AntWay

Automated **N**ext generation **T**ransport Vehicle for **W**ork **Y**ard application

Public report

Project within Fordons & Trafiksäkerhet-Automation

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Content

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

1. Summary

ANTWaY project aimed to do research within the complex work yard transport problem. This would involve developing systems for road vehicles that can adapt to be completely autonomous while at a site using continuous guidance information from the site control system. The positioning of a vehicle, its safe path to follow to reach destination, shortest and drivable route calculation, are some of the technical development that has been addressed within this project. The objective within this project was to, design, implement & integrate a highly autonomous vehicle and a site control system.
Design and Setup a functionally safe implementation of a semi-controlled autonomous manoeuvring truck for on-road application
Integration of a highly autonomous truck to a shared work space with site control
Implementation/Integration of Fully autonomous site controlled truck(s) for work yard.

ANTWaY started in spring of 2014 and run for 3 years then on. The partners is AB Volvo (VOLVO), Kollmorgen (KOLL), Chalmers Tekniska Högskola (Chalmers) & Högskolan I Halmstad (Halmstad). VOLVO being the leader of the project has done research on a safe autonomous work yard truck for outdoor environment. Kollmorgen has done research towards integrating path planning of the vehicles in the shared space, communication, traffic control and site planning. Both VOLVO and Kollmorgen has been involved in the implementation, verification and validation of a functionally safe architecture. Chalmers has had a PhD student within the project doing research on algorithms for an optimized perception platform. Halmstad has hired a Postdoc and contribute with research on path planning and interface between motion planning and site operation. The total project budget was ~25MSEK out of which the public funding has been 40,4% i.e. ~10MSEK

2. Sammanfattning på svenska

ANTWAY startade våren 2014 och löpte i 3 år. Partnerna är AB Volvo (VOLVO), Kollmorgen (KOLL), Chalmers Tekniska Högskola (Chalmers) och Högskolan I Halmstad (Halmstad). VOLVO (projektledare) har forskat på en säker autonom lastbil för utomhusmiljö. Kollmorgen har forskat på att integrera vägplanering av fordon i avgränsade men komplexa trafikmiljöer, kommunikation, trafikstyrning och rutt planering. Både VOLVO och Kollmorgen har varit involverade i genomförandet, verifieringen och valideringen av en funktionellt säker arkitektur. Chalmers har haft en doktorand inom projektet som forskat på algoritmer för en optimerad sensor plattform. Halmstad har anställt en postdoc och bidrar med forskning kring ruttplanering och gränssnitt mellan rörelseplanering och arbets processer för det avgränsade området. Den totala projektbudgeten var ~ 25MSEK, varav den offentliga finansieringen har varit 40,4%, dvs ~ 10MSEK

ANTWaYs mål är att utveckla en multimodala (manuellt styrda och fullt autonoma) lastbilar, vilka både individuellt och genom kommunikation med en styrcentral kan hantera lastning- och lossningsrelaterade uppgifter i miljöer med flera fordon, genom att använda information från centralen och närliggande fordon för att positionera sig och navigera på ett säkert och bränsle-effektivt sätt. ANTWaY projektet syftar till att lösa detta komplexa transportproblem genom automatisering. Det innefattar utvecklingen av system för fordon som kan anpassa sig till full autonomitet när de befinner sig inom ett avgränsat område där de kontinuerligt använder information från ett centralt ledningssystem. Några av de tekniska problem som kommer att studeras inom projektet är: positionering, beräkning och följning av säker vägsträcka för att nå måldestination samt beräkning av kortast körbara rutt. Målet med projektet är alltså att designa, implementera och integrera ett högautonomt fordon med en styrcentral.
-Utarbeta en säker implementation av en halvautonom (förarövervakad) manövrerande lastbil.
-Integrera en högautonom lastbil i ett fysiskt arbetsområde tillsammans med andra fordon och en ledningscentral
-Implementation av fullt autonoma lastbilar styrda via en ledningscentral

Detta projekt är det första projekt där Volvo AB har kopplat upp en autonom lastbil mot ett trafikkoordineringssystem och dispatch. Det innebar att vi måste hitta ett helt nytt sätt att kommunicera. Vi har lyckats skapa en grundläggande förståelse för vad som krävs i kommunikationen mellan lastbilen och det övergripande systemet, både i fråga om kommunikation till lastbilen och från lastbilen. Det övergripande trafikkoordinerings systemet har visat att det klarar att utför dynamisk planering i en föränderlig värld baser på inkommande information till systemet. Vi har också tagit fram tekniker för banföljning både framåt och bakåt. En mjukvarumodul för positionering tillsammans med hårdvara har implementerats och demonstrerats. Kartering har utvecklats och demonstrerats med hjälp av mjukvara och sensorer. Allt detta har integrerats dels i en lastbil som en systemlösning men också i en vidare mening som ett större system som kan hantera många anslutna lastbilar. Därmed har vi också tagit fram en system arkitektur för ett system med många fordon och en central koordinering och dispatch samt en arkitektur för den autonoma lastbilen. Arbetet har i många stycken visat sig vara betydligt mer komplicerat än vad vi förväntat oss, men slutresultatet har ofta varit över förväntan. Detta i kombination med de sex publikationer innebär att vi har en bra mål upp fyllnad. Det finns naturligtvis mycket kvar att förbättra med resultatet från det här projektet har använts i flera påföljande forskningsprojekt inom automation.

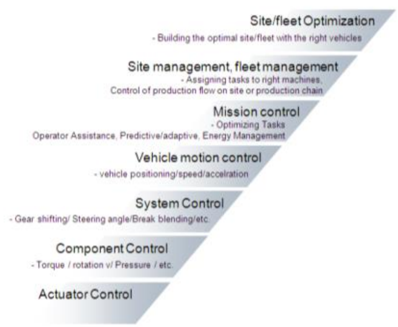
Syftet med projektet var att bedriva forskning inom automation och lägga grunden för fortsatt forskningsverksamhet inom automation i allmänhet och system med autonoma fordon i synnerhet. Målet för projektet var att bygga en forskningsplattform dvs en lastbil med släp (se bild) som kunde vara både manuellt körd med förarstöds system och helt autonom utan förare i hytten. Lastbilen skulle vara kopplad till ett centralt system. Detta genomfördes i projektet.

I projektet utvecklades en multimodal (manuellt styrd och fullt autonom) lastbil, vilken både individuellt och genom kommunikation med en styrcentral kan hantera lastning- och lossningsrelaterade uppgifter i miljöer med flera fordon, genom att använda information från centralen och närliggande fordon för att positionera sig och navigera på ett säkert och bränsle-effektivt sätt. Resultatet av detta var en förstärkning av kompetensen och forskningsmiljön kring fordonsklustret i Göteborg.

I projektet använde vi nio arbetspaket som var fördelade mellan de olika partnerna i projektet. Vi hade regelbundna möten för avstämning och diskussion kring forskningsfrågor, arkitektur, speciell tekniska lösningar. Vid fyra tillfällen integrerades hela systemet och testades och vid det sista tillfället demonstrerades det. På grund av de olika delarna nära relation till varandra har vi lärt oss ett nytt agilt sätt att samarbeta som har visat sig värdefullt i senare projekt.

3. Background

While attempting to find a solution for a multi-faceted autonomous system a deep understanding of what is available in the market and in-hand now is needed in order to know what could be achieved in the timeframe, resources and the feasibility of the mission in hand. Based on the scope an intense state of the art study and the possibility for progress beyond state of the art is undertaken in the respective field of expertise by the respective partners. Now that the world is moving towards sustainable solutions the vehicle industry faces a new and interesting challenge in its own way of sustainable solution: Automation. While researchers (google cars, DARPA etc.) and OEM's in the car industry are working on full scale automation, the commercial vehicle segment approaches this puzzle on an application point of view. Catering to this need in the transportation industry for safe, sustainable and efficient transport, Truck Automation is our step in this direction primarily aimed at solving multi-task oriented automation. Fordons & Trafiksäkerhet's automotive program presents itself with an opportunity for research and development of such a safe and efficient transport system that could help Sweden to be in the forefront of innovation in this field.



Fully automated vehicles are being explored by competitors in full scale test sites. Swedish OEMs have advantages compared to their peers, thanks to the wide range of vehicles and machines in the product portfolio. The mix allows for early market introduction in small volumes to explore and learn, then migration to high volumes of vehicles with the cost and quality benefit thereof. New market segments also open up and thus a possibility to develop and grow. In an automated function on the market. How, this should be achieved is far from trivial and lies beyond the research frontier. We hope to reach there by a strong partnership with academia. In light to all the research areas discussed above we at Volvo have two major projects that are aimed to solve different aspects of the automation jigsaw. SARPA which is an FFI funded project deals with the architecture needed for construction site automation by having highly autonomous vehicles in the loop. The demonstrator used here would be an articulated hauler. Whereas CargoANTs which is a European funded FP7 project is aimed at harbor/container terminal operation efficiency by implementing a prototype tractor trailer setup that is intelligent enough to carry out the loading/unloading operation. The ANTWaY project is thus a strategic next step to dig deeper into transformable trucks with a site control supplier as a partner in the consortium. It is our vision that by bridging these technologies Sweden will be the pioneer in Commercial Vehicle Automation.

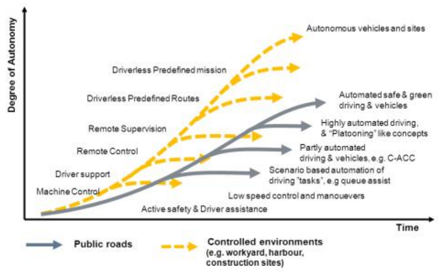
4. Purpose, research questions and method

To create the next generation of navigation systems for truck in an outdoor environment that are both flexible and safe, we will need to achieve the following scientific objectives within this project:

- Vehicle Navigation: Applying state of the art vehicle navigation methods to automated trucks maneuvering in real-world applications requiring control to be handed over between driver, site and vehicle. The method should ensure that the target location is reached in a smooth and timely manner. Collision-free navigation covers issues related to path planning, vehicle path following and control, as well as obstacle detection and modeling.
- Perception in outdoor environment: Develop a perception system that can perform localization, object detection and classification between VRU's, obstacles & other vehicles and also serve input for the information needed for hybrid-planning for collision free path. The challenge here would be to build a vehicle based sensor system for outdoor environments.
- Safety concept: Built-in safety in the system architecture using available background information about the environment to devise reliable collision-prediction solutions in the presence of moving objects. Challenges here are (i) Data association, (ii) Uncertainty in perception, (iii) Computational complexity.
- Self-Localization of Vehicle: The development of a new self-localization method for outdoor application that exploits non-artificial features of the real-world environment. To achieve this objective, we need to address very challenging scientific issues such as data association and uncertainty handling.
- Site Controlled road vehicles: In accordance with the project there is a strong dependability bond required between the site and the vehicle. The tradeoff between the intelligence in the vehicle and the site needs to be analyzed and the use cases where site or vehicle should be prioritized needs to be identified.

5. Objective

Volvo’s strategy is to develop an automation platform that supports the wide portfolio of different vehicle, vessels and machines. The platform should be able to carry everything from research together with academic partners to production systems. We believe that early implementation of automation can be made in confined environments where the variations are relatively small, regulations easy to change and investments in infrastructure can be kept small. By implementing and using technology for automation the competence will increase in Volvo, among Volvos academic partners and suppliers and thus the robustness and maturity. With higher maturity may the technology be safely introduced in the road applications where the collective effects of safety and efficiency improvements can be huge, see Figure 3 below. Construction vehicles may have much higher safety and environmental effect per vehicle with numbers as high as 50%, already for the first generation automated vehicles. Hence the customers are prepared for the relatively high cost for the pioneering systems. However, the absolute saving will be much greater for the road applications due to the high number of road vehicle, ones the technology has matured to be implemented in this segment.



We believe that it is possible to create automated vehicles where the essential parts of the decisions are distributed to each vehicle. This gives advantages in flexibility; the same basic architecture can be used for both on and off road applications. With such, highly “intelligent” vehicles it would also be possible to automate small parts of a construction site or some of the vehicles in a traffic environment. We believe that the key to handle flexible environment lies in extrapolating our current active safety functions into fully automated functions. In difference to AGVs, is our active safety functions designed to handle flexible environments in independent vehicles. ACC is already an automated function on the market. How, this should be achieved is far from trivial and lies beyond the research frontier. We hope to reach there by a strong partnership with academia.

The object is thus to further enhance the knowledge, experience and knowhow by doing research with in the automation area by;

- Building a semi-controlled (driver in the loop) autonomous maneuvering truck
- Highly autonomous truck integrated to a shared work space with site control.

This objectives have been fulfilled.

6. Results and deliverables

In the project the following modules have been implemented and demonstrated;

- Vehicle Navigation
- Perception in outdoor environment
- Safety concept
- Self-Localization of Vehicle
- Site Controlled road vehicles





We have also publicised five papers (listed below) and one Ph.D. have connected to the project.

Project Status Reports

During this project a number of project reports was sent to FFI. This is the last and final report of these reports.

System specification

The project developed a high level architecture shown below. This was done in iterative process where we integrated solutions with more and more advanced functionality for evry iteration. Key components is described below.

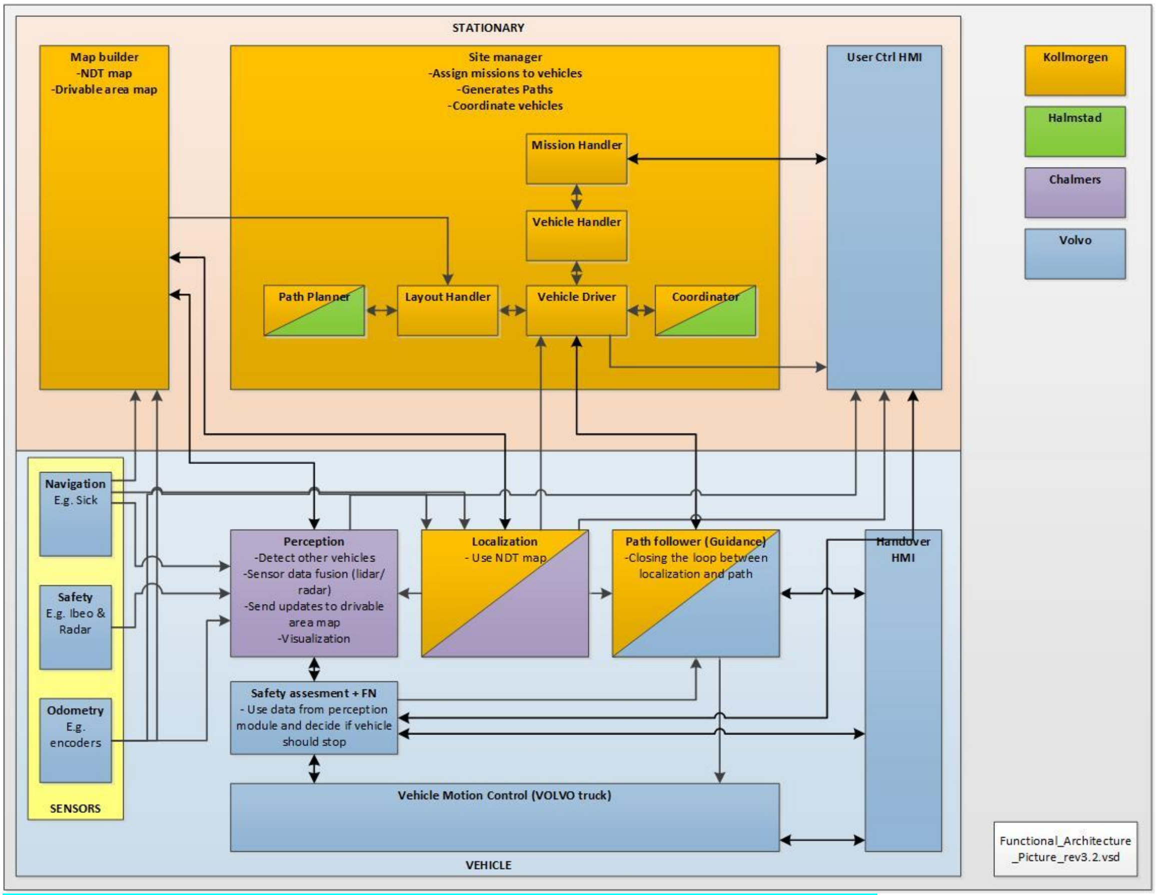


Figure 1: High level architecture divided into stationary (orange) and vehicle (blue) parts.

Relative object detection

The issue of relative to object detection module has been partly addressed directly on-site via measurements using the lidar and reprojection the obstacle into an environmental map and partly addressed in simulation and described in the paper (M. Bellone , & J. Qutteineh, 2017). In this work, the objects were detected and re-projected into a parameterized space to decrease the computational burden instead of using the classical Euclidean space.

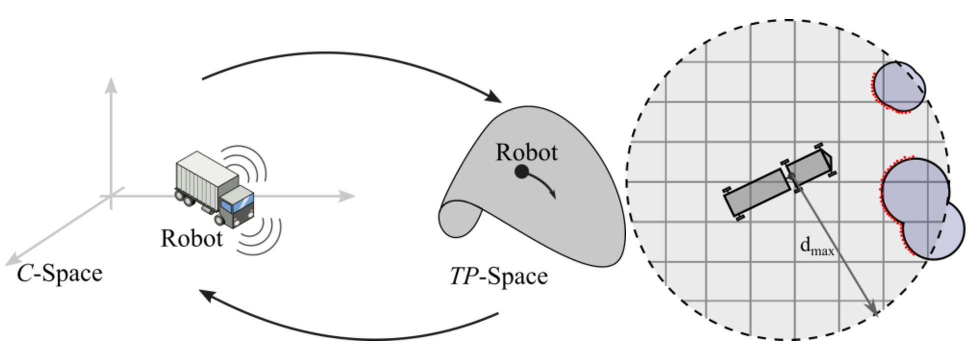


Figure: depiction of robotic truck in the Euclidean space and the relative objects transformation in the parameterized space (refer to the publication for details).

The object mapping is composed of an off-line grid calculation and an on-line mapping. The on-line part involves mapping the observed obstacles (relative to the vehicle) into the obstacles grid. In the current implementation, a range sensor is assumed located on the roof of the vehicle and placed in its geometric center. The sensor readings are organized in a point cloud and re-projected onto the obstacles grid to build the TP-obstacles. Even though this procedure must be done on-line, it implicitly takes into account any vehicle constraints or geometry. For each obstacle point projected in TP-space is easily possible to check the lowest distance value for the current trajectory, corresponding simply to its geometric coordinates in TP-space. The smallest recorded d value represents the obstacle free distance for the vehicle moving along the trajectory specified by the current in TP-space. As a consequence, the trajectory cannot contain points in the obstacle space, thus performing obstacle avoidance.

Object classification has been also addressed in the publication (Bellone et.al, 2017), in such work a stereo camera has been placed in the front of the vehicle. The 3D reconstruction and the point cloud analysis allows to detect and classify drivable part of the road and other obstacles. To achieve this level of classification a Support Vector Machine is used for the learning and classification procedure. A performance evaluation reported in the paper shows accuracy better than 85-90% for each point using a cross-validation evaluation procedure. Please, refer to the publication for further details.

Figure: Classification results obtained for on-road scenarios. Left: original visual image, Center: 3D point cloud, Right: scene interpretation, green: drivable patch, red: undrivable patch.

Ego-localization software modules

The Vehicle State Estimator (VSE) for the eco-localization is built on a truck+trailer constant velocity physical model for the ATNWaY project. The VSE is implemented on a MATLAB Simulink model, then exported and converted (by the MATLAB code generation) to a C code implementation which can be executed directly on the truck embedded computer. The VSE relies on a measurement model which, at the present stage, uses the following information: GPS (latitude, longitude), IMU (acceleration and angles rate), longitudinal velocity and steering wheel angle.

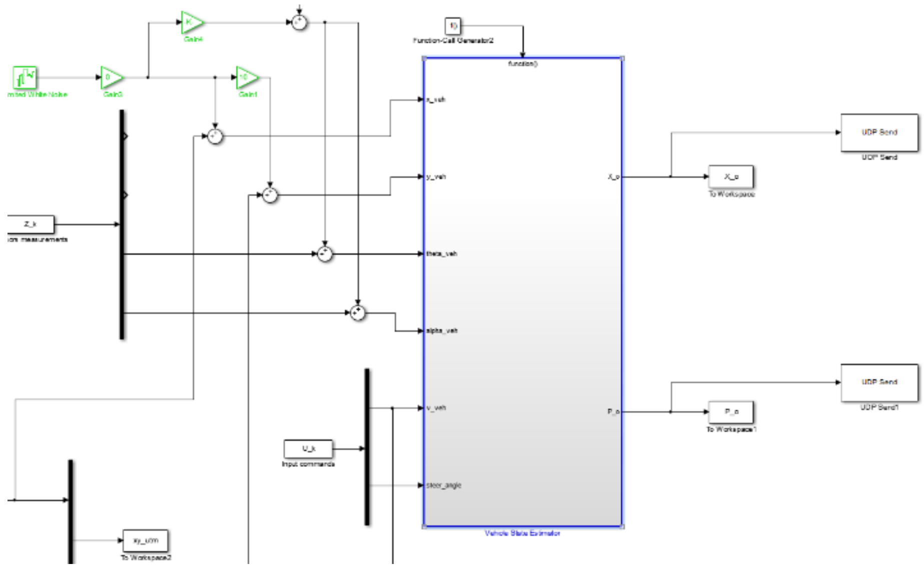


Figure: MATLAB implementation of the VSE

The measurement model is fully modular, hence it is possible to improve the estimation of the state of the truck using additional information, such as laser scanner, cameras ect. All required data comes from on-board sensors. The outputs of the algorithm are the state of the vehicle (pose and velocity) and a covariance matrix. The latter give a useful information about the reliability of the estimation.

This information should be sent via UDP (not implemented yet) to the racelogic VBOX device.

Simulations results demonstrated accuracy or about 10cm in longitudinal and lateral directions, and 0.1deg in the global orientation see figure below:

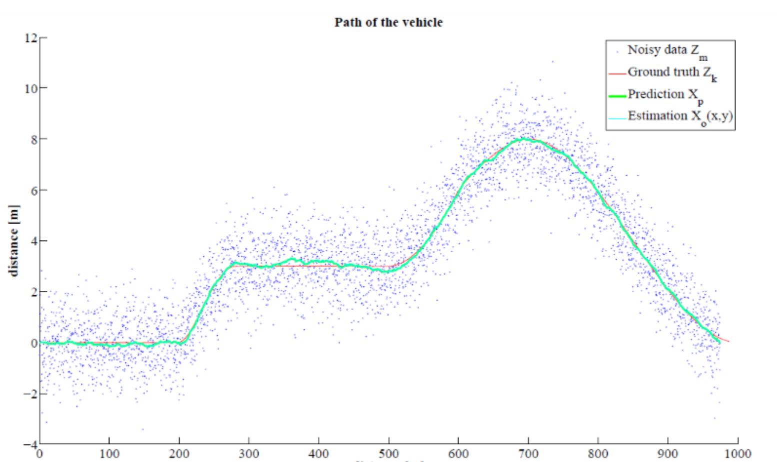


Figure: position estimation (simulation)

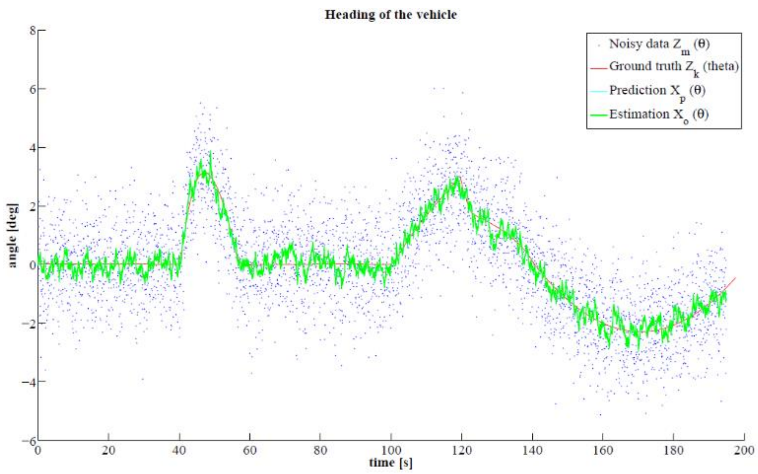


Figure: orientation estimation (simulation)

Then on-road tests including sensor validation confirmed such accuracy even though more work will be needed to increase even more the accuracy, see figures below:

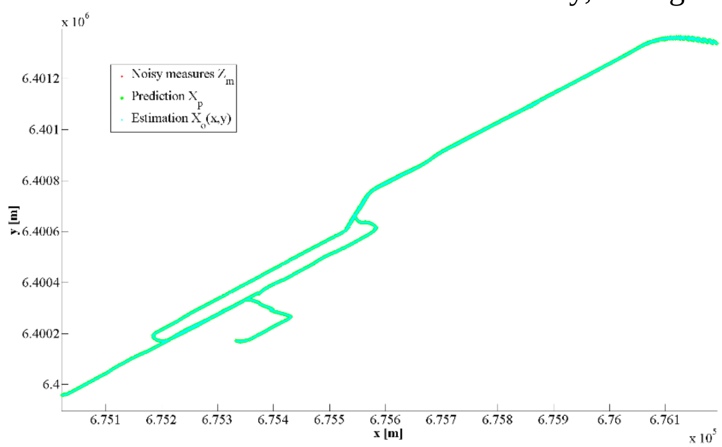


Figure: position estimation, real on-road data in Lindholmen

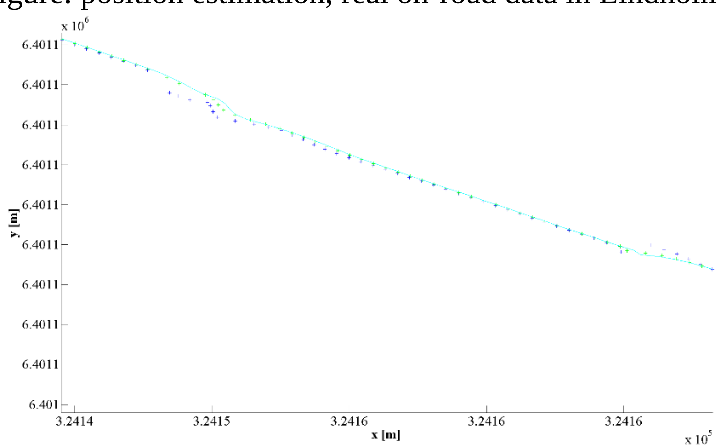


Figure: focus on position error, real on-road data in Lindholmen (global UTM coordinates are used)

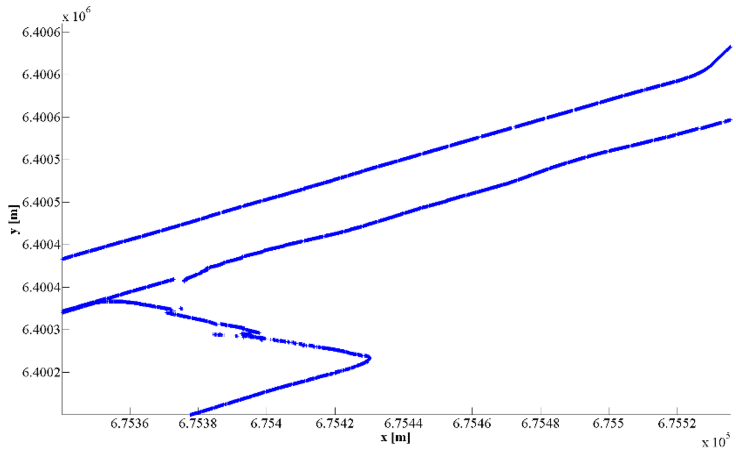


Figure xx: Noisy measurement, real on-road data in Lindholmen

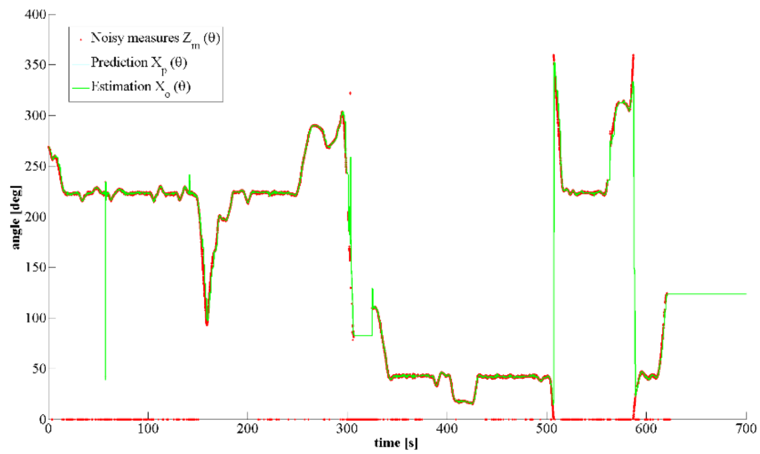


Figure: estimation of orientation angle based on noisy information, real on-road data in Lindholmen

Absolute object and environment mapping software modules

Considering the truck into the warehouse, the objects were mapped in an absolute reference frame. The environmental map is supposed to be given by the central site control, hence the remaining task for the truck is to map the objects into the global map considering its own position as given by the eco-localization module. The map is then passed to the path-planning part.

Implementation of interactive site and path planning software

To achieve real time dynamic site planning the planning load was split into two parts. The first is a global planner handled by the site planner in a centralized fashion using simplified models of the vehicles and the environment. In ANTWaY, the global planner provides paths that don't consider vehicle motion constraints and don't consider dynamic (non-static) obstacles. This enables the global planner to plan for an entire fleet of vehicles in real time. The paths generated are presented as a series of way points that are sent to the second planner (the local planner) which runs in distributed fashion across the fleet.

The local path planner running on the vehicle generates paths that consider vehicle's own motion constrains and mobile obstacles in its near vicinity. Two different but complimentary prototypes were developed and tested for ANTWaY.

The first local planner is a fast path adaptor that optimizes preliminary paths generated by the site planner (straight lines connecting successive waypoints) based on an optimization technique called "CHOMP". The technique which was originally developed for articulated robotic manipulators was extended to handle mobile vehicles and also to operate on obstacles represented by an occupancy grid. This planner is able to quickly generate paths that capture some (but not all) of the kinematical constrains of the vehicle. Test results on real truck and simulation shows that this technique performs well in fairly uncluttered environments where performance was fast and the paths generated were kinematicaly feasible (David et al, 2017a, 2017b, 2017c).

The second local path planner is a probabilistic planner based on parameterized trajectory space (TP-Space) and compliments the functionality of the first planner. This planner is especially capable of generating complex maneuvers that are required for scenarios such as parking or entering a warehouse or facility gate. The generated paths can contain multiple maneuvers in forward and backward direction that are typical in such scenarios. The planner was extended to handle path planning for articulated vehicles (e.g. Tractor-Trailer) and was tested in simulation. The results show good results even in tight spots that require a number of complex maneuvers to navigate safely. However, time required to find solution for complex scenarios was high and with relatively high variance due to the randomization approach utilized by the planner (Bellone and Qutteineh, 2017).

Path follower implementation

Path following algorithm

The path following in this project was based on the Stanley Method [1].
This method is the path tracking approach used by Stanford University's autonomous vehicle entry in the DARPA Grand Challenge, Stanley.

The Stanley method is a nonlinear feedback function of the cross track error e_{fa}, measured from the center of the front axle to the nearest path point (c_x, c_y), for which exponential convergence can be shown [1]. Co-locating the point of control with the steered front wheels allows for an intuitive control law, where the first term simply keeps the wheels aligned with the given path by setting the steering angle δ equal to the heading error $\theta_e = \theta - \theta_p$, where θ is the heading of the vehicle and θ_p is the heading of the path at (c_x, c_y).

When e_{fa} is non-zero, the second term adjusts δ such that the intended trajectory intersects the path tangent from (c_x, c_y) at kv(t) units from the front axle.

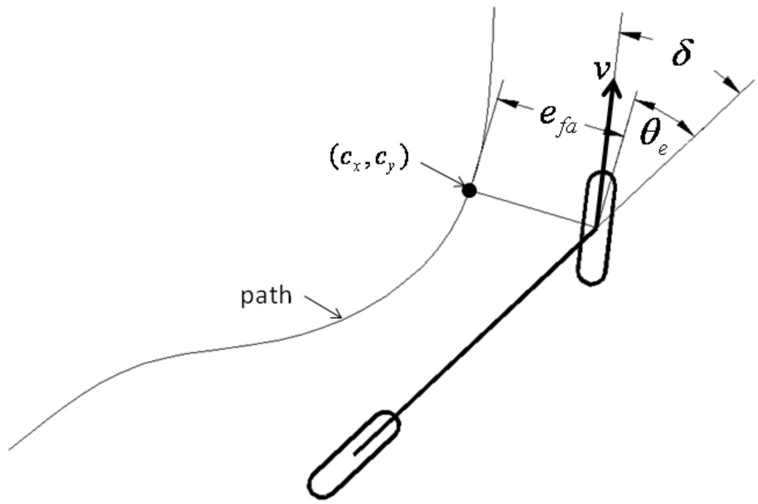


Figure 1

Figure 1 illustrates the geometric relationship of the control parameters. The resulting steering control law is given as

$$\delta(t) = \theta(t) + \operatorname{atan}\left(\frac{k e_{fa}(t)}{v_x(t)}\right)$$

where k is a gain parameter.

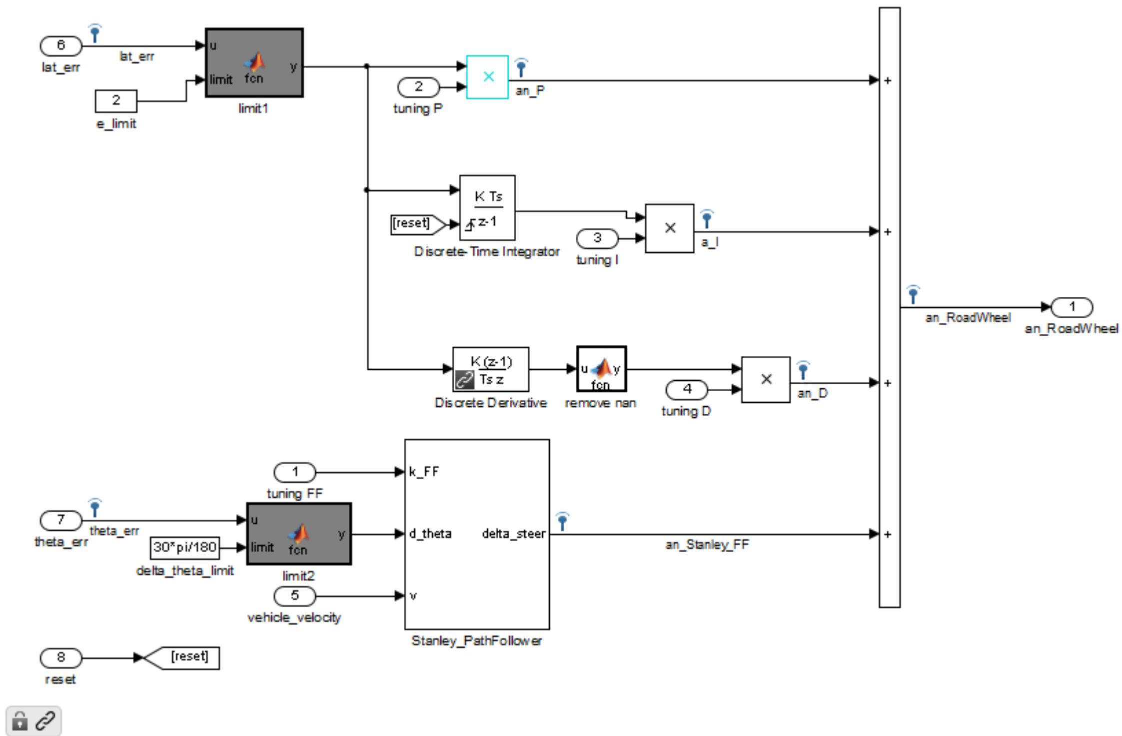
It is clear that the desired effect is achieved with this control law: As e_{fa} increases, the wheels are steered further towards the path.

Path following implementation

In this project the the path following control law was adjusted slightly from the original Stanley Method.
Due to the fact that this project only has low speed use-cases the second speed dependant term in the original Stanley Method was replaced by a standard PID controller for the lateral error. The resulting control low was given as:

$$\delta(t) = \theta(t) + \text{PID}(e_{fa}(t))$$

The implementation was done in Matlab Simulink and figure 2 shows an overview.



Figure

The upper part represents the PID and the lower part represents the θ(t) calculation.

Testing and results

The path follower was tested with a Volvo FH 4x2 Tractor.
All tests were performed on flat ground with low vehicle speed, typically 5 km/h.

The project used mainly three types of paths to test the path follower:

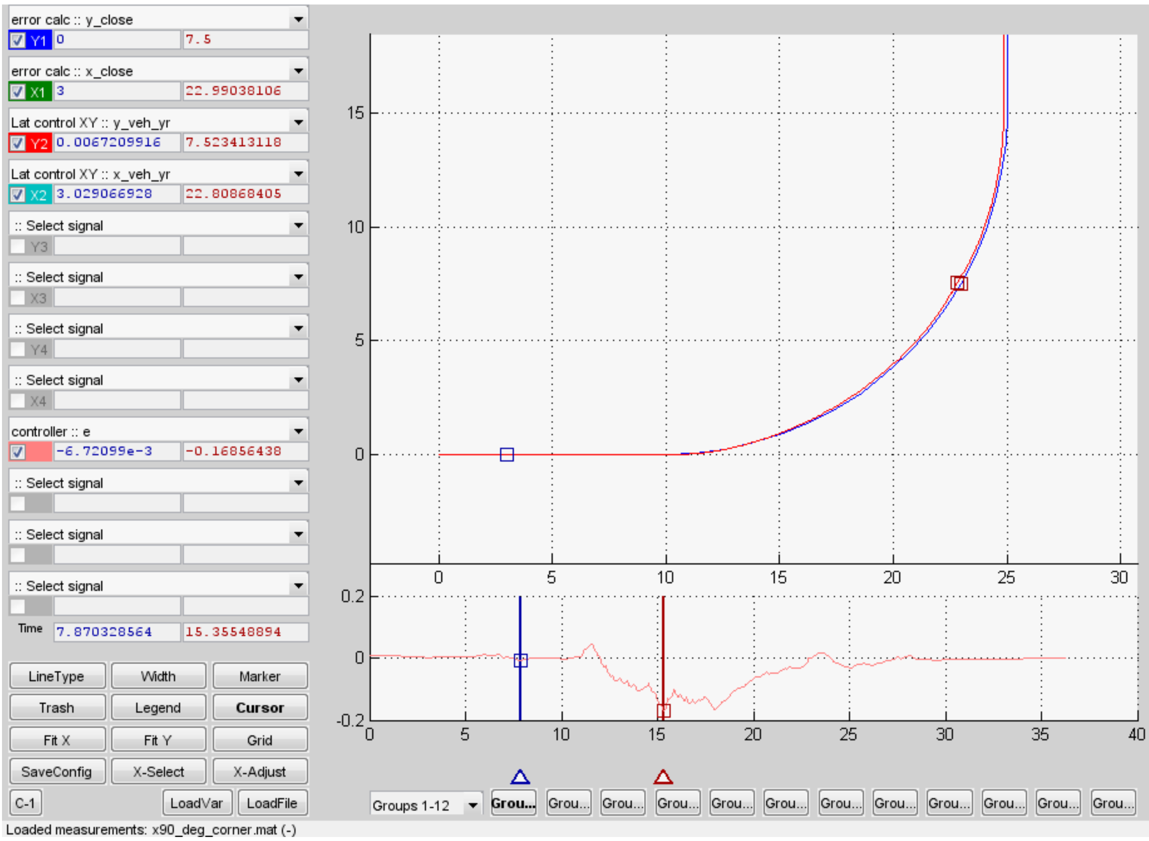
1. Mathematically generated paths like lines and circle arcs.
2. Pre-recorded paths
3. Paths that was generated by the obstacle avoidance module.

The following chapters show the path and the position of the truck for some tests where:

Blue line: Front axle path
Red line: Front axle position

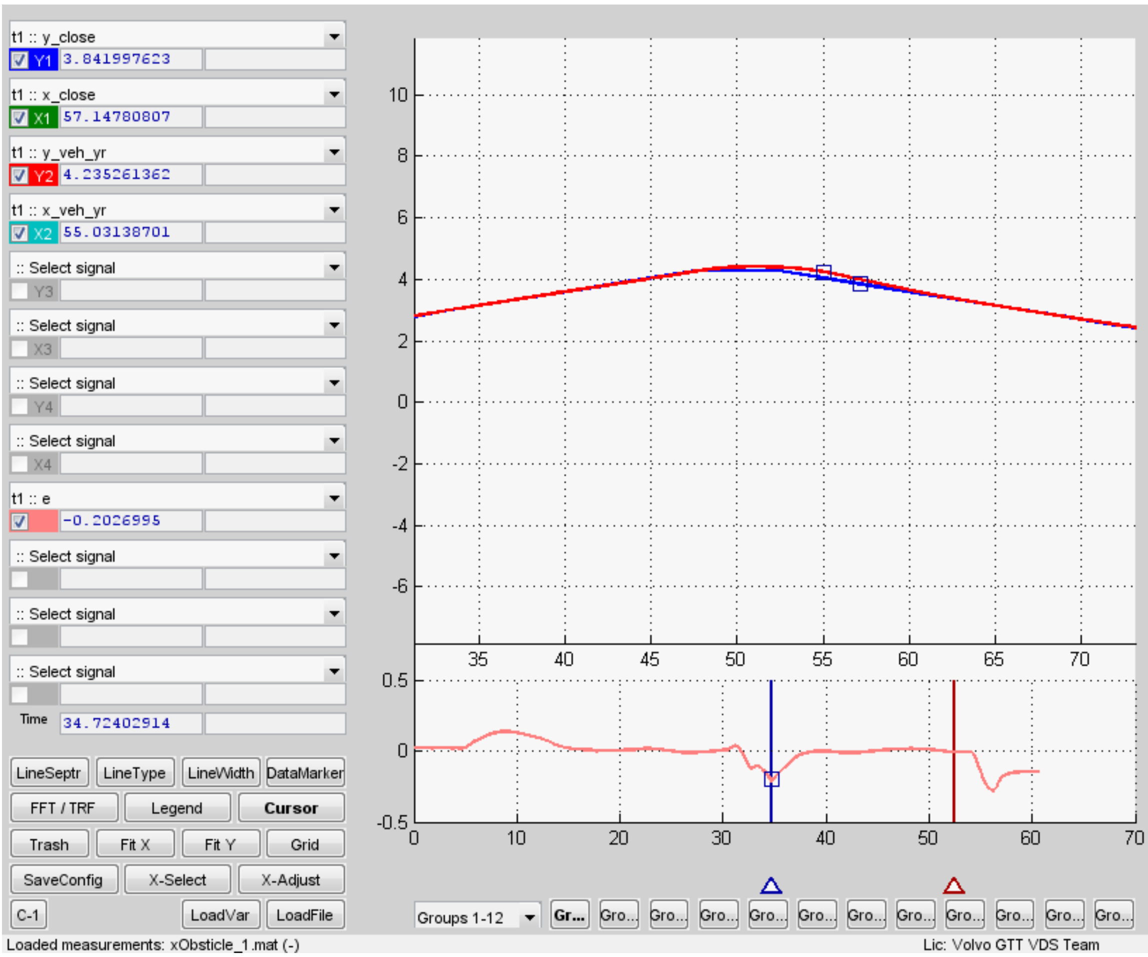
Corner

Figure 3 shows the results from a cornering test with a circle arc path. The maximum lateral error in the corner was 16 cm.



Figure

Obstacle avoidence
Figure 4 shows the results from path generated by the obstacle avoidance module. The maximum lateral error after the obstacle was 20 cm.



Site planner system setup

The site controller takes care of all vehicles and missions on the site. This includes coordination to avoid collisions or traffic jams as well as selecting the optimal vehicle for a specific mission.
The site controller maintains a map of the facility defining what areas that are "drivable" i.e. what obstacles and static objects that are present. This map is used when calculating the paths.
For test and validation of the path planner module a separate software tool called System Designer has been used. This tool can be used to manually edit the map of the site (adding static objects) and to visualize the path that will be created between two different

points. The same software module (dll) is used in the Site Planner and the System Designer.

The Vehicle Handler module takes care of vehicle organization, perform move requests and listen to vehicle status messages. The Mission Handler module sends a move request to Vehicle Handler, the module finds a free vehicle (allocates a vehicle) and sends a move request to Path Planner which performs some logic and then sends a new message to the vehicle. The module then listen to status messages from the vehicle, e.g. the vehicle is moving, or has arrived at a station. The vehicle's status is dispatched to e.g. Mission Handler.

Path Planner

The Path Planner module is responsible for coordinating a movement. It receives a request from Vehicle Handler to move a vehicle, and then requests information from Layout Handler to be able to send a path to the vehicle. The module also listen for vehicle status and I/O signals in order to update and send new Trajectory and Speed messages to the vehicle. Example: a door sends an I/O signal indicating a door is closed, Path Planner must then slow down and/or stop the vehicle. The module also sends I/O requests to IO Handler to open a door the vehicle is travelling through.

Coordinator

The coordinator is responsible for coordination between vehicles. It should make sure that no collisions or deadlocks occur. This is done by adjusting the vehicle speeds (not the paths) in a way that optimizes the total throughput of the system.

Site-vehicle interface

A wireless LAN link was used for communication between the site controller and the vehicle controller during the tests and demonstrations. Since it is a standard TCP/IP communication it can easily be changed to another physical interface if WLAN has a too short range.

The vehicle cyclically sends status telegrams to the site controller. The site controller calculates paths and manage the coordination with all other vehicles in the system.

Software + Hardware for vehicle

In the early phase of the project the Volvo FH 4x2 Tractor was equipped with a CVC600 vehicle controller from Kollmorgen. The controller was connected to the site control system with wireless LAN and to the vehicle with a CAN-bus interface. Drive paths were generated in the site controller and sent to the vehicle controller. The path follower inside the vehicle controller calculated set values for steering angle and drive speed. The values were sent to the Volvo truck controller that handled speed and steering.

In this phase of the project the CVC600 vehicle controller did the localization as well. The pose estimate was calculated using “Natural Navigation”. 2 different LIDAR sensors were used simultaneously to collect information on the surrounding objects. The LIDAR measurements were then matched to a predefined map of the environment and a position calculated. The map was generated by driving the truck manually around the area and make a "facility mapping".

The above setup was demonstrated at AstaZero in June 2015.

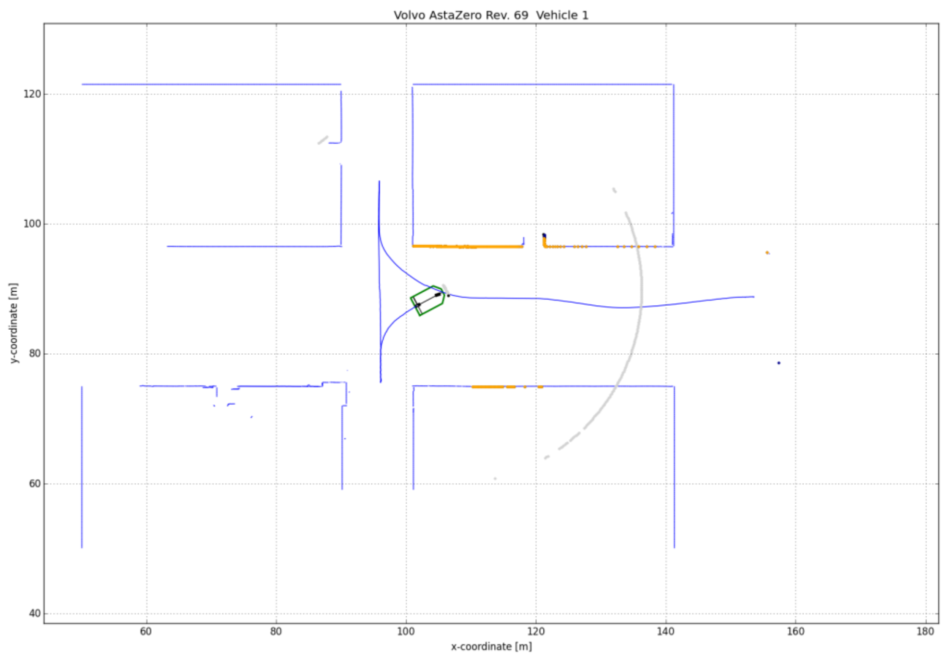


Figure: Demo at Asta Zero. The blue "boxes" is a map of the buildings in a crossing (AstaZero city area). The green symbol is the vehicle and the LIDAR sensor readings are yellow. The blue lines in the middle is a path that the vehicle has driven.

HMI

During the tests at AstaZero a System Viewer was used to visualize the facility and the truck movements. The System Viewer is a PC software that is connected to the Site Controller. It can visualize the position and status of all vehicles in the system as well as status of other equipment (e.g. if doors are open or closed).

User interaction

During normal system operation with the highest automation level, i.e. level 5 in the SAE J3016 standard, there is no or little need for HMIs, driving controls or even a cab since there is no driver on-board. However, as is the case with ANTWaY, the autonomous truck will be realized by adapting and using existing trucks, e.g. a Volvo FH tractor and to equip them with the technologies required for automated control. This also applies for the driver-vehicle interaction, where we will most likely need to complement the existing HMIs with functions and devices specifically for the autonomous system, though not for the driving task but for other tasks such as hand-over of control. We have identified two high level principles for human interaction with the automated and adapted truck:

- Any add-on user interface must not interfere or significantly alter the use of the basic driver environment (safety and efficiency must be retained when using the vehicle in manual control and normal driving task)
- In all situations and interactions, there must never be any doubt to any user – inside or external or remote - if the vehicle is in automated control or manual control

So, there is a clear need for developing new human-machine interfaces and interactions (HMIs) that supports safe use and operation of autonomous vehicles.

The identified use-cases further help us to understand where user interaction will take place, it is clear that the most important task to address is the hand-over of control between the driver and the site control system. At least the following steps are needed for the driver to hand over the control to the site system in a safe way:

Step	Description
1	The driver stops the vehicle in a gate area of the terminal and engages the parking brake (engine is still running).
2	The driver and truck is authorized at the gate by the site control system.
3	The driver initiates and requests the hand-over with a command from a mobile device in the cab or a dedicated push-button on the dashboard.
4	The site control system gives signal to the driver that it is ready to receive the vehicle in automated control. The vehicle can now be considered to be in “armed state”, meaning it can be put into automated control when given a final signal.
5	The driver puts on a safety west, exits the vehicle, and closes the door.
6	The driver performs visual inspection around the truck to make sure there are no humans or obstacles around the truck. Alternatively: There could be a system performing this task in the infrastructure of the gate area.
7	The driver leaves the gate area.
8	The driver gives a “go automated” signal to the site control system. This can be done in several ways; either using a button

	on the truck exterior or in the gate area, or using a handheld device, or perhaps via radio. After this signal has been given, the vehicle is now able to go from “armed state” to site control mode.
9	The vehicle starts automated operation by executing assignments according to the plan as defined by site control system.

Similarly, we can see the same steps more or less in reverse order when the system hands over the control back to the driver.

We have also identified other aspects on user interaction, since there are also other users to consider, for example, vulnerable road-users in the work yard area may appear in exception use-cases such as an unplanned stop of an autonomous and driver-less truck within the area. It may be needed to let the autonomous vehicle communicate the state of the automation system using visual signals on the vehicle exterior. A truck in autonomous or unknown mode may not be safe to approach.

Lastly, there will be a user interface in the Site Control System to allow planning, monitoring and decision of the whole work yard site transport system.

For a continued research and development within this project area, prototyping and user evaluations are needed in order to create a full working automated transport system for the work yard.

System use-cases

One of the first activities within the project was to identify high-level scenarios of the planned ANTWaY system and to identify more detailed use-cases in order to support system design and implementation. Three scenarios have been identified as:

- The vehicle performs transportation on public road using a semi-autonomous system to support active safety for the driver
- The vehicle maneuvers within the restricted work yard area in high autonomous mode, i.e. there is no driver in the vehicle, the vehicle is controlled by the site-control system
- The control of the vehicle is being transferred from the driver to the site-control system within the work yard area or vice-versa, i.e. the control of the vehicle is transferred from the site-control system back to the driver

From these scenarios we identified several use-cases, these are listed below and detailed descriptions of each use-case can be found in project deliverable D2.1 “Use-cases”:

Use case	Description
UC_1	Emergency accident avoidance maneuver.
UC_2	Building a localization map of restricted area.
UC_3	Driver gives truck responsibility to site control system (SCS).
UC_4	SCT drives though the restricted area to the exit gate.
UC_5	Driver takes truck responsibility from site control system (SCS).
UC_6	Reversing into parking place (docking).
UC_7	Driving out of parking place (undocking).
UC_8	Update the existing localization map.
UC_9	Collision avoidance and dynamic path planning with object recognition on fixed objects.
UC_10	Authorized personnel recognition.
UC_11	Site controlled truck encounters problem to continue normal operation.

7. Dissemination and publications

Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	A lot of lessons learned in this project have been transferred to other FFI projects within automation.
Be passed on to other advanced technological development projects	X	A lot of lessons learned in this project have been transferred to other FFI projects within automation. Examples are: Automated Safe and Efficient Transport System. Autopilot Site to Plant
Be passed on to product development projects		No, the technology in not mature enough. It still needs more research.
Introduced on the market		No
Used in investigations / regulatory / licensing / political decisions		No

Publications

- J. David, R. Valencia, R. Philippsen and K. Iagnemma, "Gradient based Path Optimization method for Autonomous Driving," IROS 2017, Sept. 2017.
  Abstract: *This paper discusses the possibilities of extending and adapting the CHOMP motion planner [1] to work with a non-holonomic vehicle such as an autonomous truck with a single trailer. A detailed study has been done to find out the different ways of implementing these constraints on the motion planner. CHOMP, which is a successful motion planner for articulated robots produces very fast and collision-free trajectories. This nature is important for a local path adaptor in a multi-vehicle path planning for resolving path-conflicts in a very fast manner and hence, CHOMP was adapted. Secondly, this paper also details the experimental integration of the modified CHOMP with the sensor fusion and control system of an autonomous Volvo FH-16 truck and a set of experiments conducted on a real-time environment. Finally, additional simulations were also conducted to compare the performance of the different approaches developed to study the feasibility of employing CHOMP to autonomous vehicles.*

- J David, R. Valencia, R Philippsen, P. Bosshard and K Iagnemma, "Local Path Optimizer for an Autonomous Truck in a Harbor Scenario," 11th Conference on Field and Service Robotics (FSR), Sept. 2017
  Abstract: Recently, functional gradient algorithms like CHOMP have been very successful in producing locally optimal motion plans for articulated robots. In this paper, we have adapted CHOMP to work with a non-holonomic vehicle such as an autonomous truck with a single trailer and a differential drive robot. An extended CHOMP with

rolling constraints has been implemented on both of these setup which yielded feasible curvatures. This paper details the experimental integration of the extended CHOMP motion planner with the sensor fusion and control system of an autonomous Volvo FH-16 truck. It also explains the experiments conducted on the differential-drive robot. Initial experimental investigations and results conducted in a real-world environment show that CHOMP can produce smooth and collision-free trajectories for mobile robots and vehicles as well. In conclusion, this paper discusses the feasibility of employing CHOMP to mobile robots.

- J. David, R. Valencia, R. Philippsen and K. Iagnemma, "Trajectory Optimizer for an Automated Truck in a Container Terminal Scenario", ICRA 2017 Workshop on Robotic and Vehicular Technologies for Self-Driving Cars, June 2017.
  Abstract: Recently, functional gradient algorithms like CHOMP have been very successful to produce locally optimal motion plans for articulated robots. In this paper, we have studied the possibilities of extending and adapting CHOMP to work with a non-holonomic vehicle such as an autonomous truck with a single trailer. A detailed study has been done to find different ways of implementing curvature constraints for the motion planner to yield trajectories for a non-holonomic vehicle. This paper also details the experimental integration of this modified trajectory optimizer with the sensor fusion and control system of an autonomous Volvo FH-16 truck. Initial experimental investigations and results conducted in a real-time environment shows that CHOMP can produce very fast, smooth and collision free trajectories for non-holonomic vehicles. In conclusion, this paper discusses about the feasibility of employing CHOMP to autonomous vehicles.

- M. Bellone , & J. Qutteineh, " Extension of Trajectory Planning in Parameterized Spaces to Articulated Vehicles". 22nd IEEE International Conference on Emerging Technologies And Factory Automation, September 12-15, 2017.
  Abstract: The main objective of this research is to study a novel method for safe maneuvering of articulated vehicles in warehouses. The presented method extends the concept of probabilistic planning on manifolds to articulated vehicles, which will be capable of driving, maneuvering and performing obstacle avoidance in any scenario. The proposed technique involves the extension of a parameterized space, developed for the reactive navigation of differential driven vehicles, to include an additional degree of freedom and use a probabilistic planner to calculate kinematically feasible trajectories. As a result, the algorithm is able to successfully generate maneuvers for an articulated truck and to navigate towards specific target points. The approach was validated using three problems representing different driving scenarios, demonstrating the possible utilization of the method in real-case scenarios. The solutions have been further benchmarked on multiple runs to evaluate success rate and to demonstrate the validity of the algorithm.

- M. Bellone, G. Reina, L. Caltagirone, and M. Wahde "Learning Traversability from Point Clouds in Challenging Scenarios " IEEE Intelligent Transportation Systems Transactions - 2017 (accepted - in press)

  Abstract: The research presented here aims at evaluating the capabilities to detect road traversability in urban and extra-urban scenarios of support vector machine-based classifiers that use local descriptors extracted from RGB-D point cloud data. The evaluation of the proposed classifiers is carried out by using four different kernels and comparing five point descriptors obtained from geometric and appearance-based features. An initial comparison among the performance of descriptors individually has demonstrated that the normal vector-based descriptor achieves an accuracy of 88%, outperforming by about 6-15% all the other considered ones. To further improve the recognition capabilities, the space of features is augmented by merging the components of each point descriptor, reaching 92% classification accuracy. A set of test scenarios have been acquired during an extensive experimental campaign using an all-terrain vehicle. Tests on real data show high classification performance for road scenarios and rural environments; the generality of the method makes it applicable for different types of mobile robots including, but not limited to, autonomous vehicles.

8. Conclusions and future research

The implementation and test of the vehicle state estimator for eco-localization demonstrated high potential for the implementation on road vehicles for the accurate position and orientation estimation. The improvement of the position estimation is considered as crucial task for the future of automation or road vehicles and the entire transportation system. Further research is required to reach the highest technological level in the fusion of eco-localization and perception systems.

The CHOMP algorithm was adapted for use on non-holonomic vehicles as well as with differential-drive robots. The results have been tested on a real-world scenario as well as in simulations where the truck with trailer was able to avoid obstacles. It has also been found that the basic algorithm of CHOMP does not allow us to capture the complete kinematic constraints of the vehicle. However, this approach has been found to work satisfactorily in fairly uncluttered environments. Future work will include in adding inequality constraints to CHOMP and improved versions of CHOMP that can truly respect the curvature constraints of the vehicle in a larger scale.

Experimental evaluations of TP based trajectory planner in synthetic environments shown that the procedure can be successfully applied solving parking problems performing both forward and backward maneuvers. Although limited to simulation, this research demonstrates that planning on manifolds constitutes a promising field of research, improving the global performances in path planning tasks. A future work on testing this planner on real life scenarios is required. Additionally, plenty of optimization room is available to be exploited to improve performance in terms of compute time and execution of more complicated maneuvering.

Thanks to a modular design of the truck (Volvo) as well as NDC8 software (Kollmorgen) it was possible to get started quickly in this project. A first test setup with a Volvo truck controlled by a Kollmorgen AGV controller was up and running after a couple of months.

The modularity has also made it possible for researchers to develop a path planner module and test it offline in the System Designer. This made it easier to test and verify the functionality without a need for the actual vehicle and site.

The main challenge in this project have not been the technical parts. The hard part has been to plan the work with personnel, vehicles and equipment since different initiatives and projects are using the same resources. There has also been staff turnover (both from universities and companies).

Another challenge has been to find a good test facility. Outdoor tests and demos were made at AstaZero but it would have been much easier with a facility inside Gothenburg. An indoor test area would have been very useful for instance when evaluating and tuning different sensors.

9. Participating parties and contact persons

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