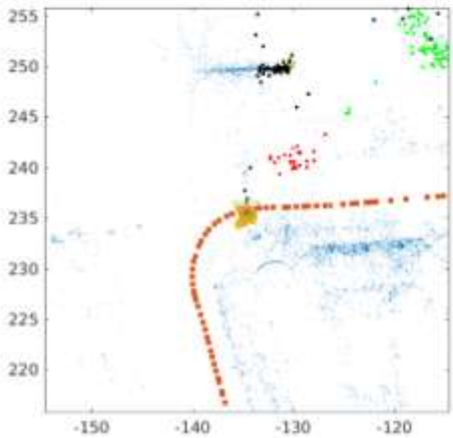
VPRP

Vehicle Positioning and Route Prediction

Public report



Fordonsstrategisk Forskning och Innovation

lvis

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För närvarande finns fem delprogram; Energi & Miljö, Trafiksäkerhet och automatiserade fordon, Elektronik, mjukvara och kommunikation, Hållbar produktion och Effektiva och uppkopplade transportsystem. Läs mer på www.vinnova.se/ffi.

Summary

The VPRP is a project coordinated by Volvo Cars cooperation where Volvo Technology cooperation and Chalmers are contributing parties. The project budget is 24,6 MSEK with finance of 12,3 MSEK from Vinnova.

When moving from Advanced Driving Assistant System to more Autonomous systems, this puts a higher requirement on accuracy for positioning and to move the car safely forward and prevent from accidents.

This project aims at developing and verifying algorithms to accurately estimate the position of the ego vehicle and predict the most likely route the vehicle will take in the road network. Insufficient positioning accuracy is one of the factors which today prevent new safety and convenience systems from being developed.

We have strived to answer questions like How can exact map position be obtained by matching the information obtained from sensors mounted on the ego vehicle (e.g. radars and cameras) with a static map? How the relative positioning accuracy between cooperative nodes can be improved by communicating raw GNSS measurement data between the nodes? How the current position accuracy of state of the art GNSS systems can be improved using e.g. more advanced GNSS receiver techniques (carrier phase detection) or using position information from other sources (LTE, infrastructure)? Is it possible to establish a driver route prediction based on earlier driver route statistics to enable reduced fuel consumptions or similar solutions?

To answer the questions, we have used methods like exploit available information sources to create a map and then developed algorithms to improve positioning and route prediction at present time.

New methods and algorithms for clustering driver destination is one examples of results during the project time.

27 publications in combination with internal reports shows that we have succeeded with our target of the project, to both achieve knowledge in positioning and route prediction system, but also develop algorithms for predict future routes and methods to achieve high positioning of the ego vehicle, something that is crucial for taking the step towards autonomous driving.

Better control of detailed traffic situations as for example lane-departure and reducing road transport environmental impact by for example better optimisation of car control and route predicion, are some examples of that we have achieved the FFI-program goals.

Beside of gained knowledge within the companies, the interest of positioning and route prediction has also grown within Academia, which is shown by the majority of new courses.

1 Executive summary in Swedish

Nedan redovisas resultat från varje arbetspaket, med undantag från projektledning. Vissa av leveranserna går in i flera arbetspaket, då till exempelvis karta och positionering i vissa metoder ligger väldigt nära varandra.

1.1 System design och verifiering

Två generationer testbilar har utrustats med surround radarsensorer, lidarsensor, visionssensor (kamera) och ett referenssystem av sensorer. Programvara för efterbehandling av dessa data har utvecklats för att synkronisera den samlade datan och att beräkna en exakt referenspositionsuppskattning. Referenspositionen har använts både för att bygga kartor och för att utvärdera positioneringsprestandan. I detta arbetspaket har metoder för att utvärdera både kartan och metoder för positionering tagits varm som används kontinuerligt på den insamlade datan. Arkitekturen för första generationens bilar, ses på bild nedan [Figure 2].

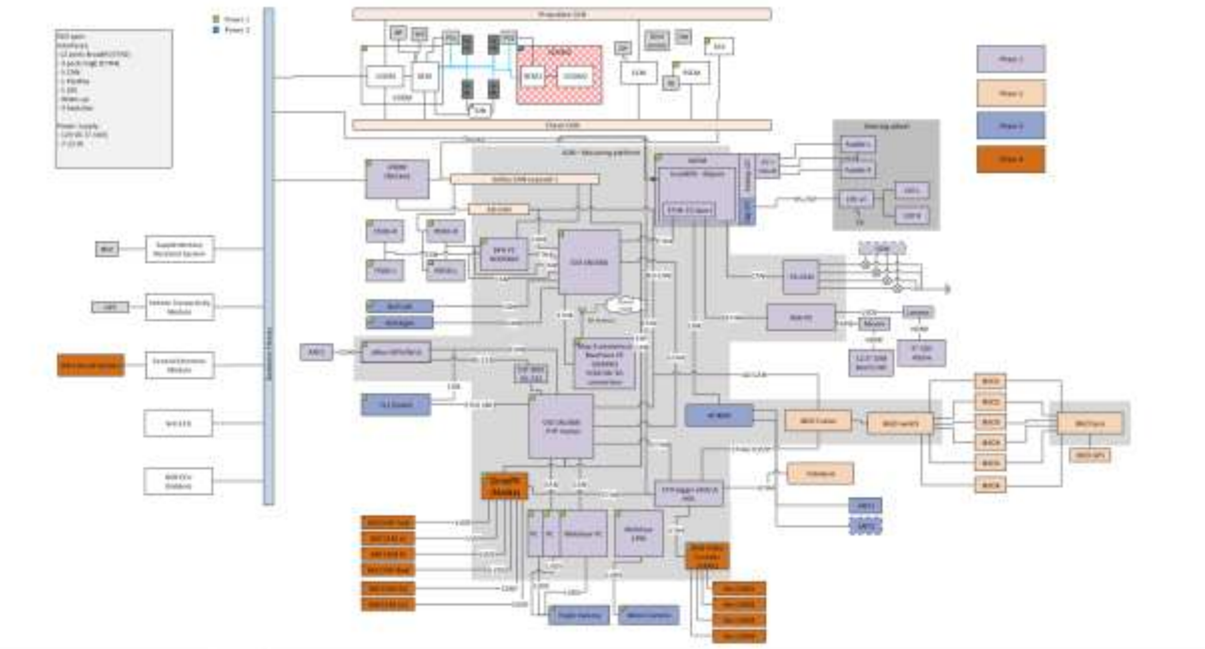


Figure 2: Architecture for the first generation of test vehicles

1.2 Lokal karta

Inom VCC/Zenuity har man inom området tagit fram ett ramverk genom att sätta ihop linjemarkeringars information från framåttittande kamera med objektpositioner från bakåttittande radar som ett första steg. Som en förbättring för uppskattning av väggeometri har man också inkluderat kartinformation vilket förlänger uppskattningshorisonten samt också utvecklat en metod för att beräkna i vilken körbana värdbilen kör i [25].

För att stödja värdbilens nuvarande syn på trafiksituationen har akademien bidragit till att förbättra placeringen av andra fordon och fotgängare genom att använda nya objektspårningsalgoritmer [1] - [4] samt utvecklade grundläggande spårningsramar [5] - [8] och prestanda metriker för dessa scenarier [9]. Några av dessa objekt är dynamiska (som fotgängare och bilar) [1] - [4] medan andra objekt är statiska (t.ex. lampposter och trafikskyltar) och genom att placera alla statiska objekt får vi en karta över vår miljö [16], [17].

Dessutom har metoder utvecklats för att beskriva vägen framför värdbilen, både med hjälp av radar och kamera [10] - [12], men också med hjälp av lidarsensorer [13] skapat en djupinlärningsmetod för att utföra vägdetektering där man från ett ostrukturerat punktmoln genererat toppbilder som kodar för flera grundläggande statistiker, t.ex. genomsnittlig höjd och densitet. Genom att överväga en toppbildsrepresentation reduceras vägdetektering till ett enkelskaligt problem som kan åtgärdas med ett enkelt och snabbt fullt konvolutionellt neuralt nätverk (FCN).

I samband med väguppskattning har även akademien utvecklat algoritmer för att uppskatta vägens form före ett värdfordon. I [10] - [12] är målet att noggrant beskriva väggeometrin (i motorvägsscenarier) upp till 200 m framför ett värdfordon, som är utrustad med en kamera, en radar och fordonsinterna sensorer. Detta syfte uppnås genom att härleda en exakt Klotoidbaserad vägmodell för vilken vi designar en Bayesian fusionsram. Med hjälp av detta ramverk uppskattas väggeometrin med hjälp av sensorobservationer baserat på formen av banmarkeringarna, rubriken på ledande fordon och positionen av vägarnas radarreflektorer. Utvärderingen av sensordata visar att de föreslagna algoritmerna kan fånga vägens form väl, även i utmanande bergsvägar.

I [13] har en djup inlärningsmetod utvecklats för att utföra vägdetektering med endast LIDAR-data. Detta innebär att från ett ostrukturerat punktmoln genereras toppbildsbilder som kodar för grundläggande statistik, t.ex. genomsnittlig höjd och densitet. Genom att överväga en toppbildsrepresentation reduceras vägdetektering till ett enkelskaligt problem som kan åtgärdas med ett neuralt nätverk (FCN).

1.3 Kartpositionering

I detta arbetspaket har vi inom VPRP bland annat tittat på hur man genom enkla sensorer kan uppnå positionsnoggrannhet.

Undersökningen i [14] utgick man från att bara använda sensorer som är vanligtvis tillgängliga på bilarna vid den tiden, t.ex. enkla GPS (Global Positioning System), tröghetssensorer och framåtblickande radar och kamera, tillsammans med en landmärkesbaserad karta. Vår slutsats, även om vi uppnådde tillräcklig noggrannhet under gynnsamma förhållanden, var lösningen inte tillräckligt robust för att hantera förlust av en informationskälla (till exempel saknade körfältmarkeringar) eller förändringar i miljön (väder, säsong, ombyggnad). Dessutom fann vi att de absoluta (globala) positionsmätningarna från typiska GPS-mottagare var inte tillräckligt noga.

Med hjälp av detta arbete utredde vi olika sätt att förbättra noggrannheten och robustheten hos positioneringsalgoritmen. I [15] utvecklar vi en kostnadseffektiv lösning för att använda GPS för att noggrant mäta odometri (rörelsen hos värdbilen) istället för att ge oss felaktiga globala positioner. Som sådan kan vi, om vi kan placera bilen i en karta, använda GPS-enheten för att utföra automatisk dödräkning av bilen under mycket längre tid än om vi bara använde hjulhastighet och tröghetssensorer. Dessutom har vi utvecklat metoder för hur man mer exakt bygger de underliggande kartorna baserat på landmärken [16], [17] men också hur man både bygger dessa kartor samtidigt som vi försöker lokalisera oss i dem [18] (SLAM).

1.4 Kooperativ positionering

Det arbete som utförts i VPRP har visat att det finns stor potential inom kooperativ GNSS (Global Navigation Satellit System) för att öka relativ positionsnoggrannhet och att stödja kooperativa ITS-applikationer och aktiv säkerhet även inom tung lastbilssegment. Grundidén bakom kooperativ GNSS-positionering är att fordon utbyter rå GNSS-mätning, data / korrigering eller motsvarande. Med hjälp av denna data kan differentieringstekniker tillämpas för att beräkna den relativa positionen mellan fordonen.

Den enklaste formen av kooperativ GNSS skulle vara att byta GNSS (kod) position från fordonet ombord GNSS mottagare. Eftersom de nuvarande GNSS-mottagarna för fordon uppnår en absolut positioneringsnoggrannhet på 2 meter i bästa fall (med tanke på RTK-system (Real Time Kinematic)) är denna information dock mer eller mindre användbar för kooperativ positionering.

I [31] beskriver vi som nästa steg utbytet av råa satellitavståndsmätningar mellan fordon. Genom att dubbeldifferensiera dessa mätningar kan man avlägsnas atmosfäriska, satellitklockfel och mottagarklockfel. Detta gör att positionens noggrannhet förbättras väsentligt. Det mätfel som kvarstår kommer antingen från sk. local multipath dvs. där signalen reflekterats en eller flera gånger innan den når mottagaren, eller mätfel i mottagarna. I tester med dyrare mottagare och antenner hittas enbart små precisionsfel och precisionen av dubbeldifferensierade lösningarna är ofta mindre än 50 cm. Samma test med billigare mottagare visar sämre resultat [31]. En ytterligare förbättring av den relativa positionen i kooperativ GNSS kan uppnås genom att utbyta och använda råa bärvågsmätningar.

1.5 Global positionering

I detta arbetspaket fokuserade man sig på att testa och utvärdera ett urval av GNSS system, för att se hur väl noggrannheten på systemet kunde upprätthållas när satellitbilden förloras, vilket presenteras i en teknisk rapport [32]. Slutsatsen blev att med bra dödräkning, så kan låsning av bärvågen erhållas nästan direkt när satellitbilden åter finns tillgänglig.

1.6 Ruttprediktering

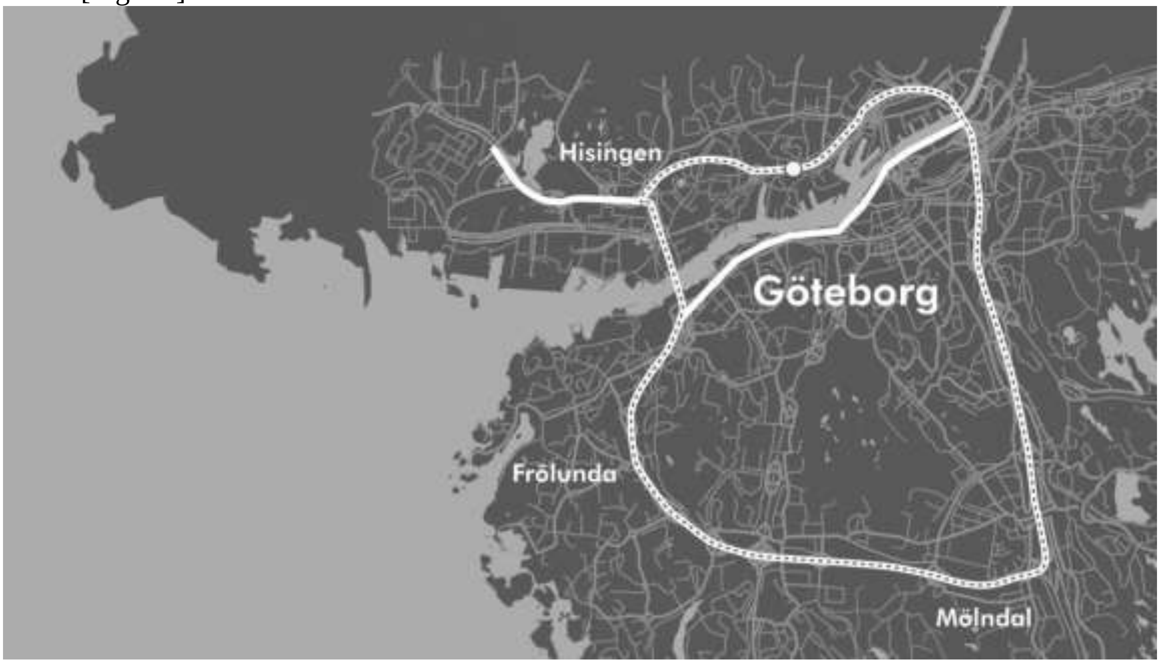
En av huvuddelarna i detta arbetspaket har varit att undersöka hur man använder sig av det repetitiva mönstret i de flesta människors dagliga pendling (hem till jobbet, jobba för att lagra, lagra hemma etc.) för att förutsäga resans slutmål när den börjar. Ett bidrag till detta arbetspaket har varit att ta fram en metod för att klustra fordonets slutposition från många resor till en uppsättning destinationer [27]. En annan metod som tagits fram är att göra effektiva kortsiktiga förutsägelser under en resa [26], vilket har visat sig ha fördelar som

Att föreslå en rimlig väg för värdfordonet är en viktig uppgift för alla självkörande fordon. En grundläggande strategi för att göra det är att uppskatta positionen i en karta och sedan föreslå en väg som håller fordonet på vägen. Den strategin bygger emellertid på mycket exakt positionsinformation, en detaljerad karta och frånvaron av fordon och hinder på vägen. Med kraftfulla maskininlärningsstrategier är det istället intressant att försöka utnyttja all tillgänglig sensorinformation och försöka styra ett fordon på ett mer mänskligt sätt.

I [21] har ett nytt inlärningsbaserat tillvägagångssätt utvecklats för att generera körbanor genom att integrera lidarpunkts moln, GPS-IMU-information och Googles körriktningar. Systemet är baserat på ett fullständigt sk. convolutional neuralt nätverk som gemensamt lär sig att förstå väg och omgivning från verkliga körsekvenser och som utbildas med hjälp av automatiskt genererade träningsexempel. Resultaten i detta arbete indikerar att det föreslagna systemet kan bidra till att fylla gapet mellan lågnivå-parsing och beteende-reflex-tillvägagångssätt genom att generera resultat som ligger nära kontroll av bilen och samtidigt är mänskligt tolkningsbara.

1.7 Global kartuppbyggnad

För att stödja positioneringsutvecklingen i WP 4 har en exakt och detaljerad karta, kallad HD-kartan, utvecklats inom VCC, vilket vi också använt oss för att utvärdera våra positionsalgoritmer. Den fokuserade testvägen för VPRP har anpassats till den avsedda rutten i Drive Me, vilket visas i bild nedan [Figur 1].



Den utvecklade HD-kartan innehåller en riklig beskrivning av exakta geometrin av körbanan som beskrivs i Zenuity internrapport [28], vilket också visar hur kartan är segmenterad i karthorisonter som möjliggör effektiv kommunikation i realtidssystem.

Ett annat sätt att jobba med karta för tunga fordon, har varit att i detta projekt tittat på metoder för att simultant jobba med lokalisering och kartläggning (SLAM). Det innebär att upptäcka och kartlägga landmärken och objekt i förhållande till den globala referensramen och använda dessa sedan för att lokalisera fordonet. Bland annat beskriver en publikation [29], denna kartläggning och landmärkningsbaserad lokaliseringsmetoden.

2 Background

The project has been running from Q3 2013 until Q4 2017 with a budget of 24.6 MSEK of which 12.3 MSEK from VINNOVA. Volvo Car Corporation (VCC) has been main responsible for this project. Participants in this project are:

Volvo Car Corporation (VCC)	(556074-3089)
Volvo Technology Corporation (VTEC)	(556542-4321)
Chalmers tekniska högskola (CTH)	(556479-5598)

Zenuity to work as consultants for VCC from 2017-05-01.

Moving from active safety systems to self-driving vehicles requires greater accuracy in positioning. However, the next generation of active security systems can also benefit from improved positioning.

Today's system has the requirement to estimate on which road the vehicle is driving, which is not safety-critical. But many features could be improved if also a lane level positioning accuracy could be achieved, i.e. determining in which lane the vehicle is driving. Examples of active safety system that could be improved with a lane level accuracy are lane keeping aid and adaptive cruise functions.

When it comes to autonomously move the car, the requirements of positioning become safety-critical. You must be able to position the vehicle in a detailed HD map with very high accuracy (<1dm) both to move the car safely forward, but also to prevent accidents for examples in intersections or crossing scenarios.

The applications are often based solely on positions provided by GNSS (Global Navigation Satellite System) systems. Existing GNNS systems are usually quite error- prone, especially in urban areas where the amount of satellites is limited and the GNSS signals are subject to multi- path effects. However, the accuracy is usually sufficient for this the navigation systems, but we see a clear demand of high precision positioning systems in the near future.

Route planning applications has been utilized in vehicles for over a decade; the most common use is traditional navigation systems, where the driver is presented with a route between two geographical positions.

This project aims at developing and verifying algorithms to accurately estimate the position of the ego vehicle and predict the most likely route the vehicle will take in the road network. Insufficient positioning accuracy is one of the factors which today prevent new safety and convenience systems from being developed. Examples of such systems are:

- **Autonomous vehicles**. These types of systems require a detailed description of the environment surrounding the ego vehicle and accurate position estimates of the ego vehicle and all other objects relative to that map. Affordable sensors available on the market today, such as radars, cameras and digital maps, can provide accurate estimates of the relative position of surrounding objects, but not a detailed enough description of the static environment or the position of the moving objects relative to the environment.
- **Active safety systems**. Most of the active safety systems today intervene in accidents caused by something blocking the path of the ego vehicle when the ego vehicle is moving straight ahead. Rear end collisions or pedestrians walking out in front of the ego vehicle are examples of such accidents which can be prevented. However, for more complicated scenarios, such as accidents in intersections, these systems need a detailed map, accurate position estimates of the objects and reliable predictions of the route the objects are intending to drive.
- **Engine optimization systems**. Several aspects of engine optimization could be improved using accurate ego position estimates and route predictions. One example is in hybrid vehicles, where knowledge of the upcoming route could have a great impact of brake regeneration optimization. Similarly, for diesel particle filter regeneration, knowledge about the ego vehicle final destination, or more precisely an estimate of the driving time and driving style to reach the final destination, could prevent incomplete regeneration cycles from occurring.
- **Cooperative ITS-systems.** Intelligent transportation systems (ITS) are transportation systems in which information and communication technologies are used to provide new and innovative services. In cooperative ITS-systems are information shared between the road users using vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communication. These systems would benefit greatly from a more accurate positioning and route prediction of the road users, since that would enable the systems to put the shared information into a context on how it would affect the ego vehicle and decide which appropriate measures should be taken.

The level of position accuracy needed varies between these types of systems, but the ambition in this project is to develop methods supporting all of them. The most demanding position accuracy requirements will be posed by autonomous vehicle systems as internal studies by the industrial partners show that these systems need to position objects relative to a detailed map with an accuracy in the order of magnitude of 0.1 m to 0.2 m. As is discussed in the state of the art section at the end of this document, this level of accuracy cannot be obtained by any commercially viable systems on the market today.

The accuracy of the route prediction can be improved by storing sensor information in a separate map layer. The stored information is related to driving statistics such as common destinations (as a function of day and time), common routes and driving style. Using statistics on how and where the driver usually drives together with accurate ego vehicle position information reliable route predictions can be obtained.

3 Purpose, research questions and method

In many relevant ADAS solutions, low-accuracy positioning is important to position a car on the correct road segment. Such solutions include slippery road-detection for example. However, high precision positioning has a big potential to both create new more advanced ADAS solutions and improve existing ones. Further, for future AD (Autonomous Drive) features, high precision positioning is crucial.

Being able to tell which lane a car is in enables functionalities such as automatic lane-changes, automatic mapping, detection of road abnormalities (accidents, road deterioration etc). It also enables prediction of probable route choices, which enables improved possibility to optimize engine functions for example. Even higher precision positioning enables possibility to do autonomous drive through intersections, better mapping and increased safety in detailed traffic situations.

All these possible solutions lead to lowered environmental impact and increased safety, both which are core values for VCC and Zenuity.

The research question for this project is divided into following areas:

- **Positioning**

  Map positioning
  How can exact map position be obtained by matching the information obtained from sensors mounted on the ego vehicle (e.g. radars and cameras) with a static map?

  Both currently available and the next generation high precision digital maps will be evaluated for this purpose. We also foresee that the ability to improve the static map with observations from the on-board sensors will be important.

  Cooperative positioning
  How the relative positioning accuracy between cooperative nodes can be improved by communicating raw GNSS measurement data between the nodes?

  Global positioning
  How the current position accuracy of state of the art GNSS systems can be improved using e.g. more advanced GNSS receiver techniques (carrier phase detection) or using position information from other sources (LTE, infrastructure)?

- **Route prediction**

  Is it possible to establish a driver route prediction based on earlier driver route statistics to enable reduced fuel consumptions or similar solutions?

To find answers to the above questions, the following methods has been considered:

- Jointly exploit all available information sources. The project considers an ego vehicle equipped with a host of on-board sensors such as radars, camera, V2V/V2I communication, enhanced map databases, GNSS and internal sensors. All these on-board sensors deliver imperfect observations of the current local traffic situation.

- Utilize statistical historic data to improve the positioning and route prediction at present time. For example, knowing that the driver typically takes a specific exit surely will help us to improve local route prediction. As such, we collect the information regarding the local traffic situation as observed by the on-board sensors in a local map and the historic information in a global map.

- Provide a framework (fusion engine) to jointly estimate parameters of interest and provide a convenient description of the surrounding traffic environment to support local route prediction.

4 Objective

The objective for this project has been:

- To find methods to accurately position the ego vehicle (globally, relative to the map and relative to other vehicles).

- Precisely predict the future route both on a local (will we take this exit?) and a global (what is the final destination?) scale.

5 Results and deliverables

Expected results from the project:

- Build the necessary competence in this field such that a positioning and route prediction system can be designed which can help realize the new active safety functions and autonomous vehicle systems.

- Present result in academic publications which describe both the mathematical derivations of the developed algorithms and performance evaluations using real data.

- Knowledge about what level of positioning accuracy can be obtained using existing sensor technologies and how much this can be improved in the future.

5.1 Result per work packages

The results will be presented below for each work package except work package 1, project management. Some of the deliveries goes over more than one work package due to that methods in different combinations can give input to more than one work package. Overview of all work packages in this project is shown in the picture below [Figure 1].

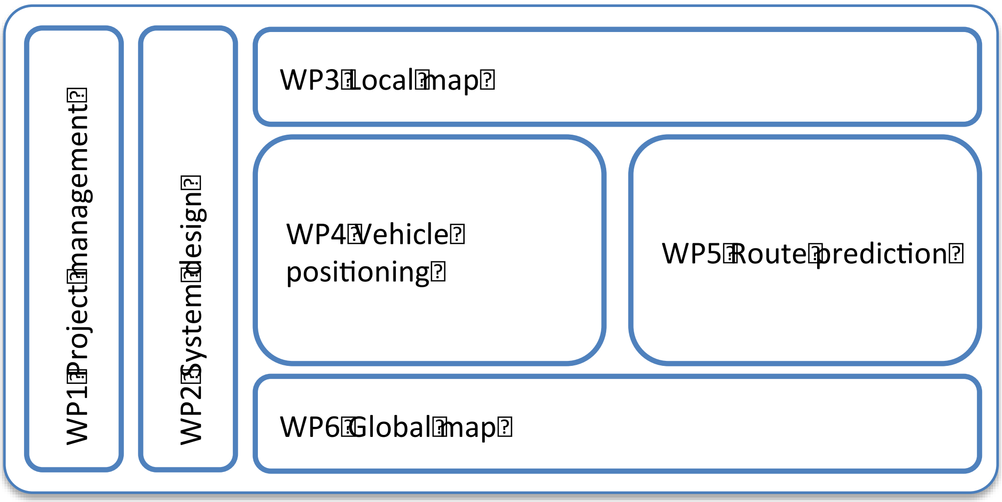


Figure 1: Work packages

WP2 System design and verification

At VCC/Zenuity, two generations of test vehicles have been equipped [Figure 2] with surround radar sensors, a lidar sensor, vision sensors and reference sensors. Software for post-processing of this data has been developed to time synchronize the collected data and to compute an accurate reference position estimate. The reference position has been used both for building maps and to evaluate the positioning performance. Methods for evaluating both the map and the positioning methods have been developed and are continuously used on the collected data. Currently a third generation of test vehicles is being developed, which seeks to improve on the many lessons learned in this project.

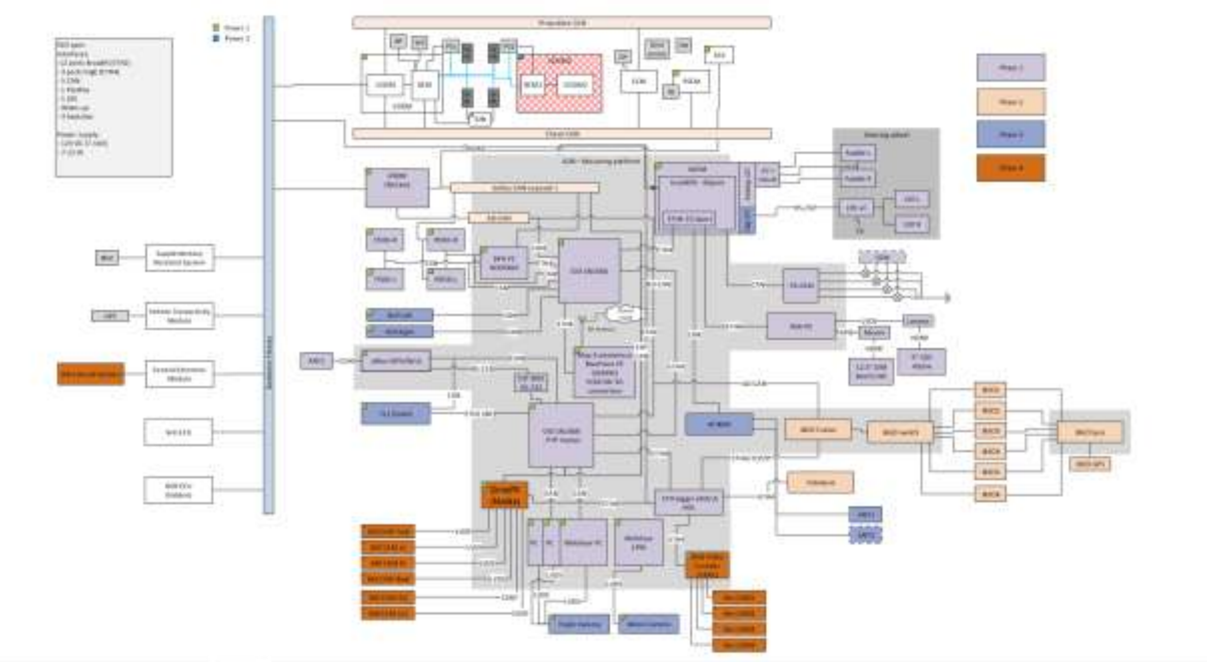


Figure 2: Architecture for the first generation of test vehicles

WP3 Local map

In creating a map of the local surroundings, the level of detail can be augmented by aggregating static 3D detections from different times, where detections from for example a camera system or Lidar sensors can be applied. A prerequisite for map aggregation is to precisely know the sensors' movements. For truck applications this is very challenging when sensors are mounted on the cab, due to the complicated dynamics of a cab that is suspended on the vehicle chassis, which in turn is suspended on the wheels. For this purpose, a cab motion model was developed and applied for filtering the relative trajectory of the vehicle. The filter uses relative motion of cab and chassis, measured by low-cost IMU sensors, combine with low-cost GNSS carrier phase measurements for accurate relative position measurements. Results show that very precise trajectories can be estimated, providing a good base for a short horizon (local) mapping system without using expensive IMU sensors. The results are detailed in the master's thesis [30] that was carried out within VPRP.

Within VCC/Zenuity, several contributions to the local map development has been done during the project within. Prior to the project we had a road estimation framework which fused lane marking information from a forward-looking camera with object positions from a forward-looking radar. In this project, we have improved the framework by also including map information which extends the estimation horizon. We have also developed a method for estimating in which lane the ego vehicle is driving, referred to as ego lane assignment. This lane assignment module is an important component for making map-based path predictions. Both the improved road geometry estimation and the ego lane assignment method is part of the deliverables to the Drive Me project with Volvo Cars. The ego lane assignment algorithm has been published in [25].

To support the host vehicle's current view of its traffic situation, academia have made contributions to improve the positioning of other vehicles and pedestrians using novel object tracking algorithms [1]–[4] as well as developed basic tracking frameworks [5]–[8] and performance metrics for these scenarios [9]. In addition, they have developed methods to describe the road in front of the host vehicle, both using radar and camera [10]–[12], and using lidar sensors [13].

In WP3, the objective is to create a local map and to understand the current traffic situation. We formulate this as an extended target tracking (ETT) problem, where we seek to position all objects in our vicinity. Some of these objects are dynamic (such as pedestrians and cars) [1]–[4] whereas other objects are static (such as lamp posts and traffic signs), and by positioning all static objects we obtain a map of our environment [16], [17]. We have studied a number of different techniques to efficiently handle the ETT problem and developed new algorithms that we argue are state of the art for the sensors that we considered.

One of the main problems that we faced while developing new tracking algorithms (see above), is that there is a lack of benchmark scenarios and useful performance metrics. To develop these benchmark scenarios, we need to be able to extract accurate trajectory estimates from data, which is a very challenging problem. As part our work on ETT, we developed new different performance metrics (among which one received a best paper award [9]) for trajectory estimates.

Related to road estimation academia have developed algorithms for estimating the shape of the road ahead of a host vehicle. In [10]–[12], the aim is to accurately describe the road geometry up to 200 m ahead of a host vehicle equipped with a camera, a radar, and vehicle internal sensors, in highway scenarios. This purpose is accomplished by deriving a precise clothoid-based road model for which we design a Bayesian fusion framework. Using this framework, the road geometry is estimated using sensor observations on the shape of the lane markings, the heading of leading vehicles, and the position of roadside radar reflectors. The evaluation on sensor data shows that the proposed algorithms can capture the shape of the road well, even in challenging mountainous highways.
In [13], a deep learning approach has been developed to carry out road detection using only LIDAR data. Starting from an unstructured point cloud, top-view images encoding several basic statistics such as mean elevation and density are generated. By considering a top-view representation, road detection is reduced to a single-scale problem that can be addressed with a simple and fast fully convolutional neural network (FCN). The FCN is specifically designed for the task of pixel-wise semantic segmentation by combining a large receptive field with high-resolution feature maps. The proposed system achieved excellent performance and it is among the top-performing algorithms on the KITTI road benchmark. Its fast inference makes it particularly suitable for real-time applications.

While intelligent transportation systems come in many shapes and sizes, arguably the most transformational realization will be the autonomous vehicle. As such vehicles become commercially available in the coming years, first on dedicated roads and under specific conditions, and later on all public roads at all times, a phase transition will occur. Once a sufficient number of autonomous vehicles is deployed, the opportunity for explicit coordination appears. In [23], [24] we (Chalmers) treat this challenging network control problem, which lies at the intersection of control theory, signal processing, and wireless communication. We provide an overview of the state of the art, while at the same time highlighting key research directions for the coming decades.

WP 4.1 Map positioning

For heavy trucks, the possibility of using perception-based sensors to map the environment around the vehicle for path planning was investigated. Most of the focus has been on lidar technology and different positioning and prediction algorithms for trajectory and localization estimation. When using lidar, a highly accurate map can be created and annotated. This can then be used together with landmark recognition algorithms for localization of the ego vehicle as well as objects detected. One thesis work [29] has been published about using lidars for map generation and localization.

The use of cheaper sensors for localization of trucks was also investigated [31]. With the use of a combination of radar, camera, imu and GNSS together with high definition maps, an accurate lane level positioning was achievable under favorable conditions. In-vehicle test showed that using this type of localization is not robust enough for autonomous vehicles on its own. Different dead reckoning Kalman filter implementations were investigated to improve the robustness of the system [31].

Related to vehicle estimation VCC have developed a generic fusion framework both in Matlab and C++, in which we can implement and evaluate concepts for accurate map positioning using different filtering techniques and using data from different types of sensors (radars, lidar and vision). The most promising of these concepts has been evaluated in a real-time environment in a test vehicle. Based on data from the sensors available, we have for instance been able to evaluate:

- Different types of sensor maps and how they affect the positioning
- What level of positioning accuracy that has been possible to achieve
- How different traffic scenarios affect the positioning performance

Some of these conclusions have been presented in the following publications [14], [15]. One example was the investigation [14] we did of the position accuracy where you expect just to use sensors typically available on the cars at that time, e.g. simple GPS, inertial sensors and forward-looking radar and camera, together with a landmark based map. Our conclusion, although we achieved sufficient accuracy during favorable conditions, the solution was not robust enough to handle loss of one information source (for example missing lane markings) or changes in the environment (weather, season, rebuilding). Additionally, we found that the absolute (global) position measurements from typical GPS receivers where not nearly accurate enough.

Using this work as a basis, we explored different ways of improving the accuracy and robustness of the positioning algorithm. In [15], we develop a cost efficient solution for using the GPS to accurately measure odometry (the movement of the host car) instead of giving us inaccurate global position. As such, if we can position the car in a map, we can use the GPS to accurately dead recon the cars position for a much longer time than if we just used wheel speed and inertial sensors. Additionally, we have developed methods for how to more accurately build the underlying landmarked based maps [16], [17] as well as how to build these maps simultaneously as we try to localize in them [18] (SLAM).

Robust cross-seasonal localization is one of the major challenges in long-term visual navigation of autonomous vehicles. In [19], Chalmers and VCC Ph D exploit recent advances in semantic segmentation of images, i.e., where each pixel is assigned a label related to the type of object it represents, to solve the problem of long-term visual localization. We show that semantically labeled 3D point maps of the environment, together with semantically segmented images, can be efficiently used for vehicle localization without the need for detailed feature descriptors (SIFT, SURF, etc.). Thus, instead of depending on hand-crafted feature descriptors, we rely on the training of an image segmenter. The resulting map takes up much less storage space compared to a traditional descriptor-based map. A particle filter based semantic localization solution is compared to one based on SIFT-features, and even with large seasonal variations over the year we perform on par with the larger and more descriptive SIFT-features and can localize with an error below 1 m most of the time.

During this work, we found that there are no good datasets to evaluate localization performance during these varying conditions, and thus we have developed our own benchmark suite in collaboration with a few other universities in Europe and Japan [20].

Practical visual localization approaches need to be robust to a wide variety of viewing condition, including day-night changes, as well as weather and seasonal variations, while providing highly accurate 6 degree-of-freedom (6DOF) camera pose estimates. In [20], we (Chalmers) introduce the first benchmark datasets specifically designed for analyzing the impact of such factors on visual localization. Using carefully created ground truth poses for query images taken under a wide variety of conditions, we evaluate the impact of various factors on 6DOF camera pose estimation accuracy through extensive experiments with state-of-the-art localization approaches. Based on our results, we draw conclusions about the difficulty of different conditions, showing that long-term localization is far from solved, and propose promising avenues for future work, including sequence-based localization approaches and the need for better local features. We will make our benchmark publicly available.

WP 4.2 Cooperative positioning

The work conducted in VPRP has shown that there is great potential in the area of cooperative GNSS to increase relative position accuracy and to aid cooperative ITS applications and active safety also in the heavy truck segment. The basic idea behind cooperative GNSS positioning is that vehicles exchange raw GNSS measurement, data/correction or equivalent. Using this data, differencing techniques can be applied to calculate the relative position between the vehicles. That is, it will not tell us where we are, but where we are in relation to each other.

The simplest form of cooperative GNSS would be to exchange GNSS (code) position from the vehicle onboard GNSS receiver. However, since the currently used GNSS receivers for vehicle achieves an absolute positioning accuracy of 2 meters at best (disregarding RTK systems), this information is more or less useless for cooperative positioning. The next step, which has been implemented within the VPRP project, is to exchange raw GNSS pseudo range measurements between vehicles [31]. By double differencing these measurements, atmospheric, satellite clock errors, and receiver clock errors are removed, substantially improving the position accuracy. The remaining errors are mostly from the local multipath and from measurement errors of the receivers. Tests [31] have shown that these errors differ between different receivers and antennas. From test series with more expensive receivers and antennas only small errors are found and the precision of the double differenced solutions are often less than 50 cm. The same tests for cheaper receivers show worse results [31].

A further improvement of the relative position in cooperative GNSS can be achieved by exchanging and using raw GNSS carrier phase measurements. The main problem in using carrier phase measurements is solving for the integer ambiguity parameters in the positioning solution. The carrier phase measurements are very sensitive to disturbances when tracking the carrier phase of the satellite signal. Thus, an object blocking the line of sight between the antenna and the satellite will cause the receiver to lose track (lose fix) and new ambiguity parameters need to be estimated. A possible solution to overcome short signal outages was investigated in VPRP [31] and showed that it could be possible to recover the fix (recover the satellite tracking) if the correct algorithms were applied.

WP 4.3 Global positioning

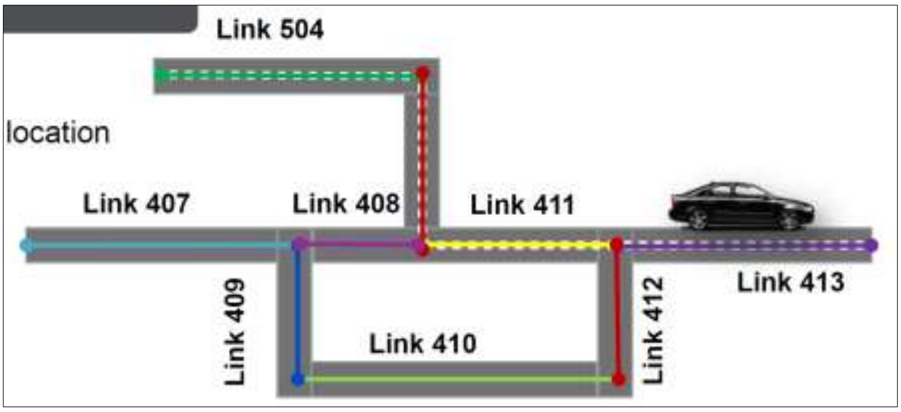
In VPRP, for commercial trucks a state of the art GNSS investigation was carried out. It showed that many suppliers and technologies are available and constantly improving. A selection of GNSS systems were tested and evaluated [32] for accuracy together with investigations into maintaining the accuracy when the view of the satellites is lost. It was understood that with good dead reckoning, carrier phase lock could be obtained almost immediately once satellite view is restored.

WP 5 Route prediction

The main idea in this work package is to explore how to make use of the repetitive pattern in most people’s daily commutes (home to work, work to store, store to home, etc.) to predict the destination of a trip when it starts. We (VCC) have made several contributions in this area. Some related to the problem of clustering the end position of the vehicle from many trips into a set of destinations [27]. Other contributions have been in making efficient short-term predictions during a trip [26].

To summarize above, the problem of short range (next link) prediction has been studied [figure 3] and we have developed a new method [27] which has two main benefits:

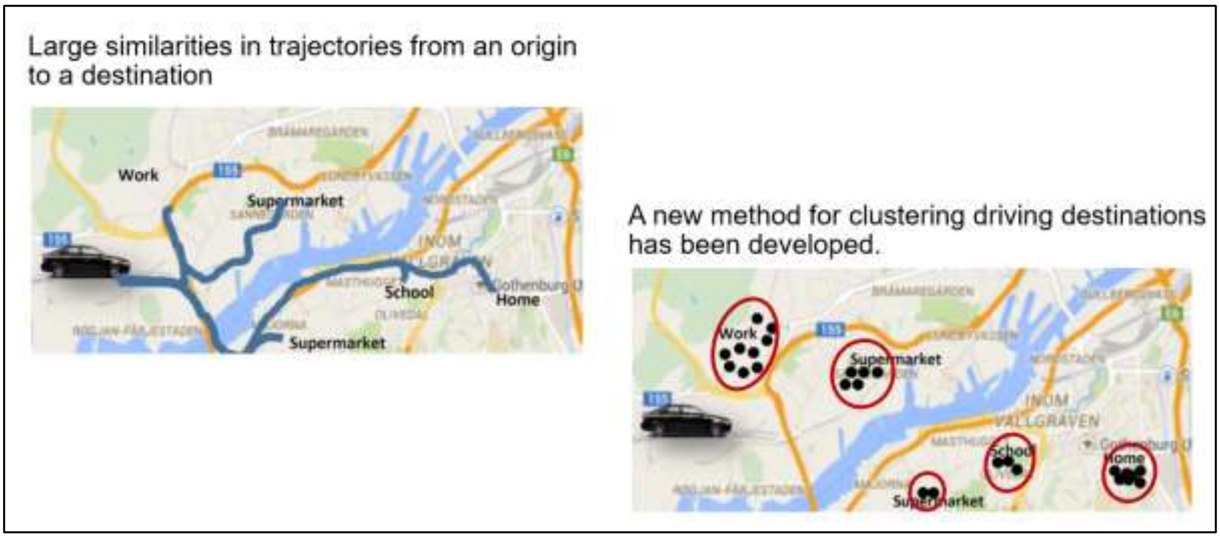
- Low real time computational complexity
- The prediction model can be sequentially updated for each new trip



[Figure 3: Shot range prediction]

Pictures below gives a basic visual overview of the new method from VCC for clustering driving destinations [Figure 4].

[Figure 4: Clustering driving destinations]



Suggesting a reasonable path for the host vehicle, is an important task for all self-driving vehicles. A basic strategy to do so, is to estimate the position in a map and then suggest a path that keeps the vehicle on the road. However, that strategy relies on highly accurate position information, a detailed map, and the absence of vehicles and obstacles on the road. With the advent of powerful machine learning strategies, it is interesting to instead try to leverage on all the available sensor information and try to control a vehicle in a more human-like manner.

In [21], a novel learning-based approach has been developed to generate driving paths by integrating lidar point clouds, GPS-IMU information, and Google driving directions. The system is based on a fully convolutional neural network that jointly learns to carry out perception and path generation from real-world driving sequences and that is trained using automatically generated training examples. The results obtained in this work indicate that the proposed system may help fill the gap between low-level scene parsing and behavior-reflex approaches by generating outputs that are close to vehicle control and at the same time human-interpretable.

WP 6 Global map building

To support the positioning development in WP 4, an accurate and detailed map, referred to as the HD-map, has been developed within VCC. The focused test route for VPRP has been aligned with the intended route in Drive Me, as is shown in Fig. 1. For this particular route, we (VCC) have both constructed detailed HD-maps and evaluated our positioning algorithms.

The developed HD-map contains a rich description of the exact lane level geometries as is described in [28], which also presents how the map is segmented into map horizons allowing for an efficient communication in real-time systems.

Figure 1: The selected test route in Dive Me

From VTEC, the concept of building a map database or populate and enrich an existing map database with object data captured by vehicles is previously proven for example in the FFI Learning Fleet project. In this project and work package, simultaneous localization and mapping (SLAM) methods have been explored for detecting and mapping landmark objects relative the global reference frame and use these landmarks for localizing the vehicle. At VTEC, two master thesis workers have been supervised, in their work on this topic, resulting in a publication [29], which demonstrates efficient landmark extraction/mapping and landmark-based vehicle localization methods.

5.2 FFI objectives and project contributions

The project focused on two out of six program targets (see bullet list below with OK) but will act as an enabler and enhance future projects addressing additional target areas such as unprotected road users.

The vehicle and traffic safety program targets:

- Intelligent safety systems: OK
- Human cognition and tolerance
- Crash worthiness (passive and active)
- Field studies (e.g. real-life safety): OK
- Unprotected road users
- Security (e.g. personal protection/integrity)

Path prediction and high accuracy positioning are important supporting technologies in the future development of safety and efficiency systems, which can provide the partners with a competitive advantage on the global market.

The contribution of the VRPR projects results to the FFI-program goals can be summarized as follow:

- **Reducing road transports environmental impact -** Through increased knowledge and results on route prediction, a better optimization of car control was enabled, which reduces environmental impact. (More effective engine-control)."

- **Reduce number of casualties in traffic -** Better control of detailed traffic situations such as lane-departures, going through intersections, entering and exiting freeways reduces the probability of accidents, since manoeuvres can be better planned and executed.

- **Strengthen global competitiveness** – Increased safety is an important topic for Volvo which strengthens competitiveness. Increased positional accuracy also enables convenience-functions which attracts end-customers.

6 Dissemination and Publications

6.1 Knowledge and dissemination of results

Hur har/planeras projektresultatet att användas och spridas?	Markera med X	Kommentar
Öka kunskapen inom området	X	Novel methods for global positioning and route prediction.
Föras vidare till andra avancerade tekniska utvecklingsprojekt	X	This result will be used in Drive Me project and further developed and used by Zenuity.
Föras vidare till produktutvecklingsprojekt	X	Result will be a part of the product portfolio at Zenuity.
Introduceras på marknaden		
Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut		

6.2 Publications

[1]	K. Granström, S. Renter, M. F.-… S. (IV), undefined 2017, and undefined 2017, "Pedestrian tracking using Velodyne data—Stochastic optimization for extended object tracking," *ieeexplore.ieee.org*	Chalmers
[2]	K. Granstrom, L. Svensson, S. Reuter, Y. Xia, and M. Fatemi, "Likelihood-based data association for extended object tracking using sampling methods," *IEEE Trans. Intell. Veh.*, pp. 1–1, 2018.	Chalmers
[3]	K. Granström and M. Baum, "Extended Object Tracking: Introduction, Overview and Applications," arXiv, pp. 1–17, 2016.	Chalmers
[4]	M. Beard, S. Reuter, K. Granström, B. T. Vo, B. N. Vo, and A. Scheel, "Multiple Extended Target Tracking With Labeled Random Finite Sets," *IEEE Trans. Signal Process.*, vol. 64, no. 7, pp. 1638–1653, 2016.	Chalmers
[5]	Y. Xia, K. Granstrcom, L. Svensson, and A. F. Garcia-Fernandez, "Performance	Chalmers

	evaluation of multi-bernoulli conjugate priors for multi-target filtering," in *20th International Conference on Information Fusion, Fusion 2017 - Proceedings*, 2017.	
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[14]	M. Lundgren, E. Stenborg, L. Svensson, and L. Hammarstrand, "Vehicle self-localization using off-the-shelf sensors and a detailed map," in *IEEE Intelligent Vehicles Symposium, Proceedings*, 2014.	Chalmers VCC PhD
[15]	E. Stenborg and L. Hammarstrand, "Using a single band GNSS receiver to improve relative positioning in autonomous cars," in *IEEE Intelligent Vehicles Symposium, Proceedings*, 2016, vol. 2016–Augus.	Chalmers VCC PhD
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[27]	Panahandeh, Ghazaleh. "Driver route and destination prediction " *Intelligent Vehicles Symposium (IV)", 2017 IEEE. IEEE, 2017*.	VCC
[28]	Sörstedt, Joakim *"HD-map interface specification"*, Internal Zenuity report	VCC
[29]	Lindholm, Robin, Pålsson, Carl-Johan *"Simultaneous Localization and Mapping for Vehicle Localization using LIDAR Sensors", http://publications.lib.chalmers.se/records/fulltext/219126/219126.pdf*	VTEC
[30]	Agnas, Edvin, Jerenvik, Marcus "*Estimation of position and orientation of truck kinematic frames",* http://publications.lib.chalmers.se/records/fulltext/238492/238492.pdf	VTEC
[31]	Jimmy Hammenstedt, Edvin Valtersson, Sudha Vana *"Vehicle Position and Route Prediction"*	VTEC

7 Conclusions and future research

Increased security and accessibility with the help of automation is more relevant now than when the project was started.

As the result section shows, we have successfully met the goals set up for the project and have as a result gained important knowledge related to vehicle positioning and route prediction. Our approach has been to first develop detailed maps using specific mapping vehicles equipped with high accuracy reference sensors, and then in a second step develop algorithms for estimating the vehicle position in this map using affordable automotive grade sensors. Future research in this area could focus on how to probe source the map using simpler sensors and instead build the map sequentially from multiple trips.

Also, in the academic world, interest in this knowledge grows, as has been demonstrated by the majority of new courses.

There are still a lot of challenges to make a robust and scalable positioning solution for the autonomous vehicle. It is clear that a combination of positioning technologies is needed as there is no standalone system that can satisfy all the requirements. As for routing it is shown that high definition maps can really help with path and behavioural planning. Further research into more robust and reliable localization is needed to solve the autonomous needs going forward.

8 Participating parties and contact persons

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