Concept and Realisation of a Holistic, Highly Flexible HiL Test System for Testing Autonomous Driving Functions

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Abstract. Autonomous driving and networked cyber-physical transport systems pose ever-increasing challenges for the development and validation of advanced driver assistance systems and autonomous driving functions. Real-time optimisation and testing in particular are associated with enormous effort and risk. A holistic, flexibly configurable, real-time-capable test bench for the entire vehicle would provide a remedy here. The following article describes the concept of the holistic, highly flexibly configurable real-time test system for intelligent vehicles in co-operating cyber-physical traffic systems (ERAGON), which is currently being developed at the Ostfalia University of Applied Sciences.

Introduction

Mobility is in the midst of a disruptive change due to the increasing digitalisation and networking of vehicles. The autonomous driving of electric hybrid vehicles in highly networked cyber-physical systems (CPS) is one of the core technologies in the digital transformation process of mobility.

The variety of applications for autonomous vehicles requires ever more diverse sensors and ever more complex and intelligent algorithms from the fields of modern control technology and artificial intelligence (AI). This results in systems that are even more extensive and complex than the already existing highly networked electronic vehicle functions [1].

The development of such systems is highly complex and requires multidisciplinary, interdisciplinary design processes based on proven rapid control prototyping (RCP) methods from mechatronics research. In a top-down process, the system complexity is first reduced by structuring using modularisation and hierarchisation. The upper hierarchy levels of the networked mechatronic system (VMS) and the autonomous mechatronic system (AMS) are increasingly characterised by intelligent autonomous driving functions and driver assistance systems (ADAS) such as electronic vehicle management and intelligent, cooperative guidance.

The model-based design of each individual subsystem is then carried out in a bottom-up process incorporating the validation processes model-in-the-loop (MiL), software-in-the-loop (SiL) and hardware-in-the-loop (HiL). Such a structured approach is essential for the design and validation of networked mechatronic systems [2].

In order to investigate the integrated overall functionality of autonomous, networked vehicles, a holistic vehicle test bench that accurately maps the overall system consisting of the road, networked vehicles and networked driving environment and at the same time stimulates the vehicle's sensors is therefore indispensable.

An evaluation of the following state of knowledge and research shows that there are many partial solutions for reliable verification for ADAS, highly automated and autonomous driving functions at AMS and VMS level and that these are also being continuously further developed. What is missing, however, is a holistic test system that enables flexible configuration of both the test specimen and the test environment under realistic and reproducible conditions at all levels of mechatronic structuring.

This article therefore presents the concept of the holistic, highly flexibly configurable real-time test system for intelligent vehicles in co-operating cyber-physical transport systems (ERAGON). Work is currently underway on this new system at Ostfalia University.

1 State of the Art

According to [3], valid functional validation is a major challenge on the progression towards autonomous driving. It must be ensured that the designed functions in the overall system are verifiably safe in terms of output quality and probability of misinterpretation [4]. It is necessary to reproducibly test as many situations as possible with which the vehicle could be confronted. If this task is to be carried out under real road traffic conditions, hundreds of millions of test kilometres will be required [5].

It therefore makes sense to supplement the test under real conditions with simulation-based procedures so that certain rare situations can still be tested safely and reproducibly. This requires a complex, real-time-capable test system that generates test conditions that are as realistic as possible using a mixture of real and simulated systems and environmental components.

To this aim, Chen et. al [6] use an integrated simulation and test platform for self-driving vehicles. Their platform offers the possibility of testing a real vehicle on a restricted test track. The special feature of their approach is that the sensor signals (GPS, IMU, lidar and camera) originate from a high-precision virtual simulation scenario and are processed by a real control unit in the vehicle to generate real driving commands. In the course of the test, the sensor technology is therefore mapped completely virtually, which means that unwanted aggregation effects can occur even though a real vehicle is present [7].

The developed driving functions can also be tested in advance without the real components in the simulation environment in offline and online simulations. The platform presented in Chen et. al. is not flexible on the hardware side. It is tied to a specific research vehicle with a prototypical control unit with fixed interfaces. This means that neither subordinate functions nor functions based on V2X communication can be secured with this structure. Due to the hardware architecture, the platform is also not suitable for incorporating AI algorithms.

The vehicle-in-the-loop methodology for evaluating automated driving functions in virtual traffic from Solmaz [8] is based on a very similar structure to Chen. Here too, a real vehicle is used on a restricted test track combined with a simulated environment. The main difference, however, is the design of the control unit for the driving functions.

In contrast to the control unit from Chen, the MicroAutoBox II from Solmaz allows flexible modification of the system under test by RCP. However, this is limited to the AMS level. Various algorithms, including those from the field of AI, can be implemented and additional signals, e.g. from V2X communication, can theoretically also be integrated. However, the test system itself is neither flexibly configurable nor free from aggregation effects. The reproducibility of the test scenarios is always questionable with test systems on real test tracks, as tyre behaviour, for example, changes depending on the weather and temperature despite simulated sensor signals.

Kanchwala [9] presents a real-time HiL vehicle simulator that clamps a real vehicle into a stationary test setup. Here, driving resistances are simulated via four electric motors that are directly coupled to the wheels. The associated target torques are determined by a real-time computer on which the test scenario is simulated. However, the focus of this system is on analysing the longitudinal dynamic driving characteristics, e.g. in virtual off-road environments. Investigations of steering behaviour or consideration of sensors and communication systems are not possible. The flexibility of the vehicle simulator is limited to testing different vehicles. Flexible configuration of the test setup is not provided.

Ying et al [10] use a vehicle-in-the-loop simulation and test platform to validate the functionality of autonomous vehicles. The associated vehicle test bench has four individual excitation units, which make it possible to map three degrees of freedom onto a real vehicle. The vehicle's sensors (camera, lidar and radar) are stimulated with signals generated on the basis of virtual traffic scenarios.

As a result, the test environment enables reproducible and fully controllable test scenarios. The simulation environment allows the integration of virtual V2X communication. However, this is not modelled in reality. This means that it is not possible to fully validate the driving functions at VMS level.

Furthermore, the vehicle to be tested cannot be modified. Although it enables the validation of various driving functions in different test bench configurations, it does not allow the prototyping of freely definable functions.

2 Methodology

The holistic model-based, verification-oriented RCP methodology is used for the development of complex interconnected mechatronic systems. By means of mechatronic structuring, the overall system complexity is handled. For this, the linked CPS is divided into hierarchically arranged subsystems with four hierarchical levels through modularization and hierarchization: mechatronic function modules (MFM), mechatronic function groups (MFG), autonomous mechatronic systems (AMS) and interconnected mechatronic systems (VMS) [11].

The result of the structuring is a functional decomposition of the overall system into encapsulated modules. The hierarchically arranged modules with their sub-functions have uniquely defined physical and information-technological interfaces in horizontal and vertical direction and form the basis for the later integration into the overall system [12].

After the hierarchical structuring and definition of all interfaces, the model-based and function-oriented design of each individual module follows in a bottom-up process. Starting with the lowest and at the same time most vital level MFM, the integration into higher-level functions then is performed on all hierarchy levels. The design as well as integration of these functions into the overall system (mechatronic composition) is done using the model-based mechatronic development cycle.

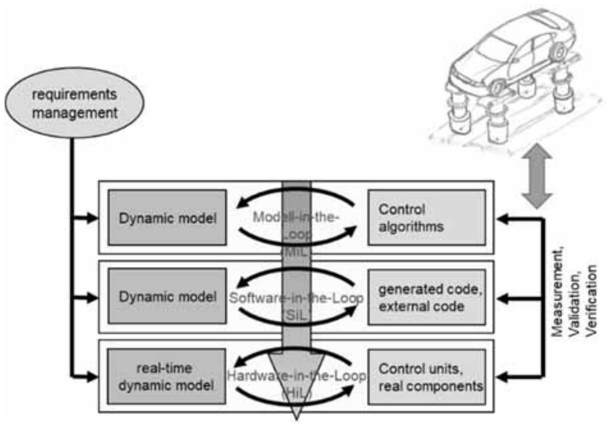

Figure 1: Seamless model-based development and validation process [11].

This is followed by Model-in-the-Loop (MiL) simulations, where control algorithms and AI are developed based on a physical or mathematical equivalent model and tested on a vehicle model.

An executable program code is generated from the simulatively tested algorithms within the context of Software-in-the-Loop (SiL) simulation by means of automatic code generation and tested offline in a virtual test bench.

This is followed by Hardware-in-the-Loop (HiL) simulations, in which a real-time vehicle model supplemented by physical subcomponents is used online to validate and optimise the algorithms and intelligent functions under real-time conditions [13]. Figure 1 illustrates the process flow.

3 Concept of the Test System

The real-time test system for intelligent vehicles in cooperating cyber-physical traffic systems ERAGON mainly consists of four modules: test bench module, real-time information processing, software and MMI communication module.

This allows the system to be flexibly configured and used for different Vehicles under Test (VUTs). Figure 2 illustrates the interaction.

All subordinate test systems are arranged hierarchically via defined interfaces. Thus, the ERAGON is able to be used flexibly in different variants for different testing purposes.

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3.1 Test Bench Module

The test bench module essentially consists of a complex excitation unit for the simulation and stimulation of a VUT by the simulated environment. An extensive environment simulation is used to create a virtual 3D world and to represent the real objects in the environment of the vehicle. The sensors can be stimulated in different ways with the data from the simulation.

One possibility is the over-the-air stimulation of the calculated obstacles by means of a physical stimulus, e.g. ultrasonic systems using ultrasonic waves via an oscillating membrane.

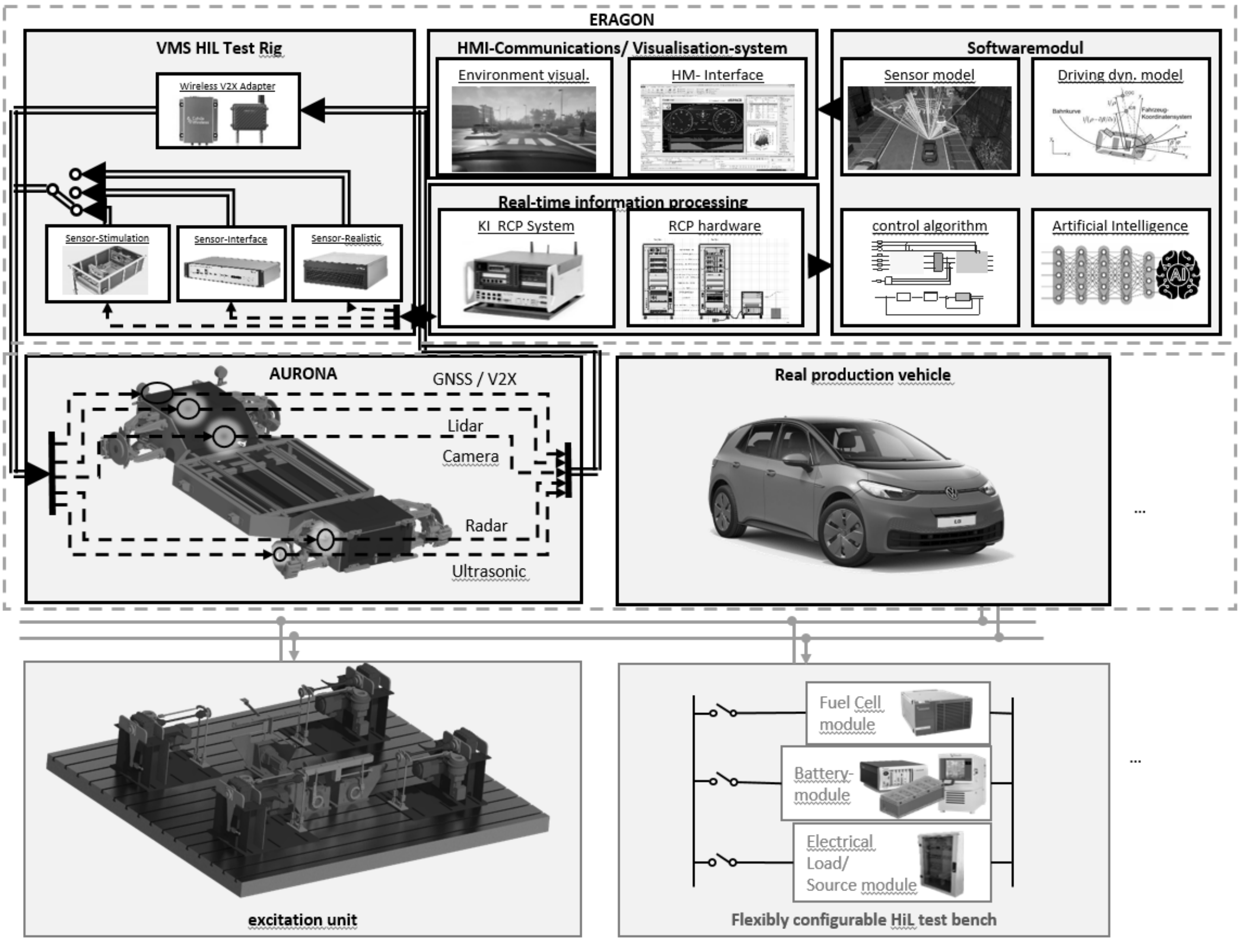

Figure 2: Concept of the ERAGON holistic testing system.

Another channel for feeding environmental signals is an additional V2X development platform for easy access to V2X communication, so that no implementation of specific communication protocols and software layers is required.

These systems provide a broad platform for implementing and coupling comprehensive traffic simulation. The core module can thus simulate a complete traffic scenario in a reproducible and realistic manner. This high degree of augmentation of reality and simulation is indispensable for testing higher-level autonomous and interconnected functions at the AMS and VMS structural levels. It makes comprehensive testing of the driving function in a CPS traffic environment at the AMS/VMS structural levels possible for the first time.

3.2 Software Module and HMI

The software module contains all the controller functions and virtual systems to be tested, like the sensor and vehicle models. In addition, calibration, scaling and signal conditioning take place here.

The software module is digitally computed and processed as a distributed calculation on several processors of the real-time information processing module under real-time conditions.

The communication module with human-machine interface, which is also used for visualization, is used for measurement and calibration tasks. Appropriate user interfaces (GUIs) are provided for this purpose. The RTI (Real-Time Interface) of the target hardware is used to control and automate the test stand.

3.3 Real-Time Information Processing

The module of real-time information processing with its various RCP systems ensures data processing. The module is equipped with several RCP systems including AI RCP system for fast prototyping of intelligent control functions, machine learning of artificial intelligence using powerful processor technology for demanding real-time requirements, and has a fast data processing and storage system for storing and managing large amounts of data.

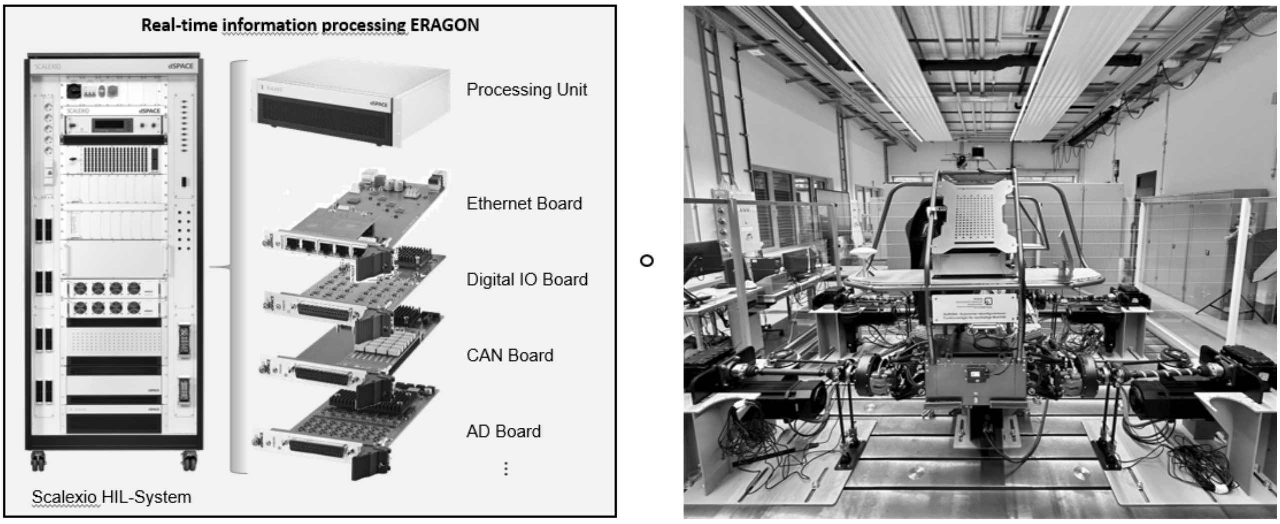

Figure 3: Concept of the ERAGON holistic testing system.

3.4 Device / Vehicle under Test

The test system is designed for flexible use. Defined interfaces to various test items are provided for this purpose. For example, real vehicles, function carriers or special test setups such as a single-track model can be used here.

Initially, an Autonomous Reconfigurable Functional Carrier for Sustainable Mobility (AURONA) is provided as a VUT.

As an RCP function carrier, AURONA is equipped with all typical environment sensors (camera, radar, ultrasound, lidar, etc.) required for highly automated or autonomous driving functions, whose interfaces are opened at various points.

In this way, the hardware components of the sensor system can be bypassed by means of RCP bypassing. The interfaces are configured in such a way that a flexibly configurable excitation of the sensors via the ERAGON can be selected. It is possible to excite the physical sensor input via sensor stimulation as well as to feed raw data directly to the electronics of the same sensor.

Furthermore, AURONA is equipped with a 5G V2X communication unit via which it can communicate bidirectionally with the V2X development platform of the ERAGON, but also with other V2X units. Thus, cooperative driving functions can also be investigated. The AURONA is also equipped with a drive and steering system.

This makes it possible to test the influence of the actuator elements in an autonomous vehicle. In this way, it is able to implement the commands for operation in a completely realistic way. These are counter actuated via the excitation unit of the ERAGON, resulting in realistic and closed-loop driving behaviour of the AURONA or also of another DUT.

4 Realisation

The test system is implemented step by step in a bottom-up process. Starting from the lowest and at the same time most vital level, the functions are implemented and subsequently integrated.

Figure 3 illustrates the partial realization of the test system. On the left is the heart of the test-rig – the Real time information processing system – with the necessary processing units and the highly flexible interchangeable interface system.

On the right side is the excitation unit in a coupled state with the RCP function carrier AURONA. The motors and gears for dynamical excitation on the vehicle chassis are exposed.

The test field itself is surrounded by a safety fence. A release control prevents people from being inside the safety area during the test operation.

Figure 4 shows the RCP function carrier AURONA. The vehicle is equipped with four direct drives and a break-by-wire system. All four wheels can be driven, braked and steered individually. GPS and LIDAR are used for position detection.

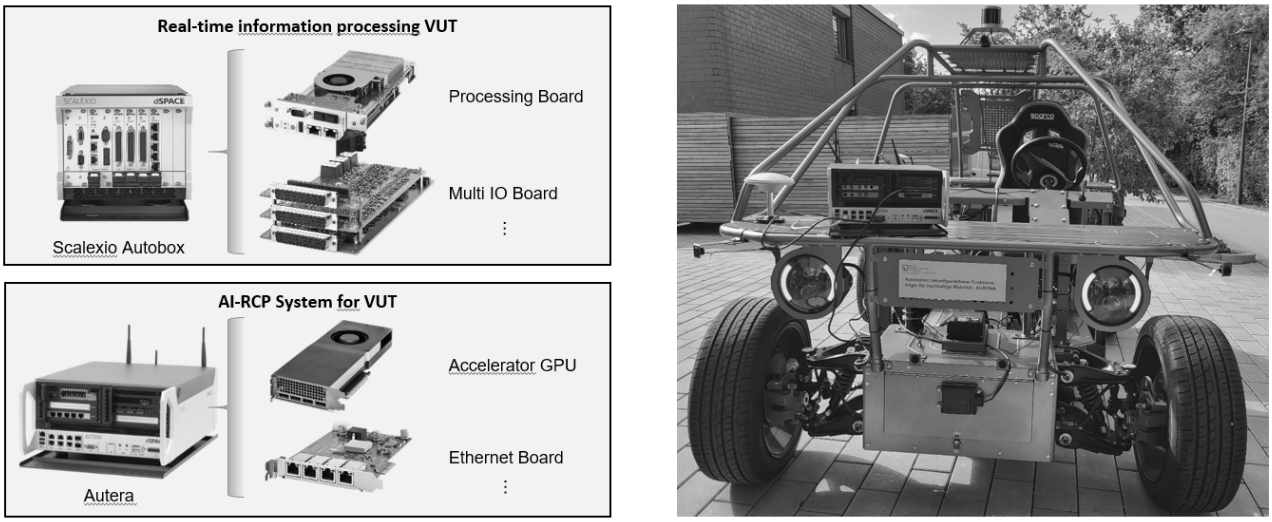

Figure 4: Concept of the ERAGON holistic testing system.

Objects are detected via camera, LIDAR, ultrasound and RADAR. Sensor data fusion with V2X data enables the creation of a complete dynamic map of the environment. On the left, the real-time data processing (Scalexio system from dSPACE) and the vehicle computer of the AURONA are shown.

Figure 5 finally shows the data coupling mechanism for the simulation, emulation und stimulation of vehicle sensors using the ERAGON test bench system.

Depending on the type of sensor excited and the measuring principle to be stimulated, a distinction is made here between the pure simulation of measurement results, the emulation of sensor measurement data and the stimulation of the physical sensor with electromagnetic radiation.

The usual approach is to completely bypass the sensor data within the simulation by assuming an omniscient system.

However, since it is highly likely that the complete capturing of all system states of a complex system will only be possible through a state estimation based on sensor data evaluation and fusion, an important component of the ERAGON test bench is the simulation of sensors and their dynamic physical behaviour.

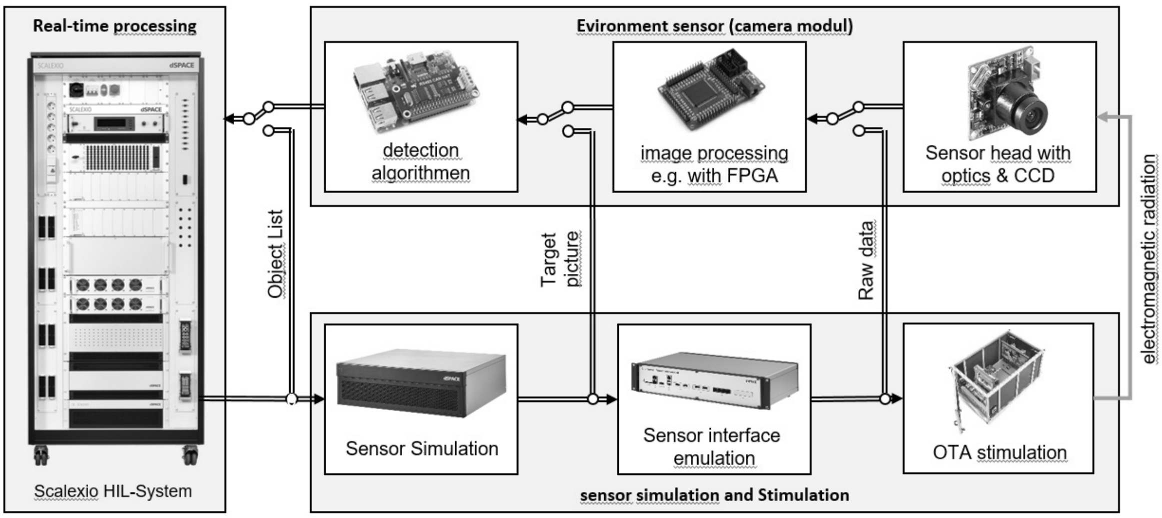

Figure 5: Concept of the ERAGON holistic testing system.

The basis is the simulation of the signal paths of the physical signals recorded by the sensors; in the types frequently used for autonomous driving functions, these are electromagnetic waves. For example, the path of an electromagnetic wave emitted by a radar sensor is tracked within the simulated driving environment using ray tracing in order to reproduce the reflections on objects and surfaces as realistically as possible.

A downstream emulation generates the exact signal that would be emitted by the real sensor measuring head, taking into account the physical properties of the sensor.

In the final step, this signal can now also be ‘shown’ to the real sensor head over-the-air by converting it into the electromagnetic radiation on which the measuring principle is based. This ensures the highest possible fidelity to reality.

5 Summary and Outlook

In this paper, the concept of a holistic, highly flexible configurable HiL test system ERAGON for testing autonomous driving functions was presented. In a closed loop together with the function carrier AURONA, this system is able to simulate and stimulate the entire autonomous vehicle system, starting from the infusion of raw sensor data via the development and testing of AI functions up to the stimulation of realistic driving situations.

The information processing of AURONA was integrated and the vehicle sensors are connected to the environment and sensor simulation.

Currently, the provided concept is under realization. In the next steps, the test system will be successively implemented and put into operation. Therefore, simulation scenarios with defined area of application are used.

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