



Cooperative localization for autonomous cars

Lessons learned from the Grand Cooperative Driving Challenge

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Outline

1. Introduction to the GCDC 2016
2. Key components to do the challenge
3. Architecture of the system developed at Heudiasyc
4. The two days of the challenge
5. Lessons learned
6. Perspectives

Introduction to the GCDC 2016

Part 1

Grand Cooperative Driving Challenges

GCDC 2011

- A270 highway between Helmond and Eindhoven.
- Cooperative platooning (sensor based-control with speed and acceleration exchange)
- 9 teams (with cars and trucks)

GCDC 2016

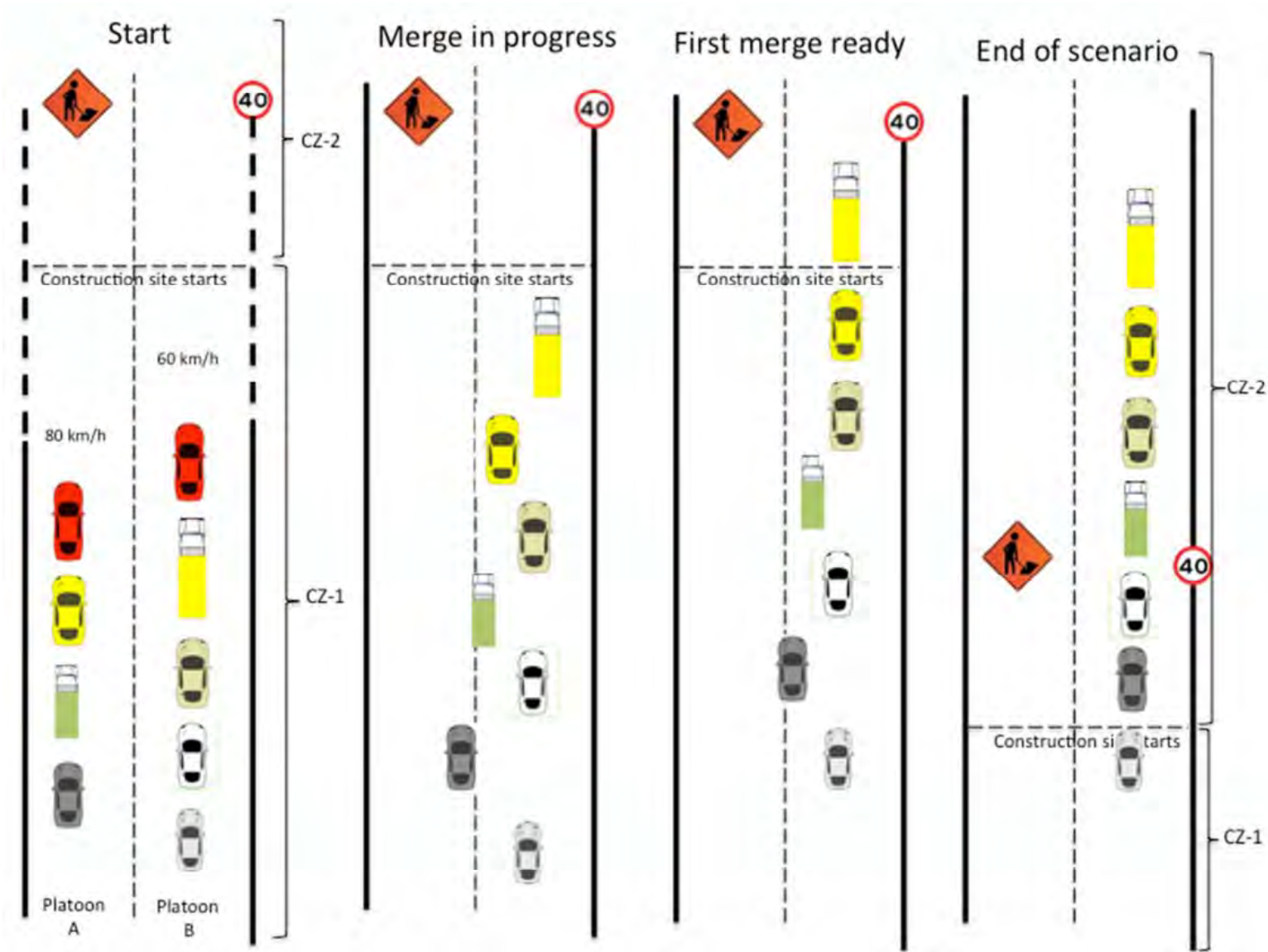
- Same place
- May 28-29, 2016
- Autonomous driving with interactions with vehicles and infrastructure
- Three different traffic scenarios
- 10 European teams.

Main Challenge

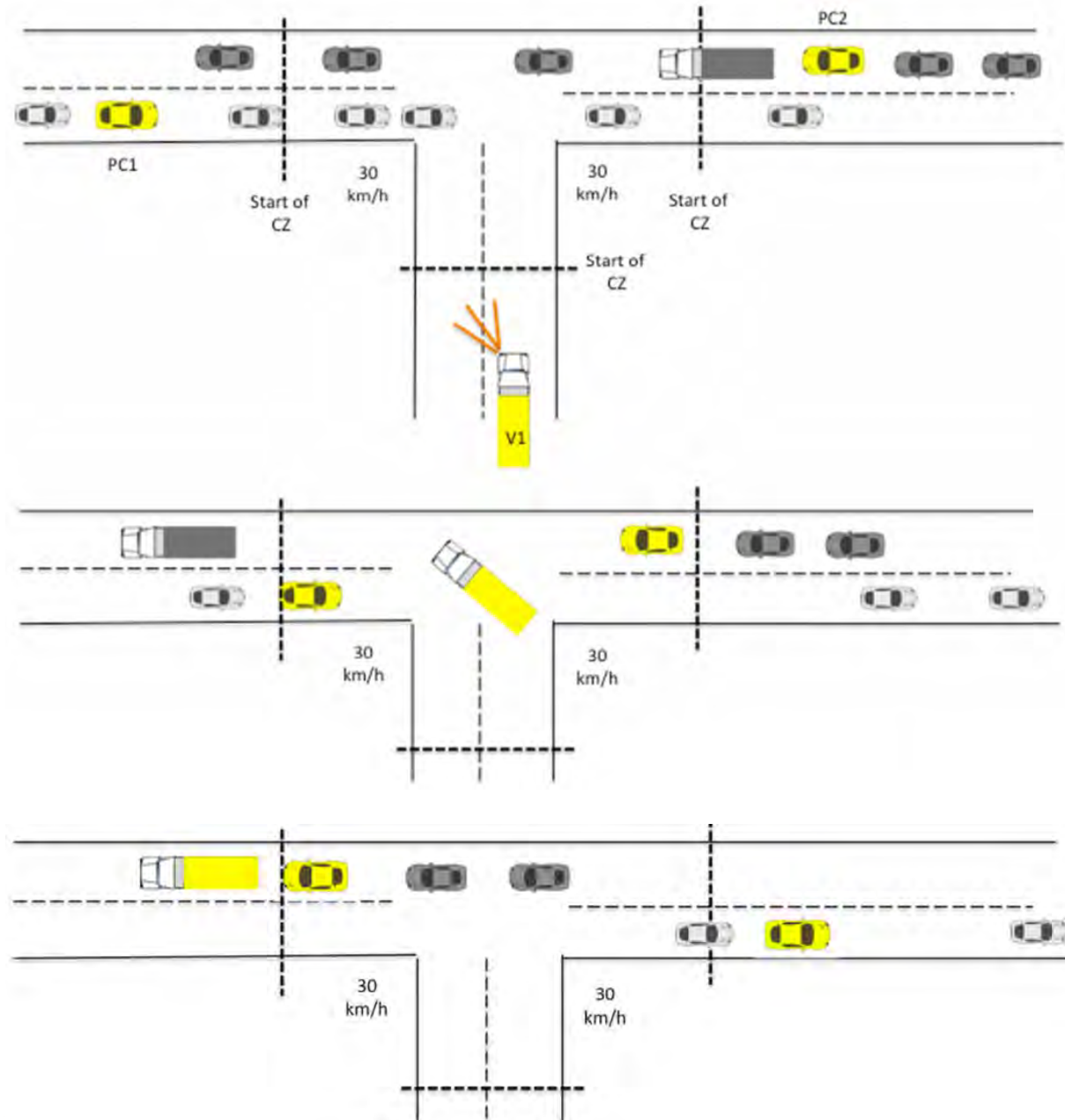
- Cooperation between heterogeneous systems implementing different algorithms



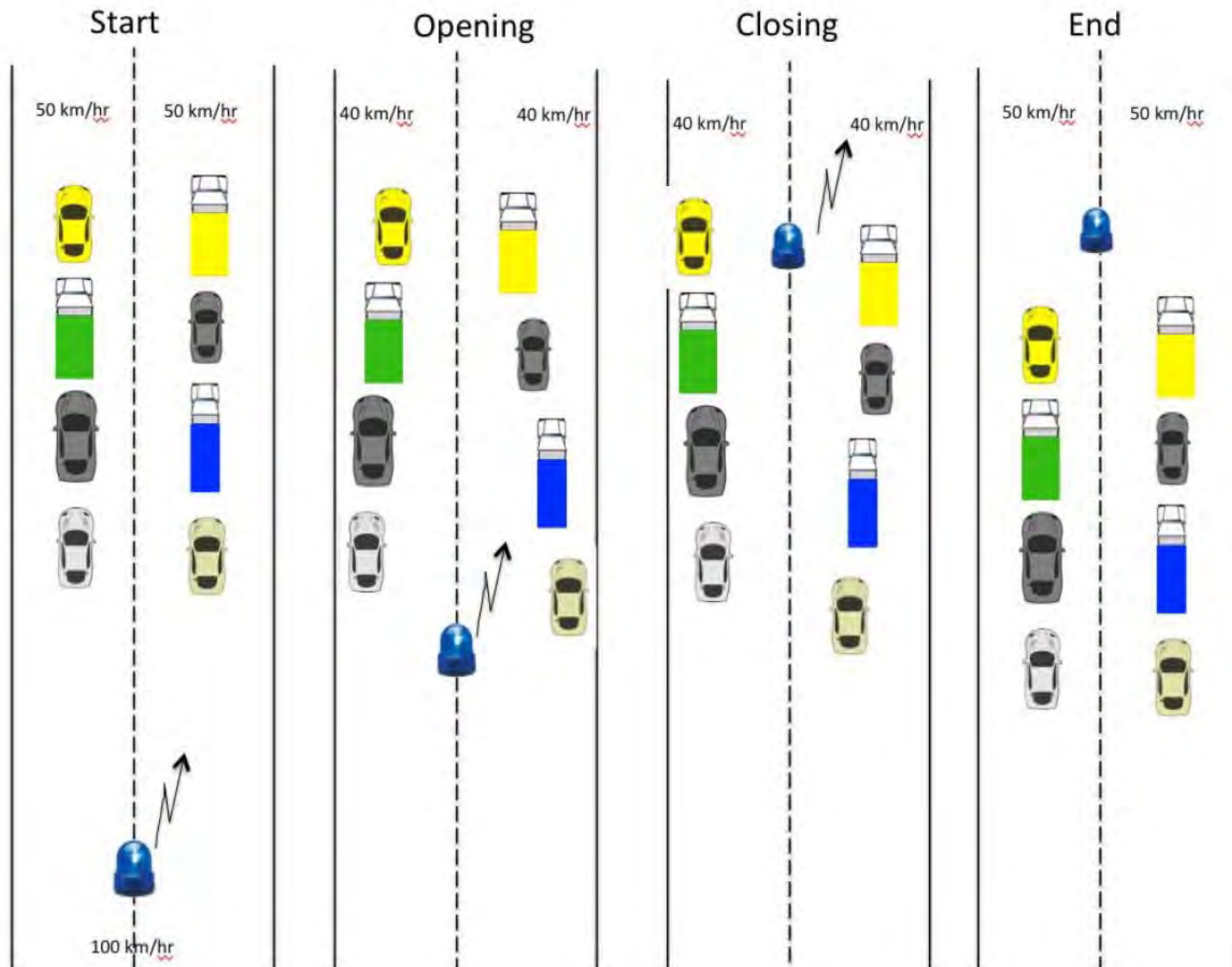
Scenario 1: cooperation on highway (merging)



Scenario 2: cooperative intersection (crossing)



Scenario 3: Emergency vehicle



Snapshot of the GCDC 2016



Teams signed up for the GCDC 2016

Universidad de Alcalá, Spain

- UAH

Chalmers University of Technology, Sweden

- Car team
- Truck team

KTH Stockholm, Sweden

- Experimental Car
- Truck team

University of Latvia / Institute of Electronics, Latvia

- EDI

KIT Karlsruhe, Germany

- KIT

Halmstad University, Sweden

- Halmstad

Eindhoven (Fontys and TU/e), The Netherlands

- A-Team

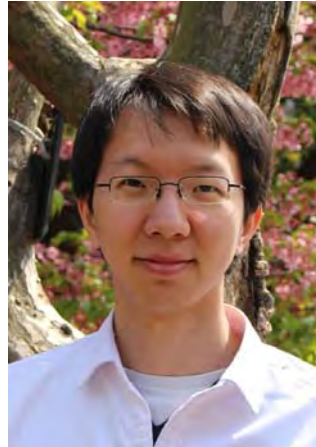
Université de technologie de Compiègne, France

- Heudiasyc laboratory



Heudiasyc team

Team Leader: Philippe XU



First participation



People involved

- 5 Profs and Researchers
- 3 Engineers
- 2 Phd students
- 2 interns
- 12 Master students



Key components to do the challenge

Part 2

Key components to participate in the challenge

- 1) Wireless Communication modem
- 2) Localization system based on GNSS positioning
- 3) Autonomous control
- 4) Human Machine Interface (HMI)
- 5) Emergency systems
- 6) External lights

Communication

Wireless communication on ETSI C-ITS standards

- Cooperative-Intelligent Transport System

Wifi mode, 5.9 GHz band (802.11p)

- Both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications.
- Implementation: ETSI ITS-G5 standard (GeoNetworking protocol and Basic Transport Protocol)

Messages

- CAM (Cooperative Awareness Message)
- DENM (Distributed Environment Notification Message)
- iCLCM (i-GAME Cooperative Lane Change Message) (non standard)

CAM Message

Vehicle information

- ID
- Vehicle type (car, truck, etc.)
- Vehicle role (emergency, roadwork)
- Vehicle size (length and width)

Time Stamp

- UTC time (in ms, ~1 minute ambiguity)

Pose

- Position (geo) + 95% confidence bound
- Heading

Kinematics

- Speed, drive direction (fwd, backw)
- yaw rate
- Acceleration

DENM Message

Typically sent by Road Side Units (RSU)

Data :

- Station type
- Time Stamp
- Event type
 - Roadworks,
 - Stationary vehicle,
 - Emergency vehicle approaching,
 - Dangerous Situation, etc.
- Lane position
- Lane is closed or not

iCLCM Message (valid only for the GCDC 2016)

Vehicle information

- ID
- Vehicle rear axle position
- Controller type (manual, automated, etc.)

Cooperative platooning

- Cruise speed, Acceleration Setpoint, Response time
- Time Headway
- Most Important Object (ID, range, relative bearing and kinematics)

Lane change

- Ego Lane ID
- Follower ID
- Matching Flag (to robustify the ID association)
- Merge request
- Safe to merge
- Merge in progress flag
- Head of left platoon

Cooperative intersection

- Distance to the center of the intersection
- Intention (intended road)

Mandatory

Every participant had to:

- Implement the protocol
- Send and receive 46 fields over the 3 kinds of message
- Broadcast frequency: 25 Hz

Localization system

Each vehicle had to implement a system estimating its geographical pose

- Position (geo) + 95% confidence bound
- Heading

In order to send it in CAM messages

Control

Mandatory:

- Cruise control and platooning

Optional:

- Cooperative platooning
- Virtual platooning
- Lane keeping
- Lane changing

Human Machine Interface (HMI)

Any device or interface between the car and the driver and the other participants to make the system understandable

Criteria:

- Transparency, Innovation, aesthetics and minimalism

Emergency systems

In GCDC, safety was of utmost importance

In every vehicle, the automatic mode must be instantly overridden by the driver by doing one of the following actions:

- Emergency stop button
- The throttle pedal
- The brake pedal
- Turning the steering wheel
- Changing the gear
- Electric parking brake

Every car had to be certified by the organizers

- Safety Workshop, 29 March – 3 April 2016, Barcelona
- IDIADA facilities

External lights

During every heat of the challenge:

- Red = Manual
- Green = Auto
- Red and green simultaneously = Problem in the car and stop the heat



Architecture of the system developed at Heudiasyc

Part 3

Experimental vehicle

Fully electric car (Renault Zoé)

Maximum speed of 50 km/h while driving autonomously



Driving modes

- **Manual**

- The driver has a full control

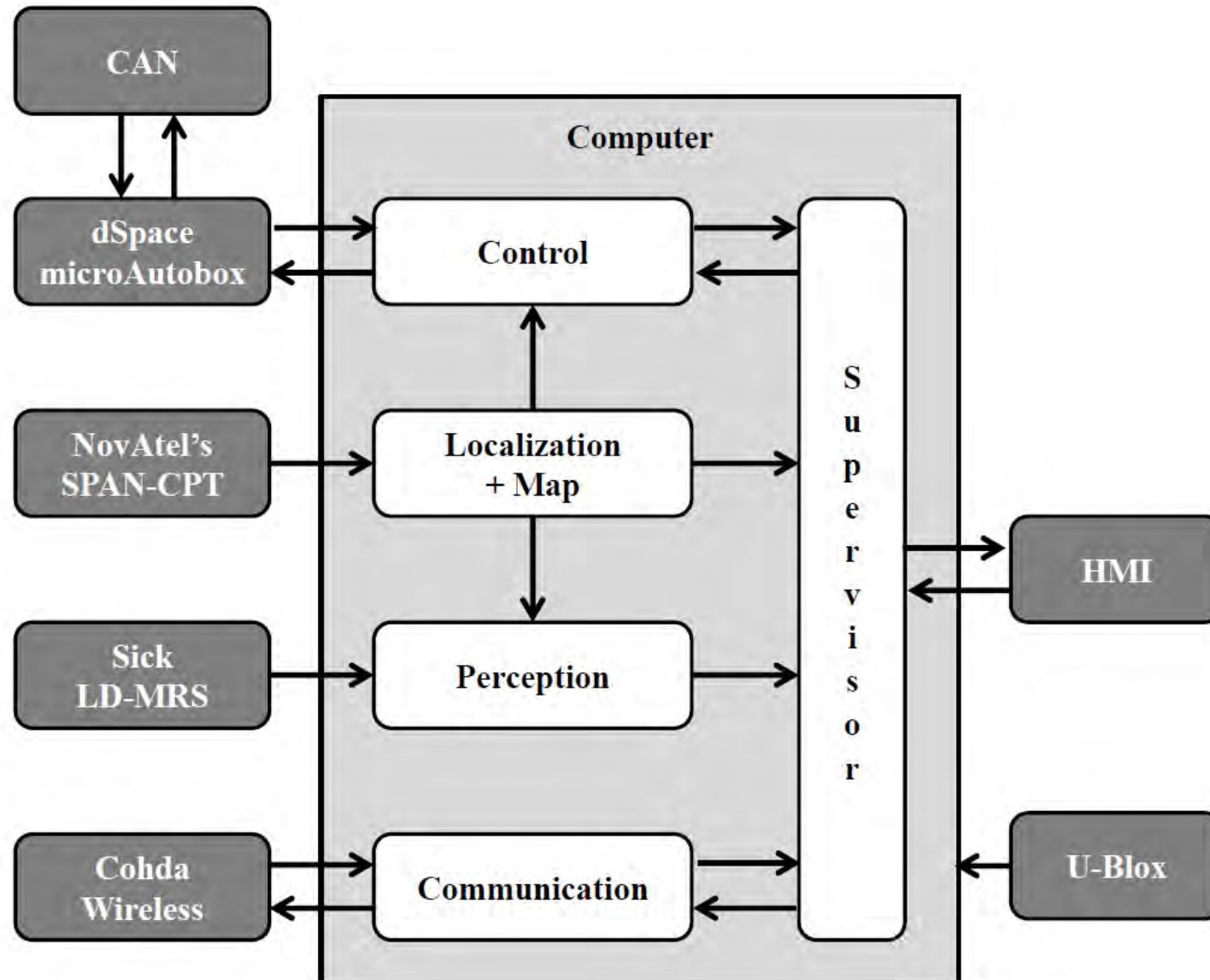
- **Autonomous**

- The system manages both longitudinal and lateral controls of the vehicle.
- Any action on the acceleration, the brake or the steering from the driver overrides the commands sent by the system and the car switches to manual mode
- To activate it, the car must be stopped or driven very slowly

- **Cooperative**

- The driver has control over at least one sub-system
- The driver might be in charge of the lateral control while the longitudinal part is done autonomously.
- Driver's actions on automated sub-modules overrode the commands of the system and only set these particular sub-modules to manual mode

System architecture



Map

The map provided by the organizers was not accurate enough

➔ We built online during the first trial of the challenge a map the center paths of each of the two lanes of the highway



Localization

NovAtel SPAN-CPT

- Inertial Navigation System (INS)
- Global Navigation Satellite System (GNSS)
- GPS/GLONASS
- Real-Time Kinematic (RTK) corrections (local base)
- 50 Hz
- Output: geographic coordinates (latitude, longitude, ellipsoidal height)

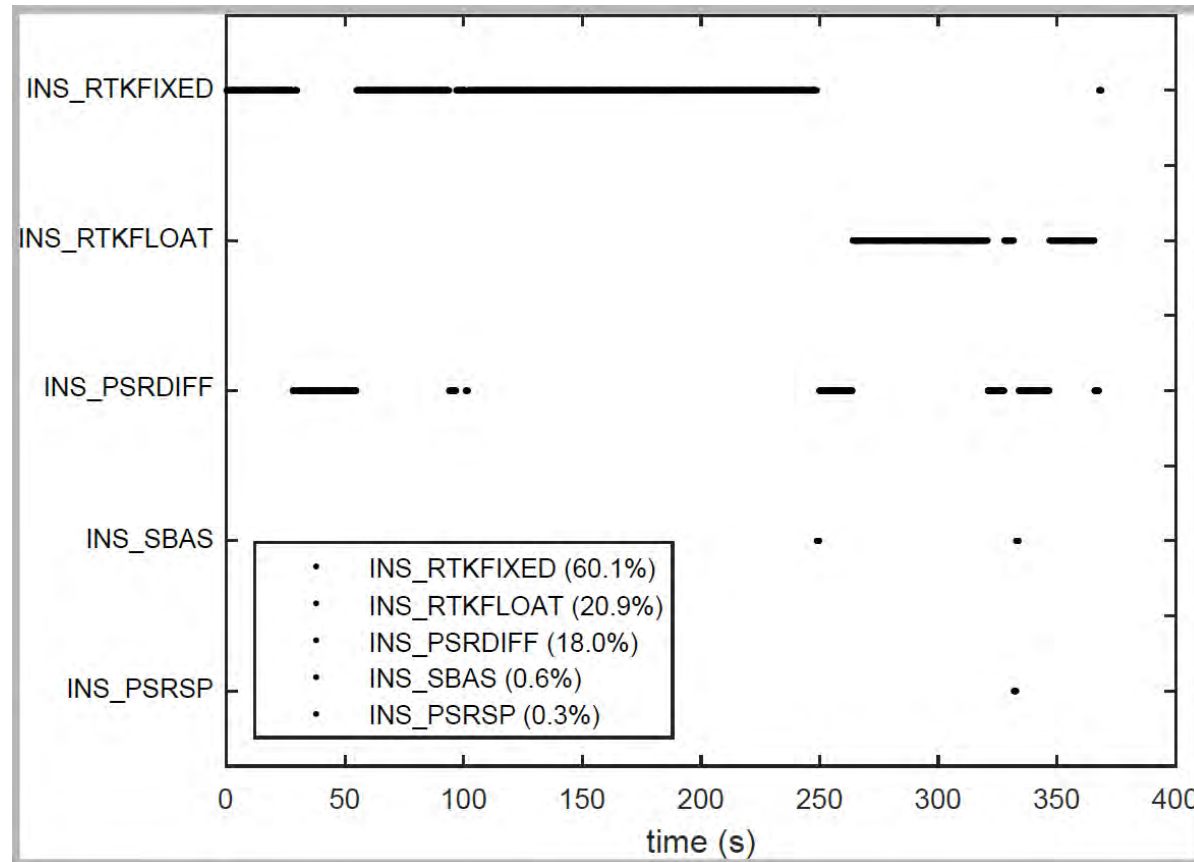
Cartesian Frame

- East, North, Up (ENU) coordinates with local origin
- 2D pose computation
- Cartesian coordinates are much more practical than Geodetic coordinates
- Homogeneous transformation (no projection) perfectly invertible

Positioning modes with their typical accuracies

Positioning mode	Accuracy
RTK fixed ambiguities solution (RTKFIXED)	~ 0.01 m
RTK floating point ambiguities solution (RTKFLOAT)	< 1.0 m
Pseudorange Differential Solution (PSRDIFF)	< 2.0 m
Satellite-Based Augmentation System (SBAS)	~ 3 m
Pseudorange Single Point Solution (PSRSP)	~ 5 m

Positioning modes during a complete merging heat



80% of the time: GNSS with sub-metric accuracy

With the data-fusion of the IMU: enough accuracy to do path following

Perception

In GCDC the perception task was highly simplified, as the environment is restricted to a straight two-lane highway with the other vehicles the only possible obstacles

For platooning two possible leader vehicles:

- The vehicle immediately in front of the host vehicle,
MIO (Most Important Object)
- The vehicle ahead of the host vehicle in the other lane (either the left or the right lane, depending on the host vehicle's current lane),
forward MIO

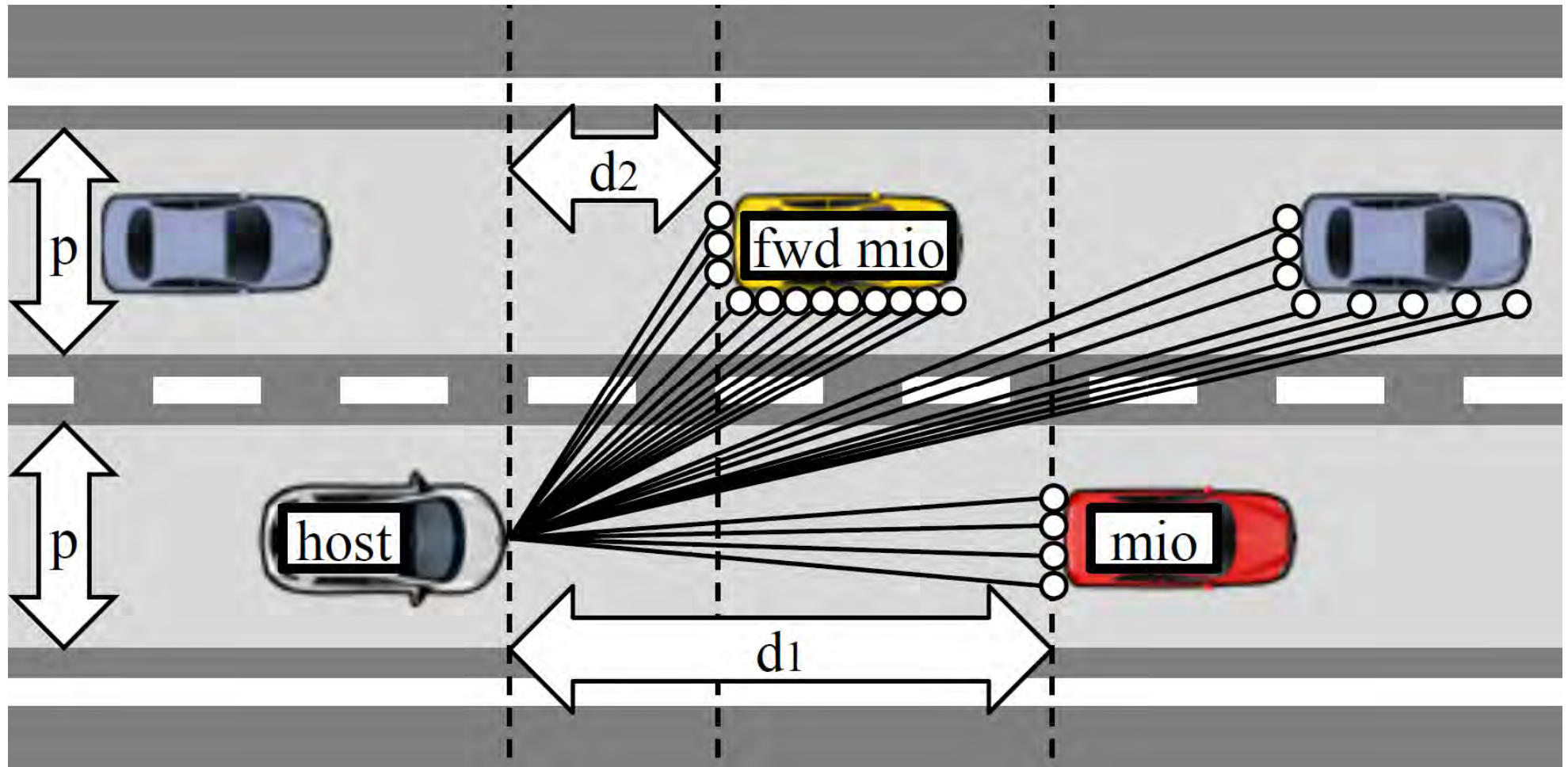
Lidar installation

Four-layer Sick LD-MRS LiDAR installed in the front bumper



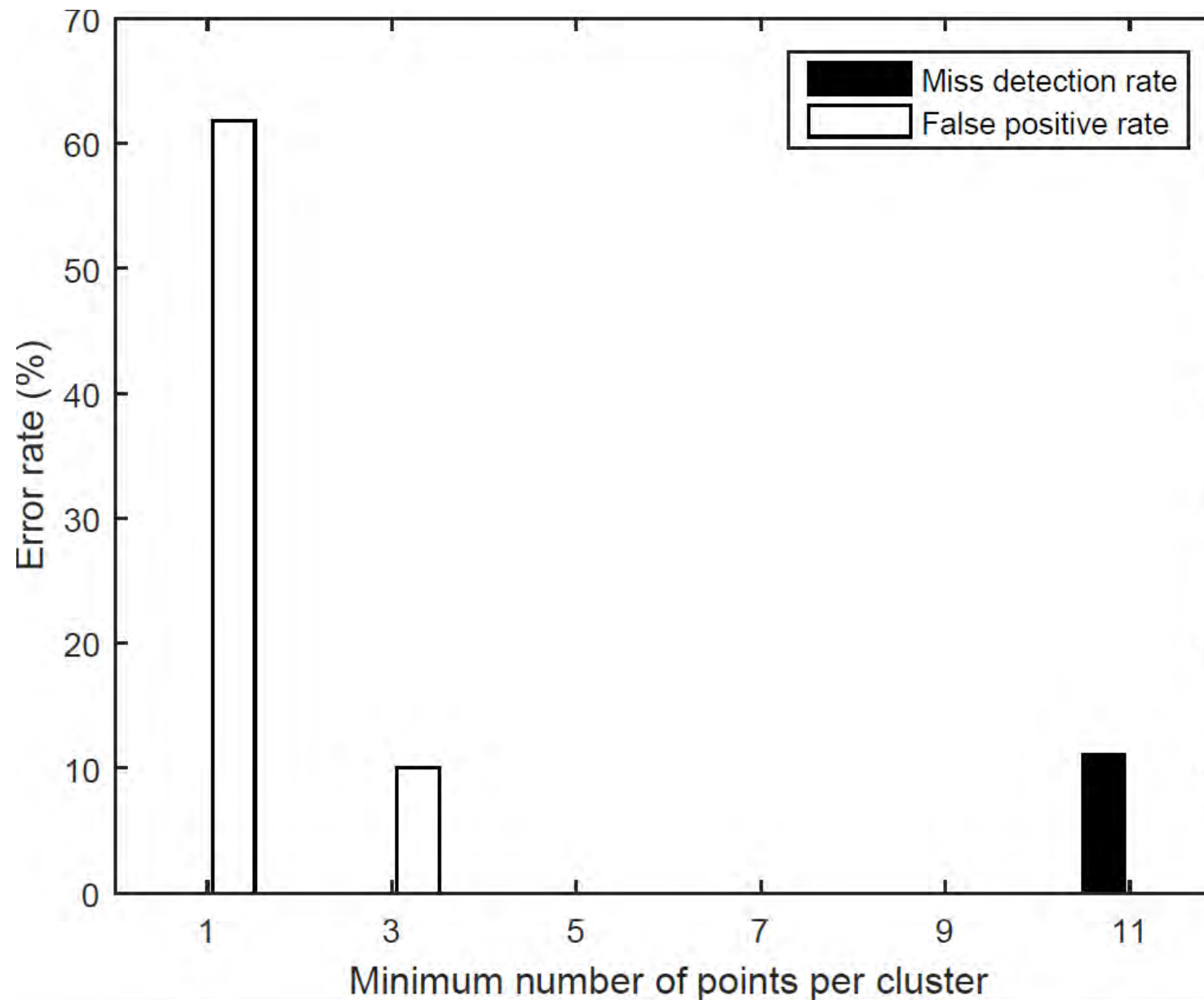
Lidar processing

Clustering of the point cloud and bounding box computation

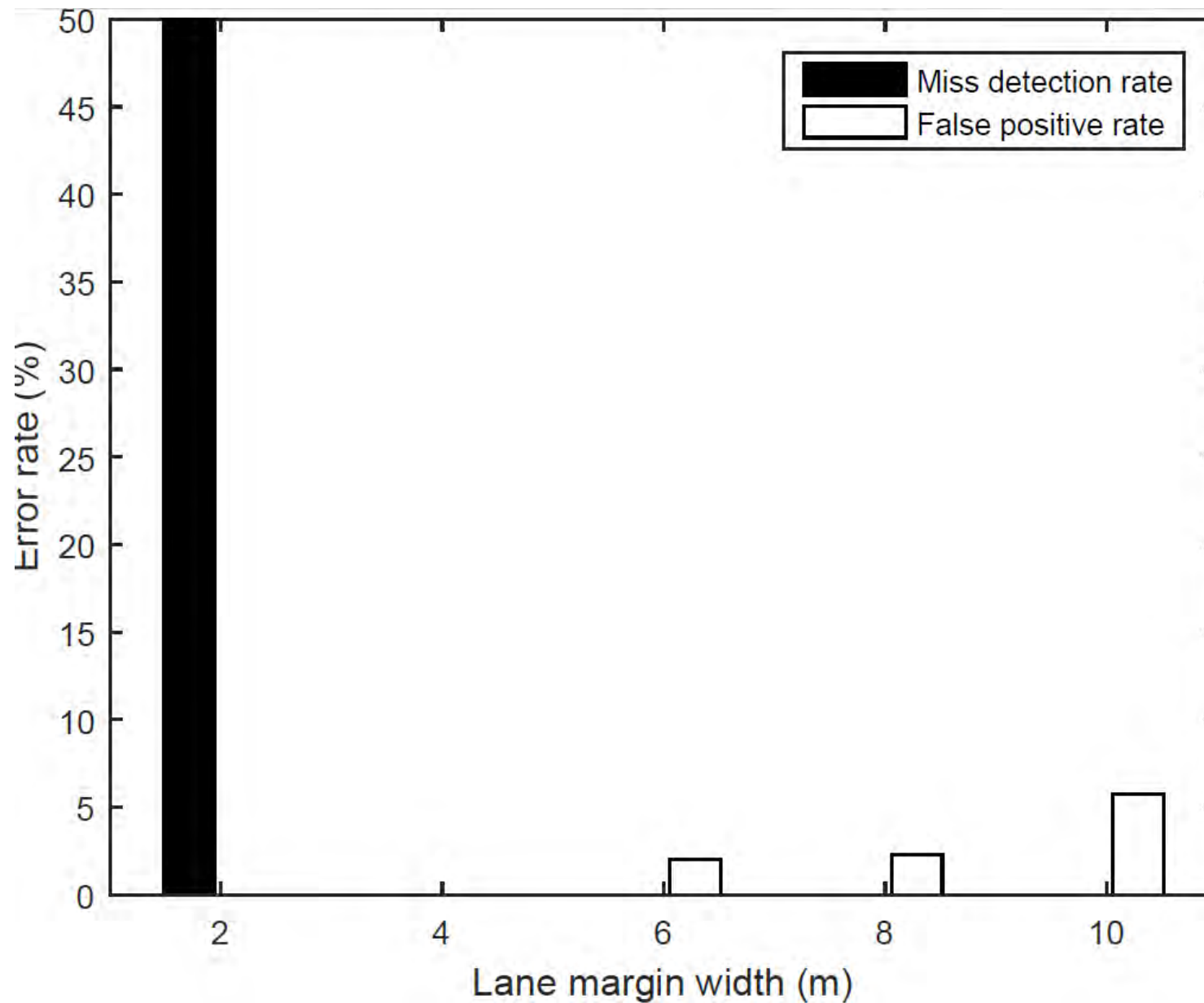


3 parameters to tune

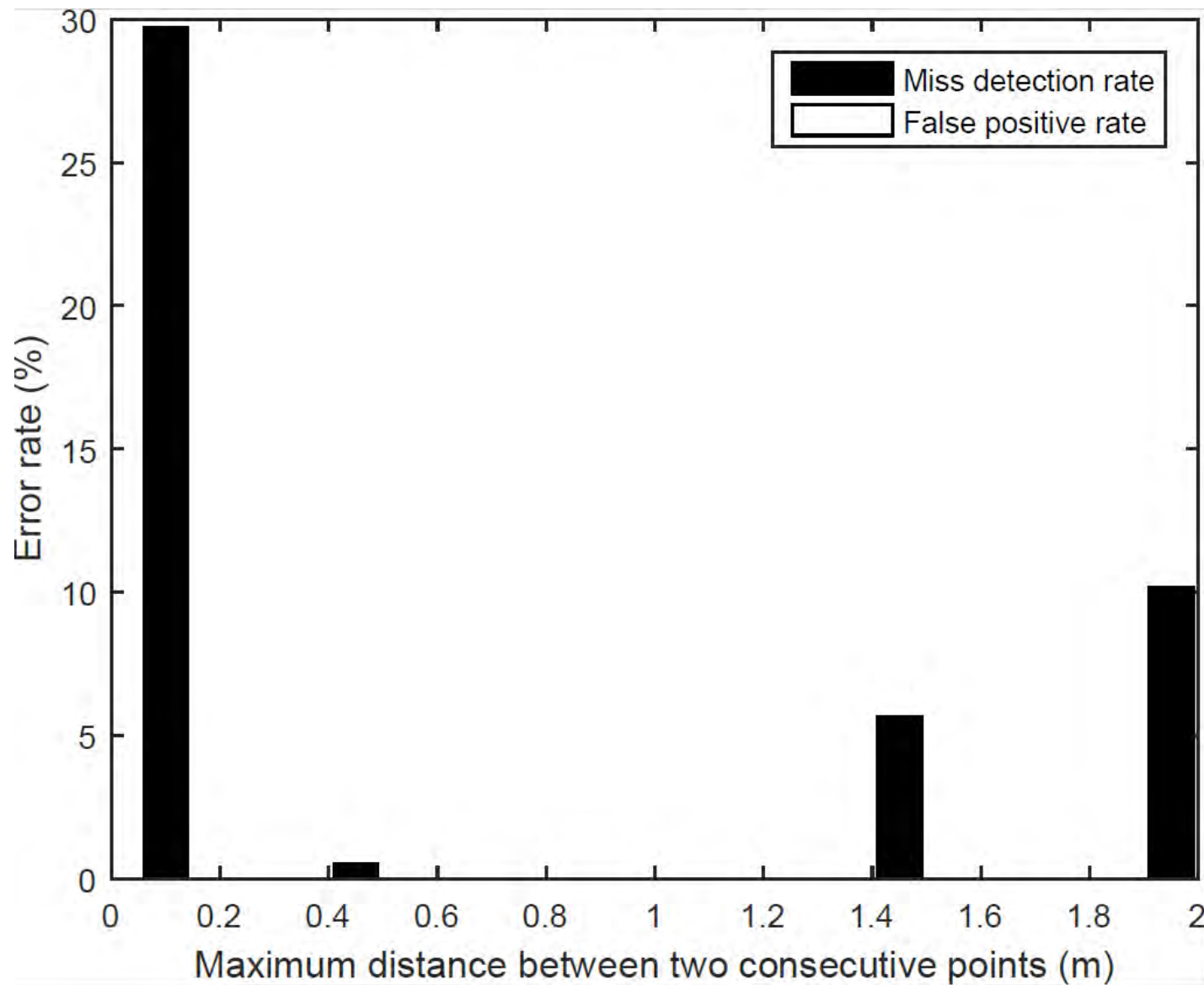
LiDAR based object detection module



LiDAR based object detection module



LiDAR based object detection module



Control

Three possible commands to the vehicle CAN bus:

- acceleration torque
- braking torque
- steering wheel angle

Figures on the motorway:

- Speed = 40 km/h
- maximum allowed acceleration = 2 m.s^2 .
- maximum steering wheel angle for lane merging = 10 degrees

Assumptions

- No slip of the wheels
- linear relationship between the steering wheel and the angle of front wheels

Longitudinal and lateral controls of the vehicles were implemented in a decoupled way

Longitudinal control

When the car was not platooning

- Cruise control with a proportional-integral (PI) controller with a direct compensation of the aerodynamic drag force

When the car was platooning

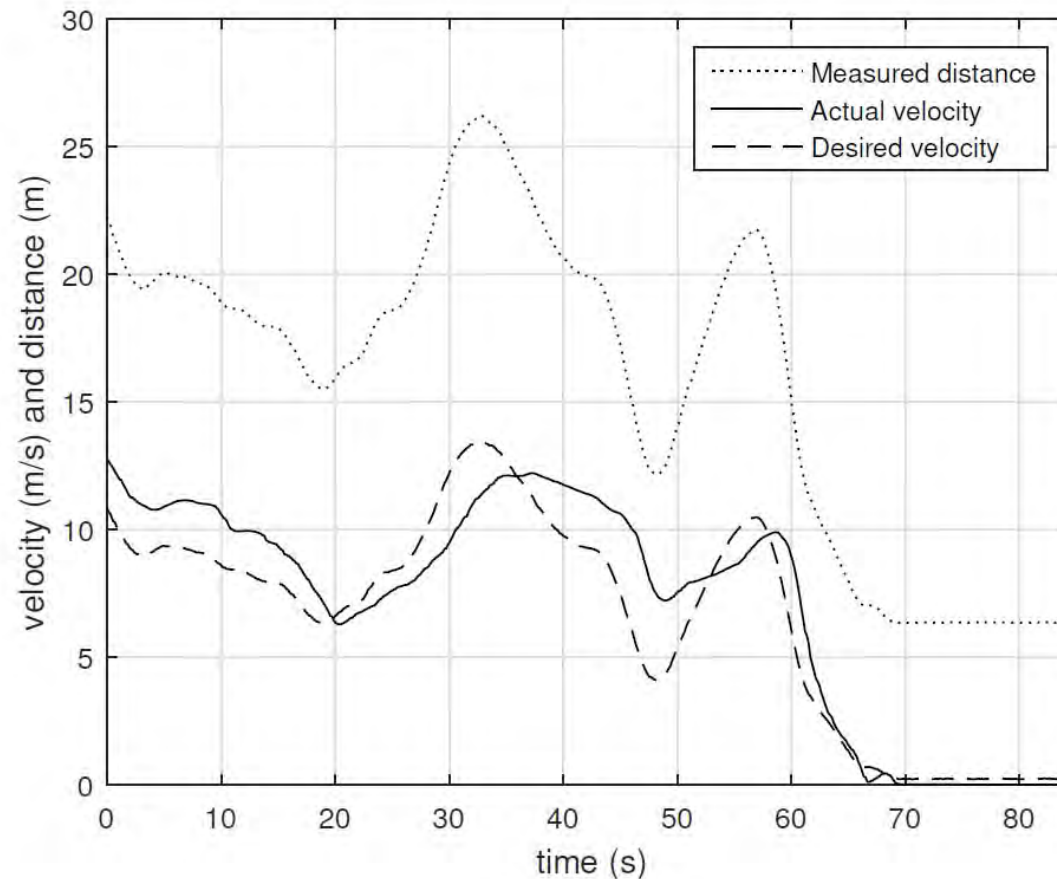
- The distance d to be respected between vehicles was specified
- $d=r+h.v$
 - r standstill distance
 - h time headway

Since a LiDAR doesn't provide a relative speed, we planned to use the speed communicated by the vehicle ahead to fix the damping ratio, but we noticed that the information coming from the other cars was not sufficiently reliable for control operations

Results

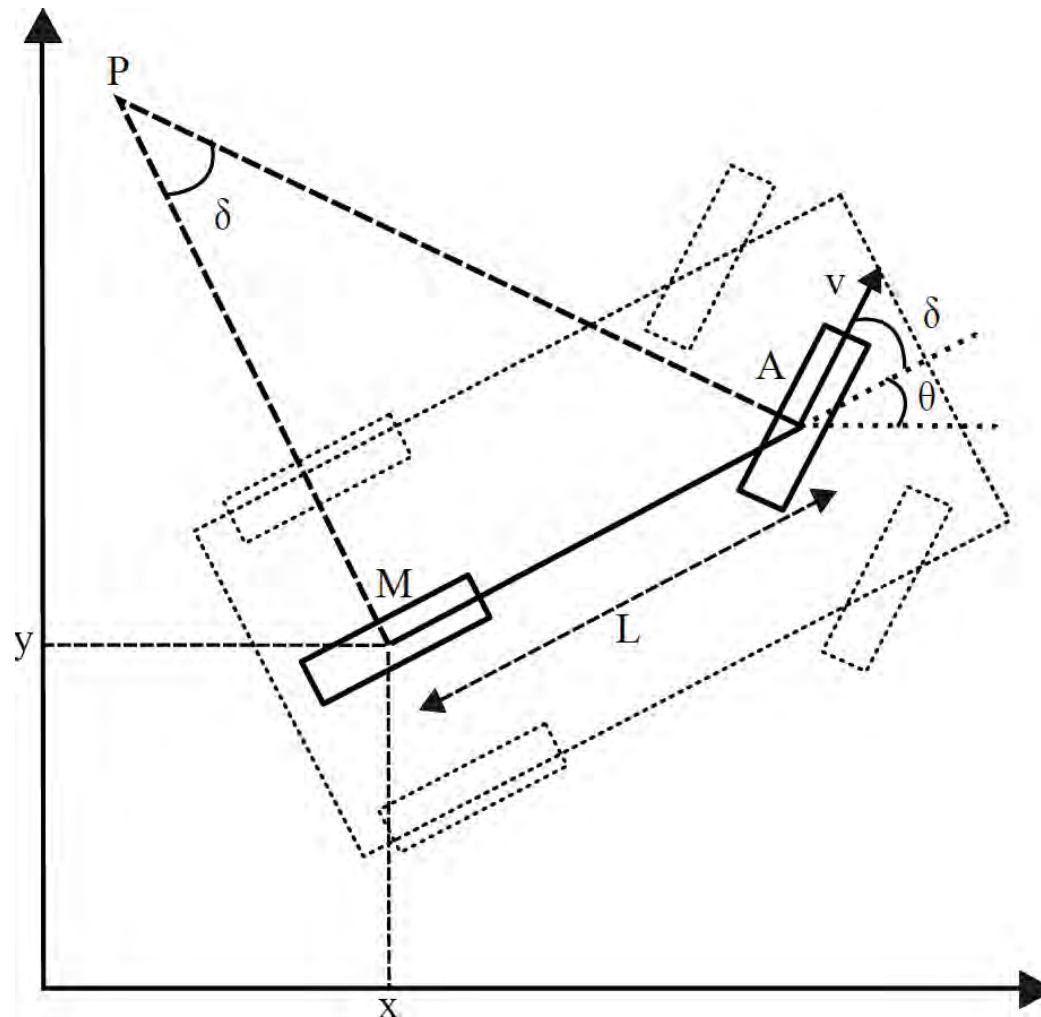
In a steady platooning state at 40 km/h

- Average longitudinal velocity error = 0.71 km/h
 - with a standard deviation of 0.03 km/h,
- Average distance error w.r.t the preceding vehicle = 1.07 meters
 - with a standard deviation of 0.04 meters.



Lateral control

Path following using Ackerman's model



Lateral control law

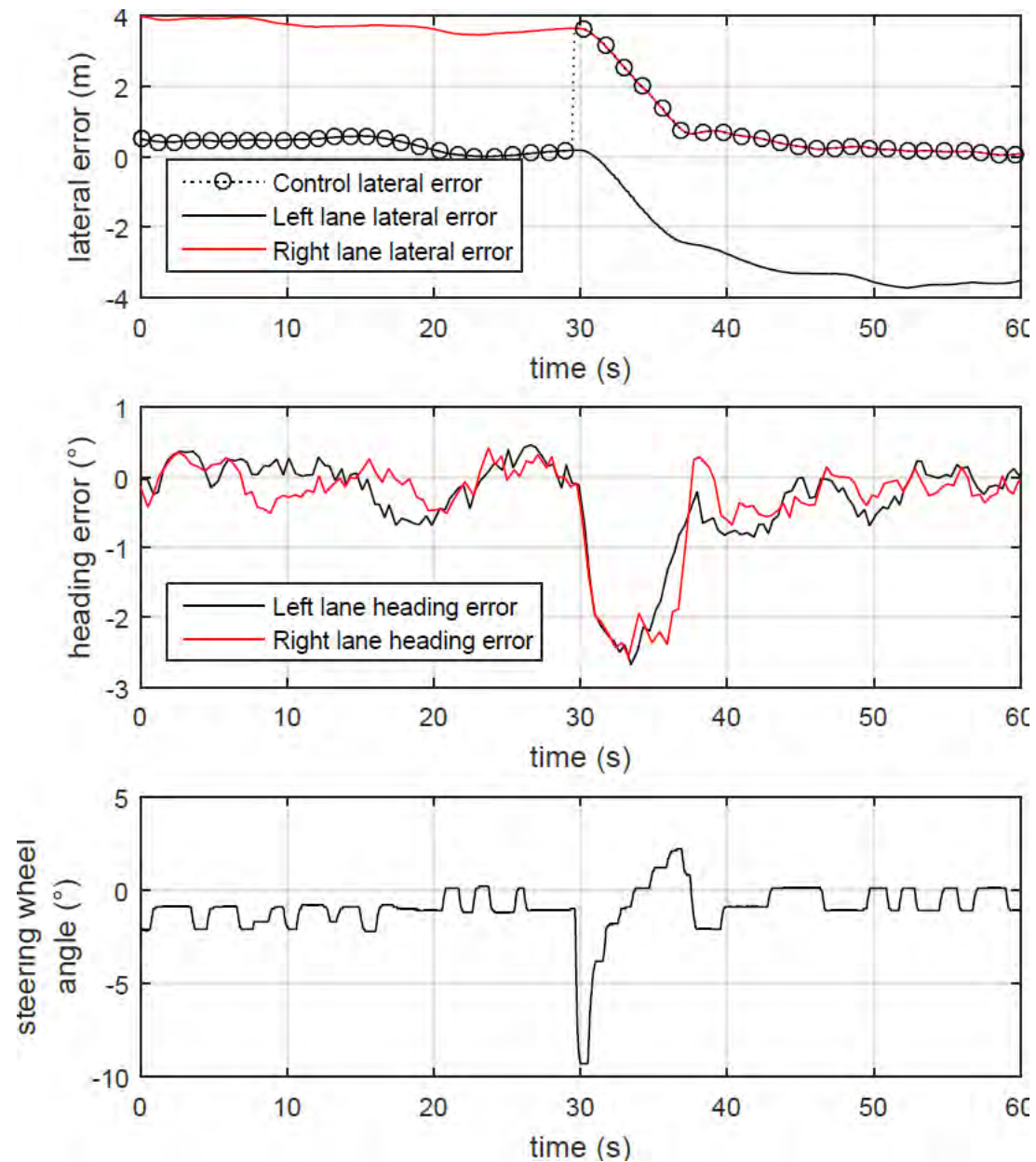
Steering controller as a state feedback with pole placement
Angle of driving wheel:

$$\delta = \frac{L}{v^2} (\alpha_1 \cdot e_l + \alpha_2 v \cdot e_\theta) \text{ and } v \neq 0$$

lateral and heading errors with respect to the path

Thanks to this law, a smooth lane change between two adjacent lanes can be implemented by switching from the current lane to the new lane without path planning

Lateral error (merging manoeuvre)



Communication

Cohda Wireless communication device

ETSI ITS-G5 standard

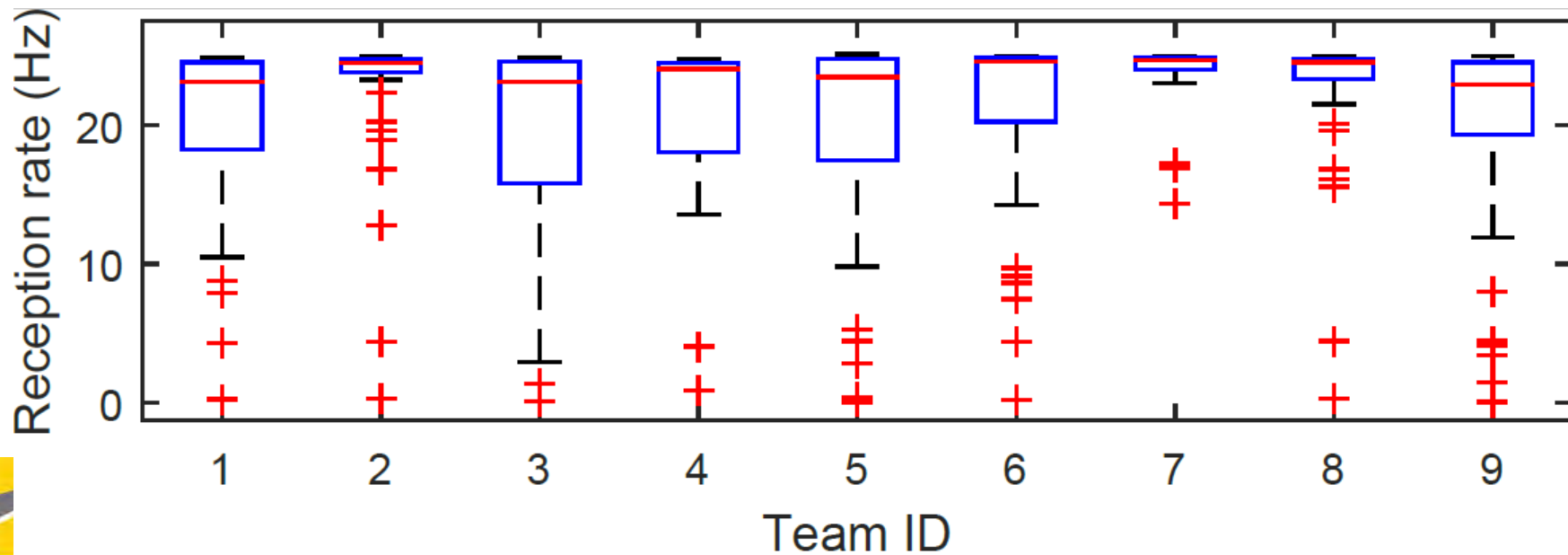
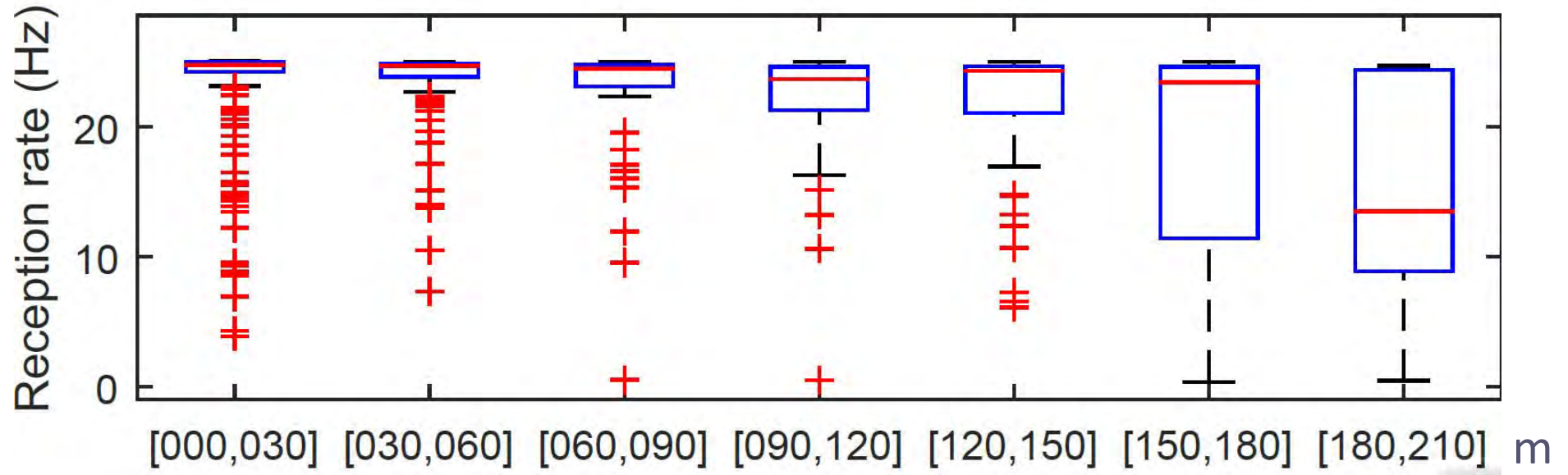
- including the GeoNetworking protocol
- BTP (Basic Transport Protocol)
- ETSI ITS-G5 stack implemented in C++

Messages were encoded and decoded on a computer communicating with the Cohda via UDP

- UDP IPv4 to 802.11p gateway for sending and receiving messages

Reception rates

Example during the challenge (received frequency of the 9 others participants)

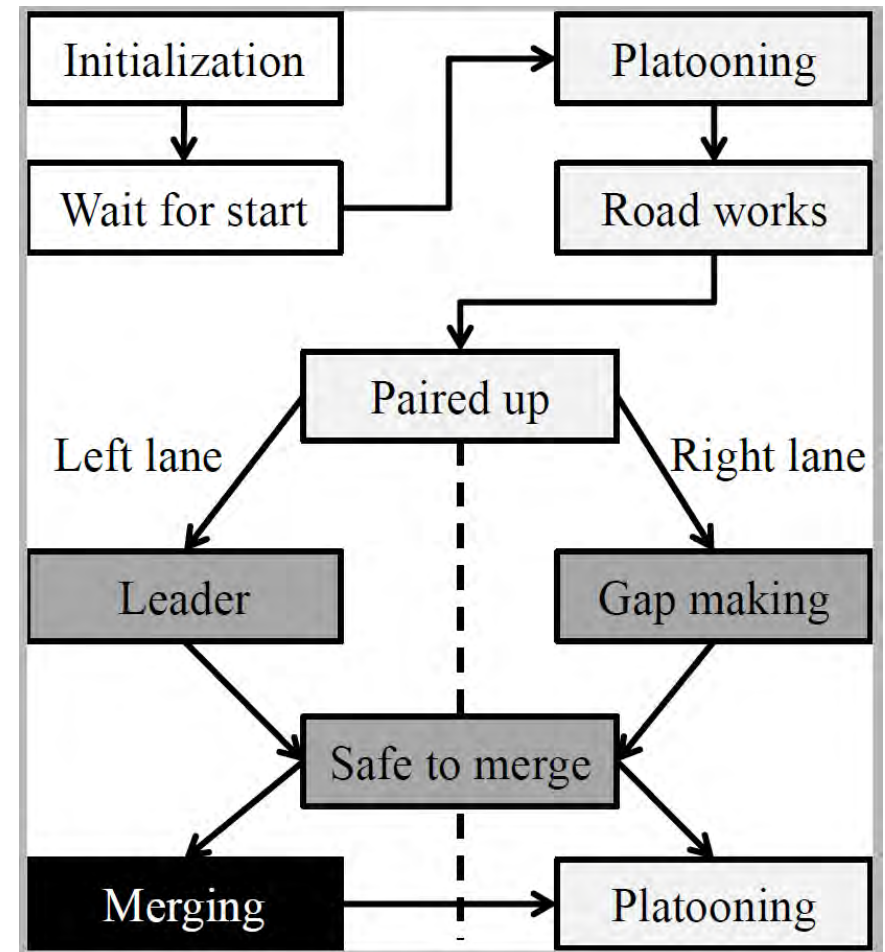


Supervision module

Supervision module connected to all the other modules

Main role:

- to follow a specific cooperative interaction protocol with the other vehicles.
- Several state diagrams for each scenario



Time synchronization

Time-stamping of each message

- Done by the supervision module

Synchronization of the computer time to the GPS time

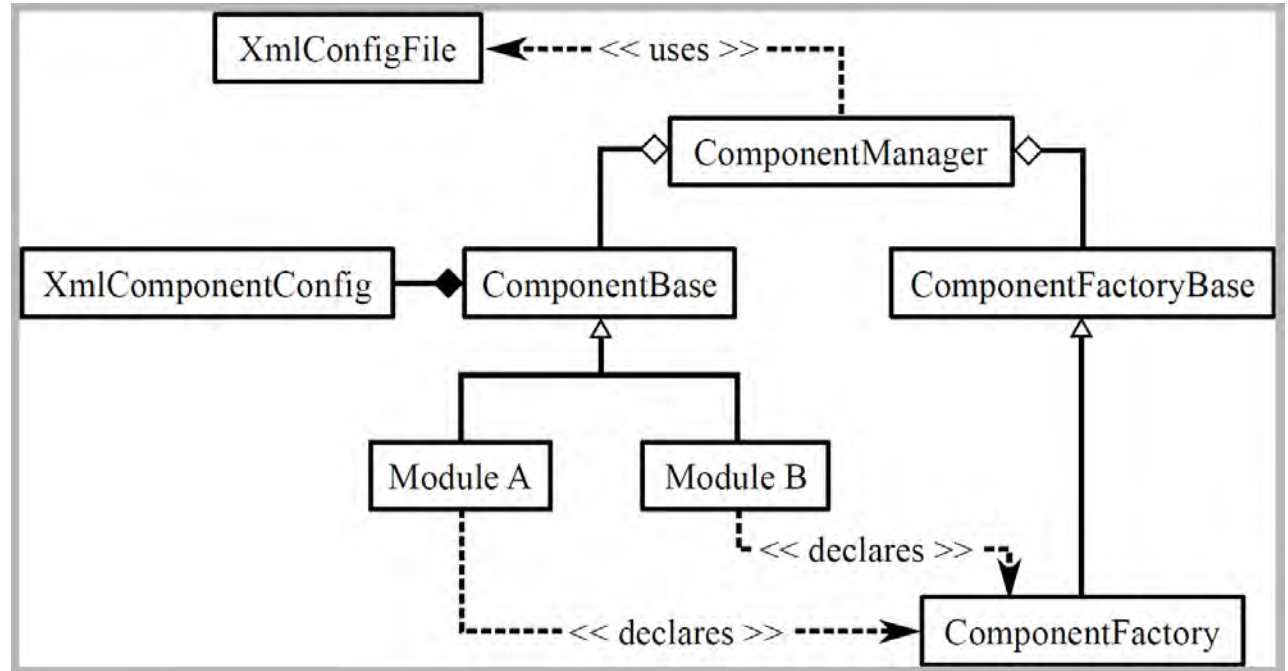
With an additional GPS receiver

- supplying 1PPS (one pulse-per-second) output to continuously
- open-source implementation of NTP, *chrony*

Sub-microsecond accuracy

Middleware

Goal: Rapid integration of different software elements for prototyping



PACPUS framework

- Home made (since 2006)
- Multi-platform (Windows, x86-Linux, ARM-Linux)
- Absolute time-stamping
- Open-source license CECILL-C, a LGPL-like license

HMI

Operator

- Launch application
- Monitor the system
- Possibility to force the state transition through the HMI
- Permanent talky-walky connection with the organizers and other participants



Safety Diver HMI

Safety driver

- Ensures the safety of the vehicle in every heat
- Takeover the control in case of emergency or in case the autonomous system has failed

Interfaces

- Driving wheel, pedals
- Dedicated screen to monitor the status of the current task



IHM during the merging scenario

Cooperation on highway scenario



AUTOMATIC MODE ON

MERGING

INTERSECTION

STOP



The two days of the challenge

28-29 May 2016

Part 4

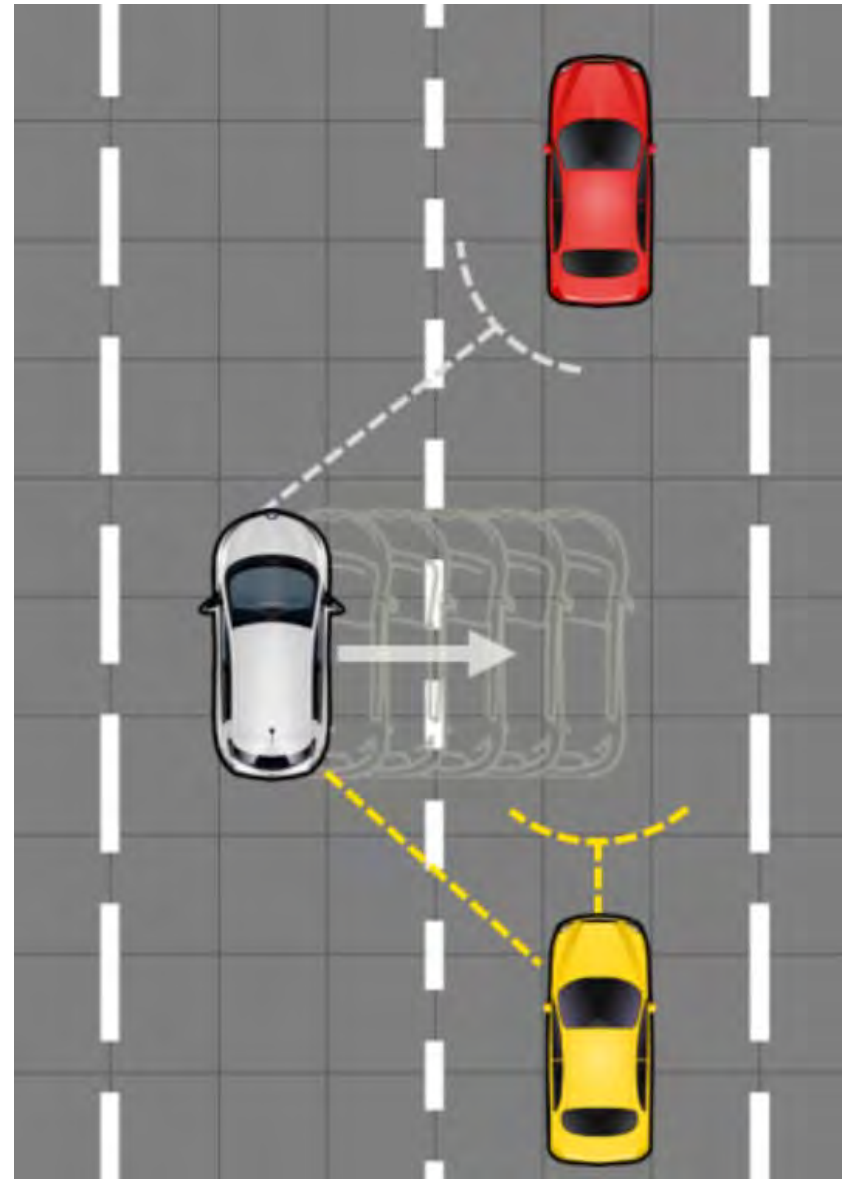


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Scenario 1: Merging

Because our car was limited to a speed of 50 km/h in autonomous driving mode, half of the merging heats were done at a lower speed (40 km/h)

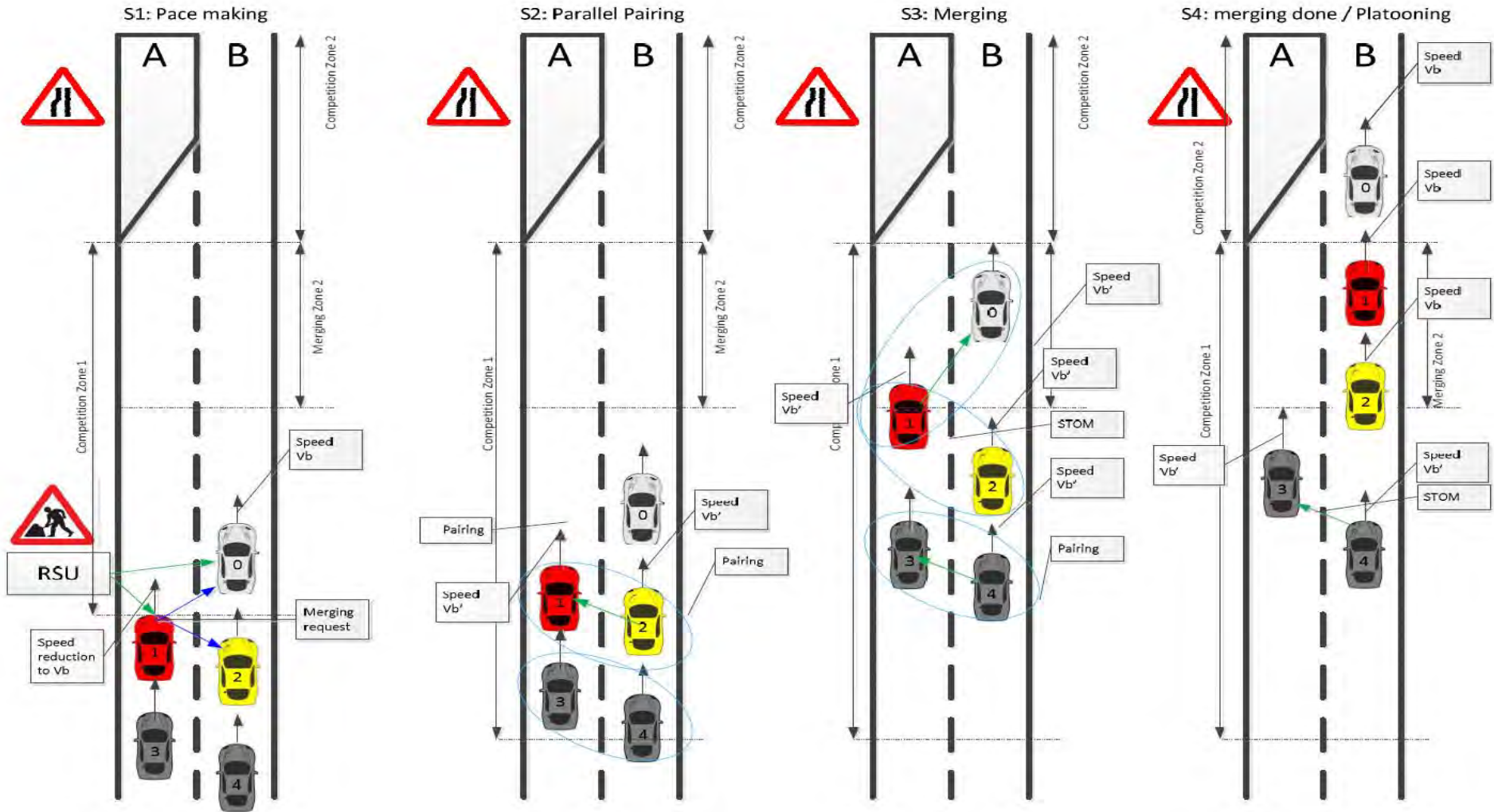
The high speed merging heats were conducted in manual driving mode



Lanes merging snapshots



Merging procedure



Merge request

Pairing
Red is the new leader of the yellow

Enough space to merge

3 can start the merging process

Heat start (for a merging scenario)



Merging during the challenge



What we did

Every vehicle had forward perception capabilities

- Backward not mandatory

During the trials, we took the decision to not use the GPS position of the others to do platooning and pairing

- Since the received positions were not enough reliable.

Platooning

- Using Lidar only with the MIO and the FwdMIO

Pairing

- We used the list of the participants given by the organizers at the beginning of every hear

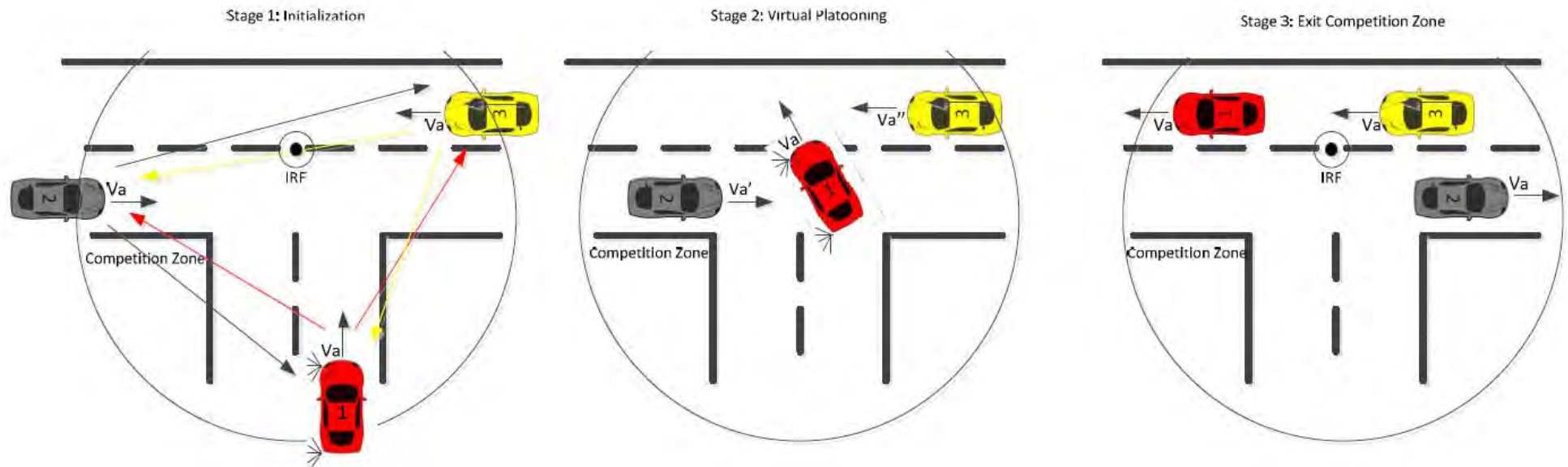
When in the right lane

- To create merging space: switch from the MIO to the FwdMIO (on the left)
- SafeToMerge when enough space with FwdMIO (on the left)

When leader on the left lane (merging to be done)

- Platoon with the FwdMIO (on the right)
- When SafeToMerge received, then do the merging by changing the path to follow

Scenario 2: Crossing



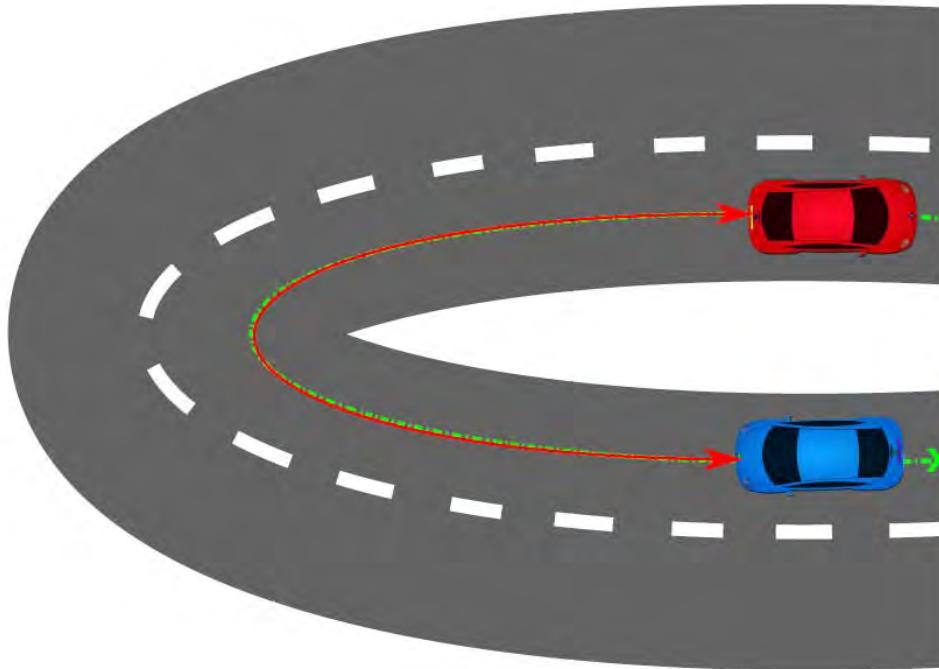
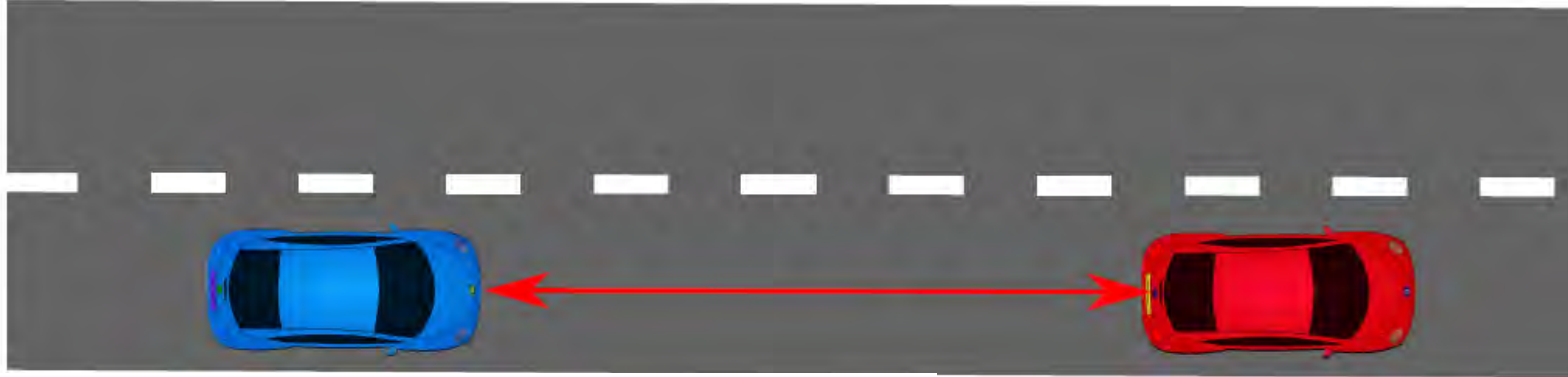
1 is a vehicle of the organizers, the challengers can be 2 or 3

Goal:

- Vehicles have to reach the competition zone at a given time with a given speed
- Vehicles 2 and 3 have to let vehicle 1 cross the intersection at constant speed
- The goal of each challenger is to exit the CZ as fast as possible (with no collision)

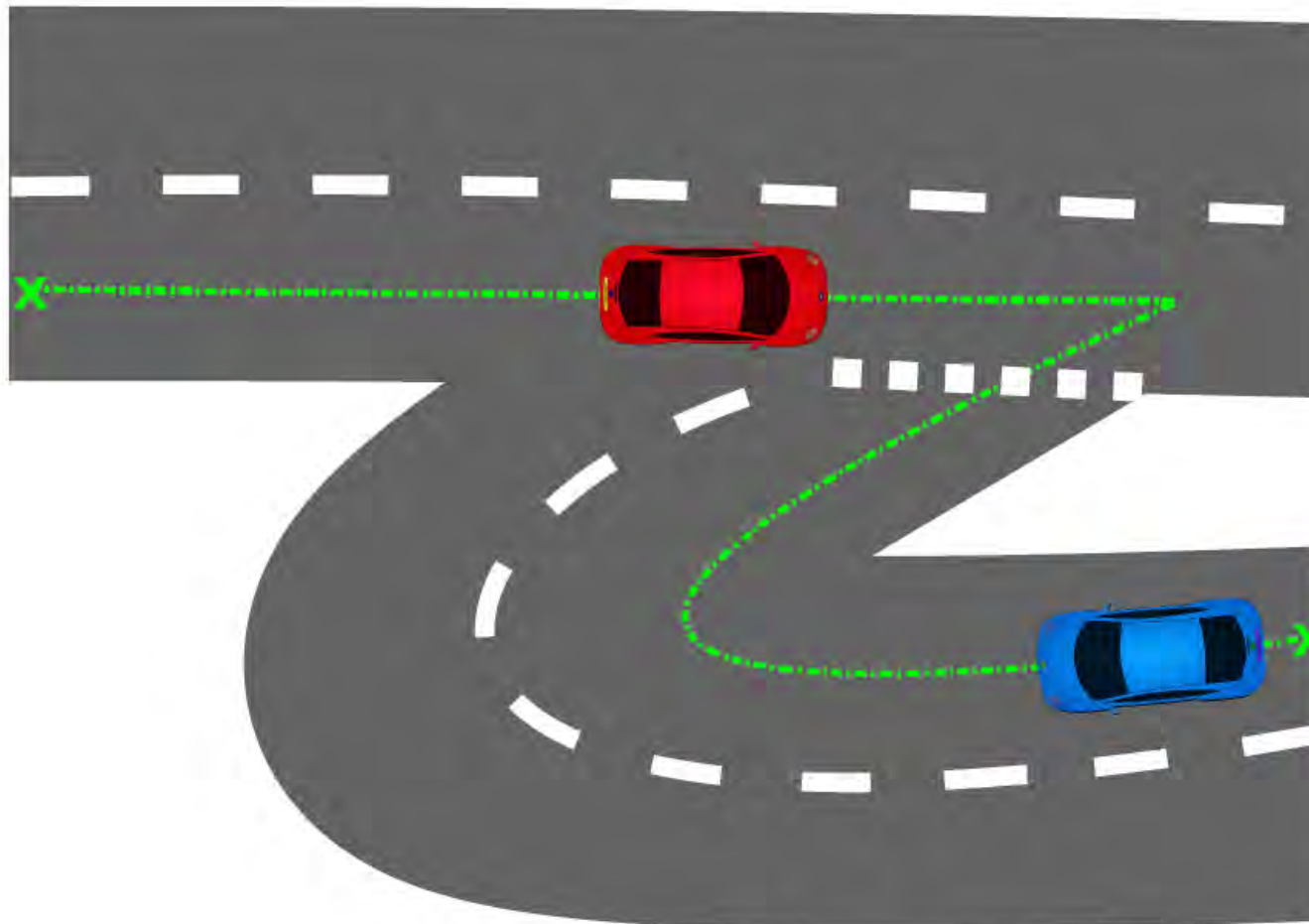
Inter-distance for platooning

In straight road, inter-distance is easy to measure (e.g. Lidar)



In curved road, compute the inter-distance along the map by using positions

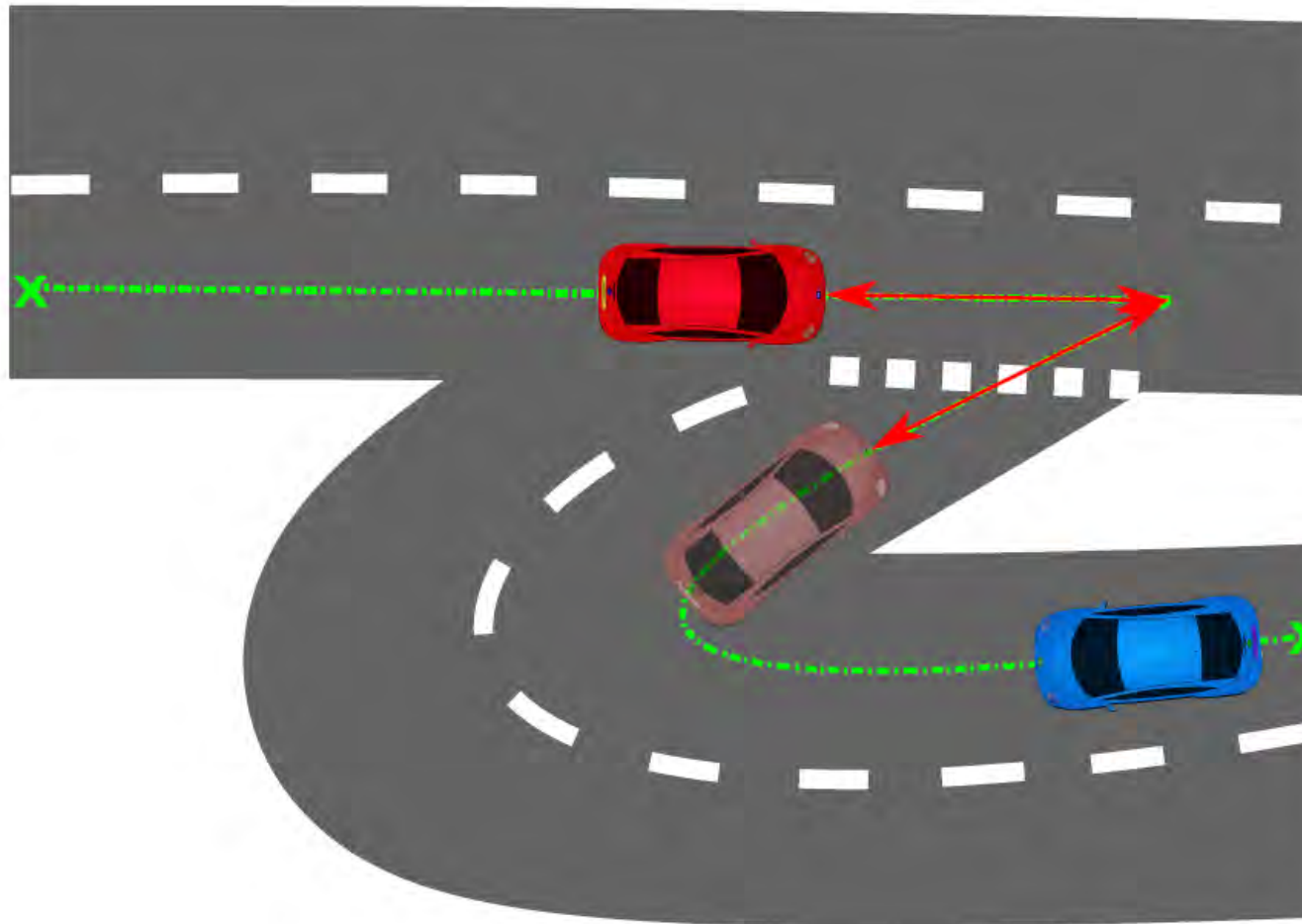
Cooperative merging using virtual platooning



The virtual platooning concept

Every vehicle

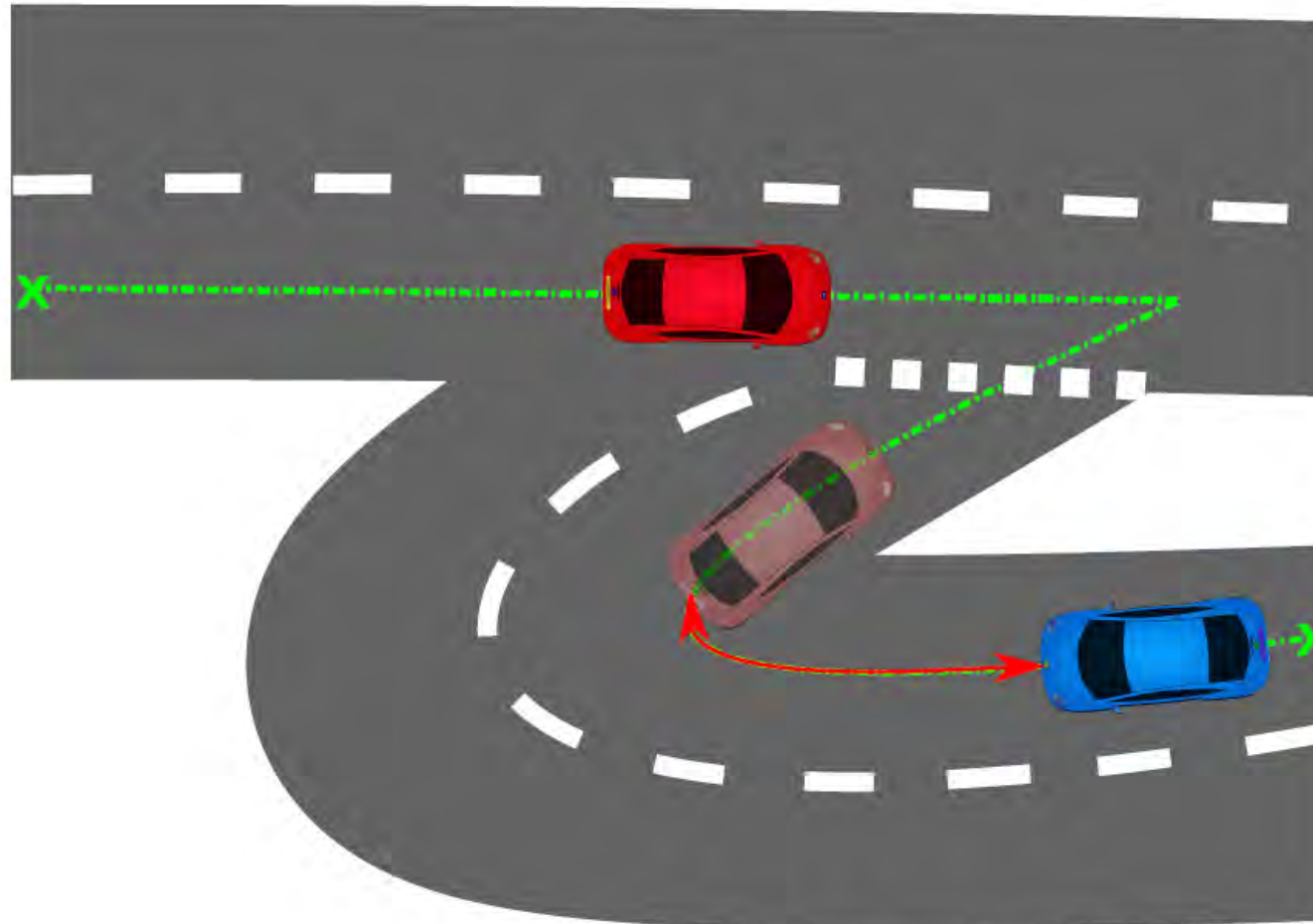
- Computes its distance to the crossing point
- Such that the others can locate it on their own path



The virtual platooning concept

In this example, the vehicle that is the closest to the intersection point becomes the (virtual) leader

Then the blue one does platooning



What we did

We did virtual platooning with the vehicle of the organizers

We used its transmitted position

- because we knew it was reliable

Procedure:

- Set the origin of the working frame at the center of the intersection
- Convert the geo-positions in this frame
- The norm of the position is the distance to the center
- Subtract your distance with the one of the organizer
- Do virtual platooning until the car has crossed the intersection

We used lidar to robustify the distance estimation

- $d = \min(\text{lidar}, \text{comm})$

Intersection crossing



Scenario 3: Emergency vehicle



Judging criteria and their evaluation

Non-technical judging

- Assistance and support
- Human-machine interface

Technical judging

- Scenario 1: Cooperative merging (8 heats)
 - Safe inter-distance, respect of merging protocol, automation level
- Scenario 2: Cooperative intersection (plenty!)
 - Safe inter-distance, acceleration profile, time to go out of the competition zone
- Overall technical score
 - sum of the 3 best heats.

Data logging

- Every received and sent message was to be logged by every participant
- The organizing team did the same

Final ranking

1. Halmstad University, Sweden
 - Halmstad
2. KIT Karlsruhe, Germany
 - KIT
3. KTH Stockholm, Sweden
 - Truck team



The other teams were not classified.

Fortunately for us, we got the maximum amount of points for the intersection crossing scenario.

Lessons learned

Part 5

Lessons learned

Integration remains a crucial issue

- Algorithms easy to tune with few parameters have to be preferred
- All the parameters have to be well identified

The determinist and sequential merging protocol led to deadlocks in case of failure of one participant

- Operators overrode the system several times

More intelligent procedures need to be elaborated

Localization for cooperative systems

Localization is crucial at the tactical level because most of the decisions are based on the location of the vehicle itself and of other vehicles in its vicinity.

Cooperative merging

- Localization is needed for data association with the perceived vehicles and received messages (to identify who wants to merge and at what location)
- Accuracy of the positions of the vehicles has to be such that there is no ambiguity
- Every vehicle has to know on which lane it is located

Intersection crossing

- Localization is very useful for improving crossing procedures in case the vehicles can't see each other

Localization for cooperative control?

Localization is **useful** for cooperative systems at the control level when the others traffic participants are **out of view**

- Lane changes, overtaking, intersection crossing in virtual platoon mode

Requirements

- Accuracy has to be good (lane level)
- Uncertainty has to be consistent (the estimation of the error has to be not underestimated)

Localization errors **may lead to dangerous situations** for cooperative control when the others traffic participants are **in the vicinity**

- Inter-distances in platoons have to be regulated with embedded perception sensors
- When crossing junctions, embedded perception sensors are necessary to secure the navigation

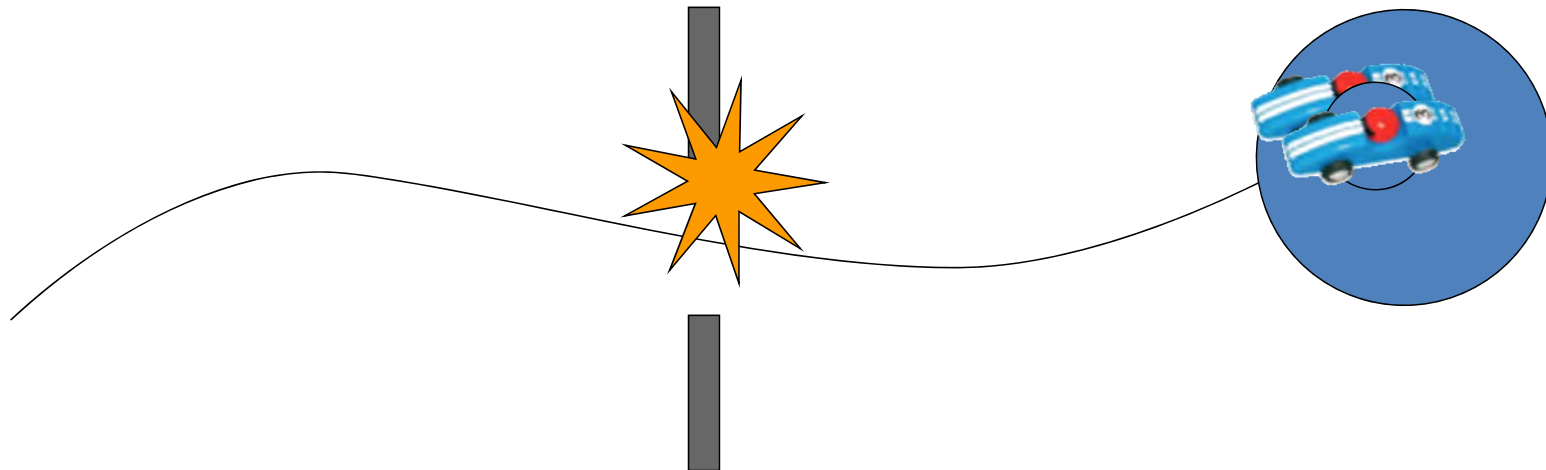
Perspectives

Part 6

Bound Localization uncertainties

If each agent estimates a bound of its localization error reliably and sent it to the other, then complex tasks can be solved safely with cooperative methods

Basic principle: be pessimistic to ensure safety



It is not optimal and it may reduce the system availability

Cooperative localization

Cooperate to reduce uncertainties, reduce pessimism and increase system availability



Conclusion

Vehicles exchanging highly dynamic information with each other is a new paradigm to improve autonomous vehicle navigation

- Useful to reduce the number of embedded sensors for navigation

Progress to be made

- Methods that guaranty the integrity of the information exchanged and control the propagation of errors and faults
- In particular, cycles of exchange inducing data incest problems have to be taken into account

Associated publication

Philippe Xu, Gérald Dherbomez, Elwan Héry, Abderrahmen Abidli, and Philippe Bonnifait. “System architecture of a driverless electric car in the grand cooperative driving challenge.”

To appear in the **IEEE Intelligent Transportation Magazine**.



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