A two-layer approach for vehicular flocking in lane-free environment

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1 INTRODUCTION

While traffic lanes were initially introduced as essential instruments for simplifying driving tasks for human drivers and increasing traffic safety, their necessity with the emergence and advancement of connected and automated vehicles (CAVs) has to be questioned (Papageorgiou *et al.*, 2021). CAVs are equipped with highly precise sensors and smart technologies for fast and reliable vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication which allow them to make fast decisions based on control and management strategies in order to avoid collisions, efficiently move forward and also cooperate with other vehicles. Papageorgiou et al. (2021) introduced a novel paradigm for freeway traffic, called the TrafficFluid concept, based on two combined principles: "Lane-free traffic" and "Nudging". Within lane-free traffic, vehicles are not limited to traffic lanes but can use the whole road width, allowing for an increase in the efficiency of traffic operations. Nudging describes the effect of vehicles in front moving in a specific direction as they sense the presence of other vehicles with a higher desired speed. As one of the subjects to be investigated further for the lane-free-environment, Papageorgiou et al. (2021) mention “the possibilities and impact of vehicle platoons within the lane-free environment”.

In lane-based traffic, platoons are formed by CAVs that are grouped in a line along one lane with a very short headway resulting in fuel saving, improved safety and increased highway capacity (Kavathekar and Chen, 2011). In lane-free traffic, vehicles can be grouped not only longitudinally but also laterally across the whole road width. We introduce platooning in lane-free traffic as "vehicular flocking" by analogy to the phenomenon of collective behavior of self-acting individuals observed in some natural species like birds, fish or ants. Numerous studies have addressed flocking for animals (Hemelrijk and Hildenbrandt, 2012), multi-agent systems (Olfati-Saber, 2006), autonomous flying robots (Virágh *et al.*, 2014), and conventional lane-based traffic (Wang and Chen, 2021). According to (Reynolds, 1987), this behavior is produced by three basic, simple rules of interaction: collision avoidance, velocity matching with flockmates and flock centering (based on the desire to stay close to nearby flockmates).

Based on these principles, this study develops an approach based on virtual forces that extends the concept of lane-free traffic by vehicular flocking. A framework in MATLAB is developed to test the proposed methodology that shows first promising results.

2 METHODOLOGY

The developed decentralized approach for vehicular flocking is based on two layers, i.e., the tactical and operational layers. In the tactical layer, the control mode definition and vehicle matching, are carried out. In contrast, the operational layer takes care of the calculation of the inter-vehicle forces and vehicle movement based on the defined motion dynamics. In the following, the two proposed layers are explained in detail.

2.1 Tactical layer

Three control modes, i.e., cruise mode, catch-up mode, and flock mode, are designed for the movement of vehicles. There are three common goals in each control mode; first, the ego vehicle should drive as closely as possible to its target speed; second, the ego vehicle should avoid collisions with obstacles, e.g., other vehicles; and third, the ego vehicle should remain within the road boundaries. The target speed of each vehicle is its desired speed in the cruise mode, the leading vehicle's speed in the catch-up phase and the flock target speed in the flock mode.

Vehicles start their journey in cruise mode. Following the flocking command, which may be triggered externally, e.g., from the road traffic management system, or internally, e.g., by a passenger's command, the ego vehicle goes to the catch-up mode. In the catch-up phase, the ego vehicle searches for another vehicle in front which is either in the catch-up or in the flock mode, adjusts its target speed based on the current speed of that vehicle and tries to reduce their longitudinal space-gap. Both vehicles go to the flock mode once their longitudinal space-gap is shorter than a defined gap. Inspired by natural flocking, a flock target speed is defined as the average desired speed of all the vehicles in the flock, i.e., flock mates. The flock's shape is defined solely based on the flock repulsion and attraction forces that lead to a self-organized flock. Such forces are calculated in the operational layer and are elaborated in the next section. Once the flocking command is released, the vehicle switches back to the cruise mode.

2.2 Operational layer

The vehicle dynamics and force definitions for the individual and group movements of vehicles are described in this section. In this work, the double integrator model for vehicle dynamics and the approaches proposed in (Papageorgiou *et al.*, 2021; Yanumula *et al.*, 2021), with some modification, are used to achieve the mentioned three primary goals for individual movement of vehicles. Compared to (Yanumula *et al.*, 2021), a new third term, as shown in (1), is added to the calculation of the x axis of the ellipse for repulsive and nudging forces. This term considers the relative speeds of vehicles and induces lower space-gaps when two vehicles are driving at the same speed, e.g., in a flock.

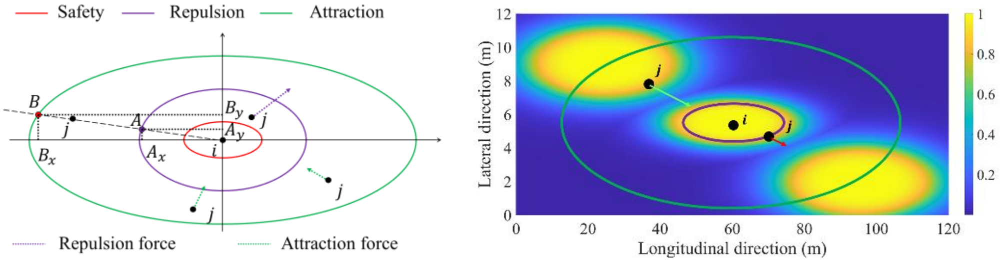
$$d_x^j(k) = s_x\left(l^i + l^j\right) + t_{1,x}\left(v^i(k) + v^j(k)\right) + t_{2,x}\left|v^i(k) - v^j(k)\right| \tag{1}$$

where $k = 0,1,\ldots$ is the discrete time index, s_x is safety factors, l is vehicle's length, $t_{1,x}$ and $t_{2,x}$ are time gaps, and v^i and v^j are the longitudinal speeds of vehicle i and j, respectively. In addition, in this work, the potential fields are placed symmetrically around each vehicle. When the ego vehicle goes to the catch-up phase, and there is another vehicle j in catch-up or flock mode in front, the target speed of the ego vehicle is adjusted based on the leading vehicle's speed. Note that we use a smoothing function to prevent abrupt changes in the target speed of vehicles when they switch to another control mode. In this mode, the ego vehicle i has one additional catch-up force (2), using a PI-controller, aiming to approach the leading vehicle j longitudinally.

$$f_x^{ch}(k) = f_x^{ch}(k-1) + k_x^{ch,P}\left(e(k) - e(k-1)\right) + k_x^{ch,I} e(k), \text{where } e(k) = d_{ch} - [x_x^j(k) - x_x^i(k)] \tag{2}$$

where k^{ch}s are controller gains, x_x is the vehicle's longitudinal location, and d_{ch} is the desired space-gap between the ego and the leader vehicles in the catch-up phase. Once the desired space-gap is attained, the vehicles go into the flock mode. The proposed flocking algorithm leads to a self-organized flock with no leader. Three ellipses, which create a related potential force, are assumed for each vehicle in the flock, as shown in Figure 1. The safety force provides the minimum safety gaps between the vehicles using repulsive and nudging forces, however, with shorter time gaps. The flock attraction ensures the flock centering attitude and allows the flockmates to drive close to each other. The role of the flock repulsion is to enable different forms of the flock. The size and shape of repulsion and attraction zones which shape the flock structure are design issues and can be fixed or adaptive based on the road geometry or traffic condition.

As shown in Figure 1.a, each vehicle j receives a flock repulsion or attraction force based on its relative distance to the vehicle i. The definition of the flock repulsion force is straightforward and is similar to safety force with the difference that the ellipsoid axes do not change with the vehicles' speed. The definition of the flock attraction force is a bit tricky and different since it takes its highest value at the attraction ellipse and decreases as the vehicle j approaches vehicle i.



a- Flock attraction force depends on the relative location of the vehicles

b- An example of flock attraction and repulsion forces for vehicle j at two different positions

Figure 1. The flock repulsion and attraction zone and forces induced from vehicle i

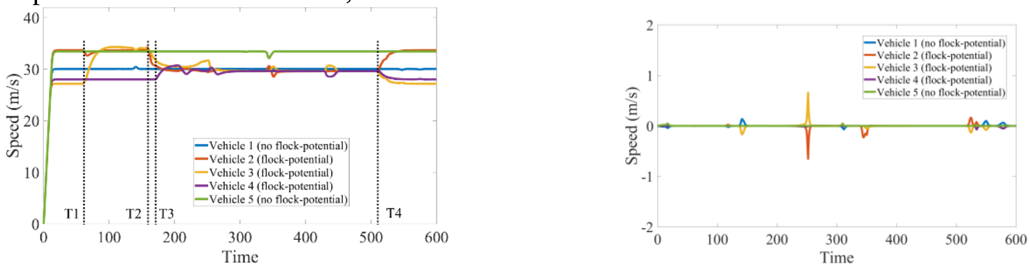
With the proposed approach, there is a balanced zone around each vehicle in which no flock repulsion or attraction applies to other vehicles. Therefore, the flock's vehicles are automatically situated in locations where the overall attraction and repulsion forces are zero or cancel each other. The attraction force definition is illustrated in Figure 1.a. For any vehicle j in the attraction zone of vehicle i, a direct line connecting two vehicle centers is drawn. The cross points of this line with the repulsion and attraction ellipses are marked with A and B, respectively. The flock attraction force F^{at} for the vehicle j applied from vehicle i is calculated as follows:

$$F^{at}(i,j,k) = 1\bigg/\left(\left[\left(\frac{x_x^j(k)-B_x(k)}{B_x(k)-A_x(k)}\right)^2+\left(\frac{x_y^j(k)-B_y(k)}{B_y(k)-A_y(k)}\right)^2\right]^6+1\right) \tag{3}$$

In Figure 1.b, an example of repulsion and attraction functions for vehicle j at two different locations is illustrated. When the vehicle j is affected by the attraction function, it is, thus, pushed towards vehicle i. The vehicle is pushed away from vehicle i due to the flock repulsion function. The effect of attraction and repulsion forces lead the vehicle j towards the neutral area between the two functions.

3 SIMULATION RESULTS

To test the proposed methodology, a simulation framework in MATLAB is developed. A highway ring road with 1 km length and 10.2 m width is assumed. Vehicle parameters such as desired speed, dimensions, and willingness to form a flock are assigned at the initial phase, as well as their initial lateral and longitudinal locations. The flocking command is time-triggered and sent to those vehicles willing to join the flock. The flock command is also released at a pre-defined time, and flock vehicles switch to the cruise mode afterwards. Two scenarios are designed. In the first scenario, the simulation is initialized with five vehicles from which three are flock-potential, while in the second one, ten vehicles, all willing to participate in the flock formation, are assumed.

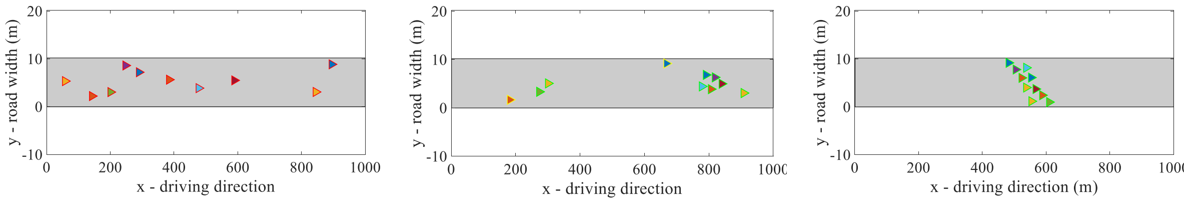


a- Longitudinal speed of simulated vehicles

b- Lateral speed of simulated vehicles

Figure 2. Longitudinal and lateral speed evolution of vehicles in different control modes for the first scenario

In Figure 2, the results of a 10 minutes simulation run for the first scenario is shown. The flocking command is triggered at T1 and is released at T4. Following the flock command, vehicle 3 adjusts its longitudinal speed to catch up with vehicle 2 and they form a flock at T2. A bit later (at T3), vehicle 4 also joins the flock, and all three vehicles drive together, with the flock target speed, until the flock command is over. In addition, the effect of the flock attraction is reflected in the lateral speed of vehicles 2 and 3, as shown in Figure 2.b. The flock vehicles go to the cruise mode when the flock command is released and take their desired speed as the new target speed. The small ripples in the speeds are the effect of nudging and repulsive forces applied between the flock vehicles and vehicles 1 and 2.



a- All vehicles in the cruise mode b- Two formed flocks; each has a follower c- All vehicles form a single big flock

Figure 3. Movement of vehicles in three different control modes over the simulation period

The results of the second scenario are depicted in Figure 3. Each vehicle, shown with a triangle, has a unique fixed colour in these figures, while its line colour can be red, yellow or green, indicating the vehicle cruise, catch-up, and flock modes, respectively. Initially, all vehicles are in cruise mode and drive individually. In the flock phase, as shown in Figure 3.b, two flocks with different sizes are formed, and each flock has a follower in the catch-up mode. Over time, the vehicles in the catch-up mode also join the flock, and since the two flocks have different target speeds, they also merge and form a single big flock. Note that the formed flocks are self-organized, and no restrictions are imposed on the flock size or the flock lateral occupancy. Note to mention that, the vehicles may seem to have a short space-gap between themselves due to the scaling of the road presentation in the plots.

4 DISCUSSION

A two-layer approach for vehicular flocking in the lane-free environment is developed in this work. To this end, three control modes, i.e., cruise, catch-up and flock modes, are assumed to control vehicle movements. A framework in MATLAB is developed to test the proposed methodology. The results demonstrate a promising characteristic of vehicle movement with collision-free behaviour. The defined flock attraction and repulsion forces lead to self-organized flocks with the requested feature. In future works, we consider flock management strategies to impose and regulate the flock size, lateral occupancy of the flock, and even consider aerodynamic effects when building efficient flock forms.

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