A Novel Formation Creation Algorithm for Heterogeneous Vehicles in Highway Scenarios: Assessment and Experimental Validation

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Abstract: In this paper a novel algorithm for the on-line creation of formations of heterogeneous vehicles is proposed for highway traffic scenarios. A two-step iterative distributed strategy is formulated which relies on Dynamic Programming and trajectory tracking. Only position measurements and basic communication capabilities for global coordination are required, while scalability is guaranteed by the underlying structure of the algorithm. In addition, spatial and velocity constraints are taken into account. The presented concept forms the basis for more sophisticated formation creation controllers. Results obtained in experiments with automated small-scale trucks show the underlying validity and practical feasibility of the algorithm.

Keywords: Autonomous Vehicles, Automotive Control, Formation Control, Automated Highway Systems, Dynamic Programming, Experimental Validation, Small-Scale Vehicles

1. INTRODUCTION

Formation creation and control is being subject of a large amount of interest in the control engineering community (see Oh et al. (2015)) due to the large number of possibilities offered by enhancements in the available technology. Fields as mobile robotics (see Desai et al. (2001)), Unmanned Aerial Vehicles (see Wang et al. (2007)) and Automated Underwater Vehicles (see Cui et al. (2010)) are experiencing great benefits from the development of more and more sophisticated formation control algorithms. These enable coordinated movements and thus enhanced energy management (see, e.g., Lotfinezhad and Ben Liang (2005)), and exploration and covering capabilities (see Cortes et al. (2004)) for a wide variety of innovative applications.

Among them, the improvement of the ground transportation systems, thanks to the possibilities offered by Connected and Automated Vehicles (CAVs), appears now to be of primary concern (see Fax and Murray (2004); Murray (2007)). To the end, most of the formation control results available in the literature for non-holonomic mobile robots, often explicitly dealing with space constraints and collision avoidance requirements, can apply to automotive formation control problems providing for safe and practically implementable solutions.

Instead, the well-known platoon control (see, among others, Liang et al. (2016); Rupp et al. (2017); Zheng et al. (2017); Zambelli and Ferrara (2019)), for which a great amount of research results exists with particular focus on highway applications, is specifically designed for automotive applications. This algorithms yield increased road occupation (thus increasing the number of vehicles possibly transiting a road without creating congestions), enhanced safety (through the elimination of human risk factors) and, in some cases, energy efficiency.

One critical aspect, currently pursued by several research groups, concerns the ability of regulating highway traffic by means of structured cooperation between vehicles (forming, for instance, platoons) and the highway infrastructure, giving rise to the so-called Intelligent Vehicle Highway Systems (see Baskar et al. (2011) and references therein) or Automated Highway Systems, see Chien et al. (1997). Despite the effectiveness of the already existing proposals, additional flexibility could be provided by means of 2-D formations. In fact, it is well known that traffic regulation can be effectively achieved for instance through the introduction of moving bottlenecks (see Piacentini et al. (2018)) of specified length and width, which move at prescribed velocities to enforce a desired traffic performance. In this context, formations should be created starting from usual highway traffic and exhibit particular features in terms of length and lanes occupation, as required by higher-level traffic controllers (thus, possibly being embedded in multilayered control architectures).

To the best of the authors knowledge no result specifically designed for formation creation in highway scenarios has been proposed so far. Such a situation poses different peculiar challenges, mainly related to the existing physical, spatial and safety-related constraints. The vehicles are in fact expected to remain in the highway and must not invade lanes in which other vehicles are proceeding. In addition, only positive velocities must be allowed, corresponding to a unique direction which can be followed by the vehicles, and non-holonomicity of the vehicles due to the steering properties must be taken

into consideration as well as possibly the lateral dynamics of the vehicles in lane-changing maneuvers.

In this paper a novel algorithm for the construction of arbitrarily long formations starting from vehicles distributed on the highway, and occupying the desired lanes is proposed . Such vehicles are required to be CAVs, or semi-automated vehicles able to exhibit CAV capabilities on demand. Specifically, it is supposed that at a certain time instant a trigger signal (possibly coming from high-level controllers) indicates the need for a formation merge in a certain area of the highway, covering a certain space and proceeding at a desired speed. Notice that, despite rectangular formations are considered in this work for the sake of simplicity, any configuration of vehicles can in principle be achieved with the proposed strategy.

The main contribution of the present work is based on a spatial reference frame attached to the leader. An iterative formation creation procedure makes use of a mixture of discretized and continuous spatial frameworks. In particular, every step can be decomposed in a first part utilizing the well-known Dynamic Programming (DP) procedure (see Bertsekas et al. (1995)) to find optimal movements for the vehicles and a second part in which a continuous trajectory is built based on the computed sequence and followed by a suitable trajectory-tracking strategy. One of the most evident advantages resides in the fact that the most time-consuming tasks (i.e. the optimizations) are carried out in safe conditions, where the possible delays caused by the computational requirements do not lead to feasibility issues (in terms of the final goal of safely obtaining the formation). The modular structure of the proposed strategy enables great flexibility that facilitates a huge amount of possible enhancements, which constitutes another important aspect of the present work.

The manuscript is organized as follows. In Section 2 the problem of creating a formation with arbitrary length and width in highway scenarios is formally stated. Then, in Section 3, the proposed algorithm is presented. In Section 4 experimental results obtained on a small-scale truck testbed are presented. Conclusions are finally drawn in Section 5.

2. PROBLEM STATEMENT

Consider a highway as a set $H = \{1, \cdots, N_l\}$ of N_l indices corresponding to ordered lanes of uniform and constant width w_l and a set $A = \{1, \cdots, N\}$ of N indexed vehicles. Automated driving features (involving both longitudinal and lateral dynamics) must be exhibited by all of the vehicles, so that they are able to execute the coordinated formation control strategy. Cooperation requires a certain information exchange, which must be guaranteed either by Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure (V2I) communication, or possibly a mixture of the two. Additionally, sufficiently accurate position measurements must be available, for instance by means of GPS.

At a certain time instant $t_1 > 0$, a triggering signal starts the creation of a rigid formation proceeding at a predefined velocity $\bar{v}$ on an arbitrary subset of lanes $\bar{H} \subseteq H$ of size $\bar{N}_l \leq N_l$ and covering a specified length in terms of number of vehicles $N_j > 1$, that may be different for each lane $j \in \bar{H}$. The vehicles in a set $A = \{1, \cdots, N\}$ are recruited, which formerly start scattered on the road, proceeding with different velocities $v_i(t) > 0$, $i \in A$ according to usual highway traffic characteristics.
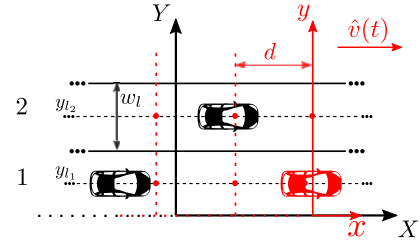

Fig. 1. A two-lanes highway, i.e. $H = \{1, 2\}$.

A spacing distance between the centers of successive vehicles $d > 0$ (compatible with their geometric features) is specified as a design parameter according to different control requirements, such as for instance safety, aerodynamic drag minimization or traffic density increase. After creation, the formation is required to proceed as a rigid body with a velocity $\bar{v}(t)$, which can be varied in time by a supervisor controller.

Remark 1. In the present paper it is assumed that all the vehicles present in a certain region of the highway are recruited as joiners of the formation (i.e. fall into the set A) and are therefore controlled by the proposed algorithm. This represents a fundamental feature, since it gives rise to the possibility of enforcing safety and decoupling of the various iterative stages of the protocol, greatly simplifying the procedure. Situations in which part of the vehicles are not willing to take part of the formation or are not able to comply with the required CAV features are subject to further research investigation, and are not covered in the present paper.

In addition, the strategy to be designed aims to solve the formation creation task as discussed above while guaranteeing scalability (i.e. N arbitrarily high) and flexibility in the implementation. This latter requirement can be translated into the request for a modular approach, in which the different phases of the algorithm (i.e. planning and execution) are decoupled. Besides increasing simplicity, this offers great opportunities for future development and possibly complex structures in which the actual implementation of the different phases can be selected online.

To formally state the problem, a global reference frame XY for the 2-dimensional highway is defined such that the (straight) lanes are placed parallel to the X-axis and the edge of lane 1 coincides with $Y = 0$ (see Fig. 1). A reference frame for the formation xy is also introduced, headed with the same angle as XY but moving along the X-axis with some velocity $\hat{v}(t) > 0$ with respect to XY. In both frames, the y-position of the center of the j-th lane is $Y_{l_j} = y_{l_j} = w_l/2 + (j-1)w_l$, $j \in H$. Now the problem can be summarized as follows:

Problem 1. Find a scalable (for $N \to \infty$) control strategy for the set of vehicles A with positions $p_i(t) = [x_i(t) \quad y_i(t)]^T$ with respect to the frame xy such that they converge to a rigid position-based formation covering an arbitrarily determined set of lanes $\bar{H}$. Specifically, after having defined the desired formation as the set

$$\mathcal{F} = \left\{ \bar{p}_{k_j,j} = \begin{bmatrix} -(k_j-1)d & y_{l_j} \end{bmatrix}^T : k_j \in \{1, \cdots, N_j\}, \ j \in \bar{H} \right\}$$

with $\sum_j N_j \leq N$, a strategy must be found such that

$$\forall \bar{p}_{k_j,j} \in \mathcal{F} \quad \exists! \quad i \in A : p_i(t) \to \bar{p}_{k_j,j} \tag{1}$$

and, at the same time,

$$v_i(t) \to \bar{v}(t) > 0, \quad \forall i \in A \tag{2}$$

under the constraints
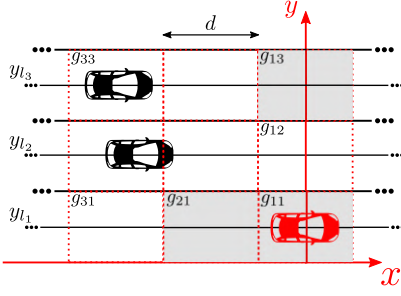
$$0 < y_i(t) < N_l w_l, \quad \forall i \in A \tag{3}$$

Fig. 2. Grid designed with $\bar{H}=\{1,3\}$, $N_1=2$, $N_2=1$ and $L_g=3$. The grey cells must be "covered" to obtain the desired formation.

and without collisions between vehicles, independently of their geometrical and dynamical characteristics (giving rise to possibly heterogeneous formations).

3. FORMATION CREATION ALGORITHM

The higher-level control layer of the architecture, at time t_1, is in charge of selecting the formation parameters $\bar{H}$, N_j $\forall j \in \bar{H}$ and d, as introduced in Section 2, to pursue a particular objective on a specified section of the highway. Consequently, a set A of vehicles is selected and required to activate the desired communication and control features. The only requirement is that communication occurs between every vehicle and the coordinator.

Once the parameters and the vehicles are selected, the global coordinator is initialized and starts to run the first phase of the algorithm as presented in Section 3.1. The vehicle with the highest X-coordinate is designed as the leader and referred to, without loss of generality, as vehicle 1 in the following. At the end of the initialization phase, the iterative procedure (second phase) is carried out until the formation is accomplished, as described in depth in Section 3.2.

3.1 First Step: Initialization Phase

As the first step of the initialization phase, all the vehicles are required to reach the desired velocity $\bar{v}$. Then, the reference frame xy is virtually attached to the leader so that $x=0$ coincides with the absolute x position of the leader $X_1(t)$. A virtual grid, which constitutes a key concept of the proposed approach, is built in the moving reference frame as depicted in Figure 2. In particular, each of the lanes in H corresponds to a "row" of the grid and $L_g \geq \max(N_j)$ "columns" with width d. Such a grid must be designed so that the whole area of interest is covered. The cells are indexed in the space $C=\{1,\cdots,N_l\}\times\{1,\cdots,L_g\}$. A map is defined, such that

$$K(j,k)=\begin{bmatrix}-(k-1)d & y_{l_j}\end{bmatrix}^T, \quad (j,k)\in C \quad (4)$$

returns the center of the respective cell in the xy reference frame given the cell indices j and k.

To each of the vehicles $i\neq 1$ the nearest cell on the same lane is assigned by the coordinator on the basis of the measured positions, taking care of possible overlaps for sufficiently high d in the case that multiple vehicles occupy the same cell. A static association map

$$\Theta:A\to C \quad (5)$$

with $\Theta(i)=(j,k)$ assigns the (j,k)-th cell to vehicle i and marks this cell using the occupation function Ω such that

$$\Omega:C\to\{0,1\}, \quad \text{with} \quad \Omega(j,k)=\begin{cases}1 & \text{if } (j,k) \text{ is occupied} \\ 0 & \text{otherwise}\end{cases}. \quad (6)$$

Once the assignment of the cells has been completed, the first control phase begins which consists, for each of the vehicles $i\neq 1$, in tracking the position of the center of the assigned cell in the xy frame. Once each of the vehicles is tracking the center of the respective cell with sufficient precision, $v_i(t)\sim\bar{v}(t)$ hold. The set $\bar{A}=\{1\}$ for which conditions (1) and (2) apply, i.e. $\bar{A}$ contains the vehicles already in formation, is defined and the second step of the presented strategy is started.

Remark 2. The first phase is fundamental for the safe functioning of the algorithm. In fact, having all the vehicles positioned at the centers of the respective cells means that there is no relative velocity. This greatly simplifies the second part of the strategy and, at the same time, makes it easier to avoid collisions since only one vehicle at a time will be allowed to gain non-zero relative velocity with respect to the others.

3.2 Second Step: Iterative Formation Creation

The second step consists of an iterative procedure applying, in a distributed way, DP and trajectory-tracking until the desired formation is reached. In particular, the global coordinator knows the association map Θ between every vehicle and the respective (tracked) cell. The occupation function Ω is made available to the vehicles in A.

A prediction horizon $P\in\mathbb{N}$ is considered, taken sufficiently long depending on L_g so that a feasible path is always possible to obtain towards any possible goal cell. Consider the cells of the grid as artificial discrete states $g(q)\in C$, with $q=0,\cdots,P$ as iteration steps inside of a DP procedure. On the basis of such states, a set of feasible actions $\bar{U}(g(q))\subset U$ is introduced, where

$$U=\{F,B,R,L,S\} \quad (7)$$

correspond to actions *forward, backward, right, left* and *still* respectively. L and R are defined as a motion forward and then in the respective direction, to explicitly consider the non-holonomicity of the vehicles. A cost is assigned to each (feasible) action equally for every vehicle, by means of the cost function $c(u(q))$, $u(q)\in\bar{U}(g(q))$. Intuitively, for instance, lane changes (actions R and L) shall be discouraged since they require complex maneuvers which could harm safety.

For every vehicle i in $A/\bar{A}$ (i.e. each vehicle which is not yet in formation), the first step of the iterative formation creation consists in performing a Dynamic Programming procedure so as to reach a particular goal cell g^*, selected and broadcasted by the coordinator. Resorting to the previous definitions, this means that an optimal sequence $u_i^*=\{u_i(0),\cdots,u_i(P-1)\}$ must be found leading from $g_i(0)$ (the cell occupied by the considered vehicle at the beginning) to g^*. Based on Bellman's well-known optimality principle, this consists in defining the cost function $J_i(q)$ so that

$$g_i(P)=g^* \quad \text{with} \quad J_i(P)=0, \quad \forall i\in A \quad (8)$$

and finding the optimal sequence u_i^* such that

$$J_i(q)=\min_{u_i(q)\in\bar{U}(g_i(q))}c(u_i(q))+J_i(q+1), \quad q=P-1,\cdots,0 \quad (9)$$

As a consequence of (8) and (9), $J_i(0)$ is the total trajectory optimal cost, corresponding to the sequence u_i^* $\forall i \in A$. Every vehicle sends its cost to the coordinator, which selects

the vehicle i^* associated with the minimum cost (in case multiple candidates exist, one is randomly chosen). The chosen vehicle is then required to perform the second stage of the iterative formation creation while the others keep tracking their associated cells centers until the next iteration. This prevents blocking situations, guaranteeing that the cells in the computed optimal path remain free.

Remark 3. The stage just described is carried out in a distributed fashion, thanks to the idea of considering the road as a fixed discretized space (i.e. the grid) in a moving frame and the situation resulting from the setup phase. As a matter of fact, each vehicle must only be informed about the selected goal cell g^* and the occupied ones in order to compute, locally, (9) and the respective sequence u_i^*. This results in a reduced computational complexity, but requires higher amount of information exchange with respect to a centralized approach, which could be nonetheless effectively adopted within this framework.

Remark 4. Every optimization is carried out such that independently of the computation time no harm to the safety arises and so robustness with respect to the optimizations durations is enforced. In fact, having the vehicles tracking their respective cell center throughout the DP computations produces zero relative velocities.

In the second step of the iterative formation creation phase, on the basis of the optimal action sequence, the sequence of cells to be traversed is computed and the centers are employed as interpolation points for the generation of a continuous path to be followed. Adopting a cubic polynomial path shape, the following formulas are considered for the spatial domain between every two generic successive cells centers $b(q) = [b_x(q) \ b_y(q)]^T = K(g(q))$ and $b(q+1) = [b_x(q+1) \ b_y(q+1)]^T = K(g(q+1))$. In particular, the Euclidean distance between two successive cells is obtained as

$$d_m = |b(q+1) - b(q)|, \quad \text{with} \quad t_m = \frac{d_m}{\alpha \bar{v}} > 0. \tag{10}$$

Note that the time parametrization is performed in (10) on the basis of the formation speed $\bar{v}$, by means of a design parameter $\alpha > 1$ such that the required maneuver speed is finally $\alpha \bar{v}$. The x-coordinate reference motion

$$x_r(t) = \frac{t_0 + t_m - t}{t_m} b_x(q) + \frac{t - t_0}{t_m} b_x(q+1) \tag{11}$$

is then computed, where t_0 is the time at which $b(q)$ is considered as the initial point and t_m denotes the (chosen) duration of the transition from $b(q)$ to $b(q+1)$, so that $t_0 \leq t \leq t_0 + t_m$. Finally, the y-reference follows as

$$\begin{aligned} y_r(t) = b_y(q) + 3(b_y(q+1) - b_y(q)) \left(\frac{x_r(t) - b_x(q)}{d_m} \right)^2 \\ - 2(b_y(q+1) - b_y(q)) \left(\frac{x_r(t) - b_x(q)}{d_m} \right)^3 \end{aligned} \tag{12}$$

The corresponding instantaneous reference yaw angle, valid in both the reference frames, is obtained by

$$\psi_r(t) = atan(y_r(t)/x_r(t)) \tag{13}$$

The trajectory that is produced by successively applying (10), (11) and (12) to all the cells that the vehicle with minimum cost must traverse can now be followed by means of standard trajectory-tracking algorithms (see, e.g. Paden et al. (2016) and references therein). For such a purpose, different methods can be adopted ranging from geometrical approaches to kinematic and dynamic ones. While the first

(a)   (b)

Fig. 3. Small-scale automated trucks employed in the experimental tests.

category has been proven effective in a number of practical applications, the high-speed nature of the highway maneuvers suggests the adoption of dynamic models. Nevertheless, due to the practical impossibility of operating with high-speed vehicles, in the testbed presented in Section 4 a simple Stanley controller (see Thrun et al. (2006)) is employed in combination with a PI velocity regulator. In fact, very low speeds prevent from the possibility of effectively model the vehicles behaviour by means of the mostly adopted dynamic models.

To exemplify this statement, note for instance how the well-known single-track model (see, e.g., Genta (1997)) requires the computation of the wheels sideslip angles, having a physical meaning only for sufficiently high velocities. In the considered experiments, where the trucks velocity is very small, singular behaviours arise which prevent an effective utilization of such models. It is worth mentioning that the requirement for accurate parameters identification poses non-trivial practical issues, which are not part of the presented concept.

After convergence to the goal cell, the minimum-cost vehicle i^* is included by the coordinator in the set $\bar{A}$ (i.e. the vehicle will not perform DPs anymore) and $\Theta(i^*) = g^*$ is assigned. Additionally, the occupation map is modified so that $\Omega(i^*) = 1$ and broadcasted to all of the vehicles, while i^* is required to track the center of g^* from the time on. The procedure is repeated for all the remaining vehicles, up to the point in which the formation is completed.

4. EXPERIMENTAL VALIDATION

An experimental validation has been carried out on a small-scale truck testbed at Graz University of Technology, Graz, Austria, that is described thoroughly in Rupp et al. (2019a,b).

Each of the trucks (see Figure 3) is equipped with low-level velocity and steering angle controllers, and is able to communicate with every other vehicle by means of UDP connections. As mentioned before, a Stanley steering controller coupled with a PI position controller, which gives the reference velocity to the built-in regulator, have been adopted. The required position feedback is given by cameras placed on the ceiling of the testbed which emulate a global positioning system. A sampling time of $10^{-2}s$ has been used for the entire system functionalities. The delays and nonidealities naturally arising in the testbed are here exploited to highlight the ability of the proposed algorithm to deal with practical situations.

In the first experiment, three trucks should achieve a triangular formation proceeding at a velocity of $0.1m/s$ on both lanes of a two-lane road. In particular, with reference to Problem 1, $\bar{H} = \{1,2\}$, $N_1 = 2$, $N_2 = 1$, and $d = 1m$. At the beginning of the experiment the vehicles $A = \{1,2,3\}$ (respectively, the yellow, red and black truck) proceed uncontrolled on the left lane, as depicted in Figure 4, where frames of the experiment over time
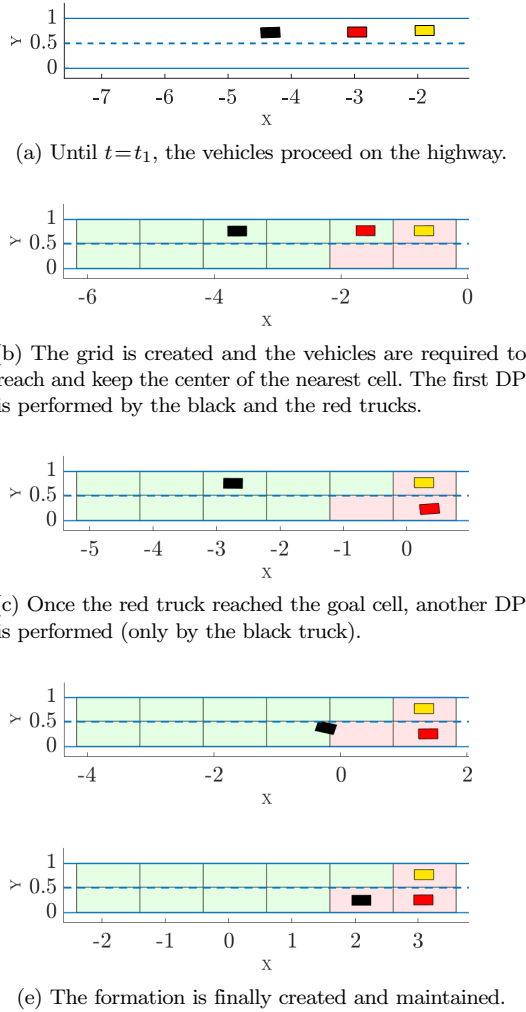
(a) Until $t=t_1$, the vehicles proceed on the highway.

(b) The grid is created and the vehicles are required to reach and keep the center of the nearest cell. The first DP is performed by the black and the red trucks.

(c) Once the red truck reached the goal cell, another DP is performed (only by the black truck).

(e) The formation is finally created and maintained.

Fig. 4. Frames of the first formation creation experiment.

are reported. At time $t=t_1=3s$, the trigger signal is received and the virtual grid is created with respect to the yellow truck as explained in Section 3.1. Then, basing on the position of the followers, the nearest cell is assigned to each of them. In particular, the map Θ defined in (5) is such that $\Theta(1)=(1,2)$, $\Theta(2)=(1,1)$ and $\Theta(3)=(2,1)$. The vehicles are controlled to reach and keep the center of the corresponding cells, as depicted in Figure 4(b). From Figure 4 it is evident that in the considered case $L_g=6$ has been chosen, while the portion of the road to be covered by the formation based on the requirements (in the leaders reference frame) is constituted by the three red cells.

Once the distance between the center of all the assigned cells and the respective vehicles becomes lower than a predefined threshold of $5cm$, the second phase is started and the first of the stages described in Section 3.2 is carried out by vehicles 2 and 3 at time $t=13.72s$, with the considered goal cell being $(1,1)$. The cost for going forward has been set to 1, to go left and right 5, to go backwards 2 and to stay still 0. Consequently, the vehicle with minimum cost is the red one ($J_2^*=5$), which then reaches the goal cell as reported in Figure 4(c) with $\alpha=1.15$ chosen as a fixed design parameter. Finally, the last iteration is performed by vehicle 3 only at time $t=21.38s$, which then reaches its position in the grid with cost $J_3^*=7$. Notice that, in this case, it is obviously not necessary since vehicle 3 is the only one left. As represented
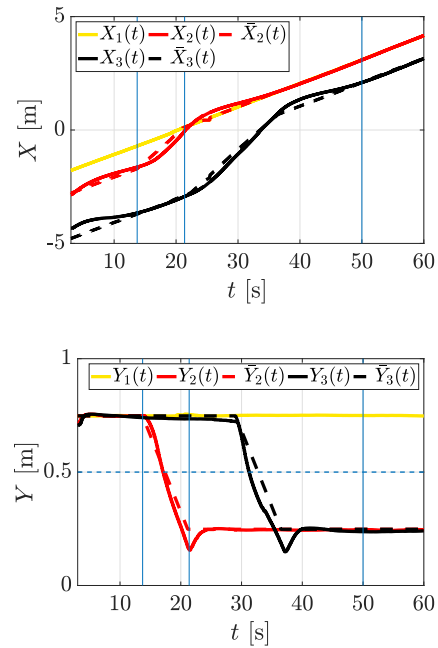

Fig. 5. X_i and Y_i coordinates of the trucks $i=\{1,2,3\}$ during the first experiment. The vertical lines correspond to the time instants reported in the results discussion and the frames reported in Figure 4.

in Figure 4(d), at $t=50s$ the formation is created as required and kept throughout all the subsequent time. The evolution of the X and Y coordinates over time of the involved vehicles are reported in Figure 5 to show the working principles of the employed algorithm. In particular, it is worth noticing how the reference $\bar{Y}_i$ changes as soon as the corresponding vehicle i is selected as that in charge of reaching the goal. At the same time, the velocity (slope of the reference $\bar{X}_i$ curve) increases accordingly. The maneuvers are safe and no collisions occur during the experiment, since d is chosen sufficiently high.

A second experiment, on a three-lanes road, has been performed and reported in Figures 6 and 7. All the design choices have been kept equal to those of the first experiment, but with different initial conditions. Also in this case the algorithm proves to be effective and no collisions occur, reinforcing the soundness of the presented approach in a realistic scenario where not considered delays and other nonidealities are present.

5. CONCLUSIONS AND OUTLOOK

In the present paper a novel formation creation algorithm has been proposed. Relying on a two-step iterative procedure, which couples discrete and continuous frameworks, a simple yet effective algorithm is described which allows to safely perform formation creation on highways, in an optimal way with respect to particular design choices and independently of the size of the formation. In fact, scalability is achieved for $N \to \infty$.

These characteristics, together with the high simplicity and flexibility of the proposed approach, constitute the main points of the present work. In fact, they enable for far more complex formulations in future works, addressing advanced features as formation reconfiguration, split and merge with other formations, as well as vehicles departure from the formation (not included in Problem 1). The same holds for "local" physical and
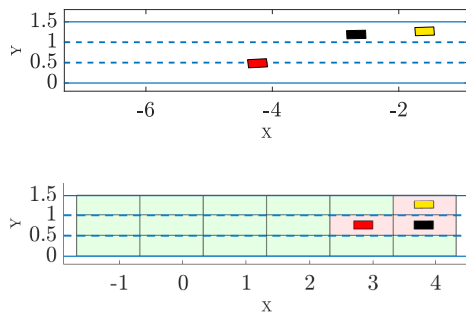
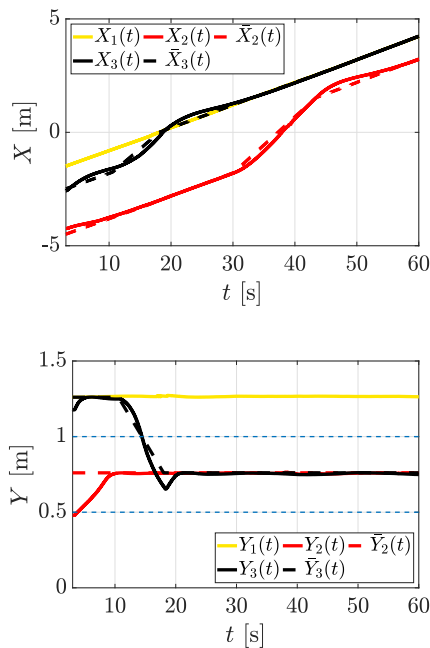Fig. 6. Initial (upper plot) and final (lower plot) frame of the second experiment.

Fig. 7. X_i and Y_i coordinates of the trucks $i=\{1,2,3\}$ during the second experiment.

safety-related issues (e.g. robustness with respect to external perturbations), which are not addressed explicitly in this work.

The idea has been effectively tested in an experimental testbed, with satisfactory results which underpin the practical feasibility of the proposed approach.

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