

# COPPLAR

CampusShuttle Cooperative Perception & Planning Platform

Public report



Project within Traffic safety and automated vehicles

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## FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which about €40 is governmental funding.

Currently there are five collaboration programs: Electronics, Software and Communication, Energy and Environment, Traffic Safety and Automated Vehicles, Sustainable Production, Efficient and Connected Transport systems.

**For more information:** [www.vinnova.se/ffi](http://www.vinnova.se/ffi)

# 1. Summary

We have the vision of developing a cooperative self-driving vehicle that can travel between Chalmers two campuses Johanneberg and Lindholmen in Gothenburg – a vision that clearly pushes the current state-of-the-art of self-driving vehicles. In order to get there, we need to be able to automatically navigate several complex traffic situations, ranging from multi-lane driving to complex and crowded inner-city traffic. For example, the self-driving vehicle needs to safely coordinate with other vehicles, navigate on narrowing streets, interact with bicyclists and crossing pedestrians, obey complex traffic rules, and handle different weather conditions.

In this project, we have jointly taken the first steps under systematic and controlled conditions to reach our vision. Firstly, we have identified, classified, and prioritised relevant traffic situations/problem formulations that extend the current state-of-the-art. A selection of the most prioritised scenarios/problems has been systematically studied through, data collection, analysis, development of new methods and tools and in-vehicle demonstration at AstaZero proving ground.

In the project we have tried to answer the following high-level research questions:

- *How can we improve the situational awareness of surrounding traffic in complex intercity traffic by, e.g., better modelling, shared perception between cooperating vehicles and improve tracking algorithms?*
- *How can we robustly determine the position of the self-driving vehicle in its pre-build internal map when the current condition is significantly different (seasonal changes, construction) than when the map created?*
- *How can we design our path planner such that we can guarantee that it is safe, i.e., that a collision is avoided with a certain probability?*
- *In what way can we utilize the possibilities that 5G communication offers to improve situational awareness, localization and path planning for cooperating automated vehicles?*
- *What system and software architectural design principles and methodologies are needed and appropriate to reliably, systematically, and continuously prototype, evaluate, or safely roll-back different software variants for safety-critical real-time applications?*

In answering these questions, we got the following results in the main areas that we have addressed in this project:

## **Situational awareness**

Novel algorithms for cooperative tracking and mapping have been developed, for lidar, radar and camera, as well as 5G measurements. The results, including experiments with the COPPLAR test vehicle at AstaZero, show that when the autonomous vehicle cooperate, it leads to improvements of the tracking of moving objects, the mapping of the stationary environment, and the localization of the autonomous vehicles.

## **Localization and mapping**

We have developed novel methods for construction sensor maps using two important sensors, namely radar and camera for which we have designed robust localization methods. We have shown that our localization methods can robustly handle the large appearance changes associated with seasonal changes as well as day and night conditions. To further push the research community to improve the state-of-the-art in long-term visual localization we have constructed a challenging visual localization benchmark, which is publicly available here [www.visuallocalization.net](http://www.visuallocalization.net).

## **Path prediction and control**

A path planner with safety guarantees has been developed and experimentally tested. A prediction layer complements the planner, which is capable of learning and predicting the motion of human road users (pedestrians, cyclists, human drivers). Such predictions are used by the planner to guarantee that collisions are avoided in probability.

## **Communication system**

We have equipped the vehicle infrastructure with 802.11p vehicular communication units from Kapsch. We have created new data formats suitable for low-latency short messages of arbitrary content. We have developed methods for cooperative awareness among multiple vehicles and performed measurements to validate these methods. Finally, we have made theoretical contributions towards using 5G signals for positioning and mapping.

## **Software**

To enable the seamless integration of the hardware and software components interacting in the COPPLAR platform, the modular and lean middleware called OpenDLV/libcluon was systematically evaluated in the COPPLAR project. The middleware libcluon is also the world's first single-file, header-only middleware, for which it was successfully demonstrated how to design and achieve a fully automated deployment of software artefacts. The middleware was used to realize open-source software components to extract data from the vehicle's environment through physical sensors, compute and share them with other software components by exchanging user-defined data structures.

## 2. Sammanfattning på Svenska

Vi har en vision om att utveckla ett kooperativt självkörande fordon som kan färdas mellan Chalmers två campus Johanneberg och Lindholmen i Göteborg - en vision som tydligt utmanar nuvarande state-of-the-art. För att lösa detta måste vi kunna navigera automatiskt i flera komplexa trafiksituationer, allt från flerfiliga vägar till komplex och trång stadstrafik. Till exempel måste det självkörande fordonet säkert samordna med andra fordon, navigera på smalare gator, interagera med cyklister och korsa fotgängare, följa komplexa trafikregler och hantera olika väderförhållanden.

I det här projekt har vi gemensamt tagit de första stegen för att nå vår vision genom att studera och lösa delproblem under systematiska och kontrollerade förhållanden. För det första har vi identifierat, klassificerat och prioriterat relevanta trafiksituationer / problemformuleringar som behöver lösas. Ett urval av de mest prioriterade scenarierna / problemen har systematiskt studerats både genom, datainsamling, analys, utveckling av nya metoder och verktyg och demonstration i fordon på AstaZeros provbana.

I projektet har vi försökt att besvara följande forskningsfrågor:

- *Hur kan vi förbättra omvärldsförståelsen om omgivande trafik i komplex stadstrafik genom exempelvis, bättre modellering, dela omvärldsbild mellan fordon och förbättrade följningsalgoritmer?*
- *Hur kan vi på ett robust sätt positionera fordonet i dess inbyggda karta då omvärlden har förändrats markant (årstidsförändringar, ombyggnationer) sedan dess kartan skapades?*
- *Hur kan vi utforma vår ruttplanerare så att vi kan garantera att den är säker, dvs. att en kollision undviks med en viss sannolikhet?*
- *På vilket sätt kan vi utnyttja de möjligheter som 5G-kommunikation erbjuder för att förbättra situationsförståelse, lokalisering och ruttplanering för samverkande självkörande fordon?*
- *Vilka principer och metoder för system- och programvaruarkitektonisk design behövs och är lämpliga för att pålitligt, systematiskt och kontinuerligt prototypa, utvärdera eller säkert rulla tillbaka olika programvarianter för säkerhetskritiska realtidsapplikationer?*

När vi besvarade dessa frågor fick vi följande resultat inom de huvudområden som vi har behandlat i detta projekt:

### **Situationsförståelse**

Nya algoritmer för kooperativ följning och kartering har utvecklats för lidar, radar och kamera samt 5G-mätningar. Resultaten, inklusive experiment med COPPLAR-testfordonet vid AstaZero, visar att när det autonoma fordonet samarbetar, leder det till förbättringar av följning av rörliga objekt, kartering av den stationära miljön och lokaliseringen av de autonoma fordonen.

### **Lokalisering och kartering**

Vi har utvecklat nya metoder för att skapa sensorkartor med två viktiga sensorer, nämligen radar och kamera. För dessa har vi även utformat robusta lokaliseringsmetoder för att positionera fordonet i dessa kartor med hjälp av nuvarande sensorobservationer. Vi har visat att våra lokaliseringsmetoder kan robust hantera de stora utseendeförändringarna som är förknippade med säsongsförändringar såväl som dag- och nattförhållanden. För att ytterligare driva forskningsfronten inom långsiktig visuell lokalisering har vi även konstruerat ett utmanande benchmark för visuell lokalisering som finns publikt tillgängligt här [www.visuallocalization.net](http://www.visuallocalization.net).

### **Ruttprediktering och beslutfattning**

En ruttpredikterare med säkerhetsgarantier har utvecklats och testats experimentellt. Ett prediktionslager kompletterar planeraren, som kan lära sig och förutsäga rörelsen hos mänskliga trafikanter (fotgängare, cyklister, mänskliga förare). Sådana förutsägelser används av planeraren för att garantera att kollisioner undviks med en viss sannolikhet.

### **Kommunikationssystem**

Vi har utrustat fordonsinfrastrukturen med 802.11p fordonskommunikationsenheter från Kapsch. Vi har skapat nya dataformat som är lämpliga för korta meddelanden med låg fördröjning och med godtyckligt innehåll. Vi har utvecklat metoder för kooperativ situationsförståelse bland flera fordon och utfört mätningar för att validera dessa metoder. Slutligen har vi gjort teoretiska bidrag till att använda 5G-signaler för positionering och kartering.

### **Programvara**

För att möjliggöra sömlös integration av hårdvaru- och mjukvarukomponenter som samverkar i COPPLAR-plattformen har vi systematiskt utvärderat den modulära och magra mellanprogrammet OpenDLV / libcluon. Libcluon är också världens första singelfil, endast header-fil, med vilken man kan utforma och uppnå en helautomatisk distribution av mjukvaruartiklar. Den resulterande mjukvaruarkitekturen möjliggjorde också för forskare att ladda upp data från fordonet för ytterligare dataanalys, såväl som distribution av ny programvara för studie av experimentella metoder. Programvaran, hårdvaran och systemarkitekturen har utvärderats iterativt på Chalmers Revere med hjälp av vår prototypbil (Volvo XC90-bil) som vi har utrustat med nödvändiga sensorer och datorinfrastruktur.

### 3. Background

When we stated this project, much of the focus of the industry was to solve self-driving cars in high-way scenarios as, for example, with Volvo Cars' DriveMe project. This is natural as this is probably one of the areas where we will see the first commercially available self-driving vehicle applications. However, we cannot stop there and there is a clear need to systematically study more complex scenarios. In this project we will go beyond the scope of DriveMe and other similar research projects by focusing on these two aspects:

#### Inner-city environments through the centre of Gothenburg

The route between Chalmers two campuses, as depicted in Figure 1, goes through the very heart of Gothenburg and involves pedestrian crossing, speed bumps, multi-lane intersections, merging traffic, trams, etc. This is challenging in several aspects, as we need, e.g., accurate self-localization in GPS denied environments, collision-free and comfortable motion planning in complex road geometries, to name a few.

#### Cooperative self-driving vehicles

In addition to developing an automated self-driving vehicle, the project will also investigate added benefits of incorporating V2X communication to study solutions for the problem of inner-city driving. By using V2X technology, vehicles can negotiate a joint cooperative motion plan as well as share their perception of the environment. Additionally, by designing smart intersections equipped with sensors and communication systems, many of the aforementioned situations can be greatly simplified.

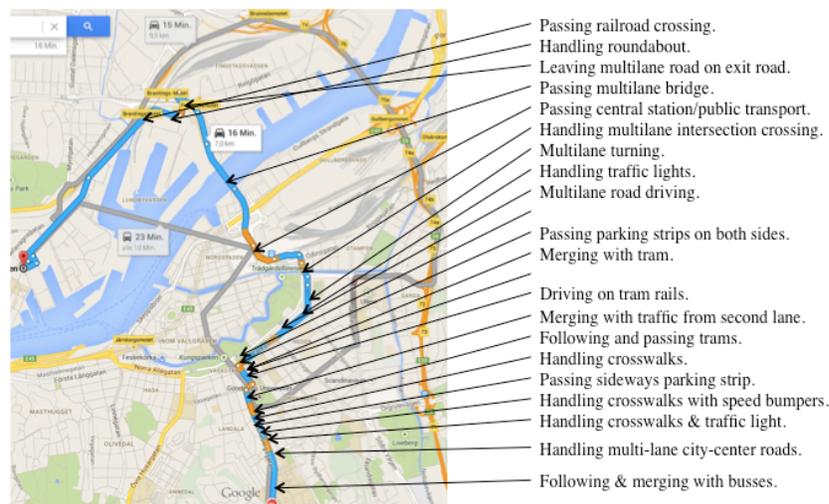


Figure 1: The aimed route for the cooperative self-driving vehicle and indicated situations.

## 4. Purpose, research questions and method

The purpose of the project is twofold; (1) develop a research platform in the form of a cooperative automated vehicle and surrounding data infrastructure with which we can collect relevant sensor data, investigate the needed software processes and test our algorithms in real-time and in a controlled environment at AstaZero. (2) Use the research platform, by collecting and analysing sensor data as well as the inherent constraints of a real-time system, to select the most important challenges needed to be solved in order to realise our ultimate goal, that our cooperative automated vehicle should drive safely and robustly between our two campuses. As such, the method for which we are selecting, prioritising and evaluating our research is directly connected to the problems that we need to solve through our research platform. Below we highlight our research questions for the different areas that we investigate in this project.

### **Situation awareness**

In the context of situation awareness, we have tackled research problems that allow us to answer research questions such as the following: When the state of the sensor platform, i.e., the autonomous vehicle, is uncertain, how can the tracking problem be formulated, such that it allows simultaneous localization and tracking? How should multiple agents collaborate and communicate their tracking and mapping results, such that the performance of each agent is improved? How can this be achieved in a way that is both accurate, and computationally efficient?

Automated vehicle perception can be improved if the vehicles collaborate and cooperate by sharing their perception. With the COPPLAR project we have shown how the estimated extent (size and shape) of a tracked object can be markedly improved when two (or more) vehicles with overlapping sensor fields of view communicate their respective tracking results. Accurate estimation of the extent is important in urban scenarios, where it is often necessary for the automated vehicle to manoeuvre close to other road users.

Additionally, we have studied how the sharing of tracking information can improve vehicle localization. If two vehicles, one with accurate self-localization and one with low quality self-localization, both observe the same object, e.g., a pedestrian, then by sharing tracking information, the localization of the second vehicle is improved significantly, without affecting the performance of the first vehicle. This was shown using data collected using the COPPLAR vehicle at the AstaZero testing grounds.

### **Localisation and mapping**

Although automated vehicles can operate in uncharted environments, most efforts aimed at self-driving cars rely on pre-constructed detailed navigation maps to provide information about the road ahead. In the COPPLAR project we have investigated both how we can build these detailed navigation maps using survey-grade dense lidar point

clouds as well as how to robustly and accurately find the current location of the self-driving vehicle in these maps. For the latter we have considered both stand-alone solutions based on observing landmarks using the vehicles on-board sensors as well as cooperative approaches where information is shared between cooperating vehicles. The methods that we have developed have been evaluated against our publicly available localization benchmarks (see [www.visuallocalization.net](http://www.visuallocalization.net)).

### **Vehicle wireless communication**

Situational awareness can be augmented through data exchange between vehicles. Control actions with additional degrees of freedom can be enabled through inter-vehicle coordination. Such data exchange and coordination require wireless communication among vehicles, which will form a mobile ad-hoc network. Supporting highly mobile, safety-critical transportation applications requires a careful design of the communication sub-system. We have studied communication resource allocation for controlling vehicles under packet losses. We have also developed and evaluated novel methods for cooperative awareness that can cope with communication delays. Finally, we have conducted an exploratory study to determine to what extent contemporary 5G signals can provide reliable, timely, and accurate location information.

### **Decision-making, cooperative motion planning and control**

In a self-driving vehicle, decision-making, motion planning, and control have to entirely rely on the perception of the surroundings based upon information from the on-board sensors and the wireless communication with other vehicles and infrastructure. Clearly, noisy sensor data and losses/delays in wirelessly transferred data result in degraded environment perception and situation awareness that a decision-making and control layer must account for. Additionally, the safety critical driving tasks executed by a self-driving vehicle require an exhaustive verification of the decision-making and control algorithms. Safety of decision-making and control algorithms can be verified through extensive simulations or in-vehicle testing and formal methods. The former is time consuming and costly, yet not guaranteed to be exhaustive, but straightforward while the latter guarantee the full coverage of the possible driving scenarios at the cost of possibly prohibitive computational complexity in complex traffic scenarios.

Our objective is to provide safety guarantees by both including “safety constraints” in the design of the algorithms and developing low complexity formal safety verification methods. Hereof, we have focused on model-based path planning and vehicle coordination techniques, where safety can be enforced by state and input constraints. We have extended existing results on the persistent feasibility of safety constraints to account for autonomous driving applications like, e.g., unpredictability of surrounding human road users. We have designed and experimentally validated coordination algorithms for multi-vehicle systems, using wireless communication and demonstrated, through simulations, the advantage of the proposed methods over existing coordination algorithms, including traffic lights, in high density traffic scenarios.

## Multi-Domain Software and System Architecture

From the project's beginning, the self-driving vehicle platform at Chalmers (Volvo XC90) was envisioned and designed to be usable in multi-disciplinary contexts from different researchers; here, COPPLAR was the key-enabling project and framework to achieve this goal.

To achieve this goal and to surpass the state-of-the-art at the project's beginning, the following pertaining research question has been identified: *What system and software architectural design principles and methodologies are needed and appropriate to reliably, systematically, and continuously prototype, evaluate, or safely roll-back different software variants for safety-critical real-time applications?*

From this research question, the following research topics have been derived and addressed:

- “Sandbox-ing” for different research projects to enable a co-existence of algorithms for the core functionality of the self-driving vehicle with different maturity levels (i.e., allowing full traceability not only in the source code of the software but also completely downstream to the running software artefacts on the vehicle, which has not been seen achieved in academic vehicle platforms),
- “Shadow” execution for different versions and variants of the same algorithm from the core functionality in parallel to compare their performance (for instance, several sensor fusion algorithms in parallel) without violating essential properties like real-time capability; for this aspect, the COPPLAR project was an excellent and unique opportunity to conduct research for this aspect for the first time in a real-time context,
- “Live”-monitoring of runtime constraints of the executed algorithms, and
- Continuous integration and evaluation of algorithms and software with the system.

The research methods that have been used to achieve the aforementioned goals comprise primarily of design science research in combination with controlled experiments. Furthermore, to achieve the research goals related to software and system architecture, case studies with the industrial partners have been conducted, analysed, and evaluated. The placement of the particular research questions and the obtained research results into the scientific landscape has been supported by extensive and systematic literature studies.

## 5. Objective

The objective of COPPLAR is to: (1) develop a prototypical and extensible vehicle platform exhibiting self-driving capabilities in a controlled test track environment (AstaZero), (2) establishing the necessary software and system infrastructure on-board and at backend to collect, analyse, and process heterogeneous large-scale data streams for our algorithms (3) incorporating algorithms for scene perception and understanding for complex traffic situations, (4) to reliably plan cooperative and collision-free trajectories.

## 6. Results and deliverables

In the COPPLAR project, we have focused on two parts; The first part focuses on developing the research vehicle platform that we can use to collect relevant sensor data, test our developed algorithms and as a use case for the development of needed software tools and architectures. The second part focuses on research to solve and develop the building blocks needed for a cooperative automated vehicle to safely and robustly navigate complex inner-city traffic. Here we look at algorithms and tools for *(cooperative) situational awareness, (cooperative) localization and mapping, communication system requirement* and *(cooperative) path planning and control*. As much of this work is well-documented in the 68 peer-reviewed scientific journal and conference papers and PhD and licentiate theses produced by this project, our focus here is to give an overview of the results and guide the reader to the publicly available paper where more information can be found.

### 6.1 Research vehicle platform development

Test vehicles, enabling real-traffic data logging and testing of developed algorithms, have played an important role in the project. The base vehicle for the COPPLAR project has been a 2015 Volvo XC90 that was provided by Volvo Cars. It was equipped with various test equipment by the Chalmers vehicle research lab Revere and was named “Snowfox”. Also, a second Volvo XC90 (“Greyfox”) was provided (production status) to act as a target vehicle when performing different test scenarios.

To allow communication with the test vehicle, enabling advanced vehicle actuation and control, additional breakout cables were installed by Volvo Cars together with a special software in one of the car’s ECU’s. This vehicle CAN communication interface enables researchers to control vehicle acceleration, braking and steering. Also signal information regarding, for example, vehicle speed, steering wheel angle, and engine torque can be obtained. No ADAS production sensor data has been shared from the vehicle.

**Volvo XC90 “Snowfox” vehicle data****Vehicle type:** XC90 5 doors**Vin No:** YV1LFA2BCG1000341**Transmission:** Automatic gearbox, AWF22**Driveline:** 4-wheel drive**Engine:** 4 cyl. 2.0 L 306 Hp petrol engine, PZEV

*Figure 2: The Volvo XC90 test vehicle “Snowfox”.*

The test equipment in the base vehicle is defined by two architectures i.e. System Architecture and Power Architecture. System Architecture refers to the combination of computation, network and sensor clusters and the Power Architecture refers to the combination of batteries, chargers, inverters, etc (electrical power supply) which provide power for the stable & smooth functioning of the components in the system architecture.

**System Architecture**

The vehicle is equipped with a set of sensors that comprises a front-facing stereo camera system (installed by Autoliv/Veoneer) mounted behind the wind screen, an additional cluster of two high-resolution color cameras operating as a separate stereo-vision system, a Velodyne 32-layer LIDAR sensor, an industrial Applanix IMU/GPS receiver and a cluster of five Autoliv/Veoneer vehicular radars. Furthermore, the sensors include cameras inside the vehicle primarily targeting documentary purposes, and a RoadScape electronic horizon module providing information about road curvature, road signs, etc. The computational capabilities of the vehicle are provided by two industrial-grade computers connected by a high-capacity network switch, as well as a Meinberg “time machine” providing GPS-synced timestamping.

### Test vehicle System Architecture

- Vehicle CAN Gateway for Control & Vehicle Data (breakout cables and ECU software)
- LIDAR: Velodyne HDL32 x 1
- GPS-IMU: Applanix POS LV-220 x 1
- Cameras:
  - Axis M1124-E (1280 x 720) x 1
  - Basler ACA2040-35GC (2048 x 1536) x 2
  - Veoneer stereo camera system (non-production)
- Radars (non-production): Autoliv/Veoneer
- RoadScape Unit: Veoneer
- Computing HW; Aaeon AEC-6590 PC and Brick CORE COMplus PC
- Network switch: Cisco IE-2000-16PTC-G-E
- Timesync HW: Meinberg M500 (PTP)

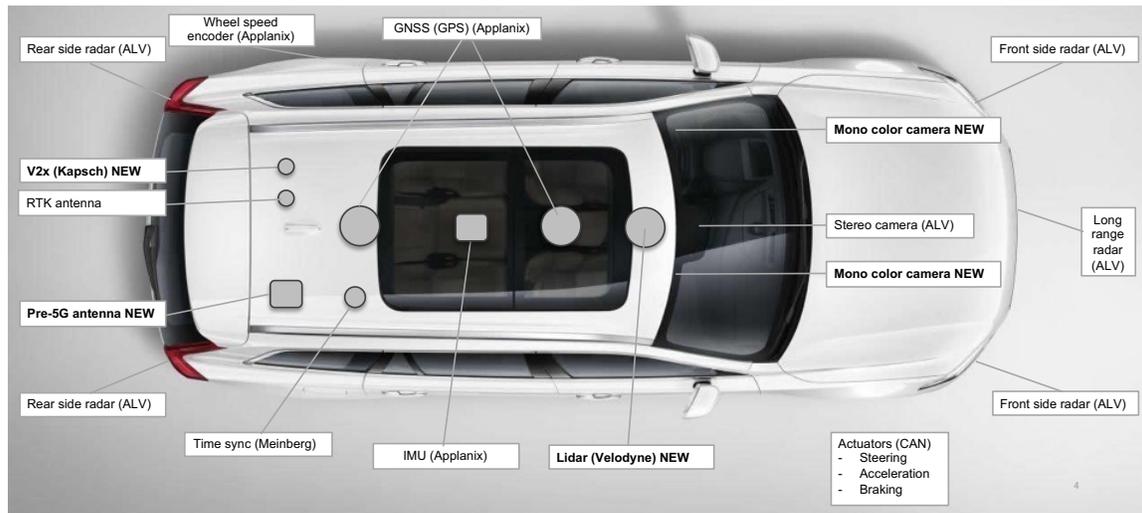
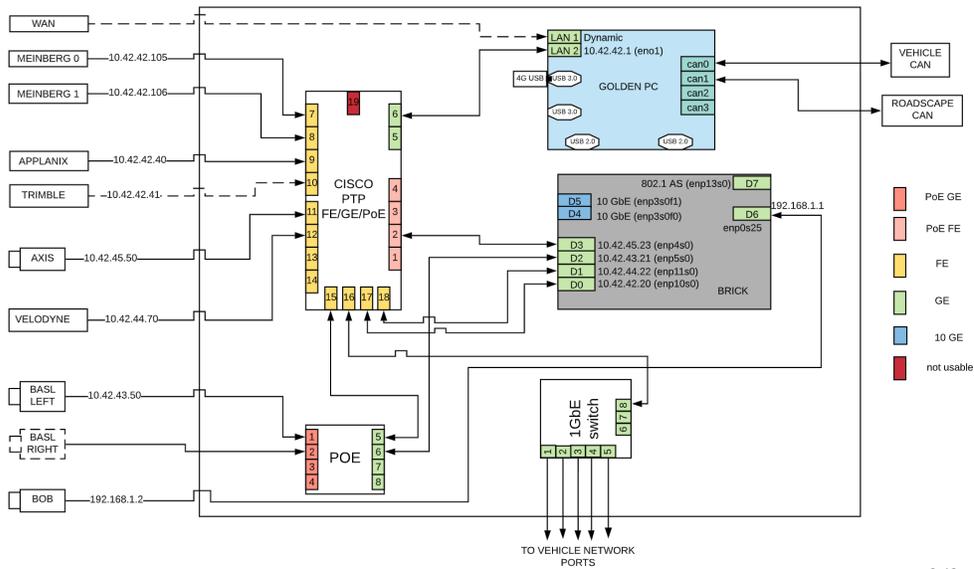


Figure 3: The Volvo XC90 "Snowfox" System Architecture.

## SNOWFOX NETWORK ARCHITECTURE 2019



(c) Chalmers Revere CC-SA-BY

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July 18, 2019

Figure 4: Test vehicle Network (System) Architecture.

### Power Architecture

The Power Architecture relies on the principle of having an Auxiliary Battery Bank to power the system components and have no link to the base vehicle battery bank (except for charging the Auxilliary Battery Bank while driving). In this way, the System Architecture is not dependent on and have no effect on the base vehicle functionality and usage. Moreover, voltage drops in the car's electrical system induced by e.g. cranking the engine will have no effect on the System Architecture. The Power Architecture allows the System Architecture to run for about 3-4 hours without need for charging. This also means idling the engine just to charge batteries can be avoided, which is very convenient when working on e.g. software at a stand-still at the test track.

### **Test vehicle Power Architecture main components**

- Auxiliary Batteries, AGM 90Ah (12V) x 2
  - With battery state of charge monitoring shunt
- Digital Fusebox x 2
  - Programmable fuses
- DC-DC Charger x 1
  - Charge while driving, 12VDC-12VDC
- Battery Charger x 1
  - Charge from grid at stand still, 220VAC-12VDC
- Inverter x 1
  - Providing 220VAC in vehicle (for charging laptops etc)
- Power Architecture Monitoring Panel x 1

## **6.2 System and software**

The software in the system is modular and the software components are organized following the so-called “microservices design”, where the COPPLAR project was the world’s first vehicular platform, where this recent trend in software architecture design has been systematically analysed and evaluated on a prototypical platform. The individual microservices that haven been provided and evaluated as part of the open-source environment OpenDLV, address the time-synchronized data gathering as well as the handling of large-scale data volumes in real-time.

A further aspect of the systematically decoupled software modules is focusing on protecting software that is under IP regulations. To realize this, all software components have been provided in a containerized infrastructure allowing simplified tracing and maintenance. The COPPLAR project enabled our research group to pioneer this aspect from the area of software engineering in the domain of automated vehicles.

The envisioned results from the COPPLAR project proposal “(1) using Chalmers ReVeRe vehicle lab to develop a prototypical and extensible vehicle platform exhibiting self-driving capabilities in a controlled test track environment (AstaZero) and (2) establishing the necessary software and system infrastructure on-board and at backend to collect, analyse, and process heterogeneous large-scale data streams for our algorithms” have been met.

In particular, the following results have been created within the project and shared among the project partners:

- a) A report describing a prioritized set of possible routes between Johanneberg and Lindholmen in Gothenburg including a systematic traffic scenario analysis; selected functional and non-functional requirements for selected prioritised scenarios have been identified.
- b) Processes and the necessary software infrastructure have been provided and evaluated in the prototypical vehicle (Volvo XC90) to enable recording, documenting, and replaying sensor data.
- c) A software architecture has been developed and systematically evaluated to meet the goals as listed in Section 4, “Multi-Domain Software and System Architecture”.
- d) Finally, to allow for systematic preparations and repeatable analysis of software components, a prototypical virtual test environment for interactive testing of the data processing chain for the self-driving functionality has been evaluated; this environment included tooling for automatically executing and evaluating software components from selected parts of the self-driving functionality as part of a continuous integration concept before deploying critical components to the prototypical vehicle.

The results from the work packages related to the software and systems have been published in journals and presented at workshops and conferences: [18] [45] [46] [49] , [54] , [57] , [59] [63] [64] and [67] .

Please note that the journal paper [18] is already the second most popular article of all times in IEEE Transactions on Intelligent Vehicles:

<https://ieeexplore.ieee.org/xpl/topAccessedArticles.jsp?punumber=7274857>

### **6.3 Situational awareness**

Situational awareness (perception) is one of the functions in the autonomous vehicle. The purpose is to make the ego vehicle aware of, interpret and understand its surroundings. This includes not only awareness of all other road users but also what their intents are (what they are going to do next?).

Vision and radar systems has shown to be fundamental building blocks for automated vehicles perception capabilities linked to their adoption as state-of-the-art sensors for ADAS features. In this project, we are expanding on this and including information from additional sensors, such as lidar, GPS, mapping, connectivity, V2X etc., the extend the perception ability in the targeted complex scenarios. Additionally, when collaborating among the vehicles, sharing perception and scene understanding, the project has advanced in solving the AD problem. Below we give more details regarding our results

connected to three sub-areas, road geometry estimation, object tracking and cooperative situation awareness.

### **Road geometry estimation**

One important safety aspect of a self-driving car is to continuously be able to estimate the geometry of the drivable road area in front in order to safely plan the path ahead. We have looked at two complimentary methods for doing this. In [16] , we fuse close-range lane geometry information from a front looking camera together with information about the trajectory of leading vehicles and road side stationary objects (e.g. guard rails) from the radar to estimate the geometry of the road up to 200 m ahead in well-structured highway scenarios. For more complex scenarios, for example inner city traffic, we in [47] develop a deep neural network that uses observations from a lidar (3D point cloud) transformed to a bird-eye view image as input and outputs per pixel classifications of drivable road surface. At the time, this was the best performing lidar based method on the KITTI-benchmark. A video illustrating the results can be found here, <https://youtu.be/0r7WQXCLqc4>.

### **Object tracking**

We have made important contributions to multiple object tracking using so called conjugate priors, specifically the Poisson Multi-Bernoulli Mixture density [58] , [26]. The use of conjugate priors has allowed us to design tracking algorithms that both give accurate tracking performance and are computationally efficient [34] . One of the most important parts of a tracking algorithm is the handling of the data association problem. In this area we have made presented data association methods that build upon so called Markov Chain Monte Carlo sampling methods [8] [14] [53] .

### **Cooperative situational awareness**

Generally, in multiple target tracking the sensor position is assumed known. For an automated vehicle, this is not always realistic assumption. In [41] [20] we present a filter for joint estimation of both the sensor state and the multi-target state. The joint filter is based on a Poisson Multi-Bernoulli representation of the multi-target state, and a variational approximation of the joint sensor-target density. A video illustrating the result of this method can be found here: <https://youtu.be/LyS1KLJdgjM>.

Estimating the spatial extent (size and shape) of other road-users is important for any automated vehicle, increasingly so in urban environments where it may be necessary to manoeuvre close to, e.g., other cars. In [20] we show that the tracking performance is improved significantly when two vehicles collaborate on the tracking; the improvement is especially significant for the estimated extent.

## 6.4 Localisation and mapping

In the COPPLAR project we have investigated different aspects of localisation and mapping related to self-driving vehicles. Firstly, we have developed methods for generating high-definition, yet lightweight, navigation maps from dense survey-grade lidar point clouds. With these maps, the self-driving vehicle gets the detailed information needed in order to safely navigate to the desired destination. Secondly, we have investigated different methods to reliably localize the self-driving vehicle in these maps using a variety of information sources. This ranges from using observations of landmarks from on-board sensors, such as, radars and camera, using the 5G communication network and by sharing map-related information between cooperating vehicle. Our contributions in all these areas are summarized below.

### Sensor-based localization and mapping

A common approach to solving the localization problem for self-driving vehicle is to build, so called, sensor maps containing the position of landmarks, i.e., structures in the environment that are stationary and can easily be detected by the on-board sensors. The basic idea is that, by associating observations of landmarks currently seen by the on-board sensors with the landmarks in the map we can accurately infer the current location of the vehicle.

In COPPLAR, we have developed methods for how to build these sensor maps for radar sensors in [14] , [56] , and for cameras in [22] , [36] , [39] . In the latter, the focus has been on solving the long-term visual localization problem, i.e., being able to localize even under severe appearance changes, such as, summer/winter or day/night. Here we propose different ways of using semantic class (building, road, vegetation etc.) of the objects observed in the camera image as a stable feature that is invariant to both seasonal changes as well as the appearance changes between day and night. This is illustrated and motivation further in this video here: <https://youtu.be/M55qTuoUPw0>.

To further push the scientific community to solve these challenging problems we have also developed a long-term visual localization benchmark presented in [30] and available at [www.visuallocalization.net](http://www.visuallocalization.net).

### High-definition navigation maps

Taking rational decisions about navigating and driving requires a higher abstraction level objects than a set of points, i.e. a point cloud that constitutes the LIDAR data. A model of the road was thus created from the data. This model attributes all data as to belonging to some object, that has a meaningful role in driver's decision making. There are existing models that are used by drivers to navigate the car: consider existing complex maps, that in conjunction with GPS, driver's knowledge and observations allow him to make navigation decisions. Existing roadmaps are insufficient for an automated vehicle: they lack important details about road structure such as lanes, obstacles and road lights, and these maps are static. We propose a set of algorithms that allow to classify road areas into lanes and junctions and thus allow navigation according to traffic rules. These algorithms

were successfully tried on AstaZero City test area; however, their semi-automatic nature will likely require further development to make use of the method in other areas.

Figure 5 shows a classification example where a satellite picture of the area is given to the left, and processed map with navigation objects is to the right. Scarlet solid objects represent impassable walls, while grey cell boundaries represent road patches (they are pictured lighter in the areas with junctions). Big yellow and blue spheres mark locations of junction entry and leave points. Lane markings are denoted with dashed pink-purple lines and road centres are points connected with a coral pink line.

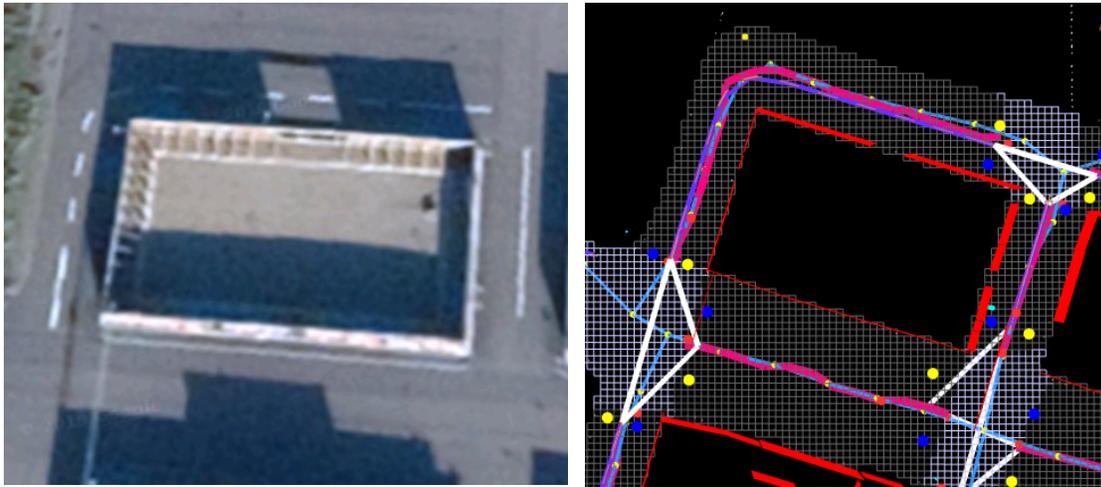


Figure 5: Aerial photo of mapped area to the left and illustration of resulting navigation map to the right.

### Global navigation and satellite system

Although the availability of accurate position from a global navigation satellite system (GNSS) is very limited, especially in urban canyons, we show in [62] how the combination of a single band GNSS receiver, standard automotive level inertial measurement unit (IMU), and wheel speed sensors, can be used for *relative positioning* with accuracy on a decimeter scale. This is implemented and evaluated in a natural driving environment against a reference system and two simple base line systems; one using only IMU and wheel speed sensors, the other also adding basic GNSS. The proposed solution provides substantially slower error growth than either of the two base line systems.

### 5G localization and mapping

During the project, we have made several key contributions 5G localization and mapping was studied in [5] [6] [7] [10] [23] [24] [25] [31] [35] [37] [44] [52] [55] . In 5G, the combination of large bandwidths and large arrays with high carrier frequencies lead to a communication system that is particularly conducive for positioning of vehicles and mapping of the radio environment. For example, 5G measurements enable highly accurate localization of automated vehicles. In [21] , we show that by leveraging the multi-path nature of the 5G measurements, a map can be built of the environment as it is

perceived by the 5G sensor. When multiple vehicles collaborate on the mapping, the map accuracy, as well as localization in the map, are both improved.

Our works span signal design, channel estimation, positioning, mapping, synchronization, as well as the trade-off between communication and localization. We have contributed to both theoretical studies (performance bounds and channel models) as well as practical algorithms. During the course of the project 5G positioning has become a study item in 3GPP (a worldwide standardization body), so that outcomes from this project may have an impact there.

### **Cooperative localization and mapping**

A final track deals with cooperative localization and mapping [3] [12] [38] [41] [43] where we developed a novel class of methods in which vehicles aid other vehicles in localization, by sharing map-related information. These methods have been validated with real data and show how a vehicle with poor localization quality can be aided by a vehicle with good localization quality, provided they observe the same scene. The method requires periodic information exchange of detected objects.

## **6.5 Communication system design**

Core research questions in COPPLAR has been how to leverage the possibilities that 5G communication can offer to support self-driving vehicles as well as what effects this will have on the communication system. To this regard, we have conducted interference analysis of vehicular communication systems, as interference will affect any kind of cooperative service (e.g., control or localization) [3] [50] [51] [60] . This analysis includes predictive studies of signal power as well as large scale interference analyses with stochastic geometry. Our main findings were that (i) the medium access protocol should be designed carefully to mitigate interference and (ii) the wireless channel is to some extent predictable, which is a property that can be exploited when designing or analysing vehicular communications. Building on this, [9] [11] [28] [29] [42] studied the impact of communication impairments on control and coordination and devised methods that can degrade gracefully under such impairments.

## **6.6 Decision making and path planning**

The research activities within COPPLAR concerning decision making and path planning have focused on two scenarios: interaction with human road users when driving in urban environments and coordination with surrounding connected autonomous vehicles. In [66] we have proposed a method for learning and predicting the motion of a pedestrian at a crosswalk. This work has generated a research track completely focusing on the problem of learning from data and then predicting the behaviour of human road users in urban traffic. The capability of predicting the motion of human road users is fundamental when planning the motion of a vehicle, as shown in [65] , where a predictive path planning

approach to guarantee in probability the avoidance of the collision with a pedestrian. An improved version of the planner in [65] has been developed, which provide safety guarantees in presence of limitation of the sensing and perception layers. An illustration of the result can be found here <https://youtu.be/0WLCItOMkYU>.

Guaranteeing safety by design is a paradigm adopted also in the coordination of connected autonomous vehicles [15] In [17] [27] predictive coordination schemes have been proposed, which have also been experimentally validated [69] (see also <https://youtu.be/kzvFeJ6aCnY>). The problem of compensating for the limitations of the communication network has been studied in [9]

## 7. Dissemination and publications

### 7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	The majority of the result from the project has been published in high-impact scientific journals and/or presented at well-renowned conferences.
Be passed on to other advanced technological development projects	X	Researchers have worked with companies making experiments and developing technology demonstrators. These results are in a number of cases being moved into development projects.
Be passed on to product development projects	X	In order to conduct part of the research, we had to develop and create new data collection platforms, training algorithm, and experiments. A number of these have served as models for improved infrastructure in industry.
Introduced on the market	X	Researchers had to create new ways of working to achieve our goals. These are described in research reports, and publications and are ready to be reused by other researchers or modified and transferred into industrial practice.
Used in investigations / regulatory / licensing / political decisions		

In addition to publishing our result in publicly available scientific journals and presenting the work at relevant conferences, during the project we have organized a number of workshops and open seminars disseminating the result of the project to our more local community and partner companies.

## 7.2 Publications

List of publications disseminating project results.

### PhD and Licentiate theses

- [1] R. Hult, *Optimization-based coordination strategies for connected and autonomous vehicles*. PhD Thesis, Chalmers University of Technology, 2019.
- [2] F. Giaimo, *Introducing Continuous Experimentation on Resource-Constrained Cyber-Physical Systems*. Lic. Thesis, Chalmers University of Technology, 2018.
- [3] M. Fröhle, *Channel Prediction and Target Tracking for Multi-Agent Systems*. PhD Thesis, Chalmers University of Technology, 2018.
- [4] E. Stenborg, *Localization for Autonomous Vehicles*. Lic. Thesis, Chalmers University of Technology, 2017.

### Journal, letter and magazine articles

- [5] A. Shahmansoori, B. Uguen, G. Destino, G. Seco-Granados, and H. Wymeersch, "Tracking Position and Orientation Through Millimeter Wave Lens MIMO in 5G Systems," *IEEE Signal Process. Lett.*, vol. 26, no. 8, pp. 1222–1226, Aug. 2019.
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## 8. Conclusions and future research

Our long-term vision is to be able to develop an automated vehicle that can safely and robustly navigate complex inner-city environments and drive between Chalmers' campuses at Johanneberg and at Lindholmen. In this project we have taken the first step to realize this vision by:

- Developing a research platform in the form of a prototype vehicle that can be used for data collection, testbench for our algorithms and as a use case for the development of needed software tools, architectures and compute infrastructure.
- Using the long-term vision as inspiration for finding and prioritizing the research questions that needs to be solved and methodically tackling these questions. As we believe that cooperation between automated vehicles in some shape or form will be an important enabling technology, cooperative aspects have been considered in all prioritized areas.
- Test and evaluate part of our algorithms in our prototype vehicle.

In this project we have focused on research questions related to *software and system architecture, situation awareness, localization and mapping, communication and decision making, path planning and control*. Below we summarize our findings and discuss future directions in each of these fields.

### Software and system architecture

The work packages related to system and software aspects successfully pioneered research within the areas of (a) “sandbox-ing” multiple research activities resulting in a safe co-existence of algorithms on a self-driving vehicle including full traceability from source code down to the running software artefacts deployed on the vehicle, which has not been seen achieved in academic vehicle platforms before; (b) “shadow” execution for different variants of an algorithm to compare their performance, where the COPPLAR project was a unique opportunity to conduct research for this aspect for the first time in a real-time context, and (c) “live”-monitoring of crucial runtime constraints of the executed algorithms to enable continuous integration and evaluation of algorithms for the system.

The successful achievements from COPPLAR enable now further research towards a recent trend in the area of software engineering, namely continuous experimentation. Using this methodology, which has been proven to be successful in non-safety critical domains like web-applications, systematic experimentation for software features can be planned, conducted, and evaluated within the automotive context. Recent research within this area also extends this methodology to automated experimentation envisioning a true evolutionary approach to “adopt required features by improving a system’s fitness to its environment”, which would complement ongoing research in the area of machine learning.

### **Situation awareness**

We have investigated both the theoretical foundations of tracking and the practical applications involving multiple cooperating vehicles and different sensor types. The research shows that the developed theoretical frameworks are useful in practice and that the cooperation can significantly improve the performance of the communicating vehicles. Several interesting research questions remain, such as investigating further the fusion of multiple sensor modes and the integration of machine learning methods.

### **Localization and mapping**

One of the more challenging problems related to automated vehicles is related to robustly positioning itself in the road network. This is central for the automated vehicle to safely navigate and follow the traffic rules. There are two main challenges; (1) finding practical and cost-effective methods for building, distributing and updating the internal map for the automated vehicles with which we (2) can design localization algorithms that are robust against, e.g., changes in the environment that are not reflected in the map or other disturbances.

A key insight into solving the second problem is to use many different independent sensing modalities and striving to make the localization algorithm using each of these as robust and accurate as possible. In this project we have, thus, investigated localization methods based on images from onboard cameras, radar observations, 5G communication signal, GNSS and cooperative localization. Our conclusion is that we see potential in all these sensing modalities and that they are complementary in nature.

Although there is still work to be done to further improve the accuracy and robustness of the localization methods for the different sensing modalities, even more work remains for solving the first problem of practical and cost-effective mapping. Here we believe that there is a great potential in using cooperative automated vehicles to crowd source the information needed to both build the maps and to keep them up to date. By collecting observation from these vehicles we can develop a cost-effective way of automatically continuously update the map in the cloud. If we are able to do this we can eliminate one of the hurdles for introducing fully automated vehicles at a larger scale.

### **Communication**

We have demonstrated the potential of cooperative perception to improve localization of vehicles, by relying on local high-accuracy sensors and off-the-shelf V2V communication. Our research has shown that V2V communication will fail in the presence of too many transmitting vehicles, due to mutual interference. Several challenges thus remain, related to synchronization of measurements and prioritization of which information to share with other vehicles. During the course of the project, 5G has become an important candidate for V2V communication, potentially replacing more conventional ITS-G5 wifi-based communication. Within the project we have performed theoretical studies on 5G as a positioning and mapping technology and believe that this will be an important new technology deserving further study.

### **Path planning and vehicle coordination**

We have addressed the problem of planning the motion of an autonomous vehicle in an urban environment, where the vehicle is surrounded by non-cooperative human road users. In order to solve such a problem, the intention of human road users has to be somehow predicted. In this project we have demonstrated simple tools and started developing learning and prediction tools based on large data sets. Future work will have to focus on the development of multi-agent learning and prediction problems, where the behaviour of human road users has to be learnt in a multi-agent setting. In this project, we have proposed a path planning framework ready to be integrated with such prediction tool, thus providing a motion planning tool, which is capable of providing safety guarantees.

We have also focused on the coordination problem for multi-vehicle systems. Although, our algorithms have been successfully validated in experiments with full-scale vehicles, several open problems will have to be addressed like, e.g., the coordination in presence of impairments of the communication network or in presence of non-cooperating human road users.

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UNIVERSITY OF TECHNOLOGY



Z E N U I T Y

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