SAMPLE PAPER

VEHICLE-IN-THE-LOOP: AUGMENTING REAL-WORLD DRIVING TESTS WITH VIRTUAL SCENARIOS IN ORDER TO ENHANCE VALIDATION OF ACTIVE SAFETY SYSTEMS

Dr. Roland Kallweit
Paul Prescher
Dr.-Ing. Matthias Butenuth
IAV
Germany

Paper Number 17-0322

ABSTRACT

Driver assistance and active safety systems are taking big steps towards greater autonomy. As the complexity and criticality of the traffic situations in which active safety systems have to intervene increases, the validation process of those functions is likewise becoming more complex, demanding and cost-intensive. Real-world tests are particularly constrained due to the fact that the increasing amount of relevant traffic situations can only be evaluated to a limited extent or with a considerable investment of cost and effort. Therefore the objective was to develop an approach which addresses these challenges.

This paper presents a vehicle-in-the-loop (ViL) test method. In contrast to existing approaches, the idea is not to embed a real-world vehicle into a virtual test environment and to test it in a cleared outdoor area. The key element of this test method is to augment the real-world test environment with virtual scenarios, which are based on virtual sensor objects.

The presented ViL test method is able to significantly enhance the validation of active safety systems. It closes the gap between simulated and real-world tests and enables to efficiently and reproducibly test active safety systems within traffic scenarios that are too complex or too dangerous for real driving tests. Therefore, it provides a promising approach for balancing safety performance, cost, and vehicle integration considerations during all development stages.

INTRODUCTION

Active safety systems are developed in order to help prevent accidents and significantly reduce fatality and traffic related injuries. As driver assistance and active safety systems are taking big steps towards greater autonomy, the complexity and criticality of the traffic situations, in which active safety functions have to intervene, increases. Therefore, the number of driver assistance systems and their functional range are expected to grow considerably in the next years [1]. Future active safety systems involve machine perception and cognition and are highly interlinked with other systems of the vehicle. Moreover, the data of various detection systems are fused in order to compute traffic situations with a maximum degree of accuracy. These systems have to cope with uncertainty in measurements and predictions as well as potential negative consequences such as false positives. The assessment of future active safety functions, therefore, is becoming increasingly complex, demanding and cost-intensive. The performance and reliability of those functions have to be validated in high-dimensional and complex traffic scenarios, including various traffic participants.

Today, advanced driver assistance systems are typically evaluated using conventional testing approaches that rely on simulative methods such as model-in-the-loop (MiL), software-in-the-loop (SiL) and hardware-in-the-loop (HiL) as well as real-world driving tests. These approaches are sufficient for assistance functions working in longitudinal traffic situations, such as adaptive cruise control, forward collision warning or emergency braking assistance. However, they are not sufficient to ensure the safety, reliability and usability of increasingly complex systems that have to intervene in various safety-relevant traffic situations, such as sudden cut in of vehicles or bicycles, crossing traffic at intersections or dynamic emergency steering scenarios with several road users [1]. Real-world tests are particularly constrained due to the fact that the increasing amount of relevant traffic situations can only be evaluated to a limited extent or with a substantial investment of effort (Figure 1).

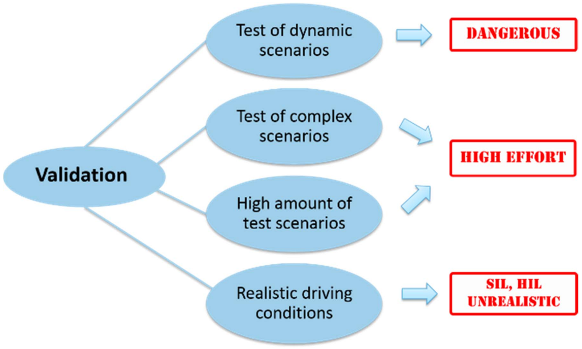

Figure 1. Validation of future active safety systems is becoming increasingly complex, demanding and cost-intensive

The challenge, therefore, is to improve testing and assessment methods and to find new ways for validation in order to keep pace with the functional growth. Otherwise, testing and assessment will become the bottleneck of the introduction of future active safety systems to the market [1], [2].

In order to address these challenges, this paper presents a vehicle-in-the-loop (ViL) test method that augments real-world test drives with virtual objects and scenarios in order to test sensor-based active safety systems. In this way it is possible to evaluate safety-relevant traffic scenarios that cannot be realized within real driving tests due to safety or complexity restrictions.

FUNCTIONALITY AND COMPONENTS

The common way to test active safety systems is to use dummy targets in collision scenarios in order to make the testing scenarios as realistic as possible [3]. Using the augmented reality (AR) technology, potential “opponents” in crash scenarios appear on a display screen located in the windshield as if they were in the same real-world location as the vehicle and the test drivers (Figure 2). Test drivers, therefore, see the virtual generated opponents moving on the real test track and are able to perceive the real vehicle reaction (e.g. a bimodal warning, an emergency breaking or steering as well as safety activities of the pre-crash phase).

The information of the opponent type and position is sent to the active safety system as part of a real test vehicle and is visualized on a mobile display using an augmented reality app. The vehicle moves towards these virtual objects that behave like real world objects.

Figure 2. ***Integration of the ViL test system into a real test vehicle***

The ego movements of the vehicle are processed towards the scene simulation to calculate the correct relative object movements. Based on the relative position of the object, the active safety system can compute its results and send the requests to the actors. This creates a closed loop between the vehicle, the scene simulation and the active safety system. The function under test can run either on the real hardware or as software on a regular computer.

The vehicle-in-the-loop test system is composed of five interacting components (Figure 3):

- Active Safety System
- Vehicle
- Command & Control
- Scene Simulation
- Visualization

The **Active Safety System** contains the function to be tested as it works within the real vehicle. It is a function based on object lists such as an emergency braking, pre-crash or emergency steering. It computes its results based on the ego data of the vehicle and object data from the scene simulation.

The **Vehicle** is the real vehicle with which the function has to be evaluated. Almost every vehicle can be used for the ViL, as long as the actors can be requested directly or via the data bus of the vehicle. In case of an emergency brake function, the breaking command, for example, is sent directly on the bus and subsequently processed by the ECU controlling the breaks. Other actors such as steering, reversible belt pretensioner or window lifts can of course be also integrated into the ViL.

The **Command & Control** unit is a communication framework for coordinating several processes inside the ViL. The whole communication is done by the command & control unit, the central component of the ViL, which cannot be replaced. Further modules used in the ViL will be connected with the command & control. All other modules can be replaced. The command & control unit reads the vehicle data, and processes them forward to the scene simulation and the active safety system. Furthermore, it processes the calculated objects of the scene simulation towards the displays and the active safety system. The communication to the AR display is realized via bluetooth. Hence, the installation in the vehicle can be done fast.

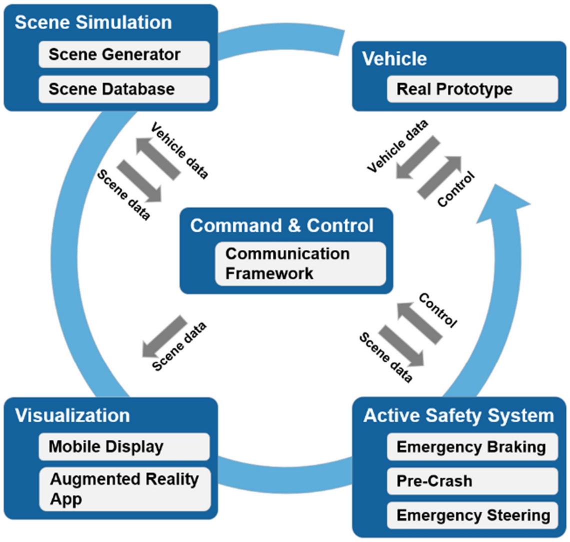

Figure 3. ***Interaction of four components coordinated by a command & control unit***

The **Scene Simulation** generates the virtual objects and scenes in order to augment the real test environment. Inside the scene simulation different kinds of sensors, sensor-specific behavior as well as deviations can be modeled. Furthermore, it respects characteristics like reach or opening angle. This results in a realistic object detection by the scene simulation. For the ViL, various objects are simulated in one scene. Such a scene represents the real world scenario which is simulated for testing. The relative movements of the objects are transmitted as an object list to the command & control unit. For computation of the movements the ego movements are used.

The **Visualization** is basically divided into three different displays: the AR display, the 3D display, and the rendered scene. The AR display consists of a mobile device (e.g. a tablet) equipped with a camera and a special augmented reality app. In this display the test scene is visualized in a realistic way as the objects calculated by the scene simulation are placed into the video stream.

Figure 4. Within the AR display crash opponents are placed into the real test environment

This leads to an augmented view of the real world and enables the test driver to evaluate the behavior of the active safety system as realistic as possible (Figure 4).

While the AR display is primarily used during the test execution, the 3D display can be used during the test or afterwards for evaluation purposes. It visualizes the scene as a 3D video. This means that the camera can move around the whole scene and enables views like birds eye view, first person view, third person view and a side view of the scene. This offers various possibilities to view the scene during testing and allows to check, for example, the distances to the objects.

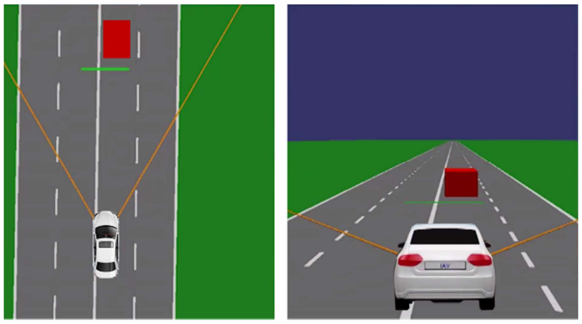

Figure 5. The 3D display provides different views of the test scenario

The rendered scene, computed by the scene simulation, is the third available display intended for evaluation purposes. It traces the whole scene in the post processing and is not available during the test. The rendering is done after the test is finished. Afterwards the results can be viewed in a browser and then be stored for documentation of the test results.

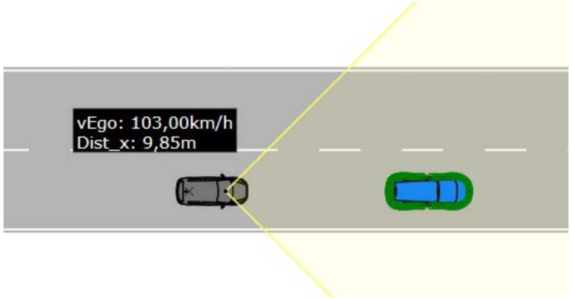

Figure 6. The rendered scene is used for the evaluation in the post-processing

SPECIFIC CHARACTERISTICS OF THE PRESENTED VIL APPROACH

In contrast to existing approaches, the idea is not to embed a real-world vehicle into a virtual test environment by mapping its movements into the virtual models and to test active safety systems in a cleared outdoor area (e.g. [4], [5]). The key element of the presented test method is to augment the real-world test environment with virtual scenarios, which are based on virtual sensor objects. The gap between HiL testing and real test drives is not closed by realizing a driving HiL, but by extending the possibilities of real test drives. The presented ViL test method, therefore, is rather a validation than a verification method. It can be used throughout all development stages in order to answer the question whether the active safety system under test meets the customer and other identified stakeholder expectations.

Another specific characteristic of the presented ViL test method is the high degree of modularity and flexibility. The modular architecture enables the adaptation of the ViL to different development situations. It can easily be mounted in every vehicle, provided that the actors can be controlled. It is only necessary to place the tablet in the windshield and to connect the tablet to a computer where the command & control unit is running (Figure 2). The whole communication is done by the command & control unit, the central component of the ViL. The communication to the AR display is realized via bluetooth. Hence, the installation in the test vehicle can be done fast.

Furthermore, the described components (with exception of the command & control component) can be substituted by other external components, thus contributing to a more representative validation and the maximization of the added value for the development of active safety systems.

USE CASES FOR VEHICLE-IN-THE-LOOP

The ViL test method can be seamlessly integrated into existing development processes. It is focused on the validation of desired properties – not only in the late development phases, but also in the early stages of function development, i.e. before the final sensor set and the control unit hardware are useable. It takes place between the HiL testing and real vehicle tests. This way, it closes the gap between simulated (MiL, SiL, HiL) and real-world tests (test drives, road tests) as shown in figure 7.

Due to the fact that in the early phases of development only models and algorithms are available, the common way to evaluate the function maturity is to use simulative test methods. For example MiL simulation to verify the accuracy and acceptability of the software models or SiL simulation for validating the behavior of generated source code. The ViL test method, in addition, enables the function developer to get a better understanding of the behavior of the algorithm interacting with real actors in a real vehicle, which he drives on a test track. In this way the ViL test method enables the function developer to reveal potential negative consequences, like false positives, in an early stage of development.

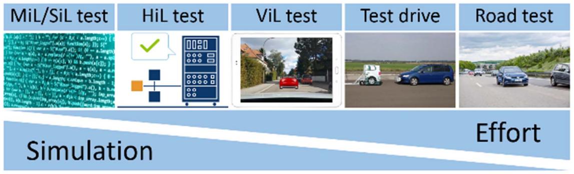

Figure 7. The ViL test method closes the gap between simulated and real-world tests

In the late development phases the aim of real test drives is to increase the functions degree of maturity before starting real-world road tests. The main challenges within this phase of testing are to identify relevant test scenarios, to execute the tests as realistic as possible, and simultaneously to ensure a reproducible and safe test execution. Therefore, the conventional way to test active safety systems intervening in longitudinal traffic scenarios (e.g. emergency braking) is to use dummy targets and limit the permitted vehicle velocity or the impact speed, respectively. As long as urban traffic scenarios are in the focus of the active safety system under test, this way of validating desired system properties is sufficient. Nevertheless, these targets are mainly designed for rear-end collisions in longitudinal scenarios and cannot be used in complex scenarios or scenarios with high relative velocities.

If an emergency brake system, for example, is aimed to intervene not only in city traffic, but also in high speed scenarios, other test methods have to be used in order to ensure a test execution with a maximum degree of realism and safety. The ViL test method is one solution for this challenge as it enables the evaluation of the performance of active safety systems in longitudinal collision scenarios with high velocities (relative velocity > 60 km/h) – without the risk of collisions with real objects, but with real-world vehicle dynamics.

In addition to longitudinal crash scenarios there are various relevant traffic scenarios that cannot be tested at the moment due to safety and complexity reasons. These traffic scenarios become more and more important as the driver assistance and active safety systems are taking big steps towards greater autonomy. Thus, the complexity and criticality of the traffic situations, in which active safety functions have to intervene, increases. Along with the already mentioned longitudinal crash scenarios with high velocities, figure 8 provides an overview of a small selection of traffic scenarios that are relevant for future active safety systems but not testable with the common methods.

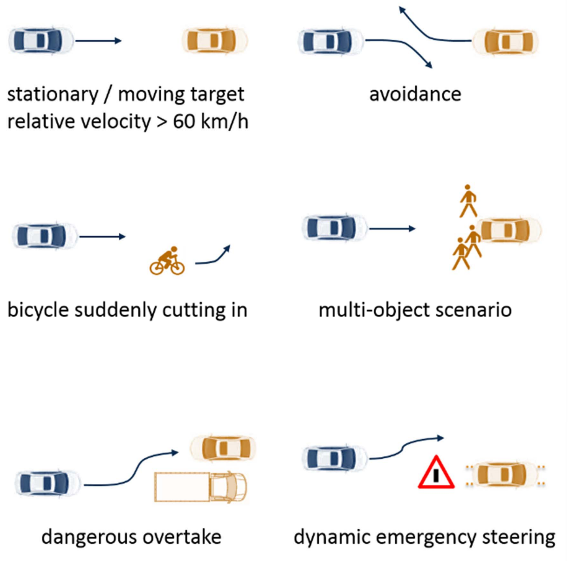

Figure 8. Traffic scenarios that are relevant for future active safety systems but not testable with common methods

As the ViL test method uses virtual objects instead of real world objects, there are no restrictions like the impact speed for a target or a limitation due to complex scenarios. In the ViL several objects with limitless speed can be placed together in one scene.

Within the late phases of system development the ViL test method can not only be used to extend the possibilities of real test drives, but also to support the calibration of the functions (i.e. the adjustment of the functions parameters and characteristics curves). When the calibration of the function is tested, the main advantage is the AR display, which enables the tester to experience the function in the augmented reality. This can lead to a better evaluation.

In all described use cases the ViL is used to test the active safety function in combination with the actors (Figure 9).

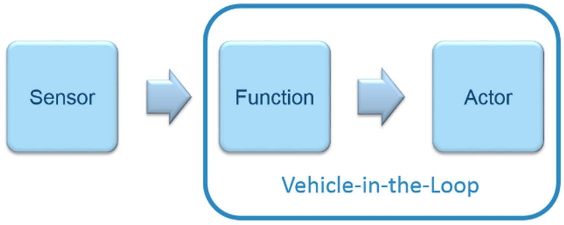

Figure 9. The ViL test method concentrates on the active safety function interacting with the real actors

The real sensors are not part of the ViL. This enables the testing of the subset function and actor. The behavior of the real sensor cannot influence the tests. The advantage of this is to test the behavior of the function with a virtual sensor modeled by the scene simulation. Various sensor characteristics can be defined, such as sensor faults (e.g. bias, noise, precision degradation) and specific properties (e.g. range, precision). The disadvantage of course is the behavior of the real sensor cannot be considered.

FIRST PRACTICAL RESULTS

By now the ViL test method has been used in longitudinal crash scenarios in order to get first experiences with the technic. Active safety functions under test have been forward collision warning, emergency brake assistant as well as pre-crash functions. The chosen test scenarios were based on common consumer protection scenarios: static, moving and braking car within the driving path of the vehicle under test as well as crossing pedestrians. The test scenarios have been executed in the common way of testing (up to a velocity of 80 km/h) as well as high speed tests that cannot be executed with conventional pedestrian and vehicle targets. The expected behavior of the vehicle was a cascade of warning, braking, closing windows and sunroof, and pretensioning seat belts.

The biggest advantage that has been gained is that testing is possible in any location without lot of time for preparation. Because of that as well as the easy switch between the scenarios it was also possible to save time compared with a normal test with real vehicles and targets. Furthermore, dangerous test scenarios, like longitudinal crashes with high velocities, were easy to test without harming the driver.

In the next development stage further steps towards a higher precision will take place. Specifically, the AR display will be adapted in order to be more precise and to adjust in a correct way to every vehicle movement, for example the nodding when the driver is accelerating or braking very fast.

FUTURE VIL APPLICATIONS

Although the ViL test method is a promising approach to validate current active safety systems in traffic scenarios that are too dangerous or complex for common driving tests, the test method will exploit its full potential in validating active safety systems within highly automated driving. In such test scenarios the test driver is only present as back-up, ready to take over if necessary. Therefore, the test driver can completely concentrate on the tested traffic scenario visualized on the mobile screen, the vehicle behavior, and the evaluation if the function under test as well as the vehicle actors behave as expected.

Especially for highly automated vehicles the presented ViL test method can be used to support the in-vehicle calibration of active safety systems. In this case the ViL can be used to support an automated calibration where the car runs highly automated on a test track and the ViL feeds relevant scenes for the calibration into the environment. Hence a broader variance of test cases can be part of the calibration with less effort. Furthermore, the calibration can take place in earlier phases of the development and critical scenarios, which are not testable in real test drives at the moment, can be part of the calibration.

Augmenting real-world scenarios with virtual objects also opens the door for evaluating sensor fusion functionalities of advanced driver assistance systems. If a camera-detected object, for example, is varied regarding its position and virtually fed into a different sensor path, a huge potential to investigate object-based sensor data fusion arises. Using virtual scenarios additionally offers the possibility to benchmark already existing algorithms and sensors.

Future use cases also appear for the testing of driverless cars. Here the car runs on a test track and random scenes can be played and the car will then react automatically. Thus the test track has some advantages of a fully automated test place, such as a HiL.

CONCLUSION

The presented ViL test method is able to significantly enhance the validation of active safety systems. It closes the gap between simulated and real-world tests and enables the efficient and reproducible testing of active safety systems within traffic scenarios that are too complex or too dangerous for real driving tests. Therefore, it provides a promising approach for balancing safety performance, cost, and vehicle integration considerations during all development stages.

REFERENCES

[1] Bengler, K., Dietmayer, K., Färber, B., Maurer, M., Stiller, C. and H. Winner. “Three decades of driver assistance systems: Review and future perspectives”, IEEE Intelligent Transportation Systems Magazine, vol. 6, no. 4, Winter 2014, pp. 6-22.
[2] Winner, H. “Challenges of Automotive Systems Engineering for Industry and Academia”, in Maurer, M. and H. Winner (Eds.) Automotive Systems Engineering, Springer, 2013, pp. 3-15
[3] Seiniger, P. and A. Weitzel. “Test Methods for Consumer Protection and Legislation for ADAS”, in Winner, H., Hakuli S., Lotz, F. and C. Singer (Eds.), Handbook of Driver Assistance Systems, Springer International Publishing, 2016, pp. 214-230
[4] Miquet, C., Schwab, S., Pfeffer, R., Zofka, M.R., Bär, T., Schamm, T. und M. Zöllner. “New test method for reproducible real-time tests of ADAS ECUs: “Vehicle-in-the-Loop” connects real-world vehicles with the virtual world”, in Pfeffer, P.E. (Ed.), 5th International Munich Chassis Symposium 2014, Proceedings, pp. 575-589.
[5] Berg, G., Nitsch, V. and B. Färber. “Vehicle in the Loop”, in Winner, H., Hakuli S., Lotz, F. and C. Singer (Eds.), Handbook of Driver Assistance Systems, Springer International Publishing, 2016, pp. 199-210