Coordinated Maneuvering of Automated Vehicles in Platoons

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***Abstract*—To eventually have automated vehicles operate in platoons, it is necessary to study what information each vehicle must have and to whom it must communicate for safe and efficient maneuvering in all possible conditions. This paper formulates the problem in terms of sensing and communicated information. By emulating platoons using a group of mobile robots, we demonstrate the feasibility of maneuvers (such as entering, exiting and recuperating from an accident) using different distributed coordination strategies. The coordination strategies studied range from no communication to unidirectional or bidirectional exchanges between vehicles, and to fully centralized decision by the leading vehicle. One particularity of our work is that instead of assuming that the platoon leader or all vehicles globally monitor what is going on, only the vehicles involved in a particular maneuver are concerned, distributing decisions locally amongst the platoon. This paper reports experimental trials using robots having limited and directional perception of other, using vision and obstacle avoidance sensing. Results confirm the feasibility of the coordination strategies in different conditions, and various uses of communicated information to compensate for sensing limitations.**

***Index Terms*—Cooperative driving, Platooning, Distributed computational architecture, Mobile robots.**

I. INTRODUCTION

THE idea of automating vehicles has been around for quite a while. In 1939 World's Fair, General Motors introduced the concept of automated highways with vehicles controlled longitudinally and laterally, freeing drivers to take on more leisurely activities [1]. Grouping vehicles into platoons also means increased road capacity and efficiency, reducing congestion, energy consumption (e.g., due to reduced air resistance) and pollution, and enhance safety and comfort.

Since then, these objectives have been addressed by different initiatives, ranging from adaptive cruise control [2] [3] and collision avoidance/warning systems [4] to truck convoy (e.g., DaimlerChrysler's CHAUFFEUR project [5]), transportation fleet [6] and demonstrations with real vehicles in settings designed to validate various goals and assumptions. The National Institute of Advanced Industrial Science and Technology (AIST) in Japan demonstrated cooperative driving with five automated vehicles equipped with inter-vehicle communication devices in the Demo 2000 cooperative driving [7]. Using differential GPS and dedicated short-range communication, a flexible platoon of vehicles was able to conduct maneuvers such as stop-and-go, platooning, merging and obstacle avoidance on an oval-shaped test track. The California Partners for Advanced Transit and Highways (PATH) worked on the design and experimental implementation of an integrated longitudinal and lateral control system for the operation of automated vehicles in platoons, using eight vehicles and magnetometers on an instrumented two-lane freeway [8]. PATH Demo 2003 featured three Class 8 trucks and three transit buses operating in platoons and performing a variety of automated maneuvers [9]. Nissan demonstrated, using three vehicles equipped with laser-radar units and spread spectrum communication devices, that inter-vehicle communication would improve string stability and headway control performance [10], while Toyota experimented with infrared LED optical devices for inter-vehicle communication [11].

These initiatives confirmed the benefits of inter-vehicle communication in cooperative driving to compensate for sensor limitations and improving reaction time by rapidly propagating information through the platoon. However, the efforts focused mainly on the low-level controllers [7] [8] [10] [12], sensor issues [5] [13], string stability [1] [14] [15] [16], minimal spacing [17] and on demonstrating the feasibility of cooperative driving scenarios in limited and controlled conditions. Group communication [18] and coordinated maneuvering (e.g., building a convoy under transient driving conditions [19]) have only received minor attention, even though they are necessary components for automated platooning. Two reasons explain this situation: 1) technological progress in sensing and communication are required to make automated platooning reliable, secure and accessible in real life settings; 2) testing with real vehicles driving autonomously requires a large-scale infrastructure with important security measures.

Manuscript received October 15, 2005. This work was supported by AUTO21 Network of Centers of Excellence, Canada Research Chair and the Canadian Foundation for Innovation.

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One alternative is to use mobile robotic platforms to emulate platooning conditions. Contrarily to simulators, mobile robots cannot model real vehicle dynamics. They do however have to deal with real world constraints such as limited perception, imprecise actions, latency, real time decision-making, embedded computing, unanticipated events, etc. Mobile robots are easier to manipulate, and no harm is done if sensor or processing failures occur. Sakaguchi *et al.* [20] used mobile robots to validate a round-robin, ring-network configuration transmission algorithm for inter-vehicle communication during a merging maneuver. Ferrara [21] used a mobile robot to validate an automatic pre-crash collision avoidance strategy. Mobile robots were also used to validate the use of GPS data for relative positioning of vehicles [22]. Once validated, the approach developed on mobile robots can be implemented on larger vehicles. For instance, Kolodko and Vlacic [23] used four Cooperative Autonomous Mobile Robots (CMARs) platforms to develop cooperative passing and traversal of unsignalized intersections using IMARA vehicles. In 2004, DaimlerChrysler and its partners initiated the European project SPARC, building from mobile robotic research to develop a new concept of active safety system for heavy goods vehicles and personal cars [24].

In this paper, we adopt a similar approach by using mobile robots to emulate platooning conditions, studying how coordinated maneuvering can be accomplished following different assumptions on inter-vehicle communication and roles. Feasibility of these coordination approaches is demonstrated along with an analysis of their performances and constraints. Such analysis reveals necessary to establish a robust implementation involving more than one sensing and communication modalities, ensuring safety procedures from possible failures in the various conditions that may occur in platoons. Our long-term objective is to design such solution, first using simple and safe mobile robots, and then on real vehicles over non-instrumented roads.

The paper is organized as follows. Section II presents related work in the fields of automated vehicles and mobile robotics. Section III describes the possible coordination scenarios between vehicles. Section IV presents the computational architecture used. Experimental setup and results are presented in Section V, followed by Section VI with the conclusion and future work.

II. Related Work

Michon [25] identified three levels in a driving task: strategic (highest level, for route planning and goal selection); tactical (intermediate level, selecting maneuvers to achieve short-term objectives such as passing cars, making an exit, merging); and operational (lowest level, for control operations). Mobile robot research successfully addresses all three levels to different degrees [26]. For this paper, our interest focuses on the tactical level.

Platooning is considered a special case of a formation control problem in mobile robotics. Formations are defined as groups of mobile robots establishing and maintaining some predetermined geometrical shape by controlling the positions and orientations of each individual robot relative to the group, while allowing the group to move as a whole [27] [28]. The coordination problem to solve is local in terms of what each robot has to do, and global at the level of the group. The simplest case involves spatial coordination amongst robots, and the more complex ones add temporal coordination of robots' trajectories and roles. Different characteristics can be associated with these coordination strategies based on perceptual (limited or complete visibility of the members of the group; using absolute or relative positioning systems; with or without inter-vehicle communication), formation (of different geometrical shapes; flexible or rigid shapes; how positions are assigned in the group) and control (centralized versus distributed; homogeneous versus heterogeneous roles; oblivious or non-oblivious; control strategy; computational architecture) [29].

The same taxonomy can be used to classify work on automated vehicles in platoons, knowing that the formation is fixed (column formation) and flexible (to handle transient maneuvers). For instance, Sakaguchi *et al.* [20] assume that vehicles are identical and operate at the same speed. Each vehicle knows its absolute position in the world and communicates all information (e.g., identification number, position, heading, headway, acceleration, speed, status) to others in the group. Merging of one vehicle between two others is the only maneuver validated, using three robots running at 100 mm/sec. A virtual vehicle is created between the two to provide space for the merging operation. However, no indication on the computational architecture is provided. DARPA Unmanned Ground Vehicle Demo II project in 1995 used a group of five vehicles, coordinating their maneuvers using DGPS, a behavior-based architecture and a shared memory to exchange information [30]. Rajamani *et al.* [8] used radar sensors to measure distance between vehicles, and magnetometers for lateral position control (providing vehicles with relative positioning information). Vehicles were controlled using a three-layer hierarchical distributed approach [31] [32]. Only one maneuver at a time was allowed in the platoon, and the leading vehicle was responsible for coordinating the actions required. For instance, a vehicle wanting to exit the platoon would first request permission to the leading vehicle; if granted the vehicle would change lane and the leading vehicle would allow the following one to close the gap. This is usually known as a centralized coordination approach.

Many other coordination scenarios can be imagined to coordinate the actions in a platoon. A decentralized coordination approach would not allow information exchange between the vehicles: decision would only be based from sensed states [33]. By explicitly communicating information between vehicles, it is possible to compensate for limited visibility of the world, and decisions can be made in a more “centralized” fashion since each vehicle knows more about the group status. Unidirectional or bidirectional communication from the maneuvering vehicle with its follower and/or leader is possible. Hallé *et al.* [34] present preliminary results of a similar study conducted in a simulated environment with perfect sensing capabilities, looking at number of messages exchanged and plans generated in four coordination scenarios (two centralized and two distributed). Our paper examines feasibility of different coordination scenarios in terms of specific perceptual capabilities, using platforms operating in the real world. Such study has not yet been done for vehicle platooning and would shred some light on the requirements for eventual deployments of cooperative automated vehicles in real driving conditions.

Another interesting discriminating factor in automated vehicles research is on the computational architecture. Two types usually prevail. Hierarchical architectures are the most common [23] [31] [32] [34] [35]. They are made of a vehicle control layer (for low-level longitudinal and lateral control), a vehicle management layer (which can be made of a regulation layer and a coordination layer) for maneuver coordination, and a traffic control layer for road-vehicle communication. The other type of architectures decomposes vehicle control into modes (or behaviors) that recommend actions to an arbiter based on their perceptions [26] [30]. Having multiple modes provides more flexibility in responding to events in the environment. In our work, we introduce a hybrid computational architecture using both types of architectural principles. It extends Lygeros *et al.*'s work [36] [33] to platoon maneuvering with imperfect conditions of the real world.

III. COORDINATION SCENARIOS

A platoon of vehicles v can be views as a string of dimension n, with v_1 being the conductor (C) of the platoon and v_n being the rear vehicle. Automated vehicles are assumed to be equipped with platooning systems that give to all the same capabilities. However, for safety reasons, we assume that only a certified driver can be the conductor of the platoon. Each pair of vehicles in the string is made of a leader (L) and a follower (F), each one possibly playing the other role in another pair of vehicles (e.g., v_4 follows v_3 but leads v_5). The number of vehicles in the platoon is allowed to change as vehicles enter and exit the platoon. We assume that such maneuvers can happen anywhere in the platoon, to minimize traffic disruption. However, we assume that a vehicle can be involved in only one maneuver at a time. Therefore, the model used in our work considers that only three vehicles needs to be involved in platoon maneuvers. Finally, we consider maneuvering of platoons, such as platoon joining or splitting, as a generalized case of one vehicle (a platoon of one vehicle in this case) entering or exiting another platoon.

We categorize coordination strategies based on communication exchanges between vehicles in the platoon. Suppose that M is a vehicle that initiates a maneuver (e.g., entering or exiting a platoon, or executing emergency maneuvers if one vehicle fails while in the platoon). Communication between vehicles can be addressed at the media level and at the coordination level. Our interest lies in the coordination level, more specifically on the exchanges between vehicles to coordinate their actions. Let us represent the sequence of exchanges between vehicles using their role as reference. For instance, $M \rightarrow L$ represents an exchange of information from the maneuvering vehicle (M) and its leader (L, the vehicle in front of it once the maneuver is completed (for entering a platoon) or when the maneuver begins (for exiting a platoon or during an emergency maneuver)). Using this notation, the eight possible coordination scenarios are:

- *Decentralized* (or fully decentralized): no communication between the vehicles. The intentions of the vehicles must be interpreted from direct visibility of their actions.
- $M \rightarrow F$: unidirectional communication between the maneuvering vehicle initiating the maneuver and its follower[1].
- $M \leftrightarrow F$: bidirectional communication between the initiating vehicle and its follower.
- $M \rightarrow L$: unidirectional communication between the initiating vehicle and its leader.
- $M \leftrightarrow L$: bidirectional communication between the initiating vehicle and its leader.
- $M \rightarrow F/L$: unidirectional communication between the initiating vehicle, its follower and its leader[2].
- $M \leftrightarrow F/L$: bidirectional communication between the initiating vehicle, its follower and its leader.
- *Centralized*: using the leader to coordinate the group once a request is made by the initiating vehicle.

The fundamental research question for automated vehicles operating in a platoon is what information is required to make vehicles operate safely in such conditions. Vehicles that can sense on their own all the necessary information for safe maneuvering in a platoon do not need communication (*Decentralized*). If communication is fully reliable and widely available, then the most secure strategy would be to communicate information forward and backward to vehicles in the platoon (*Centralized* or even broadcasting to all[3]). However, in practice, communication in a distributed system brings additional processing and creates a dependence on the coherence and reliability of the information transmitted. For instance, relaying all information to C for coordinating the group makes processing requirements for this vehicle increase with the number of vehicles in the platoon. Any error or failure of some sort will impact all of them. It also increases the capabilities required for the communication media. Using the minimum amount of communication to compensate for the sensing limitations of vehicles is therefore recommended. Information can be communicated backward ($M \rightarrow F$), forward ($M \rightarrow L$) or both ways ($M \rightarrow F/L$) in the platoon, with feedback coming from the rear ($M \leftrightarrow F$), from the front ($M \leftrightarrow L$) or both ways ($M \leftrightarrow F/L$ and *Centralized*) of the platoon. The objective is to find the appropriate strategies for automated vehicles with specific capabilities and under different operating conditions.

Possible conditions in which these scenarios can be

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[1] Braking lights play a similar role.

[2] One basic example of such strategy is the use of turn signaling lights.

[3] This brings the additional problem of ensuring coherence in the information communicated and received by all platoon members.

validated are diverse: straight-line platooning conditions, lane-changing or turning, stop-and-go, changes occurring during an entrance or an exit maneuver, failures while platooning (e.g., accident, tire failure), simultaneous maneuvers (e.g., two vehicles exiting the platoon, one vehicle entering while another is exiting), etc. Note that not all of these scenarios are possible in all cases, depending on the sensing capabilities of the vehicles. For instance, a vehicle in the middle of a platoon executing an exit maneuver requires that its follower be capable of perceiving the position of the preceding vehicles not to split the platoon. Therefore, only a subset of those scenarios may reveal to be useful in a particular setting.

IV. COMPUTATIONAL ARCHITECTURE

Fig. 1 represents the computational architecture used in our work. It is a subset of a more sophisticated architectural methodology for designing autonomous intelligent vehicles [37]. Each vehicle is programmed using the guidelines of this computational architecture, and is capable of autonomous decision-making based on sensed or communicated information. The *Behavioral Level* is made of Behavior-Producing Modules (BPM) responsible for sending commands to the vehicle's actuators according to sensed or communicated inputs and configuration parameters. BPMs implement control modes for the vehicle. The actual use of a BPM (*BPM Activation*) is determined using priority-based arbitration and conditions managed by the Finite-State Machine (FSM) at the *Recommendation Level*. The FSM coordinates the actions of the vehicles according to the coordination scenarios outlined in Section III.

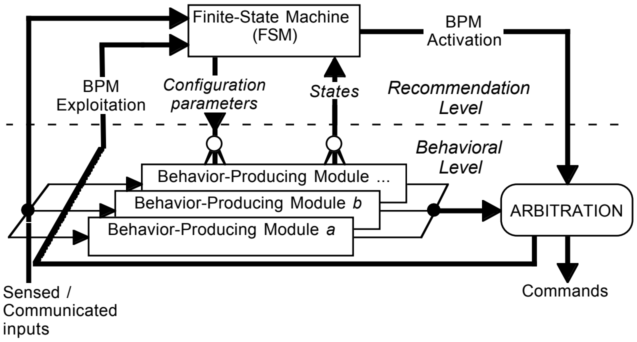

Fig. 1. Computational architecture.

Each vehicle commands its longitudinal and angular velocities. To do so, seven BPMs are used, listed from the highest priority to the lowest one:

- *Remote Control*. This BPM allows the experimenter to send commands directly to the vehicle in order to initiate a trial, subsuming all other BPMs. It is used mainly for setting up an experiment.
- *Obstacle Avoidance*. It makes the vehicle avoid an obstacle perceived in front of it while moving forward. It moves the vehicle in the direction with the most available free space, while keeping the vehicle's heading facing forward.
- *Collision Emulator*. This mode emulates the failure of the vehicle. Initiated by the experimenter, this behavior can make the vehicle stop or go in the opposite direction of the collision, set according to a specified impact velocity, angle and strength.
- *Direct Control*. This BPM is used to teleoperate the conductor of the train whenever required, to test maneuvers in various platoon conditions.
- *Follow*. Using this BPM, the vehicle stays right behind its leading vehicle at a desired distance.
- *Maneuvers*. This mode allows the vehicle to either enter or exit a platoon by following a preset trajectory (distance and angle) in relation to its leading vehicle.
- *Alignment*. This BPM makes the vehicle move as if it was on a road lane (done by following the nearest wall with our robots).

Since all vehicles use the same computational architecture, they can all be used as the platoon conductor. Note however, as indicated in Section III, that there is only one platoon conductor and it does not change during a trial. During a trial, L or F vehicles in the platoon have the following BPMs activated: *Obstacle Avoidance* (always set for safety purposes); and either *Maneuvers* (to enter or exit the platoon, as set by a configuration parameter determined by the FSM), *Follow* (when in the platoon) or *Alignment* (when not in the platoon). According to their priority level, it is only when an obstacle is sensed too close to the vehicle (based on the safety cell concept [38] setting a safety distance around a vehicle based on its velocity) that *Obstacle Avoidance* takes control of the vehicle.

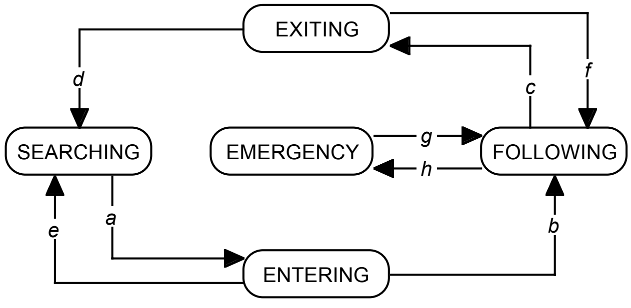

Fig. 2. Finite-state machine of a vehicle for platooning.

Fig. 2 illustrates the FSM used to manage the behavioral modalities of the vehicles. A vehicle not part of a platoon is looking to join one when it is in the SEARCHING state (activating *Alignment*). Once it finds one, it initiates the ENTERING state following the coordination strategy to test. Having successfully used *Maneuvers*, the vehicle is considered to be in the platoon and goes in the FOLLOWING state. This activates the *Follow* BPM. When a vehicle entering the platoon is detected (either sensed or from communicated information), the following vehicle remains in the FOLLOWING state, but decreases its speed to provide space for the entering vehicle. A vehicle enters the EMERGENCY state if its leading vehicle experiences failure: the vehicle can either join again the platoon if it is still possible to do so after having avoided its leading vehicle, or simply stop so that the rest of the platoon is secured. When a vehicle wants to exit the platoon (activated remotely by the experimenter), the state changes to EXITING and, once again, maneuvers are managed based on the prevailing coordination strategy. If, for some reasons, the vehicle cannot enter or exit the platoon, it takes the appropriate actions to go back to its initiating state.

V. EXPERIMENTAL SETUP AND RESULTS

To conduct experiments, we have five Pioneer 2 mobile robots to our disposal. These robots (approximately 0.45 m × 0.40 m) are equipped with front and rear sonar rings (16 sonars for proximity range sensors), a pan-tilt-zoom Sony EVI-D30 color camera equipped with wide-angle lens, wheel encoders (39400 pulses/rotation, 0.2 mm accuracy), illuminated color cylinders, wireless Ethernet (in broadcast mode) and an onboard Pentium 1 GHz. The platoon conductor is also equipped with a laser range finder, allowing it to move safely and autonomously in the corridors of our building. Robots velocities range from 0 to 500 mm/sec. Programming of the robots is done in C++ using RobotFlow/FlowDesigner [39] and Player/Stage [40] environments. A graphical user interface on a laptop computer is used by the experimenter as an interface with the robots during the trials.

It is important to note that these platforms do not allow us to reproduce the dynamics of real vehicles: they start moving for commands greater than 100 mm/sec, and stop almost instantaneously when a velocity between 0 and 100 mm/sec is provided. But as indicated in Section II, our interest is on the tactical level, and therefore we do not need to recreate dynamics similar to real vehicles.

Obstacle avoidance on the robots is done using sonars. Robots visually localize and identify each other using their illuminated colored cylinders (O for orange, Y for yellow, B for blue). Relative positioning of the vehicles is therefore directional (i.e., restricted by the field of view of the camera and its pointing direction), limited (less than 3.5 m), noisy (based on color segmentation in real life settings [36]) and imprecise. The position of the colored blob in the image [41] is used to evaluate the relative angle between two vehicles; knowing the size of the cylinders, the blob area approximates their relative distance (with an accuracy of ±150 mm). Images are processed at a rate of 10 frames per second. Such experimental framework imposes strong constraints on vehicle localization capabilities, increasing the need for communicated information between the vehicles to coordinate their actions. It also imposes the use of only three vehicles at a time, since perceiving more than three colors with closely space robots did not revealed to be reliable enough for our trials. Also, in relation to the eight coordination scenarios, only scenarios *Decentralized*, $M \rightarrow F$, $M \leftrightarrow F$, $M \leftrightarrow F/L$ and *Centralized* were validated in these trials: since leading vehicles could not see their followers, it is not possible to make the leaders act to create the necessary conditions for the maneuvers to be accomplished. In the next two subsections, two experimental protocols are validated, one for entering and exiting maneuvers and the other on recovery procedures in failure situations.

A. *Entering and Exiting the Platoon*

Starting with an empty platoon (i.e., with only the platoon conductor (O)), this experimental protocol consists of having a first vehicle (Y) enter the platoon, placing itself at its rear end. Then, another vehicle (B) enters the platoon by joining in between the two. Once this maneuver completed, the conductor of the train initiates a stop-and-go maneuver. The second vehicle (B) that entered the platoon then exits. To evaluate the impact of an unforeseen event during a maneuver, vehicle O stops during the exit maneuver. Vehicle B proceeds with the exit maneuver in such condition. Vehicle O then starts to move again, and vehicle *y* exits and leaves O alone in the platoon.

The conductor is normally set to move at 400 mm/sec. *Obstacle avoidance* is done at 300 mm/sec, while *Maneuvers* operates at 500 mm/sec. Obstacle avoidance with the mobile robots is done at a slower speed to ensure the security of the platforms using sonars as proximity sensors[4]. Operation in the platoon is safer in terms of perceptual situations (following a vehicle based on visual information, and conducting the train using laser range finder data). Inter-vehicle distance is set according to the velocity of the lead vehicle (specifically 1.5 m with C at 400 mm/sec, and 0.8 m when the platoon stops). The particularities of using the coordination scenarios presented in Section III within such experimental framework, and using the same nomenclature to identify vehicles (L for leader, F for follower, M for maneuvering vehicles), are set as follows:

- *Decentralized*. In this scenario, vehicles do not communicate with each other. For entering the platoon, vehicle M just joins in by following the first vehicle it detects (L). Vehicles in the platoon are set to follow each other at 2.0 m intervals, to provide enough space for F to see M and decrease its speed to provide safe entering maneuvers. Once M is within 5° in the center of F's field of view, F is set to follow M. For exiting a platoon, this scenario can only work with vehicles that are at the rear end of the train, since it is not possible for F following M to recognize an exiting maneuver without being able to perceive L and determine on its own that M is leaving the train. Communication between the vehicles is therefore necessary to avoid having the platoon split in two.
- $M \rightarrow F$. Once it detects L, vehicle M broadcasts its intention to follow L and initiates the maneuver. Its current follower, if one exists, recognizing the color of its leader, decreases its velocity to provide space for letting M enter the platoon. Vehicle M enters the platoon when it perceives that there is free space to do so. If a problem occurs with M (e.g., having to avoid an obstacle), it communicates with F to abort the maneuver. Otherwise, once in position in the platoon (i.e., with L within 5° in its field of view), vehicle M signals F that it is now its new leader. To exit, a similar procedure takes place: vehicle M signals to F (if there is one) its intention of leaving the platoon and the identification of its future

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[4] Note that sonars are deactivated for robots in the platoon, to avoid crosstalk. They are reactivated before a robot executes a maneuver.

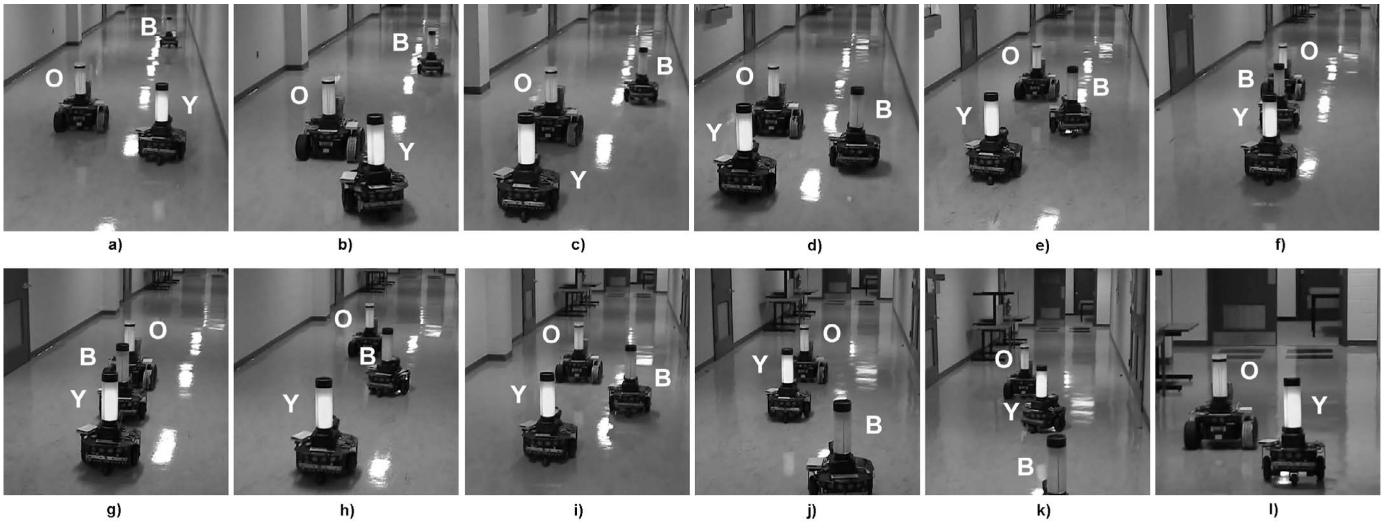

Fig. 3. Scenes of the entering and exiting experimental protocol: a) conductor O passes near vehicle Y; b) vehicle Y maneuvers to follow vehicle O; c) two-vehicle platoon with O and Y; d) vehicle B detects vehicle O; e) vehicle B enters the platoon; f) vehicle Y follows vehicle B, now part of the platoon; g) stop-and-go; h) vehicle B exits the platoon; i) vehicle Y closing in on O, its new leader; j) two-vehicle platoon with O and Y; k) vehicle Y exits; l) exit maneuver for vehicle Y done.

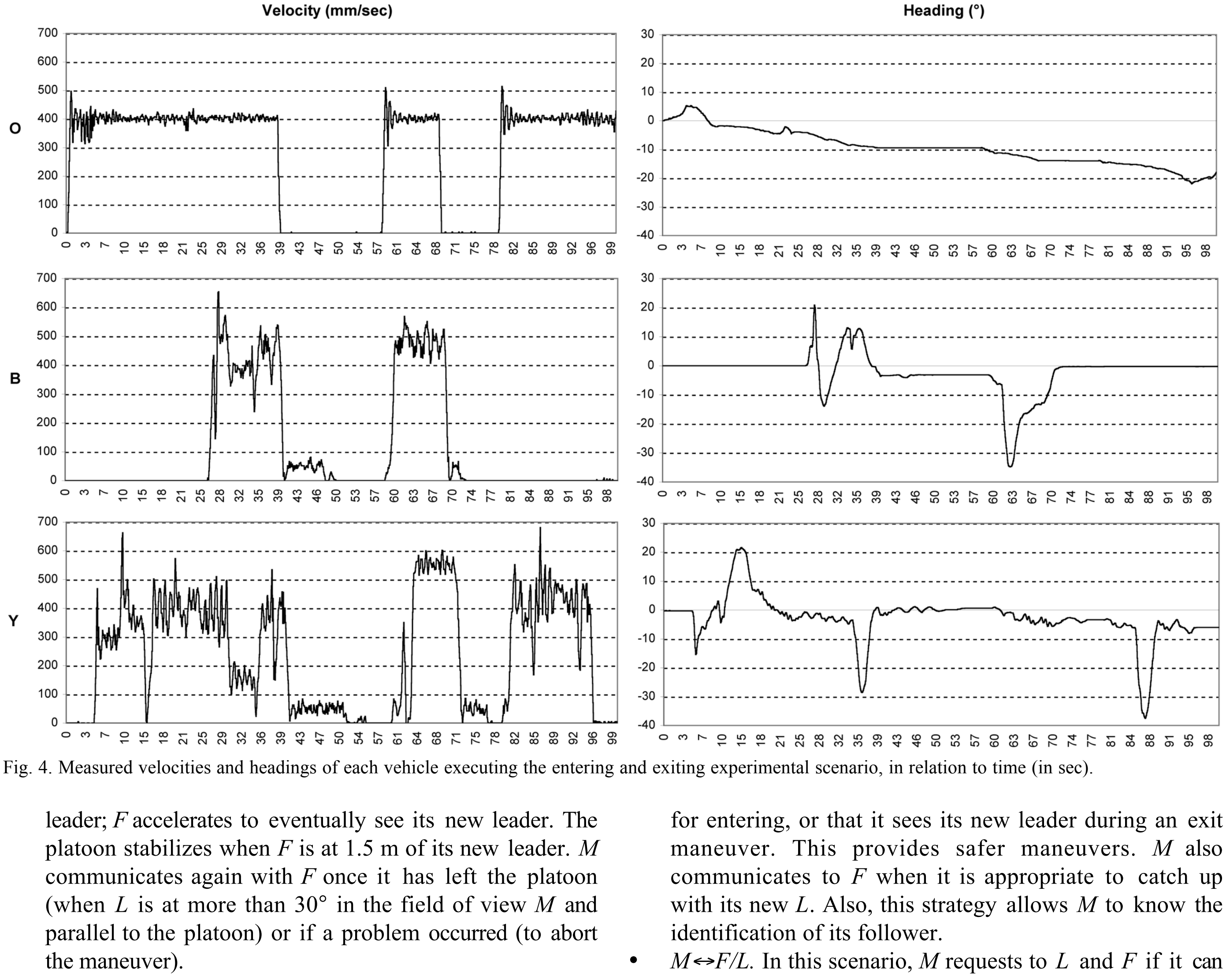

Fig. 4. Measured velocities and headings of each vehicle executing the entering and exiting experimental scenario, in relation to time (in sec).

leader; *F* accelerates to eventually see its new leader. The platoon stabilizes when *F* is at 1.5 m of its new leader. *M* communicates again with *F* once it has left the platoon (when *L* is at more than 30° in the field of view *M* and parallel to the platoon) or if a problem occurred (to abort the maneuver).

- *M↔F*. This scenario is similar to scenario *M→F*, except that *F* can now communicate back with *M* to confirm that it can enter or exit the platoon, that free space is available for entering, or that it sees its new leader during an exit maneuver. This provides safer maneuvers. *M* also communicates to *F* when it is appropriate to catch up with its new *L*. Also, this strategy allows *M* to know the identification of its follower.
- *M↔F/L*. In this scenario, *M* requests to *L* and *F* if it can enter the platoon. If it is possible, *M* communicates with *F* according to scenario *M↔F*. Once in position, *M* communicates with *L* and *F* to confirm that the maneuver

was successful. At any time, *M*, *L* or *F* can request to abort the maneuver if a problem is detected. For instance, if *L* or *F* perceives that an obstacle is approaching or that another maneuver is taking place, it can communicate that information to *M*. To exit, a similar procedure is followed: *M* asks *L* and *F* to exit the platoon; if conditions are adequate, *M* is allowed to proceed; once out of the platoon, *M* indicates to *L* and *F* that the maneuver is completed.

- *Centralized*. This scenario is similar to scenario *M↔F/L* except that it is *L* (and not *M*) that coordinates the actions of the group. Once *M* requests to either enter of exit the platoon, *L* takes charge and communicates with *F* to confirm that the maneuver can be executed. It then communicates with *M* and *F* to initiate the maneuver. Once in position, *M* communicates with *L* which relays the information to *F* confirming that the maneuver was successful. The exit maneuver follows a similar procedure, with all communication going through *L* except for the final message from *M* indicating the completion of the maneuver.

1) Illustration of a Typical Trial

Fig. 3 and Fig. 4 illustrate a typical trial, in this case using coordination scenario *M→F*. Looking more closely to Fig. 4, it is possible to recognize from O's velocity profile (measured using the robot's wheel encoders) the entering phase (0 to 39 sec), the stop-and-go phase (39 to 58 sec), vehicle B exiting while O stopped (58 to 78 sec), and the exit of vehicle Y (78 to 99 sec). Regulation of O's heading is done to make the robot remain in the middle of the corridor. Since O's heading is shown in reference to its initial orientation during the trial, the graph shows that the vehicle is moving relatively straight forward once it gets in position in the corridor. Vehicle Y is the first to join the platoon, and is capable to follow vehicle O, keeping its velocity at around 400 mm/sec starting 22 sec. At 26 sec, vehicle B is allowed to move by the experimenter, and at 29 sec it starts tracking vehicle O. At 34.5 sec, vehicle Y starts to track vehicle B instead of O, as seen from the short change in the vehicle's heading[5]. Vehicle B considers itself to be in the platoon at 39 sec. The same vehicle initiates (activated by the experimenter) an exit maneuver at 61 sec, and vehicle Y joins back O at 71 sec. It then proceeds to exit the platoon from time 85 to 95 sec.

Fig. 5 illustrates the distance perceived between a vehicle and its leader. As seen from the graph, visual perception of the vehicle is quite noisy. From 9 to 34.5 sec, vehicle Y tracks vehicle O. It then switches to vehicle B that entered the platoon. Vehicle B tracks vehicle O at 1.5 m until it stops (time 39 sec); it then comes closer to vehicle O (0.8 m) before stopping. A similar behavior is observed for vehicle Y. The platoon starts to move again, and when vehicle B begins to exit, vehicle Y looses sight of its new leader O, since the distance between the two vehicles is at the limit of the sensing capabilities of the vision system used by the robots. However, the vehicle is rapidly capable of localizing vehicle O, and closes the gap between the two vehicles (time 71 sec). It then proceeds to exit and stops, with O moving away. With strategies *M↔F/L* and *Centralized*, *L* is notified when an exit maneuver is initiated, allowing it to slow down and help *F* to see *L* right away.

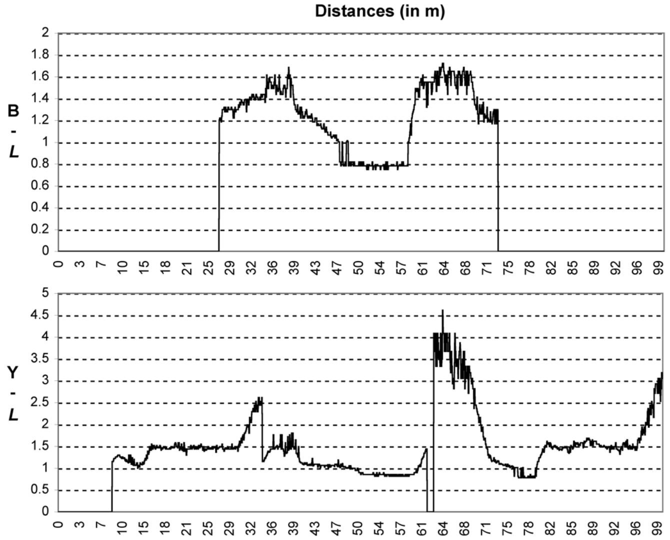

Fig. 5. Distance measured using color segmentation of vehicles with their assigned leader, in relation to time (in sec).

TABLE I

MEASURED TIME INTERVALS IN SEC FOR ENTERING / EXITING THE PLATOON

Strategy	Y-O		Y-B-O	
	Average (sec)	Std (sec)	Average (sec)	Std (sec)
Decen.	16.780 / NA	3.773 / NA	10.367 / NA	0.321 / NA
M→F	12.383 / 3.476	1.022 / 0.564	12.216 / 8.532	1.248 / 0.930
M↔F	16.127 / 3.582	2.468 / 1.023	13.076 / 7.976	1.972 / 1.309
M↔F/L	14.178 / 3.170	2.764 / 0.090	14.235 / 8.140	1.261 / 0.802
Centra.	15.166 / 3.814	4.772 / 2.069	15.764 / 9.302	2.173 / 2.440

TABLE II

NUMBER OF MESSAGES EXCHANGED DURING MANEUVERS

Strategy	ENTERING		EXITING	
	Y-O	Y-B-O	Y-O	Y-B-O
Decen.	0	0	0	0
M→F	2	2	2	2
M↔F	6	3	4	0
M↔F/L	3	4	6	3
Centra.	3	6	8	3

2) Results of the Coordination Strategies

We conducted five trials per coordination strategy, in straight and curve trajectories. Since similar results were observed in both cases, we only present here the observations in straight trajectories. Note that because of the imprecision of the vision system to localize robots and the good quality of the communication media, it is difficult to derive statistically significant comparisons between the coordination strategies. This makes time performances very similar between the strategies. Instead, our goal with this set of trials was mainly to demonstrate their feasibility (and validate the hypothesis that strategies other than centralized can be use to coordinate

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[5] This is caused by the *Follow* behavior, set to work the same in maneuvers (entering, exiting, lane change, etc.) to handle all situations with noisy and imprecise visual sensing of the robots.

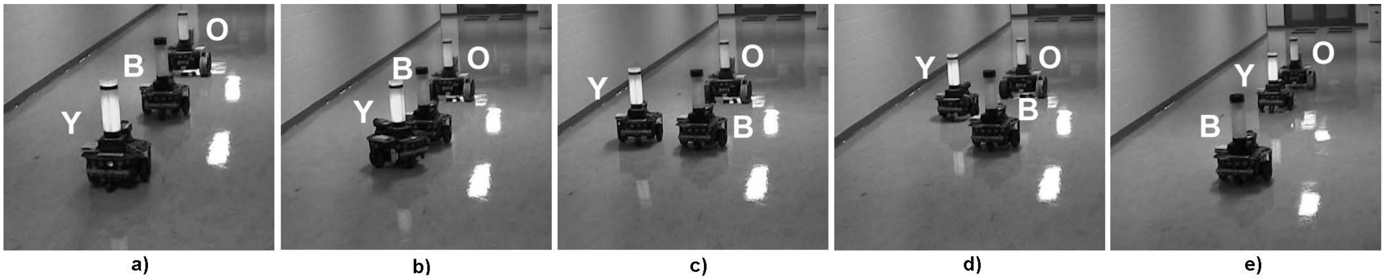

Fig. 6. Scenes of a recovery procedure with vehicle B failing in the platoon, using the *Centralized* coordination scenario: a) initial platoon; b) emergency maneuver initiated; c) vehicle Y avoids vehicle B, with vehicle O slowing down after having been notified of a problem with vehicle B; d) vehicle Y catching up with vehicle O; e) new platoon created, with vehicle O now at normal velocity.

the maneuvers of a train of vehicles), and illustrate trends derived from their usage.

Overall, the experimental protocol was successfully in all trials, except for the *Decentralized* scenario: vehicle B was successful entering the platoon three times over five trials, and as expected vehicle Y could not regroup with vehicle O when vehicle B exited the platoon. These results confirm the limitations with the *Decentralized* scenario, and the feasibility of all the others. Table I presents the observed period to execute the entrance (Y-O when Y joins O, Y-B-O when B joins the Y-O platoon) and exit (Y-B-O when B exits the platoon, Y-O when Y splits from O) maneuvers following our experimental protocol. Except for Y-O entering maneuvers using strategy *M↔F*, average times and standard deviations increase with the number of communication exchanges of the coordination strategies. A similar observation can be noted for exit maneuvers, except for vehicle B and strategy *M→F*. Measures for *Decentralized* should not be compared with others since a longer inter-vehicle distance was allowed and results were obtained on a smaller set of successful trials.

To illustrate the communication load involved with these maneuvers, Table II summarizes the number of messages exchanged when entering or exiting. The reason why more messages are sent in strategy *M↔F* for the entering Y-O case is that Y is waiting confirmation by a possible follower to initiate the maneuver; after six attempts (set empirically), vehicle Y infers that there is no follower to O and enters the platoon. For exiting, since *M* knows that it does not have a following vehicle, no message is sent. *Centralized* coordination requires additional communication exchanges since *M* communicates changes to *L* that relays them to *F* for having other actions take place in the platoon.

B. Failure While Platooning

This experimental protocol involves *L* experimenting a failure (e.g., a collision, system failure). A failure is initiated by the experimenter using the graphical user interface and the *Collision Emulator* BPM (see Section IV). The objective here is to explore the possibilities provided by the coordination strategies for handling an important failure while vehicles are in platoons. Looking at the coordination scenarios used in Section V.A, the possibilities are:

- *Decentralized*. With no communication allowed between the vehicles, vehicle *M* cannot know what *L* is doing. Therefore, it would normally stops as if the platoon just came to a full stop. However, multiple situations can occur during a collision. For instance, the vehicle can come to a complete stop, deviate from its trajectory, or even move backward because of the impact. So, with the *Decentralized* coordination strategy, *M* simply cannot take any precautionary actions to prevent from a potential collision with *L*.
- *M→F*. To take precautionary actions, vehicles must be able to communicate that there are operational (periodically sending a message like “I am alive”) or that a failure as occurred (e.g., deployed by the air bag unit when a collision occurs). This coordination strategy allows *M* to be notified that a problem occurred, and anticipates the problem. Once *M* has avoided *L*, it can either stop (to implement a fail-safe mode) or proceed to merge with the upper portion of the platoon if it is visible. Such maneuver would for instance facilitate access to an accident area.
- *M↔F*. In our trials this is similar to scenario *M→F*, since having *F* communicate back with *M* will not affect its decision. It could contribute however in helping *M* decide what to do based on sensed information from the rear portion of the platoon.
- *M↔F/L*. With this scenario, the vehicle preceding *L* can be notified that a failure has occurred. The front part of the platoon can then slow down for a potential merge with the rear part of the platoon.
- *Centralized*. This scenario is similar to scenario *M↔F/L*, except that it is the vehicle preceding *L* (and not *M*) that coordinates the actions of the group.

Fig. 6 illustrates a typical case of reconstructing the platoon after a failure has occurred. A collision is simulated with vehicle B, making it go backward at 100 mm/sec for 3 sec. We conducted five trials for each coordination scenario. With scenarios *M→F*, *M↔F* and *M↔F/L*, a failure condition was detected by not receiving the “I am alive” message for 4 consecutive cycles (requiring 400 msec), while for the *Centralized* scenario vehicle *L* communicated directly its failure state (requires 100 msec).

Table III presents the results observed over the twenty-five trials. With the *Decentralized* scenario, vehicle Y does not have enough time to avoid vehicle B and both collide. When vehicle Y is notified that a problem occurred with B, three times it can avoid colliding with B and safely stops (with not enough space to avoid B however). This was observed both with scenarios *M→F* and *M↔F*. Using scenario *M↔F/L*, vehicle Y was capable once to avoid vehicle B, but still was not able to perceive vehicle O. Catching up with the leader (i.e., having F accelerates to follow L, the leader of M) was a maneuver observed twice with the *Centralized* scenario, outlining the importance of rapid notification of a failure inside the platoon.

TABLE III
RECOVERY RESULTS AFTER A COLLISION IN THE PLATOON

Strategy	Collision	Stop	Avoid	Catch up
Decen.	5	0	0	0
$M \rightarrow F$	2	3	0	0
$M \leftrightarrow F$	2	3	0	0
$M \leftrightarrow F/L$	2	2	1	0
Centra.	2	0	1	2

These results demonstrate that different maneuvers can be accomplished to handle a failure occurring in platoons. Note that only a subset of possible cases was validated with our three robots and their visual capabilities, and more can be done following the coordination scenarios to propagate information in platoons for increased safety. Selecting the most appropriate recovery procedure to use in such situations is another issue to study in future work, always considering their requirements in terms of communication exchanges and perceptual capabilities of the vehicles.

VI. CONCLUSION

This paper addresses cooperative driving in terms of sensing and communication exchanges between vehicles. While it is agreed that communication is required with cooperative intelligent vehicles, it is important to identify the information exchanges required to make vehicles operate safely and efficiently. Globally, such work requires dealing with a large set of issues, from enabling technologies such as sensing, control, string stability [15] [16] and communication protocol [42], to their integration into a working system. Our contribution is oriented toward the integration aspect, studying the exchange of information between vehicles at the tactical level for coordinating their maneuvers in dynamic platooning conditions.

Our objective is to move away from the traditional model of centralizing decision toward the platoon leader, which requires higher communication bandwidth and processing load with the number of vehicles in platoons. Failure of the platoon leader would also be catastrophic in this case. On the other hand, it is unrealistic to believe that each vehicle would be capable of directly sensing everything that is going on in platoons: communication is required. Decentralized schemes (without communication between the vehicles) are therefore not a solution. Instead, we demonstrate that maneuvers can be accomplished using distributed and local approaches, following different communication scenarios (such as $M \rightarrow F$, $M \leftrightarrow F$ and $M \leftrightarrow F/L$) between vehicles. As a general observation from the experiments conducted, increased communication between vehicles results in more precise identification of the vehicles' states while maneuvering, which comes with higher cost in terms of time (which can be small if the communication medium is fast) and complexity (to ensure synchronization of the information shared by the vehicles). Minimizing complexity and response time while maximizing safety is the goal. This has to be set according to the sensing and communication capabilities of the vehicles. Such demonstration opens up a new set of requirements for sensing and communication schemes used to make cooperative driving systems. One possible use of our results would be to help establish communication requirements (in terms of range, broadcast versus point-to-point communication, and coherence of the information shared by the vehicles) for devices to be used with real vehicles, looking to minimize cost while still ensuring robustness, and finding the right combination of sensing and communication capabilities to install onboard in vehicles.

At the very least, automated vehicles in platoons must be capable of localizing each other, and this influences what needs to be communicated. To compensate for sensing limitations caused from having a limited (directional) view of the world with an imprecise localization of other vehicles, communication allows maneuvers (entering, exiting and recovering from a failure) to be executed adequately. Using mobile robots capable of directional vision, short-range obstacle avoidance and broadcast communication of information between vehicles in close proximity, we have characterized what each coordination scenario brings in terms of maneuvering capabilities and communication load. With our experimental settings, our results indicate that performance of coordination strategies is affected by the maneuver and the position of the vehicle in the platoon: $M \rightarrow F$ is better for entering maneuvers, while $M \leftrightarrow F$ is better in terms of time for exiting between two vehicles and $M \leftrightarrow F/L$ when splitting from the end of the train. So, instead of confirming that one distributed coordination scenario is the best in all possible cases, our results suggest that different coordination strategies may be used, as long as robustness is preserved in handling all possible situations that can occur while platooning. Fusing the information sensed by multiple sensors (e.g., combining absolute positioning using GPS with relative positioning device using vision and proprioceptive data derived using an inertial measurement unit) will surely be required for real vehicles.

The next phase in our work is to validate these trends using different sensing capabilities on the vehicles. We plan to use ultrasonic relative positioning devices [43] to localize robots in the platoon, providing omnidirectional, more reliable information and richer information for coordination of maneuvers in the platoon. More sophisticated maneuvers will be tested, such as simultaneous entering and exiting of vehicles in the platoon. After having identified the additional benefits of omnidirectional perception of vehicles, we plan to implement a robust distributed coordination scenario on real autonomous land vehicles for field testing. In an implementation using real vehicles, more than one of these coordination strategies may be required to provide robustness in handling all possible situations that can occur while platooning.

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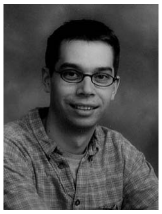

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