ANALYSIS AND VALIDATION OF PERCEPTION SENSOR MODELS IN AN INTEGRATED VEHICLE AND ENVIRONMENT SIMULATION

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1 ABSTRACT

The number of Advanced Driver Assistance Systems (ADAS) in future vehicle generations will increase steadily in order to support drivers by means of comfort-, safety- and ecology-functions. Along with the ascent of ADAS functions, the challenge for developers to prove the safety and reliability of the overall system increases. The risk for people and test equipment involved in potentially dangerous real world test scenarios and the great efforts required to achieve reproducible results in real driving tests make an alternative test method necessary.

Therefore, Audi is working together with partners on the development of "Virtual Test Drive" (VTD) [VIR01], a modular, computer-based system for the integrated simulation of a virtual vehicle in a virtual environment. VTD supports engineers throughout the development, testing and validation process of ADAS. It contains reusable components, interfaces, models and tools which can be shared by different simulation variants (Software-, Hardware-, Model-, Driver- and Vehicle-in-the-loop) and applied at different stages of the development and testing process. The VTD simulation environment enables realistic closed-loop simulations to analyze the interaction between simulation components, such as sensor systems, actuators and a model of the vehicle environment as well as the assistance or safety functions under test.

This paper presents in particular a method for the analysis and validation of perceptive sensor models generating synthetic sensor data (e.g. Video Camera, RADAR, LIDAR, etc.) in VTD. The simulated perception sensor data is compared to real sensor data in a number of selected scenarios.

The process of generating synthetic sensor data with VTD using perception sensor models starts with the recording of a real vehicle test drive in a real world test scenario. GPS trajectory coordinates as well as vehicle state data and perception sensor data are recorded during defined approach and collision scenarios between the ego-vehicle and target objects. In a second step, these data is imported into VTD and synthetic sensor data is generated by feeding the recorded trajectory and vehicle state data through VTD sensor models. In a final step the synthetic sensor data is converted to the same format as the recorded real sensor data. The aim of this conversion step is to evaluate and validate the synthetic data by using the same toolchain as it is done for the real sensor data.

The novelty of the method presented in this paper is its reusability for different sensor models, functions and test scenarios and moreover the high level of automation reachable.

2 INTRODUCTION

New generations of ADAS systems are designed towards supporting vehicle drivers in a situation dependent manner by means of safety-, comfort and ecology functions, e.g. Emergency Braking, Left Turning or Traffic Jam Assistant, see Figure 1. The driving force behind the proliferation of such ADAS systems is on the one hand, the increasing performance and integration level of Electronic Control Units (ECUs) and related sensor equipment, and on the other hand, the desire for more safety and comfort in everyday traffic situations on customer side and a growing awareness of energy-efficient and environmentally friendly driving.

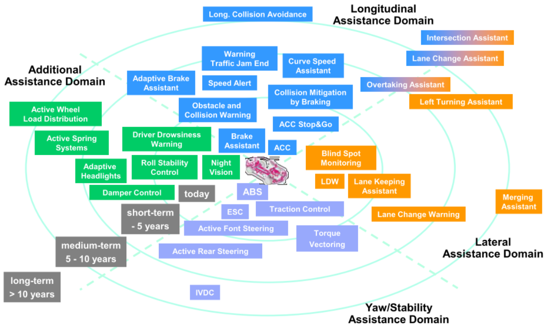

Figure 1. Roadmap for ADAS [EVA01].

The new generations of assistant systems are characterized by relying on the continuous perception of the vehicle environment through one or more ambient sensors (Video Camera, RADAR, LIDAR, etc.). These sensors acquire data about the vehicle's surrounding field, e.g. the position of other traffic participants, obstacles, traffic signs, etc.. Dependent on the specific assistance function, the evaluated sensor data is used for notification and warning purposes or also for actively influencing the vehicle's longitudinal and/or lateral driving dynamics, e.g. by executing an emergency braking, to mitigate or avoid a collision.

3 CHALLENGES

Closely connected to the increase of ADAS functions in vehicles is the growing challenge for developers to prove the reliability and safety of such advanced systems. The rising number of assistance functions integrated into a vehicle combined with the requirement of close function interconnection and the overall trend towards more vehicle variants per OEM results in significantly higher testing efforts for a vehicle's electronics in order to validate the correct functioning, safety and reliability of ADAS under the broad scope of everyday driving conditions.

Due to the great effort related to time, personnel and material resources, which is necessary to obtain reproducible test results from real world test drives and the potential risk for people and test equipment involved, especially in case hazardous traffic situations have to be simulated, an alternate, less dangerous and automatable test methodology is required for ADAS systems. This paper presents a computer-based simulation and validation methodology to address the outlined challenges in the process of developing and testing ADAS.

It is crucial for the applicability of such computer-based simulation environments as a partial substitute for real test drives to ensure that the generated simulation data can be validated against real measurements.
The validation shall ensure a high degree of correspondence between recorded sensor data of real world test drives and synthetically generated sensor data from the sensor models used in the vehicle and environment simulation system. This leads to the following requirements concerning the simulation environment:

1. The usage of virtual test scenarios which reproduce the essential aspects of the real test drive with respect to experimental setup, object trajectories and environment modeling of the test ground (see section 5.2.2)

2. The usage of validated models for the perception sensors, which show a similar measurement signal and timing behavior to the real sensor device (see section 5.2.3)

3. Automation of the comparison of real and synthetically generated sensor data (validation), due to anticipated frequent adjustments to the real sensor during the development and testing process

4. Non-proprietary specifications and interfaces for test scenarios and sensor models

Within the process of testing ADAS a particular challenge lies in the safeguarding of predictive assistance and safety functions, which actively affect the vehicle dynamics, e.g. an automatic emergency braking system. Such systems must meet very high requirements in terms of reliability and robustness. To ensure the fulfillment of those safeguarding requirements, high test space coverage needs to be achieved. As real test drives on test sites and public roads usually only permit very limited influence on test conditions such as traffic congestion, weather conditions, exact behaviour of other traffic participants, etc., the computer-based vehicle and environment simulation acts as an important additional tool for achieving high test space coverage. A vehicle and environment simulation software like "Virtual Test Drive" (VTD) therefore allows the simulation and reproduction of critical test scenarios under a wide range of parameter variations.

The simulation and testing of ADAS that actively affect the vehicle's driving dynamics, furthermore requires the usage of closed-loop simulations (see Figure 2). Only in this simulation mode the effect of the vehicle's lateral and longitudinal dynamics, e.g. a damped pitch angle pulse during braking, has direct influence on the synthetically generated sensor data.

A further reason for the application of software like VTD is the intention to accelerate the ADAS testing process. It allows for example the investigation of different sensor concepts and algorithm parameterizations in a safe und reproduceible manner even before the availability of actual hardware prototypes.

To address the challenges identified above, in the course of this paper we use VTD as an integrated vehicle and environment simulation system serving as a platform for perception sensor model validation tasks.

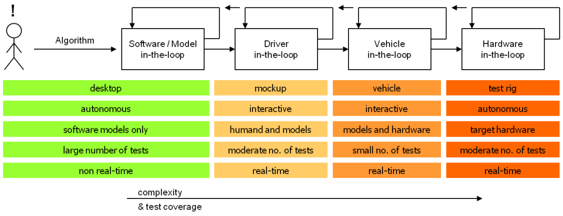

Figure 2. ADAS development process supported by VTD [VIR01].

4 OBJECTIVES

The work described in this paper pursues the following objectives based on the challenges outlined in section 3:

- Description and implementation of a methodology for the semi-automated generation of synthetic sensor data based on recorded vehicle and object reference trajectories of real world test drives
- Specification and implementation of a methodology for the semi-automated compareison of real and synthetically generated perception sensor data on object list level
- Execution of experiments for the analysis of a sensor model with respect to the correspond-dence of generated data in comparison with real sensor data
- Specification of a software interface to analyze both real and synthetically generated sensor data in a unified evaluation tool

5 METHODOLOGY

5.1 Overview

This section gives a short overview about the crucial steps to analyze and validate sensor models according to the methodology proposed (see Figure 3) in this paper:

1. Carrying out real test drives on the basis of a previously defined test maneuver catalog, see section 5.2.2. Logging experimental parameters and recording perception sensor and position reference sensor data during the test drive, see section 5.2.1
2. Automated generation of the virtual test scenario data for the simulation toolchain based on the recorded position reference sensor data, see section 5.2.2
3. Parameterization of the VTD sensor models according to the parameters of the real test drive setup and sensor equipment properties, see section 5.2.3
4. Execution of virtual test drives in VTD on the basis of the virtual test scenario data generated beforehand, see section 5.2.4
5. Recording synthetically generated predictive sensor data while running a virtual test scenario in VTD, see section 5.2.5
6. Comparison of real and synthetically generated sensor data by means of MATLAB-based analysis functions, see section 5.2.6

Steps 3 to 5 shall be repeatable in a short time frame with the aim to achieve a high degree of correspondence between the real and simulated test drive for different sensors and sensor configurations.

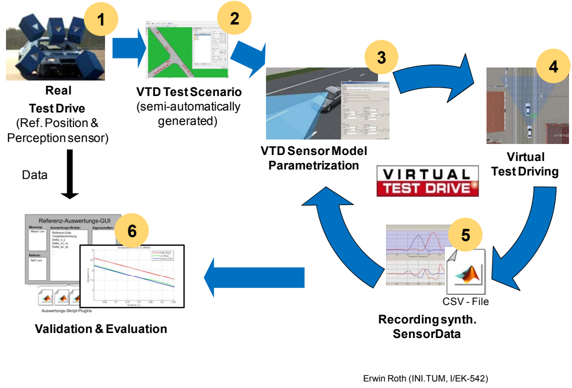

Figure 3. Methodology for sensor model validation.

The execution of the described steps requires several hardware and software tools, that were integrated into an overall process and data workflow as shown in Figure 4. The numbers within the figure reflect the corresponding process steps illustrated in Figure 3.

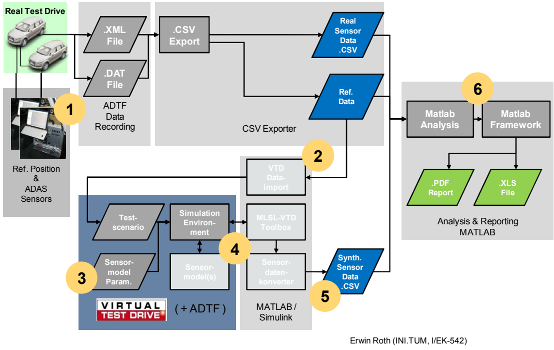

Figure 4. Toolchain integration for sensor model validation.

5.2 Procedure

5.2.1 Real Test Drive Data Recording

The recording of reference position and environmental sensor data during the actual test drive takes place by means of the so-called RefBox [TUM02]. The RefBox is installed in the ego-vehicle and if necessary also in other moving vehicles taking part in the test scenario. The RefBox system uses Differential GPS and acts as a reference for the ego-vehicle's or other moving objects' temporal change in position. Static reference objects, e.g. a pylon, which might also be involved in the test scenario are measured preliminary to the test drive by the ego-vehicle.

During the actual test drive the RefBox records reference position and perception sensor data (see Figure 5) at defined time intervals for the subsequent offline analysis. The time stamp of the RefBox is used as a global time base for the collected sensor data.

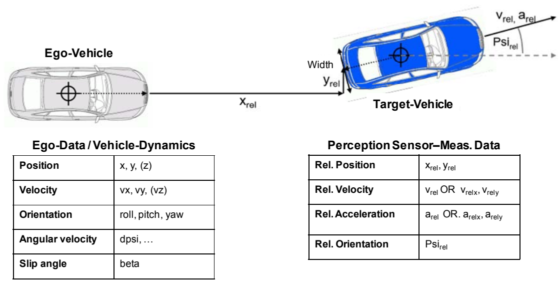

Figure 5. Parameters recorded by the RefBox-System [TUM01].

5.2.2 Automated Generation of virtual Test Scenario Data

In terms of a standardized approach for comparing synthetically generated VTD sensor data with real sensor data, an initial set of test scenarios for the import into VTD and the subsequent data comparison was defined.

A *test scenario* is described by the following characteristics in this context:

- Type of the test run

  The type of test run describes the overall category of variations in different parameters (e.g. velocity or distance variations) of the conducted real test drive. For the subsequent analysis, the test run types "straight frontal collision with a centered static object" and "curved frontal collision with a centered static object" were used.

- Discrete absolute coordinates and orientation data concerning the ego-vehicle and target objects

  The data recorded during the real test drive, as described in section 5.2.1, represents the temporal change in position of a defined vehicle body or a body-fixed reference coordinate system. It is unambiguously described by the absolute coordinates of the origin in the three spatial directions X, Y and Z of a global earth-fixed coordinate system and the three Euler angles (yaw, pitch and roll angle) of the local coordinate axes. All six variables are available for each object and each test run as discrete time series at a defined sampling rate.

- Dimensions of ego-vehicle and target objects

  The dimensions of the ego-vehicle and the target objects are known a priori and denote the dimensions of a rectangular bounding box around the vehicle or object.

- Sensor position, viewing direction and field of view

  In terms of the forward-looking sensors used, the individual test scenarios differ in the mounting location of the virtual sensor in relation to a vehicle-body-fixed reference coordinate system and its viewing direction relative to the coordinate system axes. Furthermore the sensor field of view is specified by the parameters minimum and maximum range as well as horizontal and vertical aperture angle.

Furthermore, the following supplementary Data is recorded with a *test scenario:*

- Type-specific data of the sensor

  The recorded real data is always associated with a defined sensor revision, which identifies the sensor for the respective test or reference scenario unambiguously.

- Specific information concerning the ego-vehicle

  Relevant parameters related to the real vehicle such as vehicle type, weight, used ECUs and the type of installed measuring equipment represent further information describing the test setup.

- Specific information concerning the target objects

  The target or collision objects are specified by geometry and material data.

- Specific information concerning the environment

  The boundary conditions of the real test run in terms of local time, temperature, weather and road conditions are additional parameters describing the test scenario.

The recorded trajectory and position data of the various test runs is converted in a subsequent offline process by a MATLAB framework into a data format readable by VTD. The framework provides a GUI to adapt the conversion process to some of the specific test run conditions outlined above.

During the import process the measured data is manipulated (coordinate transformations, sorting, resampling, ...) according to configurable parameter files and converted into a format readable by VTD. Based on this data format VTD is able to play back the test scenario within the measurement accuracy of the position reference sensors, exactly as it has been recorded on the real test ground (see section 5.2.1).

According to the current methodology the data import and playback take place waypoint-based using discrete position data which may be linearly interpolated. The data used for this study was measured on a flat test site, so that the subsequent analysis is limited to phenomena in the plane. The recorded reference data for the analyzed test scenarios only includes target objects, e.g. cuboids, which were positioned by test personnel. So far no natural obstacles, e.g. roadside vegetation or other interfering objects occurring in public road traffic are included. The subsequent testing and analysis steps are based on a single reference or collision object for the corresponding scenario. The automatic import of weather condition parameters is not yet possible and the parameters for the virtual sensors have to be set by hand.

5.2.3 Parameterization of perception Sensors

The parameters for the virtual perception sensors in VTD in accordance with the real sensors used in the test scenarios are configured by means of a XML configuration file or via a graphical user interface (GUI), as shown in Figure 6.

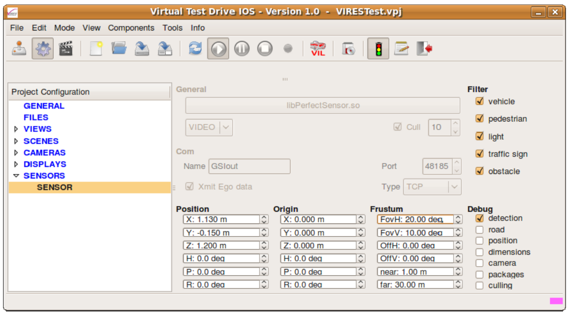

Figure 6. GUI for virtual sensor parameterization.

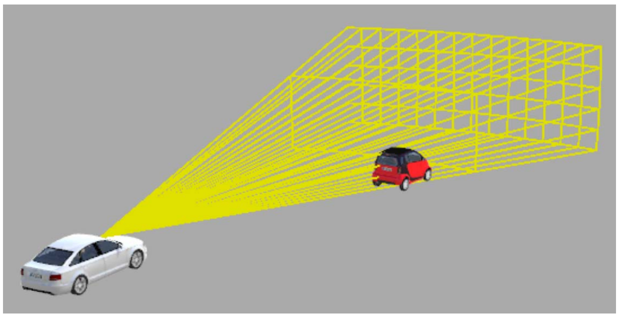

Figure 7. Target-Vehicle within sensor cone of Ego-Vehicle

The idealized sensor models included in the default distribution of VTD, which were used as a basis for the consequent analysis in this paper, use a frustum of pyramid as an approximation for the sensor field of view (see Figure 7) which is truncated on the basis of both minimum and maximum sensor range. Furthermore the aperture angle can be specified in horizontal and vertical direction. The sensor position and spatial orientation relative to the vehicle as well as the coordinate system in which the sensor indicates the measured position data can be parameterized according to the real conditions of the emulated sensors.

5.2.4 Execution of Virtual Test Drives

In order to replay the imported real test for the generation of synthetic sensor data the VTD software is used. VTD as an integrated vehicle and environment simulation tool chain provides a modular architecture (see Figure 8) for the simulation of vehicle dynamics, sensor systems, actuators and traffic scenarios with multiple vehicles and parameterizable environment conditions. The environment can be adjusted in terms of weather, light, road and traffic conditions and visualized accordingly.

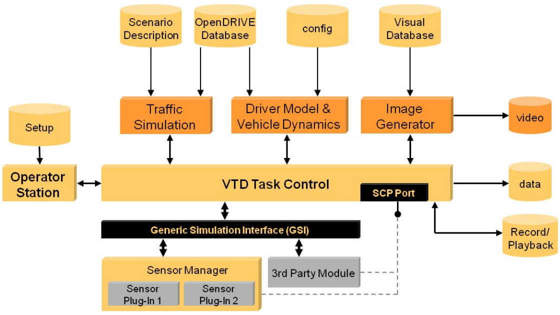

Figure 8. Modular "Virtual Test Drive" (VTD) architecture [VIR01].

With its reusable models, components, interfaces and tools VTD supports a number of open and closed simulation variants (Software/Model-in-the-loop, Driver-in-the-loop, Vehicle-in-the-loop and Hardware-in-the-loop) [TUM01] as shown in Figure 2.

For the task of analyzing synthetically generated sensor data VTD provides the Generic-Simulation-Interface (GSI), a software API that allows the reading and writing of a large number of simulation variables. In the described use case the writing of data to the GSI is used to do the positioning of the objects (ego and target vehicles) in the same way within the virtual test scenario (static or dynamic) as in the real test scenario. The necessary position reference data over time is acquired as described in section 5.2.1.

The execution of simulation scenarios within VTD can be controlled via the Simulation-Control-Protocol (SCP), which allows the querying and setting of model and simulation parameters in order to influence the global simulation behavior, e.g. simulation start/stop, setting of event triggers, etc..

5.2.5 Recording of synthetic Sensor Data

For the analysis of the synthetically generated sensor data simulating signal characteristics as they occur in real test drives, the virtual sensor data is recorded by means of the MATLAB/Simulation-VTD-Toolbox (MLSL-VTD-TB) (see Figure 9) on the same sample time basis, as the real sensor data [TUM03].

At each simulation time step the recorded data of the real test drive is imported into MATLAB and the measured values are analyzed in terms of object position and object dynamics. Subsequently the calculated data is sent via GSI using a TCP/IP based network connection to VTD.

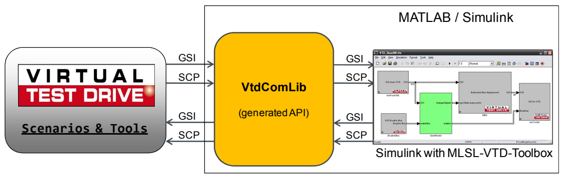

Figure 9. MLSL-VTD-Toolbox: bi-directional communication between MATLAB/Simulink and VTD.

The measured objects are simulated and visualized in VTD on the basis of the values given above. Furthermore they are used to generate synthetic sensor data for the current sample time by means of the parameterized sensor models. In a subsequent step, the synthetic sensor data is sent back to the Simulink simulation model via the GSI interface. In Simulink the received sensor data is recorded synchronously to the time basis of the real test drive. The usage of the same global time basis for real and virtual test scenarios allows the direct comparison of real and synthetic sensor data.

5.2.6 Analysis and Validation of virtual and real Sensor Data

The sensor data analysis is accomplished by the use of MATLAB scripts. For this purpose both individually created scripts as well as scripts of an organization wide sensor data analysis toolbox (called “RefReport GUI”) can be applied.

6 RESULTS

In the following the results of two exemplarily selected test scenarios imported in VTD are presented. The first scenario is a "straight frontal collision with a centered static object", the second is a "curved frontal collision with a centered static object" (see Figure 10. a, b).

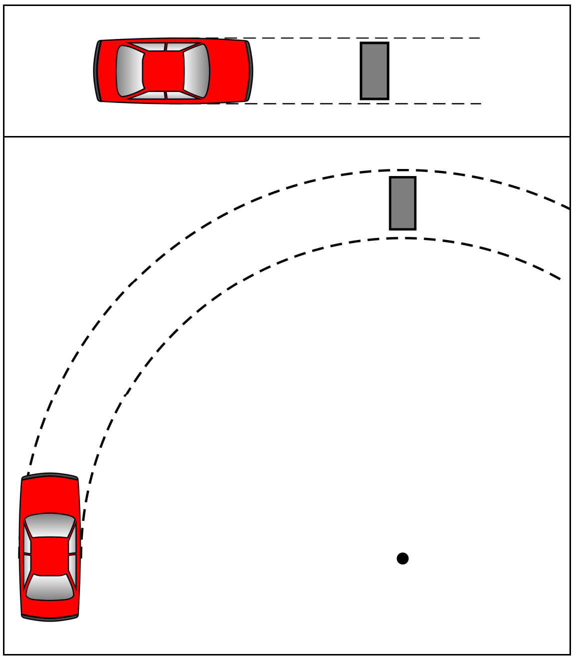

Figure 10. Test scenario type: a) Straight frontal collision with a centered static object (top); b) Curved frontal collision with a centered static object (bottom)

In the following plots the measured data for the relative position in x- and y-direction (x_{rel}, y_{rel}), as well as the relative velocities in x- and y-direction (v_{relx}, v_{rely}) are shown. The dashed blue line represents the synthetic sensor data generated with VTD. The perpendicular dashed black line at 28.9 sec. in Figures 12 and 13 and at 18.8 sec in Figures 14 and 15 represents the time of collision between the ego-vehicle and the static target object.

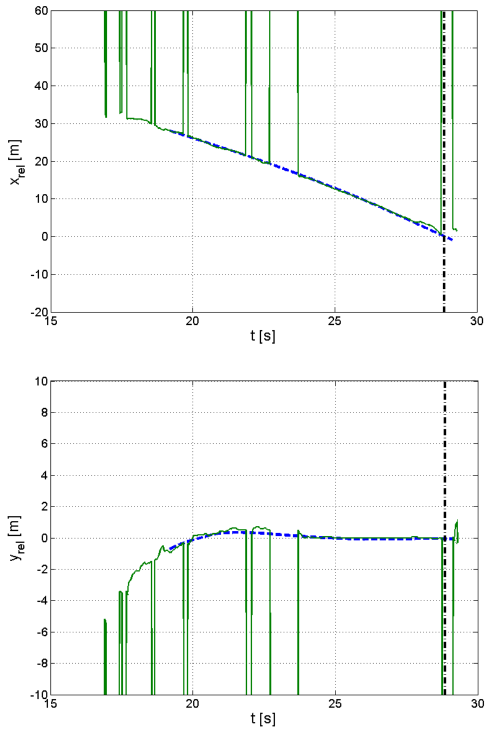

Figure 11. Real and synthetic sensor data for the relative position in the test scenario "straight frontal collision with a centered static object"

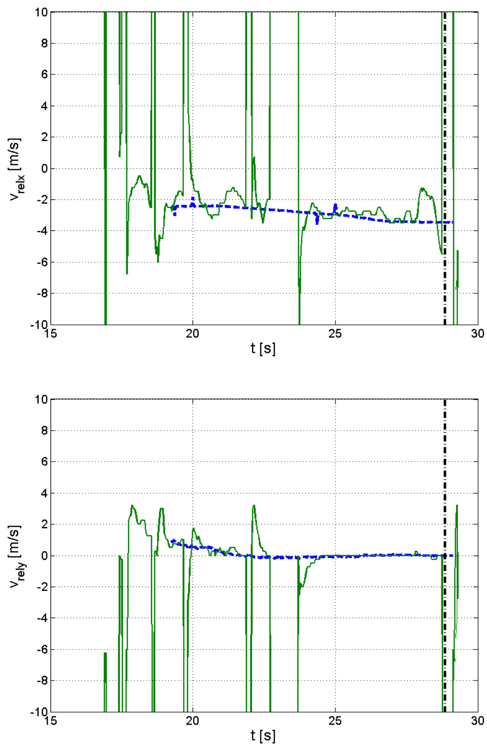

Figure 12. Real and synthetic sensor data for the relative velocity in the test scenario "straight frontal collision with a centered static object"

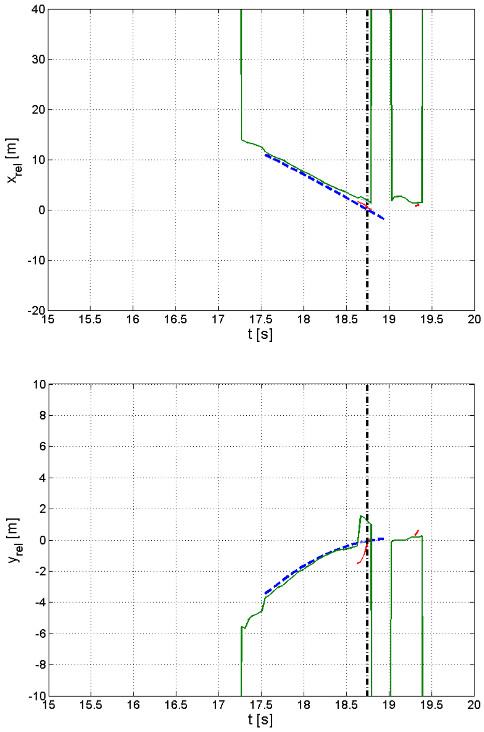

Figure 13. Real and synthetic sensor data for the relative position in the test scenario “Curved frontal collision with a centered static object”

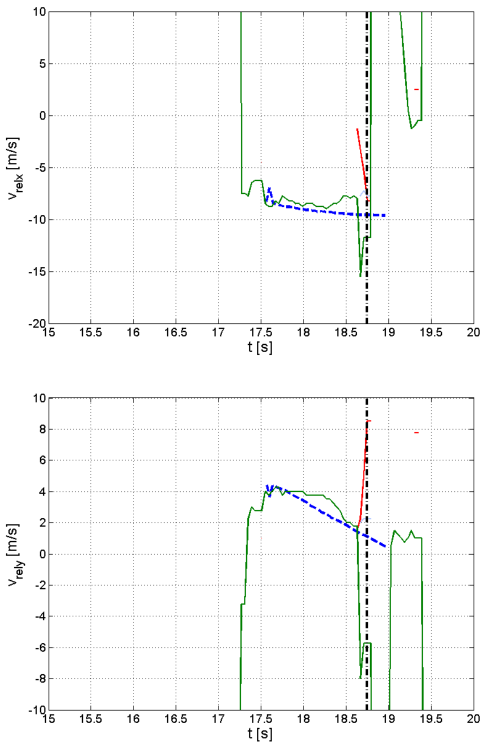

Figure 14. Real and synthetic sensor data for the relative velocity in the test scenario “Curved frontal collision with a centered static object”

The data values recorded directly after the time of collision result from the missing model for mechanical interaction between the collision partners in VTD or in the case of the real sensor data from the back-bumping of the hit target object.

All plots show a good correspondence of the measured and synthetically generated sensor data in both position and velocity values at distances larger than approx. 5 meters. Throughout the whole set of real sensor measurement data temporary target object tracking losses can be recognized. Shortly before the time of collision significant deviations of the measured and synthetically generated sensor data values are visible.

The plots of the curved driving scenario (Figures 13 and 14) show that the target object is only detected at a significantly later point of time (smaller distance to the ego-vehicle) compared to the straight driving scenario. This results from the circumstance that the target object enters the pyramidically formed sensor cone at a later point of time, as shown in Figure 7.

Moreover the circular driving scenario shows that the real sensor detects the target object as several objects shortly before the actual time of collision, as shown in Figures 14 and 15 with a red and bright blue line.

All diagrams depict the behavior that the statically parameterized sensor model in VTD has a slightly lower distance range in the specified scenarios compared to the real sensor.

7 CONCLUSION AND OUTLOOK

The steady growth in the number of predictive driver assistance functions in new vehicle models combined with the trend towards a higher number of vehicle variants per model leads to a significant rise in testing requirements in order to assure the correct functioning, reliability and robustness of such ADAS under a wide range of traffic conditions. The testing requirements can’t be covered anymore in an efficient manner by solely using real test drives. Therefore a methodology is presented to support the ADAS development and testing by using a software tool for the integrated vehicle and environment simulation. The focus of the paper lies on the method for performing semi-automated analysis and validation of perceptive sensor models. The sensor model validation process makes use of reference position and perception sensor data recorded during real test drives and allows the comparison and evaluation of the real sensor data with synthetically generated sensor data from sensor models on object list level.

The first results of a sensor model validation based on the described methodology with an idealistic sensor model of a prototypical real perception sensor are promising and confirm the basic applicability of the integrated vehicle and environment simulation for the development and testing of ADAS functions. Furthermore the results show current limitations of the approach which need to be addressed in future improvement steps.

The essential use of the presented validation methodology is related to the following aspects:

- Significant time savings through the replication of real test drive scenarios as virtual ones
- Possibility to create validated statements concerning the limitations / application range of the sensor models
- Inclusion of existing and approved tools for analysis, comparison and evaluation of sensor data
- Usage of a unified format for real and synthetically generated sensor data

Furthermore during the implementation of the described methodology several working fields were identified, which should be addressed in successive projects in order to increase the usability of the simulated sensor data for the testing of ADAS:

- Implementation of sensor models which model the most relevant sensor properties and disturbance effects as they occur on object list level of real sensor data
- Extension of the toolchain regarding the analysis and comparison of sensor raw data, e.g. camera images, radar locations, etc.
- Extension of the validation methodology to the level of functions and algorithms
- Improve the grad of automated sensor validation concerning the process- and tool-wide support of parameters related to the sensor and vehicle configuration and test scenario conditions (weather, target object properties, etc.)

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