Team AnnieWAY's Entry to the 2011 Grand Cooperative Driving Challenge

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***Abstract*—In this paper, we present the concepts and methods developed for the autonomous vehicle known as AnnieWAY, which is our winning entry to the 2011 Grand Cooperative Driving Challenge. We describe algorithms for sensor fusion, vehicle-to-vehicle communication, and cooperative control. Furthermore, we analyze the performance of the proposed methods and compare them with those of competing teams. We close with our results from the competition and lessons learned.**

***Index Terms*—Autonomous vehicles, cooperative driving, V2X communication.**

I. Research Background and Team Composition

In THE following, we give a brief review of the history of cooperative driving and introduce our team *AnnieWAY*, with which we entered the 2011 Grand Cooperative Driving Challenge.

A. Cooperative Driving and the GCDC

Driver-assistance systems already help make vehicle navigation safer and more comfortable. Nevertheless, one of the main challenges remains unsolved: An increasing amount of traffic on the streets causes congestion and environmental pollution. Traffic jams result from inhomogeneities in traffic flow, and consequently, longitudinal vehicle control plays an important role in avoiding them. However, human factors such as reaction time and perception constraints limit the possibilities to improve traffic homogeneity.

The technical basis for autonomous longitudinal control such as electronic brake and throttle has been laid by the emergence of adaptive cruise control (ACC) systems [1], which employ radar for measuring the distance and speed of a leading vehicle. However, standard ACC systems only control the vehicle's speed, depending on the distance and velocity of the vehicle directly ahead, neglecting the overall traffic situation. While these systems undoubtedly improve driving comfort, their influence on traffic homogeneity is still disputed [1], [2]. One idea to resolve these shortcomings and improve traffic homogeneity is to use vehicle-to-vehicle communication to provide the vehicle with information about the current traffic situation. If multiple vehicles ahead can be accounted for, more elaborated control approaches can be employed.

Fig. 1. One heat of the GCDC with six competing vehicles. AnnieWAY from Karlsruhe Institute of Technology is the silver vehicle directly in front of the truck.

Most approaches for cooperative driving are based on the assumption of identical technical equipment and use of the same control strategy for all vehicles in a platoon. This assumption cannot be made in the real world: different vendors will use different technical solutions. Older vehicles might use techniques that are different from those employed in newer ones. Furthermore, passenger cars, vans, trucks, and buses will be mixed on the same lane, and autonomous vehicles will share roads with manually driven cars.

The *2011 Grand Cooperative Driving Challenge* (GCDC) [3] was the first competition to implement such a realistic heterogeneous scenario. It was organized by the *Netherlands Organisation for Applied Scientific Research* (TNO) in Helmond. Participating teams had to come up with strategies that were able to perform as good as possible without knowing the algorithms and technical equipment of other vehicles in the platoon. Control strategies had to cope with unexpected behavior of other vehicles, varying data quality, and sudden failure of communication, among others. Fig. 1 shows one heat of the GCDC, illustrating the large variety of vehicles and technical solutions in the competition.

B. State of the Art of Cooperative Driving

Cooperation among traffic participants plays an important role in everyday life to ensure traffic safety and traffic flow [4],

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e.g., resigning one's right of way at a crossroads or allowing other vehicles to merge on one's own lane are frequent behaviors that are most beneficial to all traffic participants and may even resolve critical situations. While human drivers are still superior to automated vehicles in many situations, machines are able to negotiate cooperative driving maneuvers significantly faster and with fewer misunderstandings than humans.

Progress from intensive international research on automated cooperative driving has been demonstrated by numerous demonstrations. In August 1997, *Demo '97* took place in San Diego, CA, showing impressive results from the U.S. National Automated Highway System Consortium (NAHSC) on self-driven vehicles. A platoon control demonstration showed cooperative platoon driving of up to eight identical vehicles on the instrumented freeway I-15 that was closed to the public. The vehicles were automatically driving at 6.5-m spacing and at 60 mi/h (97 km/h). The key technologies were distance keeping using radar, lidar, video, and intervehicle communications, as well as lane following via roadway embedded magnets, roadway laid radar-reflective stripes, or existing visible lane markers detected with vehicle-mounted cameras [5], [6]. In *Demo 2000*, the National Institute of Advanced Industrial Science and Technology presented cooperative platoon driving of five vehicles on a test track in Japan, which included more advanced maneuvers such as stop-and-go, merging, and obstacle avoidance [7]. In May 2003, a platoon of three heavy trucks was presented by the European *CHAUFFEUR* project capable of cooperative cruise control, lane keeping and concerted lane change, and active obstacle avoidance maneuvers [8]. The German Karlsruhe-Munich Collaborative research center *Cognitive Automobiles* (2006–2010) has developed methods for ad-hoc group formation and joint overtaking, and emergency maneuvers of automated vehicles [9], [10]. Small autonomous and cooperative passenger vehicles were presented by the European *Cybercar 2* consortium in September 2008 in France. The vehicles were designed for low-speed autonomous cooperative city transportation capable of automated coordinated driving and cooperative intersection traversal [11]. Recently, in May 2011, the European *INTERSAFE 2* consortium demonstrated left turn warning, inhibition of acceleration, and automated braking in case of an imminent collision with oncoming traffic on an intersection closed to the public in Germany. The vehicles were equipped with laser sensors, cameras, differential Global Positioning System (GPS), a map of the intersection, and a V2X communication system. Additional laser sensors, cameras, and communication devices were mounted at the infrastructure [12], [13].

C. Team AnnieWAY

Team AnnieWAY is a group of researchers hosted at Karlsruhe Institute of Technology. Its overall goal is to develop and integrate new techniques for autonomous driving and to compare these techniques (e.g., on benchmarks and competitions) to other approaches. Based on the experiences made during the 2005 DARPA Grand Challenge [14] in a mixed team with Ohio State University, team AnnieWAY was formed to participate at the 2007 DARPA Urban Challenge [15] with its own vehicle called *AnnieWAY*.

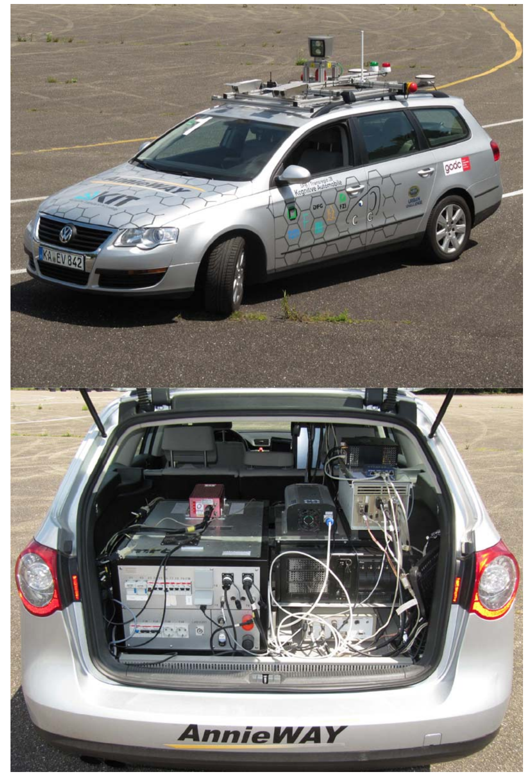


Fig. 2. Experimental vehicle (top) with its technical equipment in the trunk (bottom). The bottom image shows the power supply on the left, the GPS/INS unit on top (red box), and the control computers on the right.

The research focus of team AnnieWAY is mainly in mobile perception and scene understanding based on video and lidar sensors. This includes sensory-processing techniques such as real-time stereo matching [16], [17], 3-D scene reconstruction [18], and map generation from stereo image sequences [19], as well as scene segmentation [20] and scene understanding [21], [22]. In lidar data interpretation for autonomous vehicles, the team works on efficient segmentation [23], object tracking [24], and map generation techniques [25].

To be able to fully autonomously run a vehicle, the team also develops methods for path and trajectory planning. This includes efficient collision checking [26], trajectory generation based on fast lattice search [27], and control strategies for path and trajectory following [28], [29].

The remainder of this paper is organized as follows: In Section II, we describe our experimental vehicle, as well as the general software and hardware architecture of our system. In the subsequent sections, we discuss individual components such as the communication modules (see Section III), the environment representation (see Section IV), and the control strategy (see Section V). The final section wraps up our results and highlights lessons we have learned during our participation in the GCDC.

II. Experimental Vehicle and System Architecture

Our experimental vehicle AnnieWAY (see Fig. 2) is equipped with several modifications over the VW Passat base vehicle: Electronically controllable actuators for acceleration, brakes,

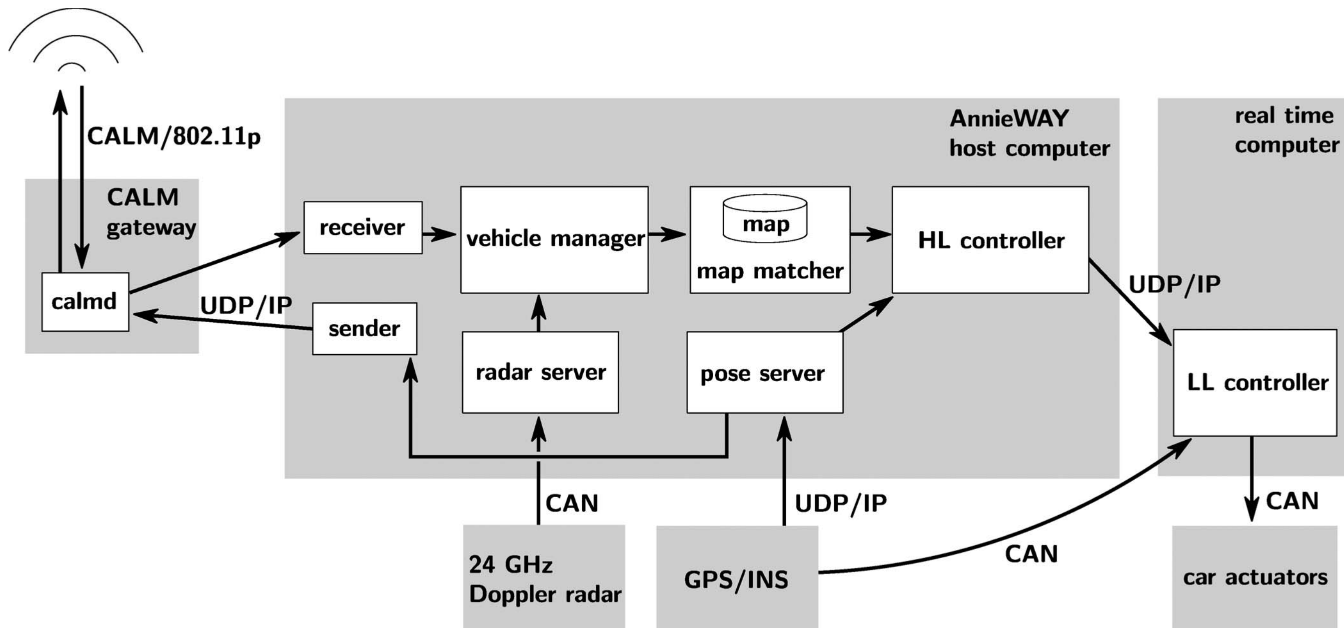


Fig. 3. GCDC system architecture. See Section II for explanation.

transmission, and steering have been added, each of which can be individually enabled. A controller area network (CAN) gateway allows sending requests to these actuators and receiving selected signals such as wheel speeds and status information. It additionally implements low-level safety components such as disengagement of autonomous functions in case that the driver needs to interfere.

Fig. 3 shows the technical components and data flow of our system employed at the GCDC. Gray boxes symbolize hardware devices, whereas white boxes illustrate software components. In the following, we briefly explain the purpose of the individual components within the categories sensors, computers, and software.

a) GPS/inertial navigation system (INS): Self-localization of the ego-vehicle is implemented by a combined inertial and satellite-based navigation system,[1] which can optionally be augmented by terrestrial reference stations. Using real-time kinematics correction, it provides precise position, velocity, and acceleration of the host vehicle.

b) 24-GHz Doppler radar: Communication-based information on other vehicles is supplemented by the radar as part of the vehicle's standard ACC system. We decided to use it for robustness reasons in case that transmitted positions of other vehicles become unreliable. The radar component is connected to the system via the vehicle's CAN bus.

To process sensor data, to plan and control AnnieWAY's trajectory, and to communicate with other vehicles, a total of three computers are installed in the vehicle's trunk.

c) AnnieWAY host computer: A Linux-based server computer performs most higher level control- and data-processing tasks. It is equipped with two six-core central processing units. A real-time database [30] serves as a virtual bus system for interprocess communication. It enables both synchronous and asynchronous queries, as well as recording and replaying of data streams.

d) Real-time computer: The connection to the prototype vehicle itself is made through a modular rapid prototyping system[2], which can meet hard real-time requirements for critical tasks such as actuator control, driver intervention handling, fail-safe functionality, and feedback trajectory stabilization. In particular, the latter is important for the GCDC as it implements the low-level acceleration controller described in Section V.

e) CALM-gateway: A separate x86-based Mini-ITX personal computer has been added for 802.11p-based communication. It runs the CALM daemon and dispatches incoming and outgoing data packages.

The architecture is completed by a set of software modules, each providing a building block to the actual GCDC system:

f) Vehicle manager: This component receives vehicle information broadcast from other platoon members and augments it with radar data. The main purpose of the Vehicle Manager is to abstract from the latency of the received data: Through extrapolation and filtering, it can provide an estimate of the platoon state at any given point in time.

g) Map matcher: The Map Matcher is responsible for assigning vehicles to lanes and hence decides which of them are in the same platoon as the host vehicle. Furthermore, it computes geodesic distances between vehicles, which serve as inputs to the high-level controller module.

h) Pose server: This process interfaces to the GPS/INS hardware via User Datagram Protocol (UDP)/Internet Protocol (IP).

i) Pose server—Radar server: This process interfaces to the radar sensor via CAN bus.

j) Pose Server—Low-level (LL) controller: The low-level controller receives a reference acceleration from the main

[1]OXTS RT 3003.

[2]dSPACE AutoBox with DS1005 PPC Board.

computer and stabilizes it based on readings from the GPS/INS. It is connected to all actuators through a CAN gateway.

k) High-Level (HL) Controller: Based on the platoon state, the high-level controller determines an optimal acceleration of the host vehicle to be passed downstream to the low-level controller.

III. Intervehicle Communication

Intervehicle communication consists of a hardware and a software layer, which will be discussed in the following sections.

A. Hardware and Drivers

The communication hardware is based on the 802.11p standard, which is an amendment to the popular wireless local area network (LAN) standard 802.11 [31] that is widely used in consumer devices. Aside from defining the transmission frequencies, gains, and ranges, the standard also specifies the basic addressing of devices using the medium-access control (MAC) layer, which is also used for wired Ethernet networks. The 802.11p standard broadcasts in the intelligent transport systems band of 5.85–5.925 GHz and was specially derived for car-to-car communication. A good overview over the standard is given in [32].

Team AnnieWAY uses two different hardware modules in the form of mini-peripheral-component-interconnect plug-in boards. For the contest, we settled on a Mikrotik RH52 card and an ECP12-5800 antenna. While testing, we also evaluated the UNEX DCMA-86P2 card, together with a DM-5500S dome antenna. Equipping two cars with the combination of Mikrotik/ECP12-5800 allows for stable communication up to roughly 800 m if an unimpeded line of sight is maintained. The roundtrip (ping) times are between 1 and 50 ms, depending on surroundings, weather, and distance. The UNEX/DM5500S combination only allows for 250–300-m communication range under the same conditions. The ping times are comparable.

The chips on the wireless LAN cards are very similar to comparable 802.11a cards. Still, kernel drivers had to be adapted to access all the required features. We based our implementation on current Atheros 5k drivers from the Linux kernel (ath5k) and on patches from older Atheros drivers provided by TNO, which are the organizers of the GCDC 2011.

B. Software

1) Protocols: The GCDC is not using the IP protocol for communicating; instead, the ISO Communications Access for Land Mobiles (CALM) protocol [33] was chosen. It uses MAC multicasting or broadcasting packages and only offers a limited addressing scheme for peer-to-peer communication. It also does not implement routing ideas but relies instead on important messages being passed on by higher level protocols. CALM is not natively supported by Linux but can be implemented in user space using RAW sockets.

The CALM protocol is very complex and offers a rich feature set and, therefore, high implementation costs. For the GCDC, a small wrapper program that essentially translates incoming broadcast CALM messages to a TCP connection and vice versa called *calmd* was provided by TNO. We based our own calmd implementation on this version but significantly improved upon the feature set and stability. We also added 64-bit compatibility. In our setup, the calmd is running on the ITX CALM gateway computer. Another process on the same computer gathers the packets from the calm daemon via TCP and communicates their content via UDP over a wired connection with the AnnieWAY host computer.

2) Receiver and Sender: Both the receiver and sender processes are running on the AnnieWAY host computer. The receiver is handling all packets that are passed over from the CALM gateway via TCP/IP, tries to unpack the GCDC payload inside the packages, and writes data into the real-time database. If no GCDC payload is found, the packet is discarded. As the CALM protocol does not offer error correction or checksumming, the receiver also implements a number of heuristics that reduce the risk of corrupt packages reaching the database.

The sender observes the database for changes and encodes corresponding GCDC packets, which are then broadcast. As all sources on the host computer are trusted, this software is significantly less conservative in its error checking, compared to the receiver.

3) Auxiliary Software: The combination of the new 802.11p standard, the new CALM protocol, and the new cards with custom drivers proved to be unstable at first. As the communication is crucial for the GCDC, much effort was put into making it as stable as possible. During the implementation, bug tracking, and network hardening steps, a number of tools proved useful. Their benefit and design intentions are discussed in the next paragraphs.

1) *CALM Sender and Receiver*: A pair of scripts that check the number of lost or corrupted packages sent via the CALM protocol over wireless LAN have been implemented. This information is vital in estimating the probability of receiving wrong information. As the CALM protocol does no error detection or correction, data that were received partly scrambled are directly passed on. These scripts also proved useful in detecting buffer over– and underruns in the kernel driver and the user-land libraries. Our system was hardened versus partly scrambled packages by adding feasibility checks of the data: We only accepted packages that were sent with a timestamp of today and GPS position in our vicinity.
2) *CALM Roundtrip Sender and Receiver*: The roundtrip receiver is an echo server for the CALM protocol: it immediately rebroadcasts everything that it receives. The roundtrip sender is sending packages with a fixed content and a defined delay between packages. It also listens for the echo replies and measures the roundtrip time for each package. Usually, networks are designed to value bandwidth over latency, e.g., by collecting many small send requests and combining them into one Ethernet frame. During the GCDC, however, low latency is more important than bandwidth. These scripts helped profiling and optimizing the roundtrip time. Overall, we achieved

to reduce it by one order of magnitude and reached data roundtrip times that are comparable to ping times.

3) *CALM Fuzzer*: To maximize stability and security of network applications, all data received from the outside must be considered unsafe, potentially broken, or even maliciously crafted to exploit vulnerability in the receiving system. To stress test our communication framework, a CALM network fuzzer was written. It floods the network with either completely random data or slightly mutated GCDC payload packages with a very high frequency. This tool helped us in tremendously testing and improving the stability of the network stack. For example, it revealed a number of critical bugs such as crashes and infinite loops in the CALM software stack.

IV. Environment Representation

The GCDC took place on a normal highway with additional infrastructure, i.e., traffic lights and speed limits. Hence, it was sufficient to model the environment as a flat 2-D world. The model was split into a static and a dynamic part. The static environment corresponds to the road with its lanes. The dynamic environment comprises all vehicles, the traffic lights, and the speed limits (which might change over time).

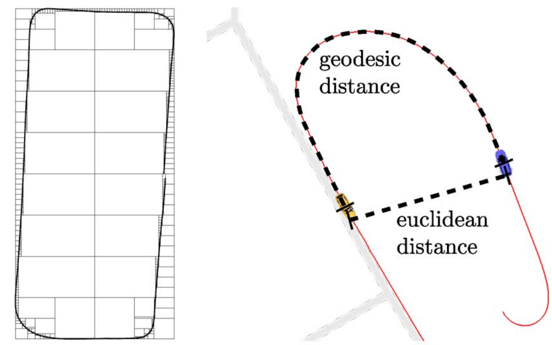
A. Maps and Matching

The GCDC competition involves platooning in scenarios with multiple adjacent lanes. To join a platoon of other vehicles, the correct assignment of vehicles to lanes is important. Furthermore, the controller needs to be precisely informed about the distance to other cars on the vehicle's own lane. We handled this by recording a map of the road *a priori*.

To this end, we recorded the vehicle's GPS coordinates while driving on the right lane. To cope with metric distances, our map implicitly defines a local Mercator coordinate system with its origin anchored at the first point of the GPS track. Our map-creation algorithm subdivides a recorded trajectory into piecewise linear segments of length 0.5 m. Further lanes can be added at a given offset, if required. In the case of the GCDC, a left lane was added 3.5 m next to the right lane, corresponding to the standard highway lane width in the Netherlands. The Mercator coordinates of the vertices are stored in a 2-D kd-tree [34], which is an efficient search structure under Minkowski metrics. Here, we compute exact nearest neighbors using the library *ANN*[3] with respect to the l_2-norm. The kd-tree structure reduces nearest neighbor search complexity from $O(n)$ for the naive algorithm to $O(\log n)$. Time for constructing the tree $O(n\log^2 n)$ can be neglected since this needs to be done only once, i.e., when the map is loaded from disc. An example of a kd-tree space decomposition is shown in Fig. 4(a) for one of our testing grounds, i.e., the Engler-Bunte-Ring in Karlsruhe.

To compute distances in between speed limits, traffic lights, or other vehicles on the own lane, we first assign these objects to their closest lane by retrieving the nearest neighbor GPS track vertex. Each center's coordinate is then projected onto the two connected line segments to obtain its *foot point*. The geodesic distance between two objects is readily obtained by summing the segment lengths falling in between those foot points [see Fig. 4(b)] For efficiency, we precompute geodesic distances of all vertices with respect to the beginning of the respective lane.

[3]http://www.cs.umd.edu/~/ANN/



(a) Kd-tree of map (b) Geodesic vs. Euclidean distance

Fig. 4. Our maps are stored in kd-trees, as shown in (a), for one of our testing grounds. This allows for fast map matching and evaluation of geodesic distances between vehicles on the same lane (b). (a) Kd-tree of map. (b) Geodesic versus Euclidean distance.

B. Vehicles, Traffic Lights, and Speed Limits

All vehicles of the GCDC, including the GCDC leading vehicle, share the same dynamic properties. This allows one to describe each vehicle at time t by a state vector

$$(l, w, \phi, \lambda, \psi, v, \dot{\psi}, a)^T$$

with l and w denoting the length and the width of the vehicle, respectively; ϕ and λ being the GPS position (latitude, longitude) of its geometric center; ψ being the heading; v being the velocity in the direction of the heading; and a being the acceleration in the direction of the heading.[4] In the GCDC, each vehicle broadcasts its own state vector, including the corresponding GPS time. According to the GCDC rules, this information should be precise enough to completely abstain from using other sensors.

Unfortunately, we discovered during the testing weeks that not all teams were able to transmit precise data. (The log of one representative run is shown in Fig. 6.) This mainly led to the following two problems: First, if the position from vehicles physically driving on a neighboring lane were broadcasted to be close to our lane (e.g., due to sensor noise), those foot points of those cars would be projected onto our lane—in the worst case directly in front of us. Clearly, this could cause an emergency brake or wrong platooning behavior. We solved this issue by ignoring all vehicles from the neighboring lane by means of a blacklist, which we manually updated before each run in the competition. Note that this was compliant with the rules of the GCDC and almost all participants made use of it. Second, GPS outage under bridges froze the position of some vehicles, causing our vehicle to stop in cases where we directly followed that vehicle. We were able to solve this issue by using the built-in

[4]The length and width of a vehicle could also be represented outside of the state vector since it does not change over time.

radar sensor. Once the vehicle ahead was within the 50-m range and tracked with high confidence by radar,[5] we put full trust into the radar measurements and ignored any broadcasted position in between our car and the radar's detection.

C. Control Requirements

Our control strategy (see Section V) implements a model-predictive controller, which does not only need the current state of other vehicles but also predicted future states. We achieved this by employing a nonlinear kinematic model that is based on the assumption of constant yaw rate and acceleration, corresponding to the movement on a circle. To achieve a smoother behavior of the controller in the velocity limits, prediction is cropped at those values.

Supplementary to vehicle states, the coordinates and the current state of speed limits and traffic lights were broadcasted from road side units. Their coordinates were directly matched onto the map, as described in Section IV-A, and fed into the controller as additional constraints.

V. Control

In the GCDC, performance of the controller would be judged by the following three criteria [35]:

1) speed: of two competing platoons, the one that first crosses the finish line scores;
2) average platoon length: should be as small as possible, without violating safety margins;
3) stability: A figure describing the stability of the controller was derived from the H_∞ criterion.

Several distinct control-related tasks can be identified.

1) Low-level control transfers desired acceleration into pedal actuation.
2) A follow controller stabilizes the desired safety distance to a single leading car.
3) A platooning strategy stabilizes a platoon of multiple cars.

After a quick recapitulation of requirements, which the GCDC rules impose onto the control strategy, we will deal with each of these tasks in a separate section.

A. Problem Definition and Formalization

Let the platoon consist of N vehicles (only vehicles that are in front of the host vehicle are considered relevant to the platoon). The state of the ith car in the platoon is described by vector $\mathbf{x}_i(t) = (x_i(t), \dot{x}_i(t))$, which contains its position and velocity. Here, position is a scalar quantity that describes the distance traveled on a reference path (cf. Section IV-A). The system model of a single car is assumed to be a simple double integrator, i.e., it has a single input $u_i(t)$, which is its acceleration $\ddot{x}(t)$. Cars are ordered by their position, i.e., $i < j \Rightarrow x_i < x_j$. Hence, the host car has index $i = 0$. Let the complete state of the platoon be the tuple $\mathbf{X}(t) = (\mathbf{x}_0, \mathbf{x}_1, \ldots, \mathbf{x}_{N-1})$.

[5]This was not the case at the beginning of a run, when the leading vehicle was standing still.

Since the arrangement of the GCDC implies a decentralized platooning strategy, we can only control the acceleration of the host car $(i = 0)$. The task of the controller is now to determine the acceleration $u(t)$ for the host vehicle, such that the following conditions hold:

1) Keep safety distance: $x_0(t) < x_1(t) - r + t_h \dot{x}_1(t)$. Here, t_h is a constant headway time, and r (*reserve*) is a constant distance. During the competition, the requirements for headway time and reserve distance were 0.6 s and 20 m, respectively.
2) Keep limits for acceleration a: $-4.5\ (\text{m/s}^2) < a < 2.0\ (\text{m/s}^2)$.
3) Keep limits for velocity v: $0 < v < 100$ (km/h).

B. Low-Level Controller

Under the assumption that a low-level controller is in effect, the host car can be controlled by a single input only, which is its acceleration. Our implementation of this low-level controller consists of two feedforward controllers translating setpoint accelerations into virtual actuations for brake and throttle pedals, respectively. This subdivision is advantageous because feedforward couplings largely differ between both pedals. An integral anti-windup feedback controller compensates for disturbances from wind, slope, etc.

C. Follow Controller

The follow controller will determine an optimal acceleration for the host vehicle based on its current state $(x_0^0, v_0^0) = (x_0(t_0), \dot{x}_0(t_0))$ and the trajectory $x_{\text{lead}}(t)$ of a single leading car. Indices placed to the upper right will designate discrete time indices in this section, with 0 indicating the current time t_0. We assume that $x_{\text{lead}}(t)$ is given. In practice, we generate it under the assumption that the lead vehicle will drive at constant acceleration, except when velocity limits must be respected. Note that the current acceleration of the vehicles in the platoon is known since it is part of the communication protocol. Hence, the control law that we derive has a single output acceleration a, and receives the current position and velocity of the host car, and current position, velocity and acceleration of the leading car as inputs. For reasons that will become clear in the next section, the control law is furthermore parameterized with a specific headway time $\tilde{t}_h$ and safety reserve $\tilde{r}$. We will designate it as function k

$$a = k(x_0^0, v_0^0, x_{\text{lead}}^0, \dot{x}_{\text{lead}}^0, \ddot{x}_{\text{lead}}^0, \tilde{t}_h, \tilde{r}). \tag{1}$$

To determine the optimal acceleration, we minimize the following functional:

$$J[u(t)] = \int_{t_0}^{t_0+T} w_{\text{dist}} [\Delta d(t)]^2 + w_{\text{acc}} [u(t)]^2 + w_{\text{vel}} [\Delta v(t)]^2 \, dt \tag{2}$$

where $\Delta d(t) = x_{\text{lead}}(t) - \tilde{r} + \tilde{t}_h \dot{x}_{\text{lead}}(t) - x_0(t)$ is the error of the safety distance, $\Delta v(t) = \dot{x}_{\text{lead}}(t) - \dot{x}_0(t)$ is the velocity difference to the leading car, and $u(t) = \ddot{x}_0(t)$ is the sought-after acceleration. The functional is evaluated up to the time horizon T (currently 10 s). The functional integrates a weighted sum of the square of these terms, using the weighting factors w_{dist}, w_{acc}, and w_{vel}. First, the w_{dist}-weighted term asserts that the goal of the controller, i.e., reaching the required safety distance, is met. Second, the w_{acc}-weighted term incorporates dampening by penalizing excessive accelerations. Finally, the w_{vel}-weighted term can be tuned to avoid overshoot. All weights were tuned during many experimental runs to give a good balance of comfort and speed.

The functional in (2) can be minimized in closed form by means of the Euler–Lagrange equation, which leads to a system of equations. This, however, does not allow accounting for the limits of both velocity and acceleration explicitly. We therefore discretize (2) by sampling $x_0(t)$ at m equidistant time steps: $x_0^j = x_0(t_0 + j\Delta t)$, $j \in \{0, \ldots m-1\}$. Furthermore, we approximate derivatives $\dot{x}_0$ and $\ddot{x}_0$ at time index j by central finite differences

$$\dot{x}_0^j \approx \Delta_c^2 x_0^j = \frac{x_0^{j+1} - x_0^{j-1}}{2\Delta t}$$

$$\ddot{x}_0^j \approx \Delta_c x_0^j = \frac{x_0^{j+1} - 2x_0^j + x_0^{j-1}}{[\Delta t]^2}.$$

The functional (2) then becomes a finite sum

$$J_d\left(x_0^0, x_0^1, \ldots, x_0^{m-1}\right) = \sum_{j=1}^{m-2} w_{\text{dist}}[\Delta d_j]^2 + w_{\text{acc}} u_j^2 + w_{\text{vel}}[\Delta v_j]^2 \quad (3)$$

with

$$\Delta d_j = x_{\text{lead}}^j - \tilde{r} + \tilde{t}_h \dot{x}_{\text{lead}}^j - x_0^j$$
$$u_j = \Delta_c^2 x_0^j$$
$$\Delta v_j = \dot{x}_{\text{lead}}^j - \Delta_c x_0^j.$$

Minimization of (3) can be treated as an ordinary extremum problem. Equation (3) is a positive definite quadratic form, and both velocity and acceleration limits can be expressed as linear inequalities. Hence, the extremum problem is a quadratic program, which can be solved exactly in a finite number of iterations, e.g., using Goldfarb and Idnani's active set method [36]. The desired acceleration can now be reconstructed from the extremum point again by using finite differencing: $a = \Delta_c^2 x_0^1$.

D. Platooning

Our basic strategy of building a controller that is capable of stabilizing a platoon can be informally described as follows:

- For each vehicle in the platoon, consider this vehicle as a single leading vehicle. Using the control law (1), calculate an acceleration based on the state of this vehicle, using a multiple of the safety distance required between adjacent vehicles. (The safety distance is multiplied by the integer index of the leading vehicle.)

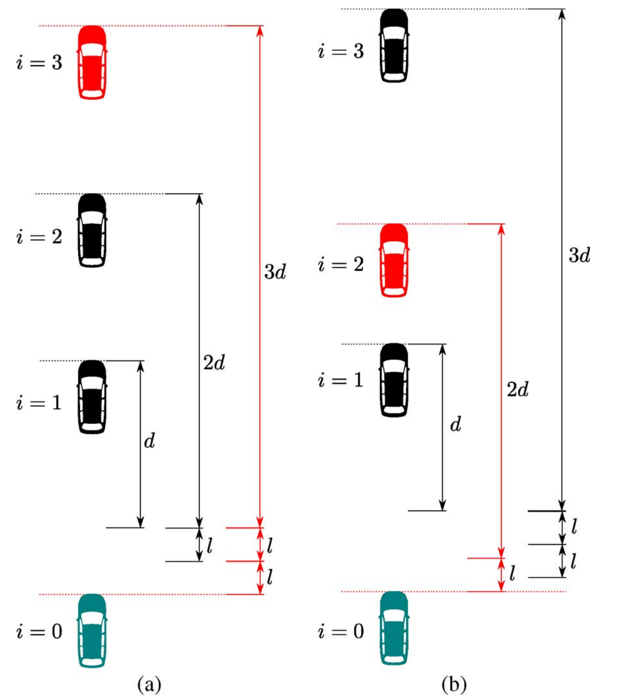


Fig. 5. Platooning strategy for host vehicle ($i = 0$). See text for explanation. (a) Lock on the leader. (b) Lock on the second vehicle.

- Out of all these accelerations, choose the *smallest* one (which is the most conservative one).

To assure stable behavior, a small *loose* or *slack* l is added to the safety distance multiplied by $i-1$, where i is the vehicle index. This assures that, in the steady state, a stable *lock* is established on the leader of the platoon, as shown in Fig. 5(a). This lock will only change if one vehicle deviates from its optimum position by an amount greater than l, as has happened in Fig. 5(b). Without the slack, the lock would, in the presence of noise, very quickly change near the steady state, which is a behavior that could possibly induce oscillation.

On the other hand, when sufficient slack is used, platoon stability directly follows from the stability of the follow controller. Note that Fig. 5(a) and (b), for the sake of clarity, convey the impression that accelerations are determined only based on the distance to vehicles. However, as has been shown in the preceding section, both accelerations and velocities of the vehicles are taken into account as well. If, e.g., in Fig. 5(a), the vehicle with index $i = 2$ was braking very hard, whereas the others would uniformly move, the lock would immediately switch to the braking vehicle since it would be the vehicle that enforces the most conservative action, i.e., the highest deceleration of the host vehicle.

VI. Results and Lessons Learned

Participating in a competition such as the GCDC is a highly motivating experience. We focused on making our vehicle reliably run during the competition. This meant that all components such as communication, sensor fusion, and control had to properly work and that the vehicle and hardware had to be ready in time. During the competition, 15 runs were driven with vehicles randomly assigned to two neighboring lanes. In

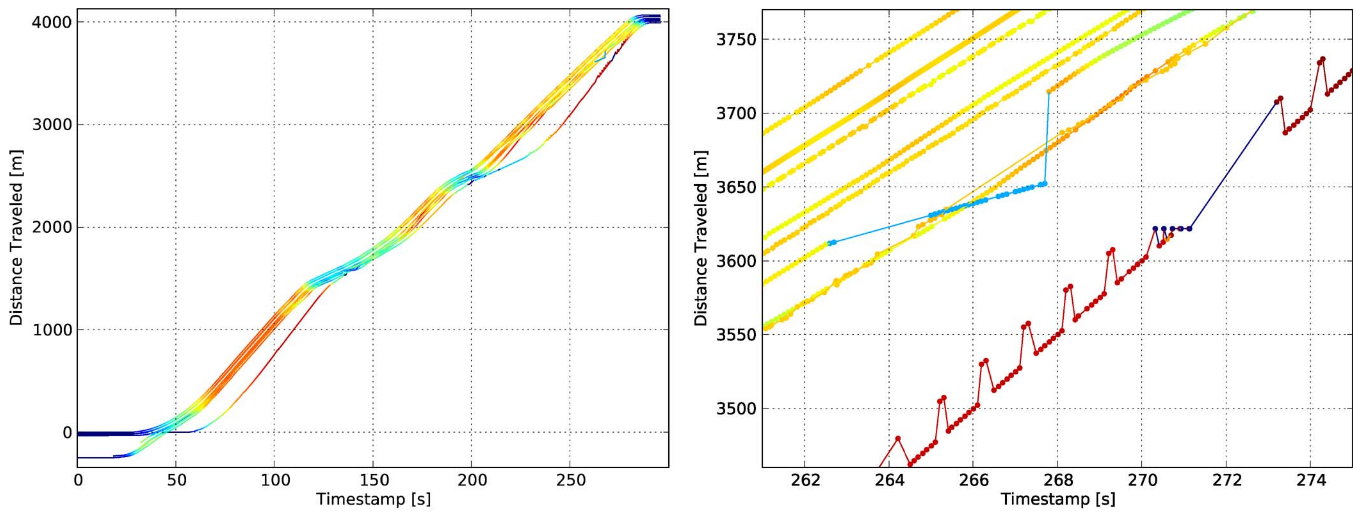


Fig. 6. Path-time diagram of a complete run as received by team AnnieWAY. Each line illustrates the distance of one vehicle over time. Travel distance 0 is defined as the starting position of the lead vehicle. The colors encode the velocity of the cars. Warm colors indicate high velocity; cool colors indicate slow velocity. The right plot shows a zoomed-in version. Here, some problems become apparent, e.g., partly wrong data sent by the last vehicle. The consequences of a highway bridge are also highlighted, as signal loss is poorly handled by some of the GPS/INS systems. (a) Whole run. (b) Detailed view.

summary, our vehicle very reliably drove throughout the whole competition, and all components worked as expected. In the end, we were awarded first place, just barely beating runners-up team Halmstad. The ranking was based on a set of criteria measuring the contribution of a team to the formation of short and stable platoons and measuring the ability to follow the lead vehicle as precisely as possible. The criteria are described in more detail in [3] and [35]. To analyze the system performance in more detail, we will describe the performance of the major components in the subsequent paragraphs.

Our Vehicle-to-Vehicle and Vehicle-to-Infrastructure-communication worked trouble free throughout the competition. We were able to receive messages up to distances of 800 m. Although this sounds promising for future applications, we have to consider that the test bed of the GCDC on a straight highway is not representative. In a more realistic scenario, problems with occlusions due to buildings and trees next to the road or due to large trucks are to be expected. The bridges over the road that were part of the GCDC test bed already provided ample problems of this sort.

Additionally, the communication protocol's aim for simplicity led to dropping all security concerns. The CALM protocol offers no encryption or source verification and standard network attacks (man-in-the-middle) are trivial to perform and potentially lethal when wrong data are relied on by controller strategies. During our preparations for the GCDC, we found that, with the current reference implementation of the CALM protocol, a maliciously crafted broadcast package is able to put all clients that were not modified to work with garbage input into an infinite loop or a crash.

One major issue during the competition was the quality of data concerning the position of other vehicles in the heat. Since the GCDC addresses a multivendor scenario, all teams used different GPS/INS systems. Although accuracy requirements were specified in the GCDC rules, the reliability and accuracy of those systems was very different, and some systems created position estimates that were very noisy over time. Moreover, in some situations, some teams sent outdated data or did not sent anything at all. This behavior has been often observed below bridges, where satellite reception was interrupted. Hence, these vehicles disappeared in our world model, or they were mapped to a wrong place. Fig. 6(b) provides an impression of the quality of the data received. The bridge problem becomes apparent at distance 3625 m: some participants only provided a position estimate and constant velocity, whereas others delivered constant velocity and constant position.

Since this problem did not allow safe autonomous operation of our vehicle, we decided to integrate the radar sensor into our system and to merge the communicated position of vehicles with the radar targets. Hereby, our policy was to put more trust in the onboard sensors than in communicated positions (see Section IV-B). From these experiences, we can conclude that additional onboard sensors are indispensable for communication-based autonomous driving. Moreover, this shows that certified high-quality GPS/INS sensors are required to enable safe operation.

Longitudinal control of our vehicle worked satisfactory. Fig. 7 shows the performance of our vehicle, following the lead vehicle during one heat of the GCDC. The controller smoothly reacted with small latencies to changes of the lead vehicle. The cooperative platooning control also worked well. Since the performance of a platoon depends on all vehicles belonging to the platoon, it is hard to measure the contribution of a single vehicle. However, the overall result of the GCDC, which was obtained by averaging over 15 heats and distributing participants in various ways, indicates that our platooning controller contributed to compact platoons on average.

Since our controller was designed in a conservative way, it did not assume any properties of the controllers in other vehicles. This fits very well to the multivendor scenario of the GCDC. Certainly, knowing the control policies of other vehicles would offer great potential for further improvements.

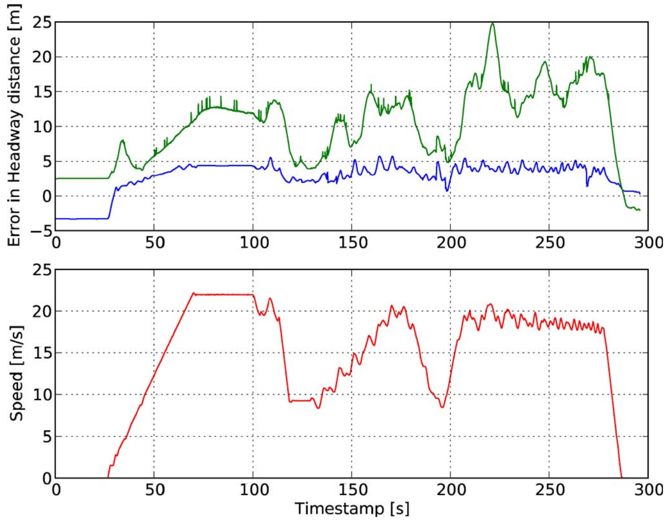


Fig. 7. Top plot shows desired headway distance minus real headway distance for (blue) AnnieWAY and (green) Halmstad in a run where both were directly behind the lead vehicle. The bottom plot shows the speed profile of the lead vehicle in the same run.

However, such an assumption would be far from being realistic considering real traffic applications.

Another concept implemented in the GCDC was explicit platoon joining, i.e., platoons are arranged explicitly sending join and confirmation messages between the vehicles. Our vehicle supported these messages to comply with the rules. However, we did not make use of the information whether a vehicle formally joined our platoon. In light of our experiences during the GCDC, the concept of explicit joining a platoon seems to be of limited use for highway scenarios.

Our participation in the GCDC has been one further step on our way toward fully autonomous driving. Our next activities will again focus more on improved environment perception as it turned out that only vehicles with reliable onboard sensors can safely act. In our view, communication-based strategies are only useful as supplement to local perception.

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