Abstract—This paper presents the implementation of a highly automated driving system on automotive Electronic Control Units (ECUs). It integrates a perception component, which uses the combination of high-level sensors to map the environment, a co-pilot, which finds an optimal trajectory in this environment and a control component, which guides the vehicle on this trajectory. The cooperation between human and automation is managed by the driving Mode Selection and arbitration Unit (MSU) and Human-Machine Interface (HMI) components. The co-pilot and control components have been implemented on AUTOSAR-based ECUs, the other components in the RTMaps environment on a standard PC. It has been first been tested on the simulation tool SiVIC and was then transferred to a physical vehicle on test track.

I. INTRODUCTION

In the past decades Advanced Driving Assistance Systems (ADAS) have become increasingly popular for making road transport safer and more comfortable. Road traffic accidents in the European Union claim annually around 40000 lives and leave almost 2 million people injured [1]. Accident analysis shows that human-inherent errors such as distraction, emotion, fatigue or drowsiness are almost the sole causative factor of these accidents. Customer interest for ADAS has significantly increased by the combination of safety and comfort functions such as in Adaptive Cruise Control (ACC) and Lane Keeping Systems (LKS). Further development of ADAS could lead to autonomous vehicles which are proposed as one of the optimum transport modes of the future [2].

Two main strategies for going towards autonomous vehicles can be distinguished. Vehicles on the DARPA Challenge [3] and CyberCars [4] now already offer a complete automation of the driving task on a private infrastructure through extensive high-tech equipment. For economical, legal and psychological reasons the alternative approach chosen by most car manufacturers is the step-by-step introduction of simple driving assistance systems which collaborate with the human driver for driving on public roads. The latter approach is followed by European 7th Framework Programme (FP7) project HAVEit, which proposes an interaction scheme between driving system and the human driver along different automation modes [5][6][7] and the French National Research Agency (ANR) project ABV [8]. Co-pilot and control components were created for HAVEit and perception components for ABV. This paper discusses their combination with a basic Mode Selection and arbitration Unit (MSU) and Human-Machine Interface (HMI) into a highly automated driving system for highways on PC and Electronic Control Units (ECUs).

This paper is organized as follows: Section II presents the system architecture and Section III the prototyping methodology and tools used to design an ADAS system. Sections IV - VII describe the components of the system: the sensors and actuators, perception, co-pilot, control and actuators, MSU and HMI. Section VIII gives the current results on the performance of the system and Section IX concludes with a perspective of future works.

II. SYSTEM ARCHITECTURE

Figure 1 gives an image of the hardware used for the system development. On the lower part, three AUTOSAR-based ECUs of Continental (with Freescale microprocessor with a clock frequency of 100MHz and 3MB ROM, 100kB RAM memory) can be seen, which currently integrate the safety critical co-pilot and control algorithms and will in later development also host the perception algorithms. A Lauterbach Power Trace II debugger with Nexus interface (upper part) and Vector CANcaseXL (lower part, not visible)
serve as interface with the standard PC (on the left-side, off the picture) which holds the environment simulator, perception, HMI and MSU algorithms. Note that in the beginning of the development, when the CAN interfaces were defined, a prudent choice of one ECU per algorithm was made. However, as shown in the result section, current algorithm cycle times would allow hosting perception, co-pilot and control algorithms on a single ECU.

Figure 2 shows the functional architecture of the co-system. As most ADAS, the proposed system imitates the human driving functions with a perception, a decision and an action component. The perception component, which combines data from camera, laser and radar sensors integrates the function of human vision. The co-pilot component is the decisional part of the system and calculates a trajectory that is optimal to the situation detected by the perception. The optimality will be expressed in the different aspects of legal and safe driving, such as keeping distance to objects, respecting priority rules, limiting speed in curves and respecting speed limitations. The automation part of the system is completed with the control component that keeps the vehicle on this trajectory, through the vehicle actuators. The dashed arrows indicate the connection of these automation components with a MSU and HMI that manage the cooperation with the human driver.

III. PROTOTYPING METHODOLOGY

A. V-cycle development with SiVIC

The classical V-development cycle is shown Figure 3. The application development starts top-down with an analysis of its general function and requirements, which is then translated into specifications. The limits and validation scenarios of the application are defined on this level. On a lower level the system architecture is defined and its components designed. At the bottom level the programming of the system and component specifications is done. In this work, we have used the simulation tool SiVIC [9] as an environment for a fast bottom-up test and validation of the application. SiVIC simulates the road environment, the embedded vehicle sensors (e.g. odometers, cameras, laser scanners) and actuators and the vehicle dynamics.

This opens up to an unlimited choice of scenarios, complex environments with numerous (sensor-actuator equipped) vehicles and different weather conditions from the beginning of the development process on, for testing the co-system to its application limits, without the need for restrictive safety measurements. After a software-in-the-loop (SIL) bottom-up test and validation, a new V-cycle is performed with hardware-in-the-loop (HIL) bottom-up tests and validation on test vehicle and test track, as indicated in Figure 3.

B. Modular architecture with RTMaps and AUTOSAR

On a PC environment, the C-coded the MSU and HMI components of the co-system in Figure 2 are encapsulated on the RTMaps platform [10]. This platform manages the internal interactions of the co-system and its connection with external components such as simulator or test vehicle.

The AUTomotive Open System ARchitecture (AUTOSAR) standard provides an equivalent functionality for the integration of algorithms on ECUs. On AUTOSAR-based ECUs the input and output content is abstracted from its low-level CAN or FLEXRAY implementation and available in meaningful physical values.

Figure 4 shows the system integration concept. The co-pilot and controller are implemented on ECU and are AUTOSAR-interfaced to the vehicle CAN. In future work, this will be done for the perception component. The less safety-critical HMI and MSU are integrated on PC with RTMaps interface. In the proposed V-cycle development, the system is connected to simulator or test vehicle.

Next sections shortly describe each of the co-system components.
IV. SENSORS AND PERCEPTION

This section presents the sensors and perception component of the system. As a human-like vision of the environment with cameras is still beyond reach of today’s technology, the perception component uses additional sensors, such as laser scanners, radars and infrastructure-to-vehicle (I2V) communication.

ADAS sensors can be divided in two groups. A first group provides information in a subject vehicle fixed coordinate axis $UV$, the second group gives information in a ground fixed coordinate axis $ST$ shown in Figure 5, with 0 indicating the subject vehicle. In this work the term local refers to the first group of sensors and the relative axis $UV$, the term global points to the second group of sensors and to the absolute axis $ST$.

A possible limitation on the use of global perception techniques (e.g. global vehicle-to-vehicle (V2V) or global infrastructure-to-vehicle (I2V) communication) is that they require an accurate and reliable subject-vehicle position measurement in a common ground-fixed coordinate axis. This can be done with an (expensive) differential GPS or with a commercial GPS if the information provided is not safety critical. In this paper a local variant of I2V communication will be used.

Figure 5: Perception of subject vehicle state, in a relative axis (UV) or absolute axis (ST)

A. Perception of subject vehicle

Information on the state of the subject vehicle is crucial for both the co-pilot and control algorithms. It also forms the backbone for other the environment perception algorithms described in Sections B and C.

From proprioceptive local sensors, (e.g. odometer, accelerometer), the subject vehicle state is obtained in the subject vehicle relative axis $UV$ shown in Figure 5.

B. Perception of lanes and objects

A method for multi-lane perception is described in [11] and a method for object detection and tracking in [12]; this gives a local description of objects in the environment of the subject vehicle in $UV$, as in Figure 6 and 7 respectively.

Figure 6: Perception of the lanes, in a relative axis (UV) or absolute axis (ST)

Figure 7: Perception of the objects, in a relative axis (UV) or absolute axis (ST)

Information on the lanes typically contains a geometrical description of each lane. Also the type of its right and left road marks (continuous or not) is important information for the co-pilot.

The dynamics of the objects are described by their position, orientation, speed and acceleration. Other relevant data are the type and the size of the object, its right and left indicator status.

C. Perception of traffic signs

This section describes how the environment description with lanes and objects can be enriched with information on the traffic signs, through I2V communication.

A short range transmitter is an example of a local I2V sensor. It is embedded in the road and only detected during the time that the vehicle passes over it. It emits the distance to the road sign in the relative axis UV shown in Figure 8. When the vehicle has passed the transmitter, the signal disappears and basic odometry is used to estimate the remaining distance to the traffic sign.

Figure 8: Perception of a traffic sign, in a relative axis (UV) or absolute axis (ST)

D. Complete perception of environment

A total environment perception that results from combining the information of the different sensors presented
in Sections A, B and C is presented in Figure 9. All data is outputted in the subject vehicle fixed $UV$ axis, which is a convenient common frame for the co-pilot and control component.

![Figure 9: Combined perception of the subject vehicle state, lanes, objects and traffic signs, in a relative axis (UV) or absolute axis (ST)](image)

V. CO-PILOT

The co-pilot generates an trajectory for the subject vehicle, which is optimal in relation to the environment described by the perception component. It is designed according to the legal safety concept, with bases system design on traffic rules [13]. This ensures safety when traffic rules are respected by all road users. In the opposite case, when traffic rules are offended by a road user, the system prevents from an accident if it can and does an emergency brake if not. The algorithm can be described in two steps, which will be shortly presented here.

A. Prediction of the trajectories of objects

In a first step the co-pilot enhances the environment map, with a prediction of the trajectory of every object in the neighbourhood of the subject vehicle, Figure 10. The calculation of trajectories is done over a period of 10 seconds; enough for the subject vehicle to come from highway speed to standstill, if needed. Legal safety supposes that an object stays on its lane and holds his speed unless the information of its brake status (for the longitudinal direction) or indicator status (for the lateral direction) point to a different behaviour. Also, objects behind the subject vehicle are believed to keep an appropriate distance from the subject vehicle, and objects in the lanes left and right of the subject vehicle are assumed not to hinder the subject vehicle by performing sudden lanes towards the lane of the subject vehicle, as indicated by traffic rules. However, in the case of information conflicting with traffic rules (e.g. the object crosses the lane mark towards the subject lane without the activation of indicators) the worst case scenario is chosen, to assure a defensive driving. In Figure 10, vehicle 3 is believed to hold its lane and vehicle 7, with indicators activated, is believed to expand between a trajectory holding lanes and changing lanes to the right.

![Figure 10: Legally safe trajectories of objects and subject vehicle](image)

B. Calculation of subject vehicle trajectories

In a second step, the co-pilot computes a legally safe subject trajectory for each of the three considered lanes (subject, right and left) based on the description of lanes and traffic signs and on the prediction of object trajectories. Each aspect of legal safety sets an additional upper limit on the speed profiles in each of the three target lanes; i.e. the adaptation of distance to objects with the same target lane, the adaptation of speed to lane curvature, speed limitations and visibility conditions. The resulting speed profile, shown in Figure 11, is calculated as the minimum of the speed profiles for the individual aspects. Based on the speed profiles for each lane, a trajectory for each lane is calculated. Figure 10 shows the subject vehicle trajectory towards the left lane, for a legal left overtake of object vehicle 7. While a legally safe trajectory in the subject lane always exists (keeping distance from the vehicle in front), trajectories towards left or right lanes can be excluded by a collision analysis with the trajectories of object coming from behind the subject vehicle. The trajectory to the left lane is proposed as optimal, when safe and faster than the trajectory of the subject lane, the trajectory to the right lane, when safe and not slower than the trajectory of the subject lane. For a more detailed description of the co-pilot algorithm, reference is made to [13].

![Figure 11: Speed profile of subject vehicle](image)

The co-pilot outputs the best trajectory in the subject vehicle referenced axis $UV$, for information for the human driver or to be executed by the controller on the vehicle. An intuitive representation of the performance indicators can also be useful to the driver.

VI. CONTROL AND ACTUATORS

SiVIC models actuators on the steering wheel and pedals for an indirect control of the vehicle and also it provides a
direct torque access to the vehicles wheels for the longitudinal and lateral direction.

In this section we make reference to the works [14] and [15] which are used for a combined direct and indirect longitudinal and lateral control of the subject vehicle on the trajectory in the axis $UV$ proposed by the co-pilot.

VII. MSU AND HMI

A. Driving mode selection

Recent driving assistance systems simply allow the human driver to change the cooperation mode at each moment. This approach is also used for the designed system. Research is now on deactivating certain cooperation modes and automatically changing the cooperation mode, depending on the state of human driver and automation, through a Mode Selection and arbitration Unit (MSU). For a complete study, we refer to the works done in the project HAVEit [5][6][7].

B. Haptic interface

The HMI is crucial for a precise and intuitive cooperation between the human driver and the driving assistance systems. An indirect, haptic control is used as powerful way for bi-directionally communicating with the driver. The actions of the automation are felt in a natural way on the pedals and steering wheel, while the human driver keeps the control over the vehicle and can still have his attention on the road. In the opposite direction, haptic control provides the co-pilot with useful information on the driver.

C. Visual interface

The visual communication interface needs to be limited to the very key messages in order not to overload the human driver with information.

Figure 12 shows the visual part of the HMI. On a physical vehicle a head-up display could be used for the projection of information, so that the driver can always keep his attention on the road. A classical speed panel with a speed needle indicating a speed of 51 km/h can be recognised. The optimal speed as proposed by the co-pilot is indicated as 30 km/h with a blue bar on the speed panel, with a message indicating that this is due to a speed limitation. The optimal lane (here staying in the subject lane) is indicated with a blue arrow. The current speed limit is indicated by the maximum value on the speed panel, in this figure at 90 km/h. A message in the middle of the speed panel indicates the driver mode; in cruise mode the vehicle takes over speed control and lane keeping control, and, if acknowledged by the driver, lane changes.

VIII. RESULTS

The current results, with the co-pilot and control components on ECU and other components on PC are presented here. Both algorithms run with a cycle time below 25 ms including reading and writing information on CAN.

Figure 12, already described in Section VII-C, shows a snapshot of the HMI during the scenario “approaching a speed limit”, with the system implemented on test vehicle.

Figure 13 shows the evolution of the vehicle speed (circle label) in function of the actual speed limit (square label). The vehicle accelerates till the human set speed of 50 km/h, with an error of 3 km/h, at time $t = 19$ s. Shortly after this, at $t = 20$ s, a speed limit of 30 km/h at 60 m is detected and the target speed (triangle label) adapted. The speed profile is such that system reaches the limit with minimal braking, just in time, at $t = 25$ s. A speed control error of 1.5 km/h can be seen.

Figure 14 shows the scenario “object overtaking”. The combination of multi-lane perception and lane change control on test vehicle is still under development; results are presented in the simulation environment. Fig. 15 shows the lateral behavior of both vehicles, the position with respect to the right-most lane mark. Till $t = 80$ s, the object has its left indicators activated, without changing lanes. As described in Sections V, the object has lane change priority over the subject; its predicted trajectories expand between a minimum target position (square label) in the subject lane and...
maximum target position (triangle label) in the left lane. For the subject vehicle, the trajectory to the right goes off the road, while the trajectory to the left has the same speed profile as the trajectory in the own lane, corresponding to distance keeping to the object that has changed lanes to the left. This is why the trajectory in the own lane is proposed as optimal to the driver. When object indicators are deactivated at $t = 80$ s, the object is no longer believed to change lanes, the system proposes a lane change to the left for accelerating and overtaking the object. This is acknowledged by the driver shortly after, at $t = 82$ s, corresponding to Figure 14. After having passed the object, at $t = 87$ s, the system proposes a lane change to the right, in correspondence with traffic rules; it is acknowledged by the driver at $t = 89$ s.

Figure 14: HMI on scenario "overtaking an object": at $t = 82$ s: subject speed is 52 km/h, a lane change has been proposed and acknowledged, object speed is 50 km/h, target speed human driver 80 km/h, speed limit 90 km/h

Figure 15: Results on scenario "overtaking an object"

IX. CONCLUSION AND PERSPECTIVES
This paper presents the integration of a highly automated driving system on automotive ECUs and PC. Its perception component based on local sensors, on a co-pilot based on the legal safety concept and control component for guiding the vehicle on this trajectory were described, and the integration of the latter two on ECU presented. The system is completed with a basic MSU and HMI that manage the human automation cooperation.

In future work, development of the system on test vehicle will continue, towards higher speeds and dynamic lane changes. Also an acceptance study will be conducted to adapt HMI and system parameters to user feedback.

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