsymbol{g}$. The follower vehicle must not startup while the elongation of the spring is smaller then the desired elongation. Consequently, we can deduce that :

$$K = \frac{\mu\ m\ g}{X_0} \tag{3}$$

where X_0 is the desired spring elongation.
k_1 and k_2 vary during the platoon operations proportionally to the variation of the two distances d_1 and d_2.
To compute the damping coefficient h a kinematic study of the "spring-damper" system should be done. Equation 2 could be written like :

$$\ddot{\boldsymbol{X}} + 2\varepsilon\ \omega_0\ \dot{\boldsymbol{X}} + \omega_0^2 = \frac{\mu}{m}\ m\ \boldsymbol{g} \tag{4}$$

where, $2\varepsilon\ \omega_0 = \frac{h}{m}$ and $\omega_0 = \sqrt{\frac{h}{m}}$.
The damping coefficient h could be deduced by solving the equation 4 to be in the critical damping case, so the discriminant is considered to be null. $\Delta = 0 \Rightarrow \varepsilon = 1$.

$$\varepsilon\ =\ \frac{h}{2 * \sqrt{K\ m}}$$

Then,

$$h\ =\ 2 * \sqrt{K\ m} \tag{5}$$

A detailed study of this model is presented in [7], were some simulation results that marks the efficiency of this model in column formation of platoon are dressed. In [6], a formal verification using the SAL model checker prove that the safety property : *No collision between two follower vehicles* is valid during the platoon circulation.

4.2 Platoon echelon formation

An echelon formation is defined with a no null lateral and longitudinal distances. To control this configuration, the same physical model (2 springs and a damper) is used, only the attachment points will change. Main advantages behind the use of this control model are : First, the use of two springs with two different and variable stiffness helps maintaining the formation by adjusting the values of both stiffness when needed. Second, the 2-springs control model is already used in column platoon formation, and it can also be used in other formation, which facilitates the transition between configurations. In fact, this transition could be simply made by changing the attachment points of the springs.

Table 1 shows five different installation possibilities of the physical model that can be adapted in echelon configurations. As in column configuration, laser range finders are used to measure the length of the two springs and the damper. Then the physical interaction model is used to compute the acceleration of the

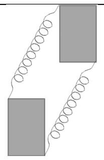
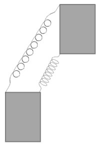
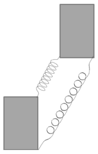
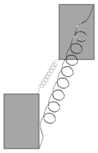
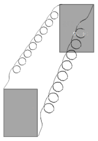
				
Configuration 1	Configuration2	Configuration 3	Configuration 4	Configuration 5

Table 1. Five different configurations of the virtual interaction model

system. To compute the parameters of the physical model (K, k_1, k_2, h) we can produce like described in 4.1 Where the two springs are replaced by one having K as stiffness, $\boldsymbol{X} = \frac{\boldsymbol{X_1}+\boldsymbol{X_2}}{2}$ as elongation, and $l = \frac{l_1+l_2}{2}$ as spring resting length.

5 Simulations and comparison of different configurations

In order to compare the five configurations of echelon platoon, simulations were done using Vivus [3] simulator, a simulator developed in the SeT laboratory [4]. Vivus incorporate a 3D Geo-localized models. This model contains also details of the vehicle physical model like tire and road contact. Simulations involve a 2-vehicle platoon. Leader vehicle is manually controlled, follower vehicle is equipped with the platoon control described in section 4. Vehicle perception is made by a simulation laser range finder having the same characteristics (range, angle, error, ...) as the real vehicle's sensor. In the five configurations, longitudinal and lateral desired distances are equal to three meter.
Two main evaluations where made :

- Evaluation of lateral error : measure of the horizontal spacing between two following vehicles and compare it to the desired lateral distance.
- Evaluation of longitudinal error : measure of the vertical spacing between two following vehicles and compare it to the desired longitudinal distances.

5.1 Evaluation of lateral error

To evaluate the lateral error, following test is suggested: the leader vehicle will turn around a building in the simulation area. During its trajectory, the vehicle will go through curves with rotation angle equal to 90 degrees. To visualize the results of this test, the trajectories followed by each one of the leader and the follower vehicles are drawn. Table 2 shows these trajectories. We also dressed in table 3 the variation of the lateral distance during the time.

The results dressed in tables 2 and **??** shows that in the five configurations the lateral distance is always close to the desired lateral distance (3 m).

---

[3] http://www.multiagent.fr/Vivus_Platform

[4] http://set.utbm.fr/

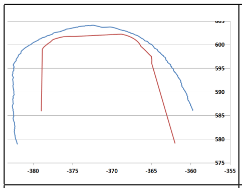
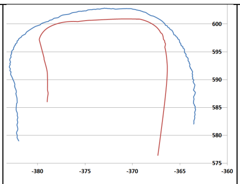
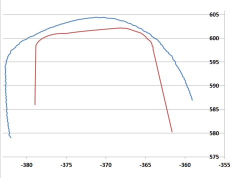
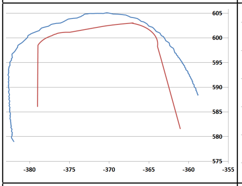
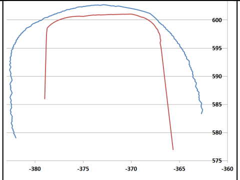
		
Configuration 1	Configuration 2	Configuration 3
		
Configuration 1	Configuration 2	

Table 2. Trajectory error during a turning case

The maximal errors are produced at the point of inflection. In configurations 1 and 4, the maximal lateral error is 30 cm. The average of this error is 10 cm (less than the width of a tire). In configurations 2 and 3, the maximal error reaches 50 cm, while in configuration 5 it reaches 70 cm.

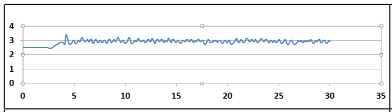
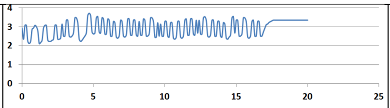
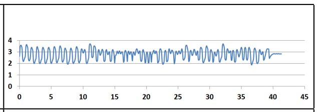
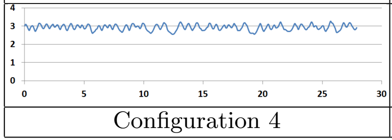
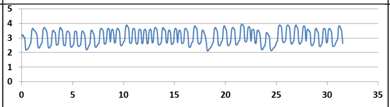
		
Configuration 1	Configuration 2	Configuration 3
		
Configuration 4	Configuration 5	

Table 3. Results of the lateral deviation. Horizontal axe represents the time in seconde, vertical axe represents the distance in meter

Conclusion of the test : Results produced by this tests give confidence to the configuration 1 and 4

5.2 Evaluation of longitudinal distance

In this test, for each one of the five configurations we measure the longitudinal distance between the leader and the follower vehicle during an arbitrary trajectory, with a vehicle speed of 7 km/h. The measured longitudinal distance is compared to the desired one (3 m). Table 4 dresses the results of the tests made on the five configurations.

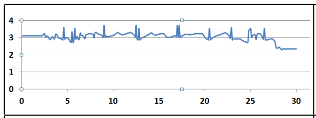
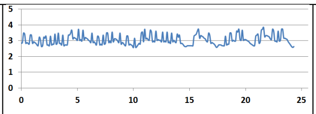
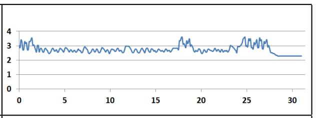
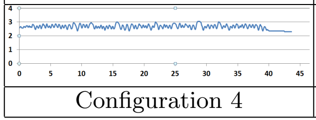
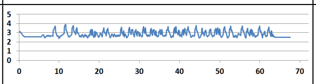
		
Configuration 1	Configuration 2	Configuration 3
		
Configuration 4	Configuration 5	

Table 4. Results of the longitudinal deviation. Horizontal axis represents the time in second, vertical axis represents the distance in meter

The graphs dressed in table 4 show that in the five configuration the longitudinal distance is always close to the desired lateral distance (3 m).
In configurations 1, 3 and 4 the maximal longitudinal deviation is 50 cm. While in configurations 2 and 5 this maximal deviation reaches the 80 cm. Adding to this configurations 1, 3 and 4 show more stable graphs, while in configurations 2 and 5, oscillations of longitudinal distance are more considerable.
Conclusion of the test : The longitudinal test shows that the configurations 1, 3 and 4 produce more advantageous results and also close to the desired ones.

5.3 Conclusion of the results

The results dressed by these tests, show that among the five configurations proposed in table 1 the first one (configuration 1) is the most suitable to address the echelon problem.
Configurations 3 and 4 show also some promising results. However, in the lateral tests configuration 1 seems more reliable than these two configurations . Consequently, we can say that the configuration 1 is the most suitable configuration to be used in the echelon platoon formation as a control model.

6 Conclusion

The goal of this paper was to find an efficient method to control an echelon platoon formation. The proposed control method bases on reactive multi-agent system where each vehicle is considered as an agent that behaves based on its perceptions. To compute its references each vehicle agent uses a virtual physical interaction model composed of two springs that attaches the follower vehicle to its predecessor. This control approach is already used to control platoon in column formation. To adapt it to the echelon formation, we suggested to show five different geometries of attachment of this physical model that differers within their attachment points. Simulations were done to evaluate the quality of each one of the five proposed configurations. We also dressed a comparison between the results produced by the five configurations, and than we concluded by finding the most suitable configuration for the echelon formation.

Future works will be devoted to : first study the installation of the 2-springs physical model in the line formation of platoon, second, to study the task of dynamic transition between formations (passing from a formation to another).

References

1. P. Avanzini, Thuilot B., and P. Martinet. A control strategy taking advantage of inter-vehicle communication for platooning navigation in urban environment. *IROS11 International workshop on Perception and Navigation for Autonomous Vehicles in Human Environment*, 2011.
2. R.W. Beard, J. Lawton, and F.Y. Hadaegh. A feedback architecture for formation control. In *American Control Conference*, volume 6, pages 4087 –4091 vol.6, 2000.
3. A.K. Das, R. Fierro, V. Kumar, J.P. Ostrowski, J. Spletzer, and C.J. Taylor. A vision-based formation control framework. *Robotics and Automation, IEEE Transactions on*, 18(5):813 – 825, oct 2002.
4. Pascal Daviet and Michel Parent. Longitudinal and lateral servoing of vehicles in a platoon. *IEEE Intelligent Vehicles Symposium, Proceedings*, pages 41 – 46, 1996. Automatic driving;Platooning techniques;.
5. K.D. Do and J. Pan. Nonlinear formation control of unicycle-type mobile robots. *Robotics and Autonomous Systems*, 55(3):191 – 204, 2007.
6. M. El-Zaher, J.M. Contet, P. Gruer, and F. Gechter. Towards a compositional verification approach for multi-agent systems : Application to platoon system. *First International workshop on Verification and Validation of multi-agent models for complex systems (V2CS)*, 2011.
7. M. El-Zaher, F. Gechter, P. Gruer, and M. Hajjar. A new linear platoon model based on reactive multi-agent systems. *The 23rd IEEE International Conference on Tools with Artificial Intelligence ICTAI, IEEE Computer Society*, 2011.
8. J.K. Hedrick, M. Tomizuka, and P. Varaiya. Control issues in automated highway systems. *Control Systems, IEEE*, 14(6):21 –32, dec 1994.
9. Contet Jean-Michel, Gechter Franck, Gruer Pablo, and Koukam Abder. Physics inspired multiagent system for vehicle platooning. In *Proceedings of the 6th international joint conference on Autonomous agents and multiagent systems*, AAMAS '07, pages 184:1–184:3. ACM, 2007.
10. John J. Moskwa and J. Karl Hedrick. Nonlinear algorithms for automotive engine control. *IEEE Control Systems Magazine*, 10(3):88 – 93, 1990.
11. D.P. Scharf, F.Y. Hadaegh, and S.R. Ploen. A survey of spacecraft formation flying guidance and control. part ii: control. In *American Control Conference, 2004*, volume 4, pages 2976 –2985 vol.4, 30 2004-july 2 2004.
12. H.G. Tanner, G.J. Pappas, and V. Kumar. Leader-to-formation stability. *Robotics and Automation, IEEE Transactions on*, 20(3):443 – 455, june 2004.
13. Myung Jin Woo and Jae Weon Choi. A relative navigation system for vehicle platooning. *SICE 2001. Proceedings of the 40th SICE Annual Conference. International Session Papers (IEEE Cat. No.01TH8603)*, pages 28 – 31, 2001.