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Cooperative Distributed Control for Lane-less and Direction-less Movement of Autonomous Vehicles on Highway Networks

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Abstract

In this paper, we introduce lane-less and direction-less movement as a novel traffic characteristic of trajectory behavior for Connected and Autonomous Vehicles (CAVs) in highway networks. We assume that there is no barrier in the center of the highway to separate the traffic flow with different directions. This assumption enables the CAVs to move not only lane-less (lateral direction) but also direction-less (longitudinal direction). By applying this concept, we can exploit the maximum potential capacity of the highways, especially under unevenly distributed directional demand. However, the elimination of the conventional notion of vehicles' movements on the separated domains of lanes and directions, can consequently increase the chaos and collision risk (and thus jeopardize safety). Thereby, we develop a cooperative distributed control strategy for the movement of CAVs in such a futuristic environment with the twofold objective of (i) providing safety in a microscopic (vehicle-to-vehicle) level and improve the traffic performance in a macroscopic (network) level.

Introduction

The advent of fully Connected and Autonomous Vehicles (CAVs) will make a revolutionary change in the existing transportation reality. The deployment of CAVs can improve the performance of transportation systems in terms of safety, capacity usage, congestion, etc. (see Kim and Kumar, 2014; Talebpour et al., 2017). Moreover, these recent technological developments enable us to provide novel approaches and solutions for the various transportation problems. For instance, thanks to the CAV technology different researchers (see e.g. Xu et al., 2018; He et al., 2018; Makarem and Gillet, 2013; Mitrovic et al., 2019) have proposed the concept of light-less intersection to increase the serving capacity of urban arterials. In this work, we aim at developing a new strategy to exploit the advantages of utilizing the new characteristics of CAVs on highway networks. Recently, new studies have been performed in this area, proposing the lane-less concept in order to increase the capacity of the freeway (Papageorgiou et al., 2019; Mulla et al., 2019; Chavan et al., 2016). Lane-less traffic can be described as the nonexistence of predefined lanes for the vehicles' movement. Therefore, the vehicles do not have to adhere to any lane discipline and are free to choose an arbitrary lateral position for their movement in the highway. This is similar to the behavior of motorcycles (swerving or oblique following of the leading vehicle) during the traffic congestion (Nguyen et al., 2014). Through this method, we can serve more vehicles on the highway cross section. So far, the control methods that have been proposed for CAVs movement are designed based on the separation for longitudinal and lateral movements that are inapplicable for the lane-less environment (Gueriau et al., 2016; Zhou et al., 2017; Zhu and Zhang, 2018). Consequently, the current research is focusing on designing an interactive control for CAVs in the lane-less environment. For example, Papageorgiou et al., 2019 introduced vehicle nudging to model the force of a vehicle to the vehicles that are in front. Chavan et al., 2016 proposed the influence graph in both lateral and longitudinal dimensions to model the interaction between CAVs. Even though the lane-less traffic can increase the capacity usage of the highway, it cannot reach the optimal point when the demand flows on different directions (left to right or light to left) of the highway are imbalanced. In this paper, we address this situation and propose the lane-less and direction-less approach to maximize the capacity usage in both directions of a highway. We introduce the direction-less concept as eliminating the conventional dedicated space for different directional movements in highways. The main idea is depicted visually in Fig. 4, where CAVs with different directions are able to use the whole width of the highway. Although the proposed direction-less method is capable of improving the performance of the highway, at the same time it increases the complexity level of CAVs movement control. CAVs in the lane-less and direction-less environment have higher risk of collisions. In this paper, we focus on designing a proper control method that can deal with optimizing the trajectories of CAVs in a lane-less and direction-less environment. The proposed distributed controller is designed such as to guarantee the safety in the microscopic level and decrease the total travel time in the macroscopic network level. The rest of the paper is organized as follows: In section 2, we present the problem statement and describe the dynamic equations that we introduce for modeling individual CAV's movement. Section 3 contains the methodology, the concepts of neighbor, threat, and threat group are introduced; afterwards, according to these concepts, we design the control method. In section 4 we provide the preliminary test results to verify the methodology and describe its pipeline. Finally, section 5 presents the next steps and future direction of the research.

1 Problem Formulation

In this paper, we aim at developing new approach to control the movement of fully autonomous CAVs in microscopic level at highway networks. We assume that there is no central barrier in the highway to separate the traffic flow with different directions. This assumption enables the CAVs to move not only lane-less but also direction-less. By implementing this concept we can exploit the maximum potential capacity of a highway. In this paper, we address this problem and develop a new method for the CAVs movement that guarantees the safety in this environment, and at the same time tries to maximize the throughput of the infrastructure for different demand patterns.

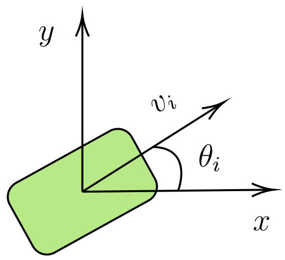

Figure 1: The diagram of the CAV movement.

1.1 Dynamic Model for CAV Movement

In this section, we model the individual CAV movement dynamics based on velocity as well as longitudinal and lateral position. In order to avoid the complexity in this level, the details related to the vehicle dynamics (steering angle, yaw rate, lateral and longitudinal forces of tiers, etc.) are excluded, and we focus on a much simpler model that can capture all the caracteristics from a traffic flow theory viewpoint. Fig. 1 shows the coordinate system of the CAV movement, where x and y are the longitudinal and lateral axes, respectively, that (without loss of generality) are always parallel and perpendicular, respectively, to the highway boundaries. The velocity is denoted by v, and θ is the heading angle. One can derive the longitudinal and lateral movement of a CAV by projecting v with respects to θ on x and y axes. Thereby, for the CAV i the movement dynamics model can be defined as follows:

$$\begin{cases} x_i(k+1) = x_i(k) + Tv_i(k)cos(\theta_i(k)) \\ y_i(k+1) = y_i(k) + Tv_i(k)sin(\theta_i(k)) \\ v_i(k+1) = v_i(k) + Ta_i(k) \end{cases} . \tag{1}$$

where $k = 0, 1, \ldots$ is the discrete time-step and T (s) denotes the sampling time. The variables $x_i(k)$ (m), $y_i(k)$ (m) and $v_i(k)$ (m/s) denote the states of the system. Acceleration $a_i(k)$ (m/s2) and $\theta_i(k)$ (rad) are the control signals.

2 Methodology

Thanks to V2V communications technology, each CAVs has access to its neighbors' information that provides them with a crucial perception for the space in their vicinity. These data enable the CAV to predict the potential collisions and detect the "threating" vehicles (i.e. vehicles that can constitute possible collisions in the near future). Furthermore, the threat vehicle may also be threatened by another vehicle; as a result, we can construct a chain of the vehicles that their movements depend on each other, denoted by threat group. Thereby, the idea is to develop a distributed MPC-based control methodology for the movement of all CAVs that belong to the same threat group.

2.1 Neighbors and threats

For each CAV, we define the neighborhood as a circle centered in the center of geometry of the CAV. We name the radius of this circle as the communication radius (Fig. 2). The communication radius must be long enough as to cover all the possible threats; moreover, the CAV must have enough time to react and avoid the collision with the threats within the time they are detected in the neighborhood border. In order to formulate this communication radius we extend the concept of safe distance in the classical car-following model. Essentially, in most car-following models, the safe distance contains two common terms. The first term expresses the impact of driver's reaction time. Besides that, the safe distance includes another term that describes the required crucial distance as a consequence of the relative speed between the leader and the follower. For CAVs, the first term is a technical spesification and can be interpreted as the distance with regards to communication time delays T_{cd}. Similarly with the car-following model the second term, namely by vital gap, is also required for CAVs. Vital gap expresses the longest gap which is required in the worst case to avoid collision. The worst case in the direction-less environment for CAV i, is when a neighbor is heading towards it with the maximum speed $v_{\max}$. Thus, for CAV i, the vital gap is the required distance to another conflicting CAV in the worst case scenario, so as to make the relative speed equal to zero:

$$\frac{(v_i + v_{\max})^2}{4a_{\max}}, \tag{2}$$

where v_i is the velocity of the CAV i, and $a_{\max}$ the maximum deceleration. Due to the fact that in our methodology both conflicting CAVs can take action, the maximum relative acceleration (deceleration) is $2a_{\max}$. Therefore, the communication radius R_i is given by:

$$R_i = T_{\mathrm{cd}} v_i + \alpha \frac{(v_i + v_{\max})^2}{4a_{\max}}, \tag{3}$$

where α is a user-defined threshold that is used for safety reasons. In Fig. 2, the yellow circle with the radius R, centered on the green CAV, demonstrates the neighborhood for this specific CAV. As mentioned above, this yellow circle represents also the maximum communication range, so the green CAV does not need to have any communication with the vehicles that are outside the neighborhood (blue vehicles in Fig. 2). For CAV i, the neighbor set N_i is defined as:

$$\begin{aligned} D_{i,j} &= \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \\ \mathcal{N}_i &= \{j D_{i,j} \leq R_i\} \end{aligned} \tag{4}$$

where, $D_{i,j}$ denotes the distance between CAVs i and j. In Fig. 2 the vehicles that are inside the yellow circle are definoted as the CAV's neighbors. The neighbors with a potential collision risk are the threats (for instance the red vehicle in Fig. 2) and the CAV only needs to react to the threats. Therefore, as the next step, it is essential to distinguish the threats from the neighbors.Finally, since the definition of the neighborhood has already considered the bounds on the distance, the only risk parameter that is left is the movement direction. In order to determine the direction with the risk of collision, we consider every CAV surrounded by a safe margin that describes the area where no other vehicles should enter at any time. In Fig. 3 the yellow rectangle with width w_{m} and length l_{m} represents the safe margin for the green CAV. The dimensions of the safe margin are defined as $w_{\mathrm{m}} = 2(w + w_{\mathrm{c}})$ and $l_{\mathrm{m}} = 2(l + l_{\mathrm{c}})$, where w_{c} is the minimum lateral distance between two vehicles moving in parallel and l_{c} denotes the minimum longitudinal distance between vehicles. In order to define the threat candidates, we denote the maximum area by connecting the CAV's center to the edges of the other vehicle's

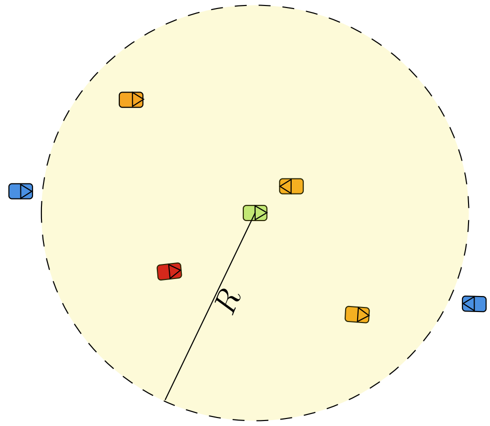

Figure 2: Graphical definition of the neighborhood. The yellow circle depicts the neighborhood for the green CAV, and the blue CAVs indicate vehicles that are outside the communication region. The rest of CAVs are the neighbors, whereas, only the red one constitutes a threat.

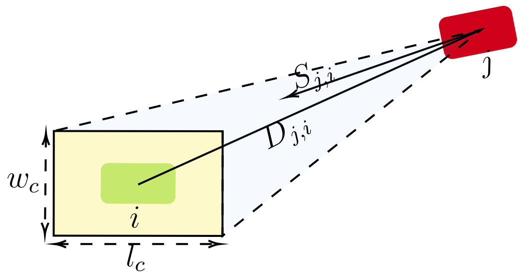

Figure 3: Threat detection. The yellow rectangle represents the safety margin for the green CAV and the blue area demonstrate the risk spectrum.

safe margin, and this determines the risk spectrum (blue spectrum in Fig. 3). A neighbor is a threat if its relative speed vector is inside the risk spectrum (check Fig. 3). For CAV i, the threat set $\mathcal{T}_i$ which is a subset of $\mathcal{N}_i$ is defined as follows:

$$\begin{aligned} &\vec{S}_{k,i} = \vec{v}_k - \vec{v}_i \\ &\mathcal{T}_i = \{kk \in \mathcal{N}_i, \epsilon_{\min} \leq \angle\vec{S}_{k,i} \leq \epsilon_{\max}\}. \end{aligned} \tag{5}$$

where $\vec{v}_k$ is the velocity vector with a magnitude v_k and an angle θ_k; $\vec{S}_{k,i}$ denotes the vector of the relative speed between CAVs k and i; finally, $\epsilon_{\min}$ and $\epsilon_{\min}$ represent the boundaries of the risk spectrum. Note that the neighbor and threat relationships are reciprocal concepts. Two CAVs that have threat relationship must take actions to avoid collision. However, each of them may also be threaten by other vehicles that should take them into account to make a correct action. As a result, we define the threat group as a chain of CAVs that are related to each other due to the threat relationship. Fig. 4 demonstrates an example of our study environment, where the red areas represent different clusters of threat groups.

2.2 Control Approach

As described in the previous section, we cluster all the CAVs with probability of the collision into the threat groups. A CAV belongs to the threat group $\mathcal{G}_i$ if it threatens at least one of

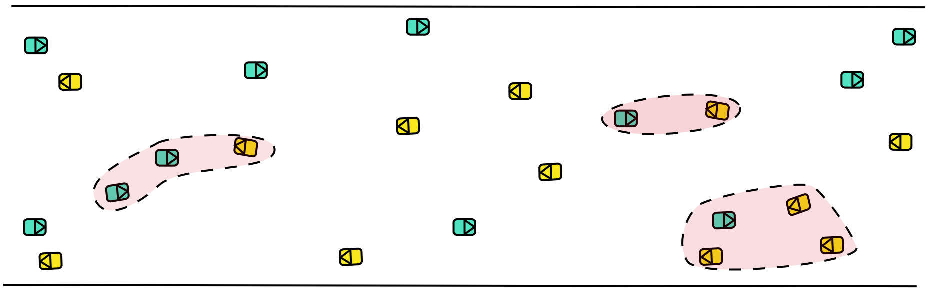

Figure 4: An example of the lane-less and direction-less movement on highway. The red areas determine the threat clusters.

the members of $\mathcal{G}_i$. The objective of this work is to control the movement of each CAV in a cooperative sense, to avoid the collision, and, besides that, decrease the total travel time by maintaining the optimal trajectory in each individual's movement. Given the fact that threat relations are based on a time-varying concept, it is crucial to have a future horizon-based controller. Model Predictive Controller (MPC) is one appropriate horizon-based controller. In principle, MPC-type of controllers have the advantage of taking into account the impact of the model predicted future behavior of the system into the current control signal derivation. This feature of MPC enables us to design the CAV's movement to avoid the neighboring threats, and at the same time, not create undesirable threats for other neighbors that will not have enough time to react to them. To this end, for every threat group $\mathcal{G}_i$ we define the MPC problem formulation as follows:

$$\min_{a_k,\theta_k} \sum_{k\in\mathcal{G}_i} \alpha_k(\theta_k - \theta_k^{\mathrm{d}})^2 + \beta_k(v_k - v_k^{\mathrm{d}})^2 \tag{6}$$

subject to:

$$-a_{\max} \leq a_k \leq a_{\max} \tag{7}$$

$$-\Delta a_{\max} \leq \Delta a_k \leq \Delta a_{\max} \tag{8}$$

$$\theta_d - \frac{\pi}{2} \leq \theta_k \leq \theta_d + \frac{\pi}{2} \tag{9}$$

$$-\Delta\theta_{\max} \leq \Delta\theta_k \leq \Delta\theta_{\max} \tag{10}$$

$$0 \leq v_k \leq v_{\max} \tag{11}$$

$$y_{\min} \leq y_k \leq y_{\max} \tag{12}$$

$$D_{k,j} \geq \frac{(S_{kj}\cos(\delta))^2}{4a_{\max}} \tag{13}$$

where k denotes the index of the CAVs that belong to $\mathcal{G}_i$. The objective function is shown in (6), and it consists of two terms. The first term is trying to minimize the deviation of the angle from desired point θ_k^{d} (which is defined by the destination, i.e., for left to right movement is 0 and for the right to left movement is π). The second term expresses the convergence of speed v_k to the desired speed v_k^{d}. The variables α_k and β_k are the weights for the first and second term, respectively. The vehicles' movement is confined with the physical constraints (8-13), where (7) and (8) demonstrate the bounds for acceleration and its variation, respectively; (9) is defined to prevent the vehicles of moving backwards; (10) shows that the angle variation is also bounded; the speed magnitude is bounded from (11); finally, constraint (12) limits the lateral position of the vehicles inside the highway. The constraint (13) is designed concerning the goal of avoiding collision with threats, where δ denotes the angle between the relative speed vector and relative distance. This equation expresses that the relative distance of a threat pair has to be greater than the required distance with regards to relative speed; this is the same concept that was utilized for the vital gap (see equation (2)), however, in this case, we define it more precisely. The required distance is based on the projection of the relative speed vector on the relative distance line that is calculated by $S_{kj}\cos(\delta)$.

3 Preliminary Results

There are simple but effective tests that can evaluate the performance of the proposed control strategy. In this section we report the results of one simple experiment as a proof of concept. We have designed a simple test case with two CAVs to investigate the applicability and efficiency of the methodology and its pipeline. For this reason, we assume two CAVs in a highway moving on the same lateral position towards each other. The CAVs initial configurations and physical parameters are identical. Fig. **??** demonstrates the test case results. The two CAVs detect each other as a threat at time 16.4s; afterwards, following the commands that result from the MPC framework discussed in the previous section, they change their heading angle and increase their relative lateral distance to 2.26m. This way, they manage to pass the same longitudinal position at time 17.9s without collision. The results confirm that the physical constraints are satisfied, however, more experiments need to be run to investigate the effectiveness of our proposed control scheme.

4 Conclusion and Future Work

In this paper, we introduced the concept of lane-less and direction-less movement as a new possibility for CAVs behavior in highway networks. To represent the relations between CAVs in this environment, we presented the notions of neighborhood, threat, and threat group. Thanks to these three relation-based notions, we developed a cooperative control strategy for CAVs movement based on MPC. The control objective is defined so as to avoid collision and meanwhile retain the optimality in traffic performance. Finally, we demonstrated the functionality of the proposed method with a simple simulation experiment. For future work, we aim at providing more complicated test scenarios to evaluate more aspects of the proposed method. Eventually, we aim at simulating various traffic flow phenomena and characteristics of CAVs traffic on a highway, and compare the results with the merely lane-less strategy to show the advantages of adding the direction-less freedom.

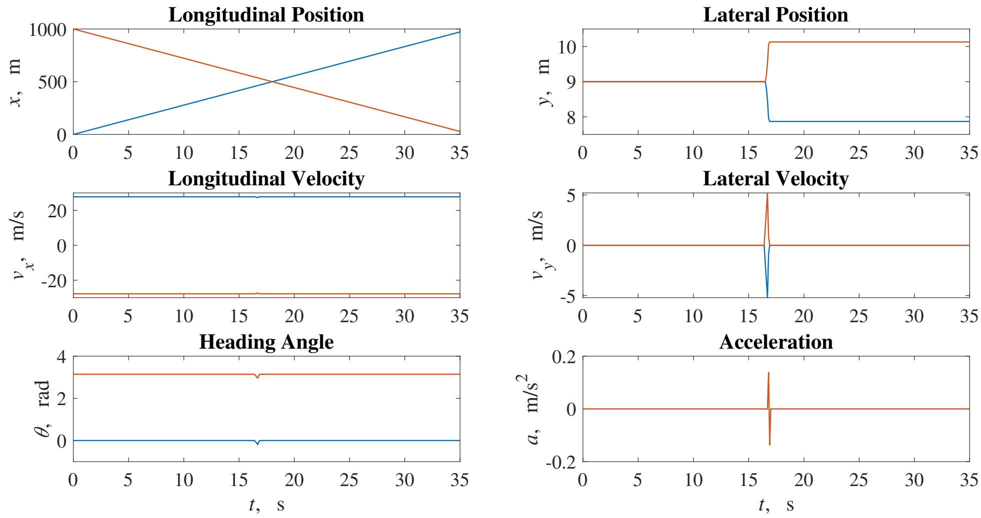

Figure 5: The results of the simulation for two identical CAVs heading toward each other.

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