PRORETA 3: An Integrated Approach to Collision Avoidance and Vehicle Automation

System Description, Requirements and Preliminary Results

PRORETA 3: Ein integrierter Ansatz zur Kollisionsvermeidung und Fahrzeugautomatisierung

Systembeschreibung, Anforderungen und erste Ergebnisse

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Summary The article describes first results of the research project PRORETA 3 that aims at the development of an integral driver assistance system for collision avoidance and automated vehicle guidance based on a modular system architecture. For this purpose, relevant information is extracted from a dense environment model and fed into a potential field-based trajectory planner that calculates reference signals for underlying vehicle controllers. In addition, the driver is supported by a human-machine interface. ▸▸▸ **Zusammenfassung** Der Beitrag beschreibt erste Ergebnisse des Forschungsprojektes PRORETA 3, das die Entwicklung eines integralen Fahrerassistenzsystems zur Kollisionsvermeidung und automatisierten Fahrzeugführung auf Basis einer modularen Systemarchitektur anstrebt. Hierzu werden relevante Informationen aus einem dichten Umfeldmodell extrahiert und in einem potentialfeldbasierten Trajektorienplaner verarbeitet, der Führungsgrößen für unterlagerte Fahrzeugregler generiert. Zusätzlich unterstützt eine Mensch-Maschine-Schnittstelle den Fahrer zielgerichtet bei der Fahrzeugführung.

Keywords Driver assistance, free space representation, potential field-based collision avoidance, system architecture, human-machine interface ▸▸▸ **Schlagwörter** Fahrerassistenz, Freiraumbeschreibung, Potentialfeldbasierte Kollisionsvermeidung, Systemarchitektur, Mensch-Maschine-Schnittstelle

1 Introduction and Motivation

State-of-the-art driver assistance systems relieve the driver and hence significantly contribute to traffic safety. Nowadays, however, systems are usually limited to specific use cases and have been designed separately, not given the opportunity to cooperate in order to facilitate synergy effects between them. Advanced Driver Assistance Systems (ADAS) roadmaps indicate that the number of assistance functionalities will increase steadily [1]. Additionally, there is a strong trend towards a greater variety of the manufacturer's vehicle models and platforms. This situation is assumed not only to strain ADAS development due to the increasing overall system complexity, but also to cause the driver to have to manage the many individual functionalities and Human-Machine Interfaces (HMI), which may lead to a visual and mental overload [2]. In order to overcome these problems, PRORETA 3 aims to integrate and expand different coexistent assistance functionalities into a combined system for intervening and preventive active safety approaches.

The article at hand describes the state of development of the interdisciplinary research project PRORETA 3, in which Continental AG works together with the Institutes of Automatic Control and Mechatronics, Ergonomics as well as Automotive Engineering of the TU Darmstadt in order to develop new ADAS solutions. Thus, the results of the previous two projects of the long-term research cooperation PRORETA are taken into account, which can be found in [3] and [4]. The first project considered two vehicles moving in the same direction. If the driver of the rear vehicle does not react to the obstacle in the same lane, the system triggers an emergency braking and/or automatic steering in order to avoid the collision [5]. The second project was devoted to the prevention of overtaking accidents on rural roads. By predicting the trajectories of the three involved vehicles, a dangerous overtaking maneuver is recognized and adequate warnings and full braking interventions are activated [6]. The third project aims at the extension of the realized functionalities by trying to protect the driver in more complex traffic situations, in which dynamic and static obstacles are not restricted to any specific configuration.

Therefore, the functional requirements of PRORETA 3 are twofold. In order to protect vehicle passengers in critical traffic situations, an integrated *safety corridor* mode as a paradigm for a safe and collision-free driving area for the own vehicle is being developed. The corridor's boundary is reached in case an automated emergency maneuver is determined to be necessary in order to avoid an upcoming accident with regard to the arbitrarily structured static environment, dynamic objects as well as to situationally-specific information like road lanes. In case of such an event, the system takes control in order to follow a safe, accident-avoiding trajectory if the driver did not react to a target-oriented driver support strategy in advance.

To make it more effective, the *safety corridor* mode is extended by the mode *cooperative automation*, a semi-automated, maneuver-based vehicle guidance concept that relieves the driver of the vehicle stabilization task in order to decrease the latent risk of the overall situation and to prevent a critical traffic configuration in its beginnings. In this mode, the driver can assign desired vehicle maneuvers, like a lane change or turning in an intersection, and the automated system executes them, taking the actual traffic rules into account. Within this approach and in constrast to highly-automated or fully automated vehicles, the driver is obligated to show constant vigilance in road traffic in order to comply with German traffic law [7].

In opposition to other research projects concerning semi- and highly-automated driving using a cooperative approach [8; 9], PRORETA 3 focuses on the integration of the collision avoidance function *safety corridor* as a tie between solely intervening and automated vehicle guidance concepts by also using the accident-avoiding trajectory as a permanent control variable for the *cooperative automation* mode. Furthermore, a fixed level of vehicle automation and standard HMI input components aim to create a legal and near-series automation concept as an intermediate step between state-of-the-art assistance systems and fully automated driving.

The intent of this article is to describe first results of the assistance concept, starting with an overview of the required functional modules of the system architecture in Sect. 2. In the following, the state of development of the respective module algorithms are presented. Section 3 is devoted to the environment representation with focus set on a grid-based free space detection and its compact representation whereas the requirements and strategy of the trajectory planning module based on a potential field approach are described in Sect. 4. Last but not least, the HMI is presented in Sect. 5.

2 System Architecture

2.1 Motivation and Requirements

The term "system architecture" is defined as a description of the system's structure in terms of its components, their externally visible properties and the relationships among them [10]. Therefore, the architecture design is a key tool for reducing the overall system complexity and accounts for an efficient development process. The role of the architecture design within the overall system development process is to bridge the gap between requirement analysis and implementation. Hence, it is embedded within the left-hand specification branch of the well-known V-Model, which has proven itself as a development paradigm for complex technical systems [11]. Within these process steps, the top-down development of the logical-, hardware- and software-architecture is derived.

Within the present section, focus is set on the design of the logical architecture for vehicle automation in the context of PRORETA 3. As an important precondition, it is necessary to clearly identify the functional and non-functional requirements of the overall system. A scenario-based, use-case-driven approach has proven to be beneficial in order to assemble the functional requirements based on the main assistance goals as described in Sect. 1. Therefore, the desired system behavior is put into the context of relevant accident scenarios based on an

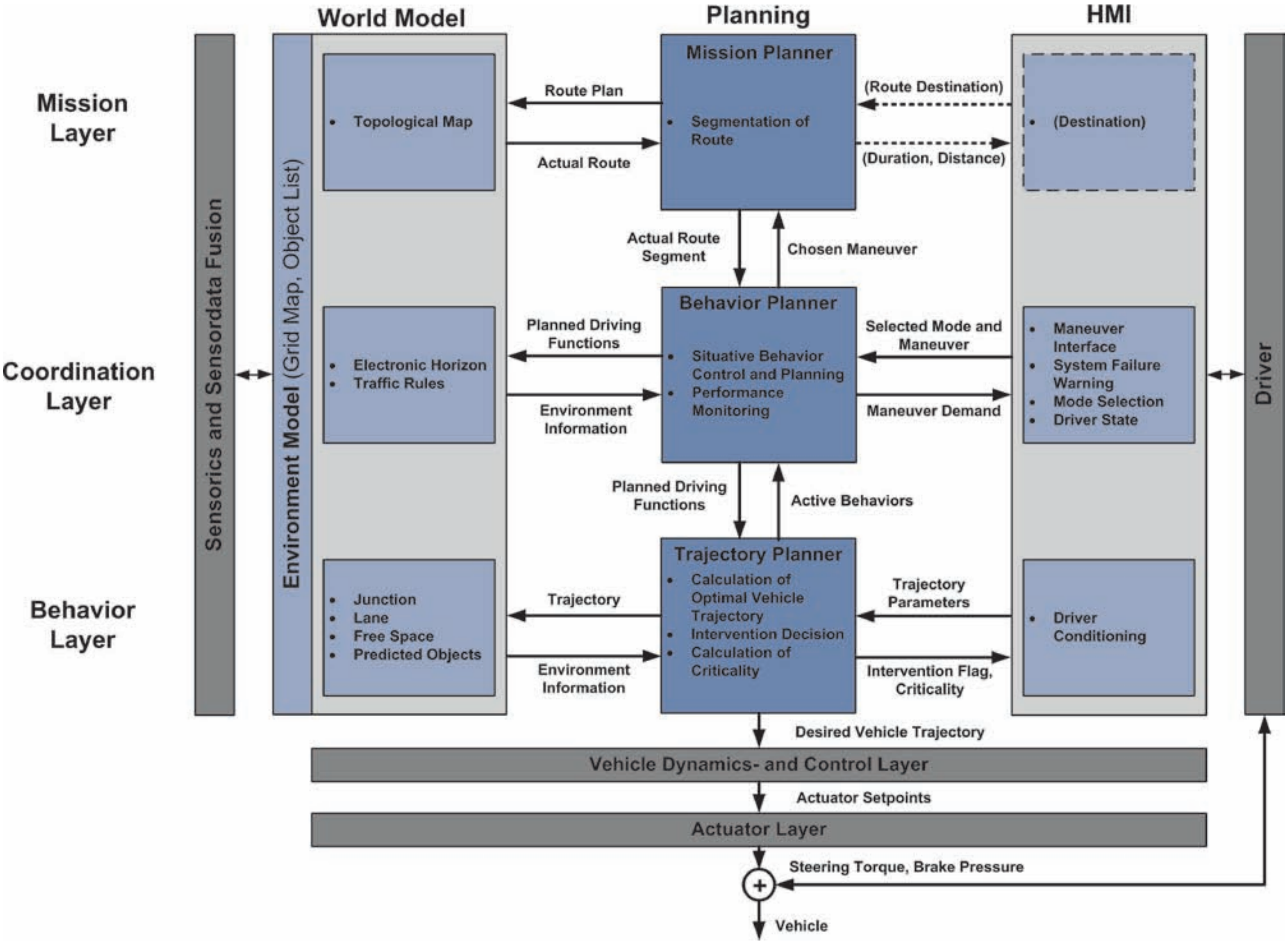

Figure 1 Top-level module view of the PRORETA 3 archictecture.

in-depth analysis [12], e. g. accidents in longitudinal and lateral traffic, as well as basic driving maneuvers for vehicle automation [13], such as automated and on-demand lane change or turning maneuvers. Non-functional requirements like the reusability or testability of single software modules to allow component validation also must be taken into account. An important architectural heuristic that promotes these requirements is modularity, which suggests an encapsulation of related functions into one logical software module [14].

The logical architecture is derived based on these requirements. Most state-of-the-art automated vehicles are designed using hierarchically layered architectures in which high-level planning modules decompose a given driving task into a sequence of low-level vehicle motion behaviors [15]. This design approach allows both reactivity as well as long-term, deliberate planning, which are the key requirements for time-critical accident prevention measures on the one hand and semi-automated maneuvering in complex environments like road traffic on the other hand. Exemplary implementations of multi-layered architectures for automated vehicles are described in [16; 17].

However, in the field of robotic architectures, only basic approaches like [18] of driver-vehicle interaction concepts have been described so far. In the field of ADAS, state-of-the-art *cooperative automation* concepts like [8; 9] present a specific interaction concept but either do not adress its correlation with the logical architecture in detail or do not describe a solution how to integrate a collision avoidance functionality. Therefore, Fig. 1 shows the proposed top-level module view, which, as a novelty, incorporates the HMI as an integrated element of the architecture itself and enables collision avoidance as well as a high degree of vehicle automation at the same time.

2.2 PRORETA 3 Architecture

The architecture's logical structure in Fig. 1 is based on three hierarchically arranged horizontal layers, whereas each layer itself again consists of three main modules – a world model, a planning module and an HMI module.

The **world model** provides the planning modules with information in order to make situationally-appropriate decisions. In it and for each layer, specialist submodules interpret environment-specific information to create an understanding of the current traffic situation, whereas the grade of this information is shifting from abstract to detailed for lower levels of hierarchy. Part of the world model is the environment model, which consists of a grid map-based representation of the static and an object list for the dynamic environment. A possible solution for the underlying sensor data fusion module is described in [19] as a result of the PRORETA 1 project. The **planning modules** receive high-order tasks and split them up into lower-order tasks. Finally, the **HMI** column is needed for the driver interaction, e. g. to warn the driver in case of a critical traffic situation or as an interface for the driver to communicate desired vehicle maneuvers.

In the following, the tasks of the layers are explained shortly. Within the **mission layer**, the mission planning module splits the actual vehicle route into route segments and delegates a matching task to the underlying behavior planning module, e. g. in order to handle the system behavior at an intersection. Its input comes from a graph-based topological map to identify intersections and connecting road segments. The main module within the **coordination layer** is the behavior planner which requests appropriate vehicle behaviors in a situationally-dependent manner coming from the maneuver input of the HMI module. To this end, it gathers necessary information from the world model, e. g. the current phase of the traffic light or intersection characterisitcs such as the number of lanes for each direction. The third layer is called the **behavior layer**. The corresponding trajectory planner calculates a safe vehicle trajectory that can be used for both PRORETA 3 modes as described in Sect. 1 and passes the resulting desired trajectory to the control layer, which itself provides the actuator setpoints for the underlying actuator layer. For the *cooperative automation* mode, specific vehicle behaviors need to be implemented that modify the calculation of the safe trajectory in order to achieve maneuvers like lane changes or turning. In order to achieve this task, the world model's environment interpretation must provide more specific information in a spatial and timely range (cf. Sect. 3) compared to higher layers.

In contrast to other concepts of *cooperative automation* [8; 9], a significant difference prevails in the fact that the driver has permanent, direct mechanical access to the actuator output values, i. e. the steering torque and brake pressure, since there are no energetic insulating by-wire interfaces, which must be taken into account in terms of the driver input arbitration strategy in future work. Further details on the hardware architecture regarding the sensor infrastructure as well as the HMI- and actuator devices are described in Sects. 3.1 and 5.1 respectively.

In the following, a selection of important modules and their interactions are presented, beginning with the environment model of the world model and its specialist submodule of free space detection.

3 Environment Representation and Interpretation

3.1 Motivation and Requirements

A solely object-based environment model as, for example, used in today's emergency braking systems [20; 21], is insufficient for the proposed approach since it cannot represent unstructured or only slightly-structured urban and rural environments. These include, amongst others, parked cars, trees or traffic islands as obstacles that the *safety corridor* must take into account as well as the structure of traffic junctions, which is required for the mode *cooperative automation*. Therefore, the requirement of a dense representation becomes obvious that serves as a basis for arbitrarily shaped free driving space detection as well as for subsequent situation analysis and interpretation algorithms. For this purpose, a Dempster-Shafer-based online grid mapping algorithm generates a local map of the static driving environment by fusing the sensor information of an off-the-shelf automotive long range radar and an automotive stereo camera. The grid map itself – originally introduced in [22] and in the meantime evolved to a standard representation in probabilistic robotics [23] – tesselates the environment into finitely many equally spaced grid cells each encoding the evidence of being occupied depending on the sensor readings. Figure 2 shows an exemplary grid map in which white corresponds to free and black to occupied and not yet mapped areas. Intermediate gray levels encode free and occupied evidences in between[1].

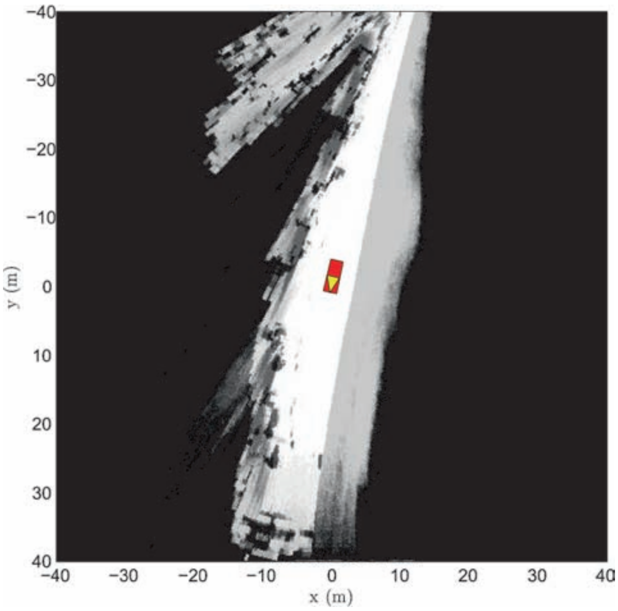

Figure 2 Exemplary grid map acquired from on-board environment sensors.

In contrast, dynamic objects are tracked in a standard object-based manner within a multi-sensor, multi-target tracking architecture in order to update an object list with their associated states[2]. The sensor configuration –

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[1] We treat unknown and occupied areas equally in order to get a conservative free space estimation that prevents the vehicle from planning evasive maneuvers in unknown regions. Further details concerning the mapping itself can be found in [24].

[2] Although there already exist approaches of using a dynamic grid map as an environment model (see for example [25]), we decided to apply the mentioned twofold representation because of lower computational costs.

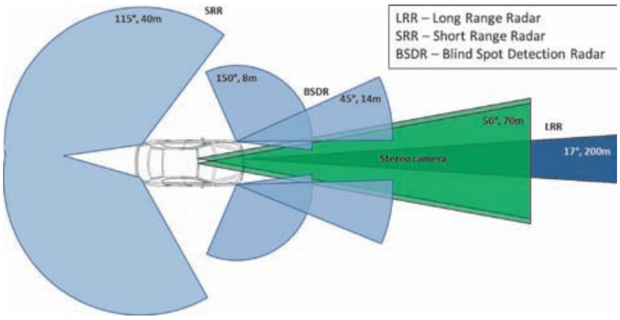

Figure 3 Fields of view of the on-board environment sensors.

consisting of a stereo camera, a Long Range Radar (LRR), two Short Range Radars (SRR) and two Blind Spot Detection Radars (BSDR) – is visualized in Fig. 3.

Consequently, an almost 360° view is achieved for the recognition of dynamic obstacles.

However, the pure environment model is just the first step towards an understanding of the situation and not directly applicable for subsequent algorithms such as evasive trajectory planners or functions of the mode *cooperative automation*. To that end, a robust and interpreted representation of relevant information must be extracted from the environment model and preferably described in a compact, suitable way. Considering the dynamics of the scene, this mainly consists of the prediction of the future motion of the tracked entities whereas the static situation interpretation primarily needs to contain a robust junction, lane and free space detection. The specialist submodule for the latter is presented in the following section, which robustly extracts free space information from the online-generated grid maps.

3.2 Grid-based Free Space Detection and Representation

The main aim of the PRORETA 3 free space algorithm – already described in more detail in [26] – is a generic and robust detection of arbitrarily shaped free space and its representation in a way directly suitable for the trajectory planner described in Sect. 4. The free space detection builds upon the grid map of the environment model and treats it as a grayscale image in order to perform a morphological grid map image analysis [27]. In order to separate areas the vehicle cannot reach or fit in due to its dimensions, a morphological opening is carried out first.This limits the free space to reasonable regions. Afterwards, the H-minima transformed gradient image of the opened set is used as a segmentation function for a subsequent watershed segmentation. In the following, the free space segment is selected as shown in green in Fig. 4 in an exemplary construction site scenario.

The boundary pixels of the free space segment are further traced in order to acquire a free space hypothesis.They are treated as virtual measurements for a time-variant Kalman filter that estimates and keeps track of the control points of a two-dimensional closed free space B-spline contour. This contour tracking introduces an easy to parameterize spatio-temporal filtering of the free space region. The results are shown in Fig. 5 in which the control points of the estimated B-spline are marked in red while the evaluated spline curve as a final free space delimiter is shown in green.

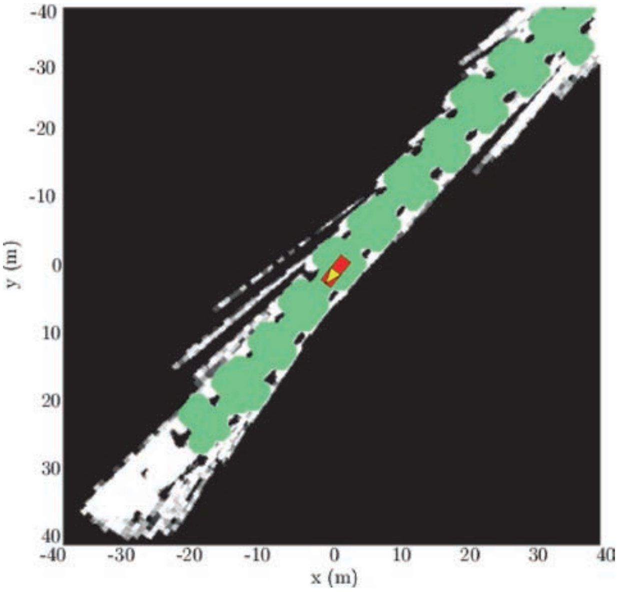

Figure 4 Free space segment overlaid in green over the original grid map.

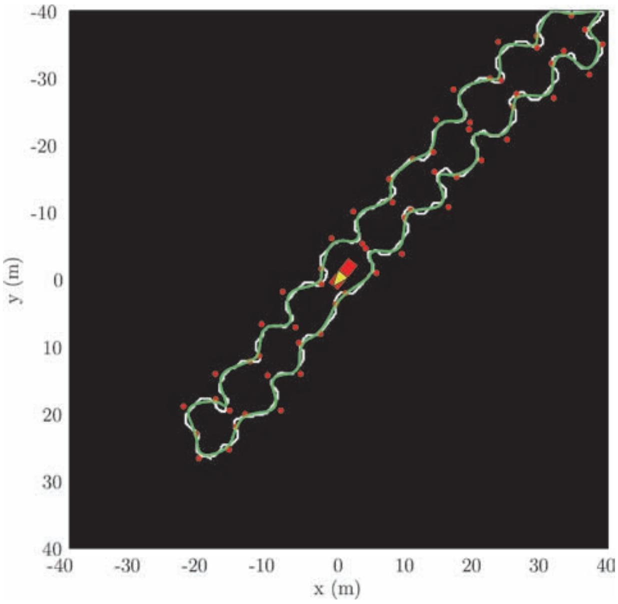

Figure 5 Free space filtering and description by B-spline contour estimation [26].

The contour smoothly follows the borders of the free space segment depicted in white. The final free space information is visualized in Fig. 6 via projection onto the image plane.

In contrast to existing free space detection methods, the applied algorithm incorporates the vehicle's dimensions, includes free space not located directly in the line of

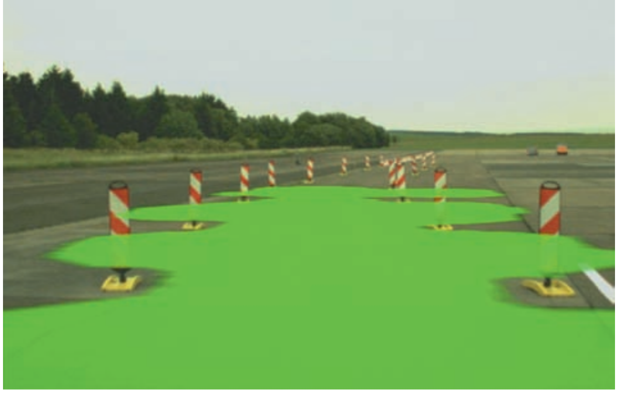

Figure 6 Free space visualization via projection onto the image plane.

sight and provides an additional robustness due to spatio-temporal filtering. The B-spline control points themselves serve as a compact, parametric representation and can be transferred even over low data rate busses to the trajectory planner, which is described in the following.

4 Trajectory Planning and Decision Making

4.1 Motivation and Requirements

As discussed in the introduction, the aim is to develop an integrated approach for trajectory planning regarding aspects of several desired assistance systems; in effect, the replacement of particular assistance functions by one planning algorithm for the specialist submodule "Trajectory Planner". Another challenge is that the trajectory planning must exploit the whole free space in critical situations.

To meet these requirements, the following approach consists of planning a future trajectory which is the safest by means of a cost functional. The resulting trajectory can be used for both the *cooperative automation* as well as for the *safety corridor* modes in a framework which contains trajectory planning and decision making.

4.2 Trajectory Planning

The task of finding a collision-free trajectory does not only exist in automotive problems, but also in nautics, aerospace and robotics. Robotic collision avoidance problems with non-holonomic robots and constrained workspace are very similar to collision avoidance for vehicles. Therefore, some robotic methods have already been applied to automotive collision avoidance. Geometric methods [28] have been found to be unfavorable for complex scenarios with more than one obstacle [29]. In comparison, rule-based methods require a huge set of rules to handle urban scenarios [30]. Potential field-based methods provide collision avoidance in complex scenarios with a theoretically unbounded number of obstacles [31]. Therefore, the suggested approach builds upon a potential field-based method that is further combined with optimal control theory in order to incorporate the dynamics of the ego vehicle. This has already proven to be beneficial in the field of ADAS [32], but is extended within PRORETA 3 to take dynamic obstacles into account. The scope of this section is focused on lateral planning because research for longitudinal planning is still in progress.

Combination of Potential Field Method and Optimal Control Theory

A potential field is a particular kind of hazard map. Obstacles are represented as potential hills. The potential field of the road rises on the road border and has its minimum along the middle of the right lane. For reasons of discussion and explanation, the road environment is modeled by a straight one-way road. We suggest a road-fixed coordinate system whose x-axis is aligned along the road. The potential fields of the static environment $P_{\text{stat}}(x, y)$, based on lane markings, free space border and static obstacles, and of the dynamic environment $P_{\text{dyn}}(x, y, t)$, are added to obtain the final potential field

$$P_{\text{total}}(x, y, t) = P_{\text{stat}}(x, y) + P_{\text{dyn}}(x, y, t)\,. \tag{1}$$

A respective example of a potential field with two obstacles is shown in Fig. 7.

According to this, the safest way to drive through the environment is to follow the bottom of the valley throughout the potential field. But not every resulting trajectory can be considered as possible because of the vehicle lateral dynamics and kinematics constraints, summarized by

$$\dot{\boldsymbol{x}}_{\text{v}} = \boldsymbol{f}(\boldsymbol{x}_{\text{v}}, u)\,, \tag{2}$$

with the vehicle state vector $\boldsymbol{x}_{\text{v}} = [x_{\text{ego}}\ \ y_{\text{ego}}\ \ \psi\ \ \beta\ \ \dot{\psi}]^T$ and the steering input $u = \delta_{\text{H}}$. The state vector consists of the vehicle position x_{ego} and y_{ego}, the yaw angle ψ, the side slip angle β and the yaw rate $\dot{\psi}$. Furthermore, restrictions such as the constrained steering wheel angle δ_{H} and Kamm's circle [33], which describes the limitation of the longitudinal and lateral forces between tires and road surface, are present.

Therefore, the similarity to an optimal control problem becomes obvious that is formulated as

$$u^*(t) = \min_u J \tag{3}$$

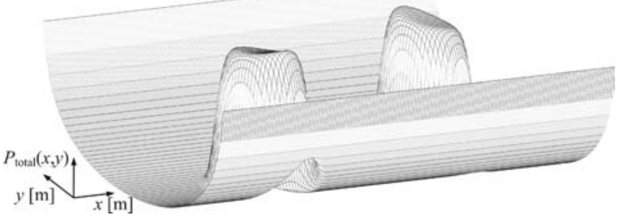

Figure 7 Example of a potential field $P_{\text{total}}(x, y)$ composed of the road potential and two obstacle potential hills.

with

$$J = \phi(\boldsymbol{x}_{\mathrm{v}}(t_{\mathrm{f}})) + \int_{0}^{t_{\mathrm{f}}} \left(P_{\mathrm{total}}(x, y, t) + \frac{1}{2} r u^2 \right) dt\,, \tag{4}$$

w. r. t.

$$\dot{\boldsymbol{x}}_{\mathrm{v}} = \boldsymbol{f}(\boldsymbol{x}_{\mathrm{v}}, u)\,, \tag{5}$$

$$\boldsymbol{g}(\boldsymbol{x}_{\mathrm{v}}, u) \leq \boldsymbol{0}\,, \tag{6}$$

according to [32]. An optimal input $u^*(t)$ from $t = 0$ to $t = t_{\mathrm{f}}$ is searched which minimizes the cost functional (4) with respect to the dynamic model (5) of the vehicle and the state and input constraints (6). The cost functional itself consists of a Mayer-Term $\phi(\boldsymbol{x}_{\mathrm{v}}(t_{\mathrm{f}}))$ which penalizes the final state, an integral term which contains the potential field $P_{\mathrm{total}}(x, y, t)$ and an actuator energy term $0.5ru^2$ with the weighting factor r. The optimal trajectory $\boldsymbol{x}_v^*(t)$ is obtained by substituting $u(t)$ by $u^*(t)$ in (5). This optimal control problem must be solved periodically to react to unforseen changes of the environment such as prediction errors of the dynamic obstacles. This receding horizon concept is used in model predictive control [34]. Because of the nonlinear dynamic model (5) and the nonlinear cost functional (4), the theory of nonlinear model predictive control (NMPC) must be applied. The real-time implementation is a very current subject of research, where promising-sounding approaches such as [35] already exist.

Simulation Results

An exemplary traffic scenario visualised in Fig. 8 is used to show first simulation results of the proposed trajectory planning approach. The ego vehicle drives along a straight one-way road at constant velocity ($v_{\mathrm{ego}} = 12\,\mathrm{m/s}$) while a dynamic obstacle ($v_{\mathrm{obs}} = 4\,\mathrm{m/s}$) approaches from the top with the objective of crossing the road. The view of the obstacle is obstructed by a wall. Figure 8 shows the evasion maneuver of the ego vehicle at four different points in time. Blue represents $T_1 = 3\,\mathrm{s}$, red $T_2 = 5\,\mathrm{s}$, green $T_3 = 7.75\,\mathrm{s}$ and yellow $T_4 = 8.25\,\mathrm{s}$. At T_1, the obstacle is not yet visible to the ego vehicle and therefore, the resulting trajectory is planned along the road. At T_2, the obstacle becomes visible to the system and an evasion maneuver is planned. The green and yellow trajectories show that the ego vehicle avoids the collision and moves back to the middle of the road after the evasion.

The lateral vehicle dynamics within (5) are modeled by the linear single-track model [33] and extended by the vehicle kinematics equations

$$\begin{bmatrix} \dot{x}_{\mathrm{ego}} \\ \dot{y}_{\mathrm{ego}} \\ \dot{\psi} \\ \dot{\beta} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} v \cdot \cos(\psi + \beta) \\ v \cdot \sin(\psi + \beta) \\ \dot{\psi} \\ a_1 \cdot \beta + a_2 \cdot \dot{\psi} \\ a_3 \cdot \beta + a_4 \cdot \dot{\psi} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ b_1 \\ b_2 \end{bmatrix} \delta_{\mathrm{H}}\,, \tag{7}$$

$$a_1 = -\frac{2\,c_{\mathrm{f}}}{m\,v} - \frac{2\,c_{\mathrm{r}}}{m\,v}\,, \quad a_2 = -1 + \frac{2\,c_{\mathrm{r}}\,l_{\mathrm{r}}}{m\,v^2} - \frac{2\,c_{\mathrm{f}}\,l_{\mathrm{f}}}{m\,v^2}\,,$$

$$a_3 = -\frac{2}{J_{\mathrm{z}}} l_{\mathrm{f}}\,c_{\mathrm{f}} + \frac{2}{J_{\mathrm{z}}} l_{\mathrm{r}}\,c_{\mathrm{r}}\,, \quad a_4 = -\frac{2}{J_{\mathrm{z}}\,v} l_{\mathrm{f}}^2\,c_{\mathrm{f}} - \frac{2}{J_{\mathrm{z}}\,v} l_{\mathrm{r}}^2\,c_{\mathrm{r}}\,,$$

$$b_1 = \frac{2\,c_{\mathrm{f}}\,i_{\mathrm{s}}^{-1}}{m\,v}\,, \quad b_2 = \frac{2\,l_{\mathrm{f}}\,c_{\mathrm{f}}}{J_{\mathrm{z}}}\,i_{\mathrm{s}}^{-1}\,,$$

with mass m, yaw inertia J_{z}, steering gear ratio i_{s}, velocity v, sideslip stiffness c_{f} and c_{r} of the front/rear tires and the distances between front/rear axle and center of gravity l_{f} and l_{r}. The static environment potential field $P_{\mathrm{stat}}(x, y)$ is derived only by the lane markings.

The simulation will be extended by using the free space description of Sect. 3. The road potential $P_{\mathrm{road}}(x, y)$, for example, can be designed in dependence of lane markings as well as the free space border which enables the full usage of available maneuvering space in emergency situations. Computing a potential field, based on the free space description, can be achieved by determining the shortest distance between the point (x, y) and the B-splines of the free space border. The smaller this distance, the higher the potential value is at the point. Further work will be the real-time implementation of the trajectory planning for lateral planning based on [35] as well as an examination of appropriate modifications of the cost functional.

4.3 Intervention Decision Making

To provide an outlook on the further progress of our research within this field, a concept for intervention decision making is presented. A decision making algorithm first analyzes the resulting trajectory with respect to validity and subsequently decides if an intervention is necessary. Figure 9 shows a block diagram of the planning and decision framework. Subsequently, the desired and

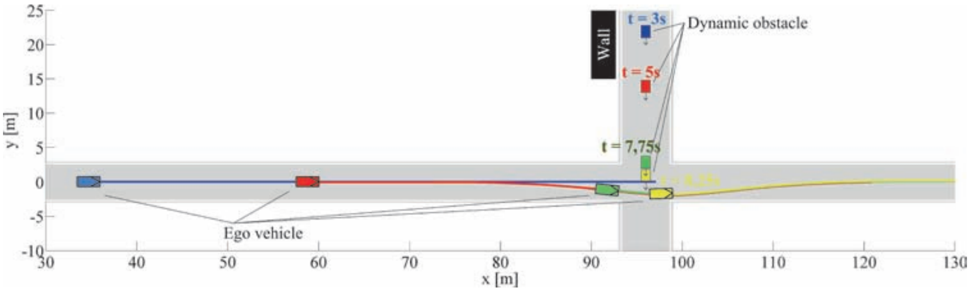

Figure 8 Trajectory planning results for an evasion with a crossing dynamic obstacle (blue: $T_1 = 3\,\mathrm{s}$, red: $T_2 = 5\,\mathrm{s}$, green: $T_3 = 7.75\,\mathrm{s}$, yellow: $T_4 = 8.25\,\mathrm{s}$).

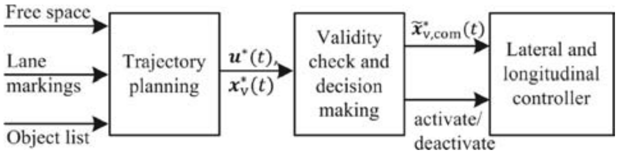

Figure 9 Block diagram of trajectory planning and decision making.

validated trajectory is given to a longitudinal and lateral controller (cf. Fig. 1), see for example [36], which are outside the scope of PRORETA 3.

The *safety corridor* mode will be executed by using the intervention decision making. The derived future trajectory will be observed by the decision maker that triggers an intervention if some thresholds are exceeded. Next steps are the identification of these boundaries as well as the definition of the required trigger signals. An intervention decision based on the friction demand between tires and road surface is under investigation.

On the contrary, the *cooperative automation* is a semi-automated system; hence, the intervention decision making is reduced to the validity check, because the desired trajectory $\tilde{x}_{v,com}^*(t)$ is continuously given to the controller.

The following section explains the HMI that represents the link between the driver and the vehicle.

5 Human-Machine Interface

As the driver is already highly engaged by the driving task, the interaction with the vehicle must be as efficient as possible [37]. As described in Sect. 2, the main task of the HMI is to provide the driver with specific assistance content in critical traffic situations within the "driver conditioning" module on the one hand as well as to enable maneuver-based driving in the mode *cooperative automation* on the other hand. The former is described in the following section.

5.1 Safety Corridor HMI

As PRORETA 3 aims to develop an integrated approach for driver assistance in terms of functional support of use cases, a central aspect is also to assist the driver in an integral way. This stands in contrast to state-of-the-art ADAS, which only focus on specific accident types as well as assistance strategies. As an example, a blind spot warning system alerts the driver if a car is in the blind spot during a lane change but is not able to intervene while current emergency braking systems intervene without providing well-directed information in advance to avoid an impending accident.

In order to mitigate driver errors, an effective ADAS must be able to assist the driver by a set of strategies: Providing relevant information, warnings, action recommendations and, finally, interventions. This comes from the fact that driver errors result from associated causes such as lack of perception or misinterpretation of essential information, wrong decisions made by the driver or faulty execution of driving tasks [12]. For each of the strategies, specific support content is defined as explained in the following.

The support content of the strategies classified as "information", which means that information is given to the driver that complements his perception, and as "warning", which means that the information provided has been interpreted by the assistance system, is derived from the user context defined by the user-centered design process [38].

The user context consists of three parts: The environment of use given by the traffic situation, the driver's tasks, described by maneuvers needed to pass the traffic situation [13] and the driver errors that can happen in this situation [12]. This context is derived from the overall system use cases, which describe possible accident scenarios for the mode *safety corridor*. The characteristics found for each of the three parts of the user context are permuted to be able to derive specific support content in any configuration of situation, maneuver and driver error. Subsequently, equal content is grouped so that the result is a manageable set of assistance content that works in all use cases. As an example, content on the level "information" contains the spatial position of a relevant traffic object.

The support content of the strategies "intervention" and "action recommendation" that aims at provoking particular steering or braking operations of the driver, is directly given by the planned safe vehicle trajectory, coming from the trajectory planning module.

In order to provide this content to the driver, physical HMI devices are needed. Optical devices are a reconfigurable cluster instrument and a novel HMI that consists of optical elements located below the windshield, on the door panels and above the rear window. The advantage of this user interface is that information and warnings can be submitted with spatial reference [39]. Haptic feedback is given to the driver by active steering wheel torque, accelerator pedal with active force feedback and seatbelt pretensioner while audio speakers are used to provide acoustic content.

5.2 Cooperative Automation HMI

As described in Sect. 2, important HMI functionalities need to be addressed to enable an implementation of the *cooperative automation* mode. Cooperative automation is thereby characterized by the intensive interaction between driver and automated system based on mutual information, recommendation and approval in order to encounter the driving task more effectively than without one another [9; 40]. Although this approach has been investigated before [9; 41], it has never been implemented in a testing vehicle. This, however, is one important objective of PRORETA 3. The challenge stems from the fact that the driver, although being relieved from lateral and longitudinal vehicle guidance, still must supervise the automation due to system limits – and be ready to regain control. Research has shown that regaining control can cause problems because of the driver's loss of situation awareness using automated systems [42]. The goal is to develop an interaction concept that relieves the driver but at the same time minimizes the risks of automated car guidance, i. e. maintains the driver's mode and situation awareness [42; 43].

According to [40], there are two different approaches for maneuver input by the driver: *Simultaneous* and *sequential* assistance. Simultaneous assistance means that driver and assistance system have an effect on the vehicle at the same time; sequential assistance means that driver and assistance system influence the vehicle in an alternating or discrete fashion such as activating a maneuver by pushing a button [44]. In PRORETA 3, the suitability for maneuver-based driving of both approaches is under investigation using common interfaces such as steering wheel, pedals, steering column lever and steering wheel buttons.

6 Summary and Outlook

Within this article, first results of a next-generation assistance concept have been presented, which allows system interventions in critical traffic situations. Additionally, a solution of how to embed this *safety corridor* into a concept of *cooperative automation* is proposed. Based on a hierarchically layered architecture, the functional modules required for this purpose have been highlighted. The environment representation is based on an object list and a dense grid map for the static world which are interpreted by appropriate subsequent specialist modules of the world model. As an example, an already implemented free space detection algorithm that represents the relevant free space information in a compact way has been described. Moreover, first results of the trajectory planning and decision making module algorithms have been presented. Finally, the associated HMI has been discussed by presenting a first assistance concept for *cooperative automation* and *safety corridor*.

Future work includes the improvement, extension and testing of the algorithms – including their interactions within a software simulation environment. In parallel, an experimental vehicle is set up in order to prove the suitability of the concept in real traffic scenarios.

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