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Vehicle platoon control with multi-configuration ability

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Abstract

Vehicle platoon approaches found in literature deal generally with column formations adapted to urban or highway transportation systems. This paper presents an approach in which each platoon vehicle follows a virtual vehicle, in order to cope with issues such as different platoon geometries. Those different types of formations can be encountered in a wide range of field such as the military or agriculture. A platoon formation is composed of a vehicle which assumes the platoon leader role (generally human driven) and other vehicles which play the follower role. A follower vehicle assigns a local leader role to one of the vehicles it perceives. The approach presented here bases on a predefined translation of position, by a follower vehicle, calculated from the perceived position of its local leader vehicle. This translation depends on the desired platoon geometry, expressed in terms of a predefined longitudinal and lateral distance of a follower vehicle relatively to its local leader position. Each vehicle is implemented as an agent which makes decisions depending only on its own perception.

Keywords: Multi configurations, Platoon, virtual vehicle, reactive agents, simulation.

1. Introduction

Over the last years a number of projects, such as PATH [1] or CRISTAL ², have dealt with the platoon concept as an approach to increase the traffic safety and efficiency on urban area and highways. a vehicle platoon can be defined as a set of vehicles, that move together while keeping a predefined geometrical configuration, without any material coupling [2]. The most widely studied platoon configuration is the column, also known as train configuration, where vehicles are placed one behind the other. This configuration is mostly adapted to urban or highway transportation. Other kinds of formations can be considered, such as line, echelon and arbitrary. Each one of those configurations possesses interesting properties in relation with application fields such as military operations or agricultural activities.

The relevance of platoon systems in those fields is due to several reasons. In urban public transportation systems, platoons can bring flexibility by being able to adapt dynamically the size of the trains to users demand. In harvesting applications, platoons with vehicles placed side by side can significantly reduce the duration of plowing. In military

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operations, platoons allow to increase the security of persons and supplies, particularly if many platoon vehicles are unmanned.

In many platoon systems such as [3] and [4], each vehicle in the platoon determines its own position and orientation only from its perceptions of the surrounded environment. In this context, the reactive multi-agent paradigm is well adapted. Reactive agents are simple entities that behave based on their own local perceptions [5]. The interest of those approaches results from their adaptability, simplicity and robustness. In this case, platoon configuration can be considered as the result of the self-organization of a reactive multi agent system (RMAS). A platoon multi-agent system can then be defined as a set of agents, each one corresponding to a vehicle. Two agent roles can be distinguished: platoon leader and follower. Platoon leader behavior: the agent interacts only with its environment (road, obstacles, ...). Follower behavior: the agent bases on local perceptions to perform decision making. In this case, a follower vehicle can identify one of its neighboring vehicles as a local leader vehicle, even if a local leader vehicle is generally not aware of this role.

Different approaches have been considered. According to [6], general military solutions are based one of the three following approaches:

- **Unit-center-referenced:** each agent computes the position of a unit center by averaging the x and y position of all the agents involved in the formation. Then it computes its position relatively to this center unit.
- **Leader-referenced:** each agent computes its position relatively to the leader agent position.
- **Neighbor-referenced:** each agent is linked to a specific leader chosen among its neighbors. The agent then computes its position relatively to this leader.

The goal of this paper is to present a platoon approach able to deal with different kinds of configurations. This proposal bases on a reactive multi-agent system where each vehicle can be considered as an agent. There is a platoon leader agent and each follower agent has one of its neighbor vehicles as local leader (neighbor referenced approach). The basic idea consists, for a follower vehicle, in following a moving target-position obtained from a geometric translation of the perceived position of its local leader vehicle. As a consequence, the follower vehicle follows a virtual leader vehicle as if in a column configuration. The predefined geometric translation of the local leader's position depends on the adopted platoon configuration, expressed in terms of lateral and longitudinal distance among neighbor vehicles. This paper is structured as follow: section 2 defines the possible platoon configurations that can be encountered. In section 3, a detailed description of the running of platoon in different configurations is exposed. Then, section 4 puts the emphasize on the performance of the presented algorithm by dressing some experimental results. Finally, section 5 concludes by giving a list of possible future works.

2. Definitions and state of the art

2.1. Definitions

Platoon is a set of vehicles that moves together while keeping a particular geometrical configuration without any material coupling. Before defining the different configuration that a platoon can take, lateral and longitudinal distances (fig.1) have to be defined. These parameters are used in the geometrical definition of a platoon formation.

- **Lateral distance** represents the horizontal spacing between two neighbor vehicles.
- **Longitudinal distance** represents the vertical spacing between two neighbor vehicles.

Configuring a platoon formation relies on the definition of both lateral and longitudinal distance. Depending on the values of these, several platoon configuration can then be designed. Among these the most useful can be defined as follow:

- **Column configuration** This configuration, represents the traditional form of platoon where vehicles are placed one behind the other (cf.figure 2). In this configuration, lateral desired distance is null. Column configurations of platoon, are mostly dedicated for the transport of passengers in urban or highway transportation systems.

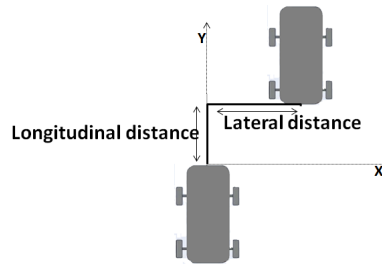


Figure 1: Lateral and longitudinal distances

- **Line configuration** In this configuration, vehicles are placed one beside the other (cf.figure 2). In this configuration, longitudinal desired distance is null. This configuration can be dedicated for the public transport, but it can also be used in the agricultural environment, for soil tilling for example.
- **Echelon configuration** In this configuration, vehicles are in a column formation but each is offset from the preceding by a lateral distance as in one side of a "V"(cf.figure 2). In this configuration, lateral and longitudinal desired distances are both not null. This configuration can be dedicated to agricultural and military environment.
- **Arbitrary configurations : wedge formation** Arbitrary configurations can holds many geometrical forms, produced by the combinations of two or three of the configurations described above. These configurations are mostly used in military environment. In wedge configuration for instance, lead vehicle is followed by echelons of vehicles trailing to the right and the left forming an inverted "V" formation (cf.figure 2).

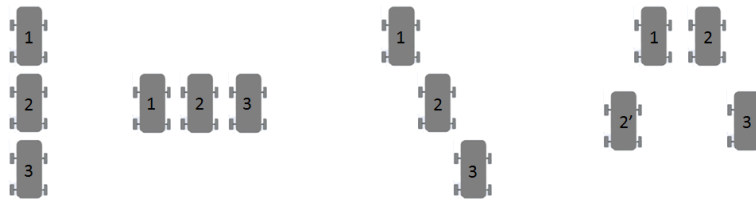


Figure 2: Configurations of platoon. From left to right : column, line, echelon, wedge

2.2. State of the art

In the literature of platoon systems, two main trends of control can be found : Global and local approaches. Global models consist in a localization of vehicles relatively to a common global referential. Then the decision can be made globally, these approaches are then called centralized, or individually for the decentralized approach. Then, global centralized approach relies on one specific entity that determines some reference information (steering, speed, orientation...) and broadcasts it to vehicles in the platoon. Among global platoon systems we can cite [7] and [8] for instance. Global approaches shows precise trajectory matching. However, they are tied to sophisticated technologies for global positioning (RTK GPS for instance) and reliable vehicle-to-vehicle communication network. By contrast, local approaches are always decentralized (i.e. where each vehicle calculates its own references based only on its perceptions). These rely only on distance measurement devices (laser range finder, camera,...) which are generally less costly than device required in global solutions. Since only a local view is accessible, the results obtained in trajectory matching are not as good as in global systems. Generally, anticipation error in curves is observed. As example we can quote [9], [2] and [10].

Turning back to military solutions enumerated in introduction, these can fit the global/local classification. Unit-center-referenced and leader referenced approaches can be considered as global (the control can be centralized or decentralized). By contrast, Neighbor-referenced technique is local and decentralized. In table 1, we distinguished

between centralized and decentralized approaches, with global or local perception.

Perceptions / Control	Centralized	Decentralized
Global	Leader-Follower approaches [11] Virtual structure approaches[12]	Leader-follower, unit center [6]
Local	None	Neighbor-referenced [13] Leader perception [14], [15]

Table 1: Summarizing table of different proposed control approaches

From now on, we can focus on the way to realize the platoon function for various configuration. To address this problem, inspiration can be taken from many works in the domain of mobile robots. To tackle the robot formation control problem three main approaches can be encountered: behavior-based, leader-following and virtual structured strategies.

In **behavior based** strategies ([6], [16], [13]...) each robots is associated to a desired behaviors (e.g. formation keeping, obstacle avoidance...). The final control is derived by weighing the relative importance of each behavior. A behavioral based approach, is a decentralized approach, so it requires less communication between agents. However, due to the difficulty of the mathematical analysis, maintaining the formation cannot be guaranteed.

In **virtual structured** strategies ([17], [12], [18]...), the whole formation is considered as one virtual rigid body. Consequently, it is fairly easy to maintain the formation, because the system moves as only one body. In the other hand, a virtual structure approach requires a lot of communication between robots.

In **leader-follower** approach ([11], [19], [20]...), one robot (or more) is considered as a leader robot, and follows a defined trajectory. Other robots, follows the leader, and maintains a desired distance and orientation to the leader. The main problem of this approach is that it depends heavily on the leader vehicle to achieve its goal.

The virtual structure and the leader-follower approaches are both centralized approaches, that requires communication of the state of the leader vehicle or of the virtual structure to each robot of the formation.

Our proposal can be considered as a neighbor-referenced strategy where the reference neighbor is viewed as a local leader. This local leader is supposed to follow a specific trajectory even if this one is computed through another local leader-follower relation. Each vehicle is then considered as a reactive agent which goal is to follow a local leader taking into account its perception and platoon geometry constraints. In figure 2, for each agent i , correspond the leader $i - 1$. The follower agent perceives its leader and computes its reaction relatively to it.

3. Virtual leader perception and platoon control

3.1. Global point of view

As exposed before, each vehicle in the platoon can be seen as an agent that acts based only on its perceptions. For each agent we define a leader among its neighbors in the platoon. The agent computes its references based on the position of its leader by trying to maintain the desired lateral and longitudinal spacing and the orientation of its leader. Column formation platoon control functions are now well known and expose reliable properties. Consequently, it as been decided to base our approach on this elementary function. So, the key step is to translate leader local position in vehicle agent referential in order to be able to use column platoon function and integrates desired lateral and longitudinal distances.

Figure 3 shows the behavior of follower agent. This behavior is a cyclic combination of three sub-behaviors :

- **Perception** : The follower vehicle perceives its leader in its perception range, and measures the lateral and longitudinal distances. The perception angle for each agent is equal to 360° ³, so the agent is able to percepts all its nearest neighbors.

³this characteristic corresponds to real laboratory vehicle

- **Virtual leader position computation** : The follower vehicle defines a virtual leader in order to use the column platoon function.
- **Column Platoon Control Model** : Using a column platoon control model, the follower vehicle computes its acceleration, then it computes the reaction as a function of its dynamical characteristic and speed.

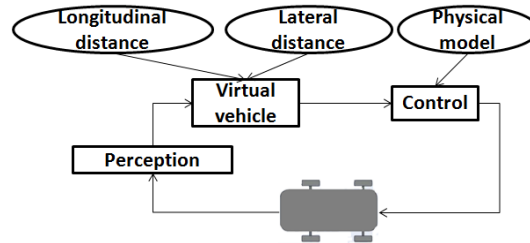


Figure 3: Figure that shows the behavior of the follower agent

3.2. Virtual leader position computation

A virtual Leader is an image of the perceived real leader computed from the application of two translations (longitudinal and lateral). The translation is computed so as to transform the initial problem into a classical column formation. Consequently, the virtual vehicle has to be placed in front of the follower agent. Once the column formation is obtained, a platoon control algorithm defined for linear platoon can be applied.

The position of the virtual leader can be determined using the following equation :

$$\begin{cases} x' &= x + T_x \\ y' &= y + T_y \end{cases}$$

Where (x, y) is the position of the leader, (x', y') is the position of the virtual leader and T_x and T_y are respectively the lateral and longitudinal translation that should be applied in order to achieve the desired position of the virtual vehicle. Depending on the column configuration T_x is even null or equal to the positive or negative value of the desired lateral distance. By same for T_y , the value is even null or equal to the positive or negative value of the desired longitudinal distance. For example, in a column configuration the leader and the virtual leader are superposed, so $T_x = T_y = 0$, while in an echelon configuration $T_x = -Lateral\ distance$ and $T_y = 0$, ... Figure4, shows the different steps followed by an agent in order to computes its reference : The vehicle starts by the perception its environment to detect its leader, then it defines its leader using the equation presented below, and finally it computes its references using a physical interaction model for column configuration.

3.3. Physical interaction model

A vehicle in a column configuration uses a physically-inspired interaction model composed of two springs and a damper shown in figure 5, this interaction model is described in detail in [4]. In our system, this interaction model is placed between the follower vehicle and the virtual leader. Parameters involved in this system are :

- k_1 and k_2 , the two stiffness of both springs.
- h the damping coefficient.
- l_0 , the spring's resting length.

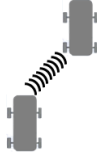
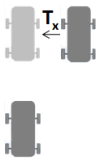
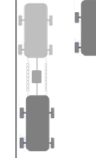
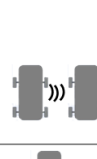
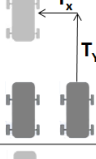
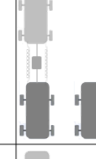
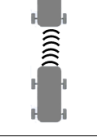

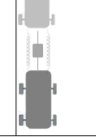
	Leader Perception	Virtual leader definition	Installation of control model	Lateral translation (T_x)	Longitudinal translation (T_y)
Echelon				Lateral distance	0
Line				Lateral distance	Longitudinal distance
Column				0	0

Figure 4: Figure that shows the different steps followed by the follower agent in order to defines its leader and install the physical interaction model. the virtual leader is represented with the light gray color

Follower vehicle computes three distances: d_1 and d_2 , the length of each one of the two springs, D , the length of the damper, this distance is called inter-vehicle distance.

The interaction model is used for two main reasons. First to maintain the inter-vehicle stable at the desired distance. Second, to guarantee a good trajectory matching, by making the follower vehicle follows the same trajectory of its predecessor : the virtual leader. Three forces intervenes in this model :

- Force of each spring : $\vec{F}_{si} = k_i * (d_i - l_0)\vec{u}_i$, where $i \in \{1, 2\}$, and k_1 and k_2 are respectively the stiffness of the first and the second spring.
- Force of the damper : $\vec{F}_d = h * (\frac{\Delta D}{\Delta t})\vec{u}$

Using the second law of Newton (equation 1), follower vehicle deduces its acceleration and then by integration it can deduces its speed and orientation.

$$m\vec{\gamma} = k_1(d_1 - l_0)\vec{u}_1 + k_2(d_2 - l_0)\vec{u}_2 + h(\frac{\Delta D}{\Delta t})\vec{u} \quad (1)$$

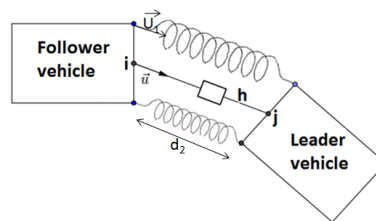


Figure 5: Physical interaction model

This model as been used and tested with real cars. Moreover, stability has been proved using classical physical studies (Lyapounov,...) and formal approaches using SAL. These results are exposed in [21].

4. Simulations and results

4.1. Experimental tool

To assess the quality of our approach, realistic simulations have been done using VIVUS simulator [22], a vehicle simulator developed by the SeT⁴ laboratory. VIVUS is based on PhysX for real physical behavior, and Unity3D for good 3D performance.

This software can simulate behaviors for each vehicle such as Perception with laser range finder or cameras, physical reaction between elements (wheels, car's parts,...),... Physical reaction are computed using the same physical law as real world (collision, gravity,...) and considering the peculiarity of the environment (friction with soil, materials of soils and walls,...). VIVUS has already been used to test various intelligent vehicle algorithms such as linear platoon control [23] and [4], obstacle avoidance and driving assistance [24], and intelligent crossroads simulations in [25].

4.2. Test area

Simulations were performed on a 3D geo-localized model of the city of Belfort (France). Two different trajectories have been chosen (cf figure 6). In the first trajectory, vehicles have to turn to the left with a rotation angle equal to 90°. In the second one, the vehicles turn left and then right, for each curve the rotation angle is equal to 45°.

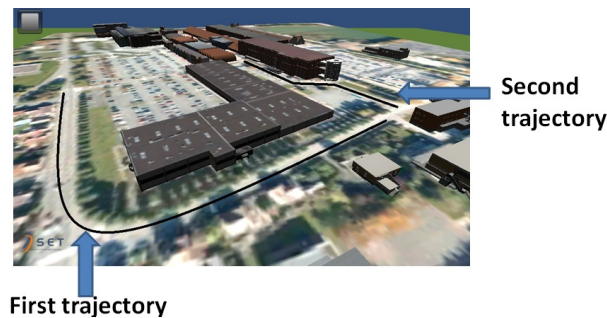


Figure 6: Trajectories used in simulation

In order to obtain realistic results, 3D model and a physical model of the real laboratory intelligent cars (called "Set Cars") are used. Table 2 shows two different models of the SetCar, while table 3 shows the main parameters of these cars.



	
SetCar 1	SetCar 2

Table 2: The SetCars used in simulation

4.3. Performed simulations

In order to study the stability of the follower vehicle, two series of tests have been performed :

- Variation of longitudinal distance : Consists in studying the evolution of the longitudinal distance in time, comparing the longitudinal distance to the desired longitudinal distance.

⁴<http://set.utbm.fr/>

parameters	SetCar 1	SetCar 2
Mass	450 kg	600 kg
Maximal acceleration	1.5 m/s^2	1 m/s^2
Maximal deceleration	3 m/s^2	3 m/s^2
Maximal power	4 kW	5 KW
Maximal speed	7 m/s^2	7 m/s

Table 3: Vehicles parameters

- Variation of lateral distance : Consists in studying the evolution of the lateral distance in time, comparing the lateral distance to the desired lateral distance.

Table 4 shows the different desired distance used (longitudinal and lateral) for different configurations.

Form	Desired longitudinal distance	Desired lateral distance
Echelon	3 m	3 m
Line	Null	3 m
Column	3 m	Null

Table 4: Desired distances in different configurations

4.3.1. Evaluation of longitudinal deviation

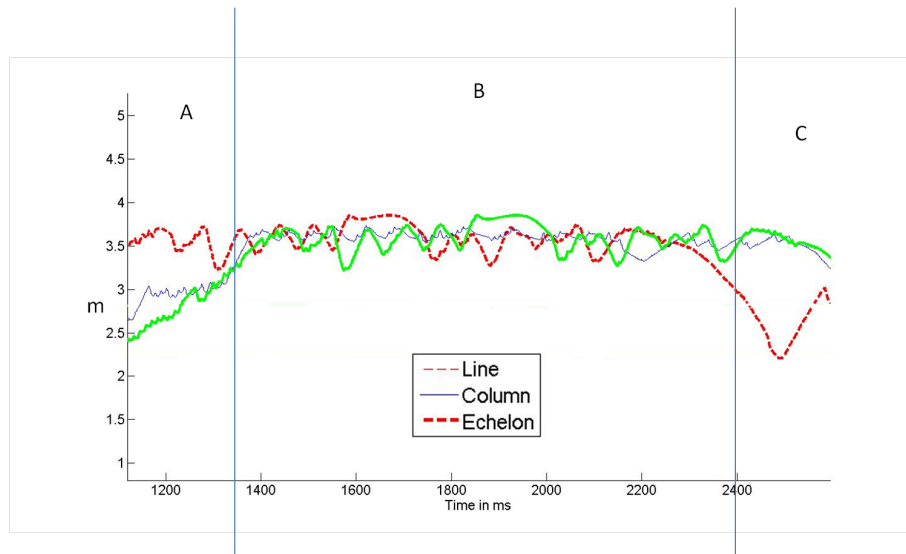


Figure 7: Longitudinal deviation

In this test, we evaluate the variation of the inter-vehicle distance between the vehicle and its virtual leader, by comparing it to the desired distance (3 m), and to the security distance (2 m). The security distance is the minimal inter-vehicle distance that could be reached without a risk of collision in column configuration. Figure 7 shows the variation of the inter-vehicle distance in the line, column and echelon formations. We can see that the inter-vehicle distance in the three configurations is quietly the same. In Zone (A), the leader vehicle accelerates to reach its maximal

speed (7 km/h). As we can see the inter-vehicle distance increases, then after less than 200 ms in the zone (B), where the vehicle speed is stable at 7 km/h. The inter-vehicle distance stays also stable around the desired distance. The Zone (C) corresponds to a quick braking of the leader vehicle, the inter-vehicle distance stays always above the security distance.

4.3.2. Evaluation of lateral deviation

Figure 8 shows the trajectories of 2-vehicles platoon during a turning of 90° , in the cases of column, echelon and line formations.

In the column formation (figure on the left), the maximal lateral error is around 1 m at the point of inflection. this error decreases after the inflection point to reach a value smaller than the width of a tire (20 cm).

In the echelon formation (figure in the middle), the vehicles behaves as in the column configuration, with a little distinction. Indeed, during the inflection, the two vehicles move close to each other before re-stabilizing at the desired distance.

In line configuration (figure on the right), vehicles behave the same as in the column configuration, but with a larger deviation.

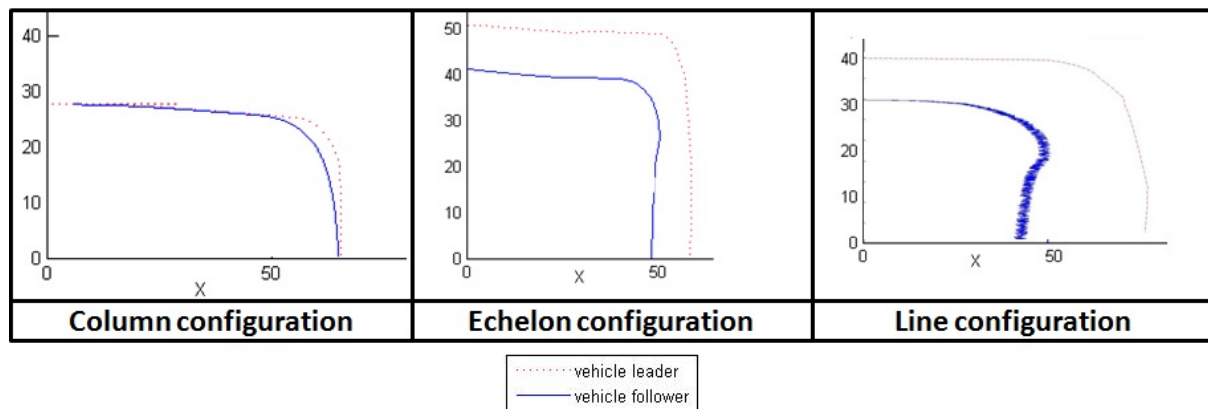


Figure 8: Trajectories of a vehicle and its leader in column, echelon and line formations.

formation	column	line	echelon
average lateral deviation	0.57	0.95	0.74
average longitudinal deviation	2.79	3.02	2.96

Table 5: summarize of analysis

Table 5 shows the average lateral and longitudinal distances between follower vehicle and the virtual leader. This table shows that these average values respect the constraints and safety distances in all formations. This table with the tests above shows that the line configuration is the most difficult to control especially in curves. We are now working to improve the model to limit and reduce oscillations between leader and follower.

5. Conclusion

The aim of the paper was to expose an algorithm for platoon control with multi-configuration ability. This approach is based on a neighbor referenced method in which the follower perception is modified in order to transform the desired spatial formation into a classical column. Then, a column platoon control based on a virtual springs and damper is

used. This platoon function has got interesting properties such as stability and security. Simulations were made using VIVUS simulator. These simulations shows satisfying results about the platoon trajectory matching in column, line and echelon formations.

Future works will be devoted to several key points aimed at improving the proposed solution. On the one hand, experiments using real laboratory vehicles ("SetCars") have to be done in order to test the performance of the algorithm in real conditions of perception, control,... On the second hand, efforts have to be made in order to improve line formation results.

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⁵<http://web.utbm.fr/safeplatoon/>