Virtual Validation Method of Automated on-Sight Driving Systems for Shunting Operations

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Research paper

Abstract

Virtual scenario-based testing is considered best practice in the development and validation of highly automated driving functions. A scenario describes a holistic and coherent test setup in a use-case oriented environment in order to make a claim about the validity of derived test results. Railway kinematics are characterized by the system immanent track guiding allowing narrow clearance to infrastructure. High masses and low coefficients of adhesion result in long stopping distances. In addition, shunting is performed on sight whereas train line operation is performed on signaling. Ensuring a sufficient safety distance to obstacles, high sensor performances in range and resolution is required for real-time sensor-based object detection. A stable object classification and subsequent obstacle warning is mandatory for trouble-free automatic train operation (ATO). To validate the perception-based decision making, the following target braking or acceleration, the driver model and actuation systems, a huge number of situations has to be considered. Regarding time, cost and feasibility, real world operation cannot provide a complete set of necessary tests, thus, virtual scenario-based testing, also used for validation of advanced driver assistance systems in automotive engineering, is adapted. Therefore, a photorealistic railway environment designed along physical properties is developed. According to the layout and design of the system under test (SUT), the physical sensor positions and characteristics are simulated. Raw sensor data is emulated and looped out to the SUT respectively, where the driving decision is made. The decisions are wrapped and looped back to the vehicle model, an integrated module as a part of the simulation environment. Scheduled scenario set-ups including static and dynamic elements as well as expected system behaviors are defined as concrete test cases.

Keywords

virtual testing, simulated sensor, validation, ATO, virtual engineering

1 Introduction

Freight transport capacity in Germany, shown in Figure 1, is growing steadily. In 2019, the rail freight transport share accounts for 18.5% of the total transport performance (17.9% in 2020 (Statistisches Bundesamt, 2022)). Driven by international climate targets and the potentials of rail road systems in terms of energy efficiency resulting in low emissions (Bistry et al., 2022), the coalition agreement of the German government aims to increase the rail freight transport share to 25% by 2030 (SPD, Bündnis 90/Die Grünen, FDP, 2021). Within the governmental traffic flow forecast of 2014 (Bundesministerium für Digitales und Verkehr, 2016), a 38% increase in total freight transport capacity is assumed from 607,1 bn tkm in 2010 to 837,6 bn tkm in 2030. Hence, it is expected that the railway transport performance will more than double over the same period.

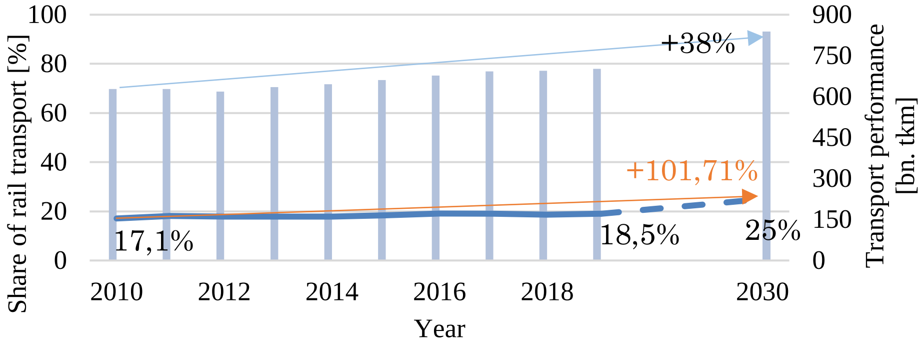

Figure 1: Development of cumulated freight capacity of rail, road, water and air from 2010 to 2019, including a forecast to 2030 (bar chart), and the corresponding share of rail transport (blue line). Compared to 2010, rail freight transport capacity is expected to more than double by 2030 (orange arrow). (Schuldt et al., 2013; SPD, Bündnis 90/Die Grünen, FDP, 2021; Statistisches Bundesamt, 2022)

The bottleneck of rail freight transport with single waggons or groups of waggon are the processes on shunting yards. Both, long downtimes and thus occupied tracks as well as high personnel expenses result in low competitiveness compared to road freight transport (Bistry et al., 2022). Enhanced by staff shortages, process automation through driver assistance and driverless rail operation is pursued as a solution approach (Blumenschein, Matthias et al., o. J.), such as demonstrated for metros (Wang et al., 2016) and in the near future also branch lines (Vogler Andreas, Künzler Robert, 2021). The motivation is strengthened by advantages seen in flexibility, faster operations, lower costs, higher safety level, better energy efficiency (Wang et al., 2016) and enrichment of the work of the staff. Hence, recent research is widely interested in Automatic Train Operation (ATO). The funded programs ATO Sense and ATO Risk of the German Centre for Railway Research (Deutsches Zentrum für Schienenverkehrsforschung, DZSF) define a framework for the functional requirements and risk acceptance criteria of ATC systems (*ATO-Risk/Sense*, 2021). However, there is no standardized end of line validation process certifying the system safety. A reference point for this, for instance, is the related research project PEGASUS, where a similar contribution is elaborated for the specific use case *highway pilot* in the automotive sector (Pegasus, 2020).

The validation of highly automated driving functions demands for a systematic testing procedure (Maurer et al., 2015). Following ISO 26262, a scenario-based testing approach is proposed in order to validate predefined system requirements within a coherent holistic context (Jipp, 2020). Therefore, a precise knowledge-based description of the scenery and the task to be fulfilled by the automated system are required. Test scenarios represent realistic situations of a particular use case including typical environments and elements such as specific objects as well as weather and light conditions in a certain parameter range. Variations in these parameter spaces lead to multiple concrete test cases for each functional scenario (Menzel et al., 2018). A test case is furthermore specified by pass-/fail-criteria defined by the expected system behaviour including acceptable deviations. In order to formulate these a related research program is initiated and will be contributed along the development of an on-sight-ATO-system. In Section 2, the operating environment and the specific functions of the shunting loco is described.

Test drives in the field are safety-critical and time consuming marked by high expenses. The scope of the test variety is immense, as every eventuality of operational use must be recreated. This becomes significant when operations at all times of the day and weather conditions are considered. However, test tracks are rare and in case of system failure, major damage to property and personal injury is not prevented. In terms of safety as well as economic and ecological efficiency, application of digital twin technology is a viable approach. Digital twinning is applied for planning and process surveillance within production engineering and becomes more and more decisive in other industries (El Saddik, 2018). Simulated system behaviours based on physical models and high optical resolutions of renderings enable an all virtual photorealistic process monitoring and hence, scenario design. In order to simulate participating systems sufficiently, the architecture and communication between subsystems of a perception based ATO system is presented in Section 3. Virtual testing considers the simulation of photosensitive sensors as well as the physical behaviour of lidar sensors. The emulated data is looped to the system under test (SUT) where the driving decision is made. Available simulation environments are designed for road vehicles and do not provide the level of detail required for railway vehicle applications. For instance, neither track bed, switch positions nor specific signalling or different railroad vehicles such as locomotives and wagons of different types can be pictured along physical properties, which severely compromises the validity of the tests.

Since ATO is becoming more and more feasible due to progresses in sensor technologies, a simulated test environment specifically for the application within railroad systems engineering is developed. Initially, the focus is on perception-based decision-making systems for shunting processes. These can be broken down to repetitive work steps operated on sight at low speeds. The development is driven by a recent automation project at the shunting yard Munich North of Deutsche Bahn AG. Contributing the licencing process of the automated system, the simulation environment is set up for independent black box testing. Ensuring an efficient innovation process on both sides, the development of the ATO system and the according test environment are coordinated by means of a test plan. Final end of line field tests of the ATO functions are used to verify the quality of simulated test results for this system.

2 Shunting Processes

During regular operation, train formation plants, i.e. shunting yards, are areas only entered by qualified personnel wearing warning vests aware of the risks and hazards. Vehicle maneuverings are performed on sight at velocities up to 25 km/h, in case of free track up to 40 km/h. As shown in Figure 2, in the simplest case, the yard can be separated into three areas. The arrival tracks, where mainline locomotives arrive and park freight wagons. A distribution zone, where high speed switch settings organize the wagon sorting into the classification tracks, where wagons with identical destinations are formed to new trains and the exit tracks, where these new train formations wait for a locomotive to leave the yard again on the way to the final destination.

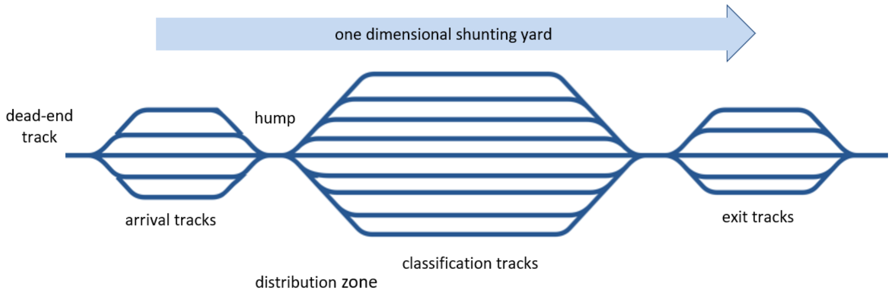

Figure 2: Schematic of a one-dimensional shunting yard.

In the arrival track the wagons are decoupled. The regular operation field of a shunting locomotive is between the dead-end track and the hump. Approaching from the dead-end track, the shunting locomotive is attached to the decoupled, unbraked wagons in order to push these over the hump. According to a dynamic switch setting in the distribution zone, the individual wagons or wagon groups roll one after another into the respective classification track following gravity. The speed of movement of the locomotive within this process is remotely controlled from the control centre since the driver of the locomotive at the end of the wagons cannot see the head of the pushed wagons. Once the last wagon rolls down into the target classification track, the locomotive driver takes back control of the vehicle. Commanded by radiotelephone from the control centre and confirmed by signals, the manoeuvre back to the dead-end track is initiated and performed by the driver. The driver continuously checks the track for obstacles, signs and light signals and must react accordingly at an early stage, since the braking distance of a shunting locomotive at 40km/h requires clear visibility of approximately 120 meters to detect any obstacles and stop safely. Automation of the shunting processes is widely discussed and objective of research and development projects since lately the year 2000 (Shabelnikov & Olgeyzer, 2020).

The most recent objective of research and development is the so called “digital shunting yard, Munich North” (*„Digitaler Rangierbahnhof“ soll Güter auf die Schiene holen*, 2021). Thereby the automation of four major elements is considered. First of all, a new coupling system (“Digitale Automatische Kupplung, DAK” – *english: DAC* - digital automatic coupler) is developed in order to speed up decoupling and coupling processes that still have to be carried out manually today. Second, artificial intelligence-based video camera surveillance checking wagons and cargo for damage and malfunctions. Third, the automatic brake function test for each wagon before leaving the shunting yard as part of a new train. Last but not least the automation of the shunting loco itself. For this purpose, the work steps of the locomotive are broken down into repetitive elements of action, the so-called "use cases". Thereby, a use case is understood on the one hand for the locomotive, on the other hand for the test method presented in this work. Typical use cases are delimitable elements of a specific shunting order, such as check, move, approach, attach, pressing-up, push-loose, follow, etc.

3 Automatic Train Control

Providing a holistic testing method for a certain system in a specific environment requires an understanding of the processes, the functional principle of ATO and its system architecture. Automated driving by means of driverless operation is initially feasible for self-contained systems such as metros, for instance operating in Nuremberg since 2008 (Railway Technology, 2008). The aim of railway automation rolled out to the route network is an optimized driving performance, including energy efficiency (Licheng et al., 2017) as well as a better passenger comfort and safety level(Amendola et al., 2022). Nevertheless, external disturbances jeopardize safe operation. As a first step, driver assistance systems are introduced. In the process, the human driver is gradually relieved of responsibility. The remaining degree of driver responsibility is depending on the grade of automation (GoA) according to IEC 62290-1:2014 (Schnieder, 2021). For line operation in passenger transport, these range from 0 to 4 and are defined as follows.

GoA0: Train operation on-sight. The train driver is responsible for the basic driving functions and ensures the train running safely without the use of assistance systems.

GoA1: Non-automated train operation. The driver ensures the safe operation of the vehicle. Stopping at red signals, meeting speed limitations and collision avoidance applying brakes automatically is supervised and might be advised by the system.

GoA2: Semi-automated train operation. The driver is responsible for operation in stations and continuously monitors the track. Driving functions are controlled by the system.

GoA3: Accompanied driverless train operation. All functionalities including operation in stations are covered by the system. Operation under human responsibility.

GoA4: Unattended train operation. Detection and managing emergency situations may be covered by the control centre.

The overall system of automated driving on rails is also referred to as Automatic Train Control (ATC). The ATC system includes the Automatic Train Operation (ATO) and is furthermore broken down to the subsystems Automatic Train Protection (ATP) and the Automatic Train Supervision (ATS). Within the ATP incorrect processes and track access is prevented. The Limit of Movement Authority (LMA) is derived from the current speed, the estimated braking distance and the distance to that point the train must stand still. This information is obtained from the track side and due to on-board sensors. The ATP responds a braking curve independently to the ATO and applies the brakes if necessary. Furthermore, the ATP sends the track occupation information to the ATS component. There, the positions of the vehicles are monitored and compared to the scheduled positions. The ATS is responsible for smooth processes due to planning vehicles, routes and rides. Using track side spots, the ATS is communicating with the ATO system, which is separated into trackside and on-board components. The ATO system receives the LMA and other information such as track-free-messages to control the main driving functions. Thus, the ATP has to fulfil certain safety and integrity requirements and works independently. The principle working schedule is shown in Figure 3.

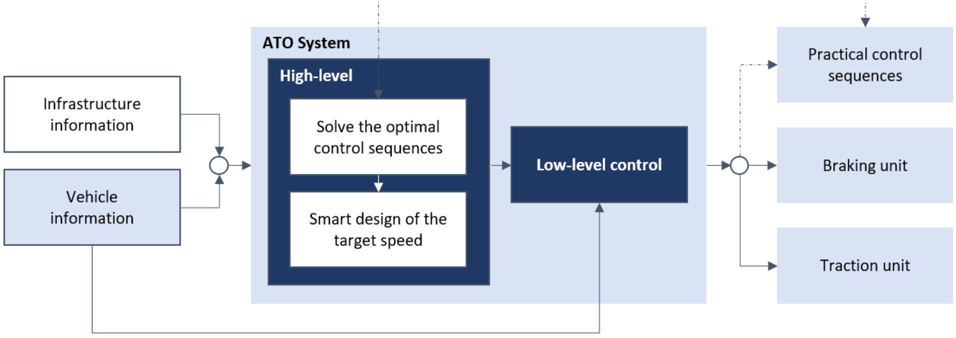

Figure 3: Schematic of the control sequence of an ATO system (Su et al., 2015)

Formal design, requirements and architecture, the development process as well as the verification and validation process are organized in a V-model structure. The requirements are continuously evolving and the testing is framed by some real case missions (Amendola et al., 2022) For the software development of the system itself and for the communication interfaces between the modules, the CENELEC EN-50128 (*Railway applications*, 2020) standard applies.

Thereby the ATO system is separated in a locally steady part (Track Side - TS) and the On Board (OB) System (Amendola et al., 2022). Information about the infrastructure, as well as the driving mission such as a shunting order (when operating in a shunting yard) is transmitted from the Control Centre (TS).

Data from the train itself is obtained by standard sensors such as derailing, fire sensors etc., the perception based automated operation requires a precise localization unit and further sensing devices observing the clearance profile in front of the vehicle for obstacles.

3.1 Modular On-Board System Architecture

In 2017 the Institute for Vehicle Technology in Nuremberg (IFZN) demonstrated the fundamental feasibility of applying ATC on a shunting locomotive, introducing local 3D obstacle detection (Cichon & Schaal, 2018; Koch P.,Vollet J.,Gleichauf J., Schaarl R., Falgenhauer R., Cichon M., May S., 2020). Thereby, a basic layout of the system architecture including a specific wording definition, shown in Figure 4, is introduced.

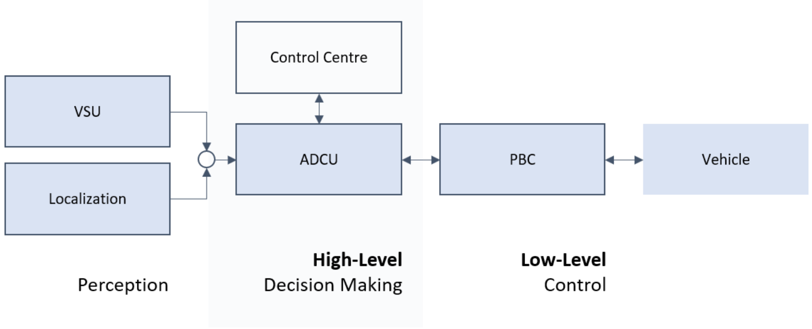

Figure 4: Principle architecture of a perception-based driving decision making and control system

The Vehicle Sensor Unit (VSU) is equipped with calibrated sensors such as RGB camera, B/W camera, IR camera, Radar, Lidar and supersonic systems. In the VSU the first stage of data processing is organized in sensor data fusion algorithms followed by object detection and respective classifications. Defined along the exact positions and dimensions of detected objects, an object list is forwarded to the Autonomous Driving and Control Unit (ADCU) where the high-level operation decision is made. However, the VSU might also forward raw sensor data. In this case, the data fusion must be processed downstream. Parallelly, a GNSS antenna setup sends the current positioning of the vehicle itself. The data is transmitted via Ethernet (UDP/TCP-IP) protocols for both perception subsystems, the VSU and the localization respectively. Based on these and a remotely transferred shunting order received from the control centre, the ADCU is configured.

Inside the high-level component ADCU the shunting order is reviewed. Based on the information provided from the perception systems and the current state of the vehicle, the

ADCU monitors the clearance profile and sets the ATO-command, i.e. start/ accelerate/ cruise/ decelerate/ stop, depending on LMA and the existence of obstacles in the driving path. This command is forwarded to the low-level component Power and Brake Control (PBC) in form of acceleration- or deceleration curves including a target distance and target speed. The PBC is a modular interface to the vehicle itself. For each vehicle the layout of the PBC must be adapted to the specific actuation and system behaviour of the drive train and the interfaces transferring related data. Furthermore, the PBC sends vehicle specific data such as speed and balise information, diagnose and condition data back to the ADCU.

3.2 On-Board Interfaces and Communication

The modular system architecture demands for an exact definition of the interfaces between each component. A precise definition of the data streams enables a flexible replacement of modules and also allows fetching and pushing data for testing purposes of each component during the development and validation processes. A common lay out is less connecting respective modules than applying a Message Oriented Middleware (MOM Server) serving as a central mediator. Within a “publisher/subscriber (pub/sub)” principle, data or messages are sent from the respective source to the middleware, where target components fetch the data of interest, also referred to as payload. Thereby, the messages are divided into an application header and the body containing the payload. The header describes the payload type and is visible for searching algorithms of subscribing systems interested in specific information payload. The communication principle is referred to as header-based pub/sub system, shown in Figure 6. (Henjes, 2010)

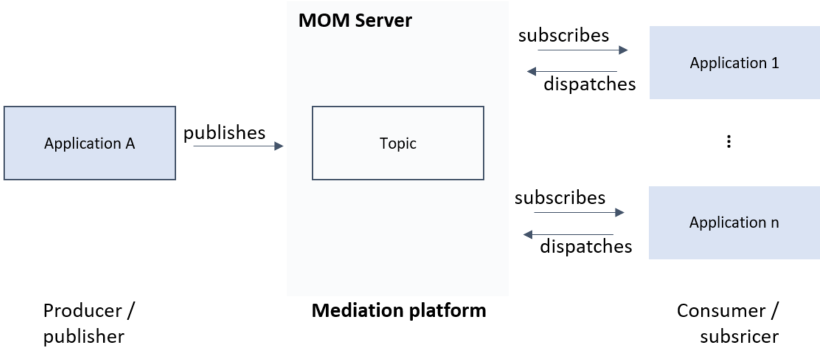

Figure 5: Publisher/ Subscriber Communication Principle (Henjes, 2010)

At least in early development and prototyping stages, common protocols for data exchanges are Ethernet based, such as the User Datagram Protocol (UDP) and the Transmission Control Protocol (TCP) respectively. Using UDP, data is sent with a low effort not depending on an existing connection to the receiver component. TCP sets up a reliable end-to-end connection. So-called sockets serve as end points allowing sending and receiving data between components. Thereby, multithreading is enabling parallel requesting. (Abts, 2010)

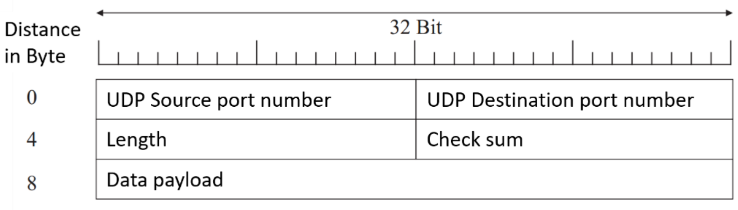

Figure 6: UDP Control Information (Mandl, 2018)

The header of a UDP data stream, as shown in Figure 6, is defined by eight bytes containing the source and destination IP address as well as the respective port number. Furthermore, an optional check sum and the total length or size of the message is included. The length of the messages is not constant but limited to $\mathbf{2^{16} - 1 = 65.535\,Bytes}$ (8 Byte Header + 65.527 Byte Payload). In case this threshold is exceeded by the payload data size, an efficient segmentation is required and numbering the sub-packets is helpful for checking and reassembling the data set at the receiving end. Both sending and receiving ends include a defined socket, i.e. an UDP instance. At the sending socket the message is separated, packed into the UDP data format and send to the destination port number where the data stream is decoded again. (Mandl, 2018)

3.2.1 Shunting Order

Every movement is initiated by the external operator. A shunting loco can be used for different tasks or missions, covered by the so-called shunting order, specifying successive work steps that are processed. A wireless communication system is used to forward a specific data set from the control centre to the vehicle. The data sent within this process define a concrete shunting order. The data is structured at least as follows. A consecutive order number (1) indicates a new shunting mission to be carried out. It is used to ensure operating in the right order of processing. The operator ID (2) indicates the person initiating a new operation. Since several automated vehicles might be operating in the same network, the vehicle ID (3) specifies the target vehicle. A time stamp (4) sent from the control centre and verified on the vehicle offers a safety redundancy in the sequence of individual orders. The same applies to the current position of the vehicle (5), which is used to verify the conformity of the infrastructure-side process status with that of the vehicle. The shunting order (6) describes the working steps to be processed. In case of pulling or pushing a wagon or a coupled wagon group is included in an order, the respective mass (7) and length (8) is required for model-predictive control (Makarow et al., 2018). Transmitting the target track (9) and -position (10) including the driving direction (11) completes a shunting order. This data is used for continuous monitoring and verification of the process. The release information (12) is the digital equivalent to optical signals confirming the right positioning of switching points and a free rail track. In case of emergency, running operations must be aborted remotely from the control centre (13).

3.2.2 Sensor Data

Each sensor provides a specific data stream. For safe operation on sight at least a ranging device is required for object detection (obstacle existence). Furthermore, optical systems can be applied for object classification (obstacle rating) and edge detection (Schubert & Obst, 2017). Since mono-camera systems provide a two-dimensional image, the depth information must be obtained from a ranging device. The information types provided by sensors typically applied are distinguished as illustrated in Figure 7. The images sent by the RGB camera are defined by pixels. The point cloud sent by the laser scanner holds 3D coordinates of each laser ray reflection point at an object. Both, laser scanner, i.e. light detection and ranging devices (Lidar), and camera data are sent via UDP.

Figure 7: Sensor data, optical RGB camera (left) and according point cloud from laser scanner (right), recorded during test drives in the shunting yard Munich North in December 2021 (IFZN)

3.2.2.1 RGB Camera

Optical systems are mostly used for object classification and track detection, i.e. determining the exact radius of curves in front of the vehicle to recognize the driving path and project the clearance profile to the trajectory (Kober et al., 2017). Furthermore, the optical system can be used to confirm the localization based on predefined landmarks (Becker et al., 2017). The RGB camera captures a video and sends pictures with a camera specific resolution in a certain frame rate. The payload of the UDP data stream contains the values for red (R) green (G) and blue (B) for each pixel of a single picture and the according pixel number.

3.2.2.2 Laser Scanner

Depending on the sensor type the communication varies for active and passive sensors. Active sensors such as laser scanners often provide a dynamically adjustable scanning pattern function. Changing this pattern according to a certain scan command requires a communication channel from the command layer in the VSU to the sensor. On the other hand, the sensor sends the collected environment data to the processing layers. Depending on the sensor supplier, individual protocols are used. The payload of such a data stream sent from a LiDAR laser scanner is given by the so-called point clouds. These are encrypted by three cartesian coordinates or spherical coordinates including the radius as the absolute distance to a certain point and also the reflectivity or the intensity of a certain reflection to the sensor. For UDP messaging these are encrypted to the data payload for each ray.

In terms of measuring principles, three methods are distinguished. Pulsed time of flight techniques (TOF) multiply the speed of light in a medium by the time a light pulse takes to travel the distance to a target. As the light travels to the target forth and back the time is halved to give the actual range value. A second approach is given by the amplitude modulated continuous wave (AMCW) technique. Maintaining a constant frequency f_M, the distance is deduced from the phase shift $\Delta\Phi$ occurring between reflected and emitted rays. The third approach is the frequency modulated continuous wave (FMCW) technique. Thereby the frequency of the emitted waves is periodically shifted. The reflections are mixed with the emitted source, creating a beat frequency that is measure of the probed distance. The CWFM method showed an even higher accuracy and an improved resolution and long-range values compared to the previous techniques TOF and AMCW approaches and is especially useful in outdoor environments. The main benefit of the FMCW method in autonomous vehicle applications is the ability to simultaneously sense the speed value and direction together with the range based on the Doppler principle. (Royo & Ballesta-Garcia, 2019)

3.2.2.3 Localization

Automating a mobile system presupposes a precise knowledge about its localization. The higher the grade of automation to be achieved, the higher the requirements for accuracy in localization and mapping (P. Gilliéron et al., 2006). As shown in Figure 8, the specifications of positioning systems for highly automated driving assume an accuracy of a few centimetres (P. Gilliéron et al., 2006). Commercial GNSS systems provide data based on an airborne and a ground-based subsystem. The data given by satellites is affected by various disturbances but improved to a certain degree using correction algorithms. Thereby the exact positions of ground-based sub-systems are used to monitor and update the relative positioning of the satellites and limit the deviations due to recalculations. The integrity of the resulting positioning fluctuates between five and twenty centimetres. (Watzenig & Horn, 2017)

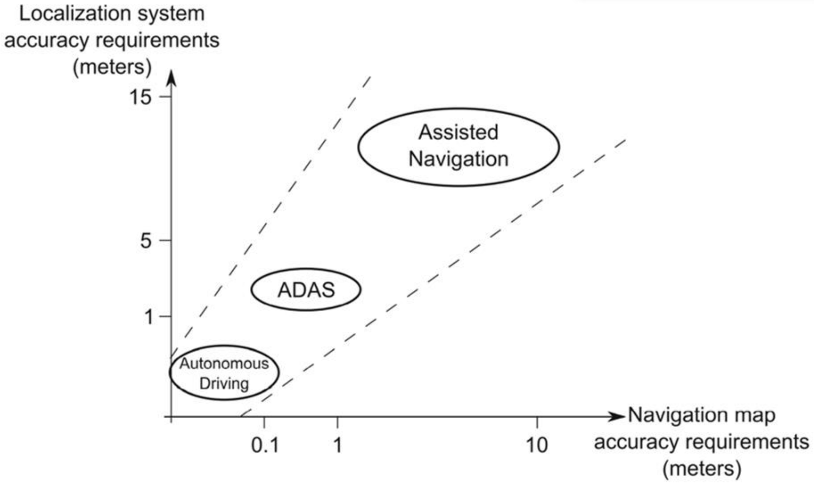

Figure 8: Requirements for localization and map accuracy in the development of highly automated driving functions (P. Gilliéron et al., 2006; Watzenig & Horn, 2017)

The data set of every positioning information includes lateral (lat) and longitudinal (lon) coordinates as well as the according altitude (alt). The exact protocol is depending on the supplier. When automating a road vehicle localization also refers to the positioning of the vehicle on the road, relatively to a specific lane (Watzenig & Horn, 2017). For shunting railway vehicles, the localization refers more to the vehicle position in the yard and the actual track. In order to increase the accuracy of the positioning digital maps and land marks can be used. The map is used to correct the lateral position to the actual track. Longitudinal correction requires further information, for instance from the camera module. Therefore, specific curves or certain objects in the shunting yard are utilized for orientation. Digitally mapped elements may be recognized by the high-level based on camera, Lidar or balise information.

3.2.2.4 Sensor Data Processing

The first processing steps mainly focus on filtering in order to reduce noises and increase the data quality. Unnecessary information is cut out to increase system performance. For instance, reflections of the ground-level are not further processed. Similarly, the camera images are truncated to the relevant field of view (FoV). For an efficient communication with the processing units downstream, the sensor data is fused, analysed and handed over in form of an object list, a small file format. Therefore, complementary or redundant sensor information is used to identify objects and wrap the point clouds into summarizing bounding boxes, as shown in Figure 9.

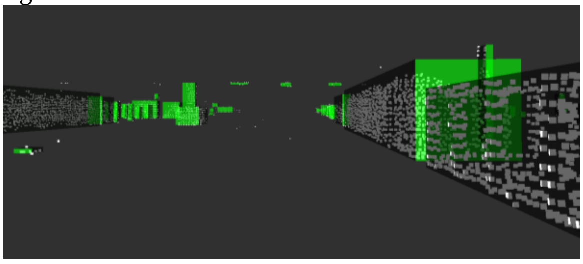

Figure 9: Point cloud after cutting ground level and merging objects to bounding boxes

Based on corresponding camera pictures detected objects can be classified applying artificial intelligence (AI) and deep learning algorithms, a data base containing pictures of possibly occurring objects in a huge variation. The object list holds the positions of the objects, their orientation and dimensions, their velocity including direction as well as the respective classification, i.e. the type of the obstacle. Subsequently, the driving decision is made in the autonomous driving and control unit. (Schnieder, 2019; Watzenig & Horn, 2017)

3.2.3 Autonomous Decision and Control Unit

Initiated by a shunting order transmitted from the control centre, the high-level component Autonomous Decision and Control Unit (ADCU) sets the driving command based on the object list from the VSU, the positioning from the localization device and information about the state of the vehicle. In accordance with a digital map, the high-level monitors the objects relatively to the driving path and communicates the driving decision to the low level.

3.2.4 Power and Brake Control

Depending on the system behaviour, i.e. the vehicle drive-train, the braking system and secondary actuation systems, the commands from the ADCU are translated to control the vehicle. For modular implementation of the automated system regardless of the vehicle type, the PBC is designed as the only interface between the vehicle and the automated system. Since vehicle specific data is required for an appropriate driving decision making in the ADCU, the interface between these two components is laid out bidirectional. The dynamic driving behaviour differs for each vehicle. For an efficient vehicle control, measurements in different weather conditions resulting in different friction coefficients are required for a model predictive control (MPC). Based on the system dynamics during acceleration and deceleration, so-called brake and acceleration curves are derived to control a certain speed change over a certain distance. The relations between external influences, masses and the drive/braking power are used to derive the vehicle kinematics in order to replicate a correct model of the vehicle behaviour.

4 Virtual Scenario-Based Testing of Highly Automated Railway Driving Decision Making Systems

Already during first development processes of automated systems test data is required for algorithm and logic verification. For this purpose, simulated data can be applied. End-of-line validation and licensing of highly automated driving functions is not standardized yet. Therefore, the so-called scenario based testing is introduced for the validation of predefined requirements within realistic situations of particular use-cases (Bagschik et al., 2017). As demonstrated since 2014, virtual test drives are performed as a part of end-of-line-testing (Neumann-Cosel, 2014). For the validation of highly automated railway systems, a four-stages approach, is considered. Therefore, the application of virtual testing is elaborated. The research presented focuses on the development of a simulated railway environment (LAB) including a digital model of vehicle and sensor systems for closed-loop testing of ATO functions. The LAB is parameterized based on real-word measurements to emulate realistic sensor data.

End-of-line testing starts with virtual Software-in-the-Loop tests. A two-stage hardware-in-the-loop test is used to test the ADCU-computer performance and the VSU under laboratory conditions. Reconstruction of critical and some basic test cases in real word rail tracks (FIELD) finalize the testing procedure. During the development of the virtual testing method, field tests are used for specific measurements and data collections. These test results are used for the validation process of the LAB environment itself, i.e. the quality of virtually performed tests.

4.1 Virtual Software-in-the-Loop testing

The SUT is fed with emulated data, decisions made by the ADCU are looped back in order to move the digital target locomotive through the 3D-LAB-environment.

Virtual testing requires simulated data streams of each input parameter of the SUT. As discussed, these are sent by the respective instances.

For a simulated test run of the SUT, these data streams must be generated and forwarded to the SUT using the respective specific UDP in a certain repetition rate. In each case, this rate is depending on the system specific characteristics. The SUT output on the other hand directly communicates with the interfacing module PBC, linked to the vehicle. In an all simulated loop, digital models for both the PBC and the vehicle kinematics are required.

For a holistic closed loop testing as required for highly automated driving functions, each module must be represented in the LAB. The developed architecture of the LAB is organized in a toolchain, as schematically shown in Figure 10.

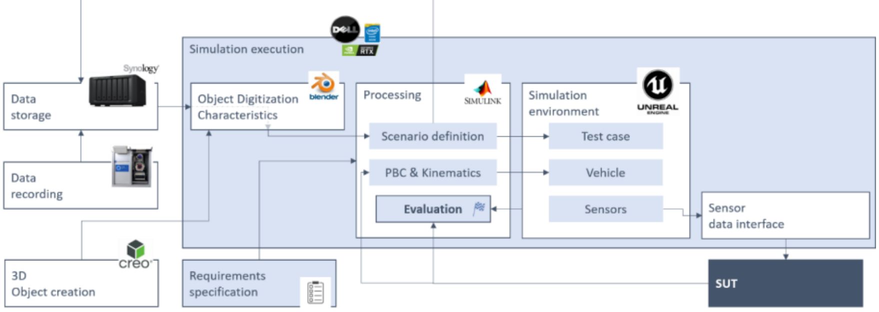

Figure 10: Virtual closed-loop testing toolchain of highly automated driving systems

Therefore, different frameworks and tools are used to embed and represent the physical sensors, the kinematic behaviour of the vehicle co-simulated in MATLAB Simulink, the 3D photorealistic environment where a test scenario is set up as well as processing units, where communication protocols are simulated and decisions made are interpreted. For test case description execution and evaluation, initially a scenario is defined.

4.2 Scenario design

Scenarios are defined for typical environments including static and dynamic elements such as objects and weather or light conditions. The method of describing a test scenario is introduced in 2013 (Schuldt et al., 2013) and developed from a four- to a six-layer model (Menzel et al., o. J.; Pegasus, 2020). Specifically for the railway sector, an approach presented within the PEGASUS project is adapted and reinterpreted. The six-layer-model model separates the layers rail layout, infrastructure components, temporal changes, traffic participants, weather and digital information such as shunting order, as shown in Figure 11. Designing a simulated scenario requires digital models of both the static environment and dynamic objects. Together with a shunting order and pass-/fail-criteria, derived by the expected system behaviour and an acceptable deviation, a test case is defined. For virtual testing typical elements are reconstructed based on real world data measurements. Thereby, the reflectivity of different materials, as well as sensor characteristics and noises in different conditions are investigated. Using different software tools such as computer aided design and blender, each element of a scenario is designed. For the visualisation of a scenario, a photorealistic simulated environment is created within the physics engine Unreal®. Unreal® is a development framework, originally developed for gaming and animation purposes. As part of a feasibility analysis, simple models of the individual components were tested for multiple competing products in order to verify their applicability with regard to strategic long-term competence development in virtual testing. Thereby, the Unreal® engine showed advantages in graphic resolution, performance, community support and accessibility.

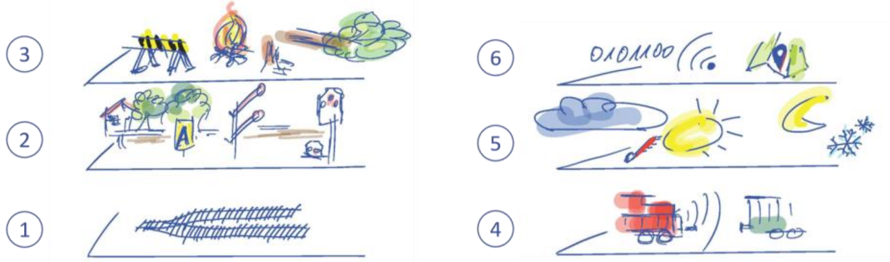

Figure 11: IFZN Six-layer-model of scenario generation for railway applications

The scenario editing is an extensive methodologic procedure. For a meaningful end-of-line validation a huge variety of test cases must be derived and adjusted to the system requirements. Parallelly to the research presented, another focus of the IFZN is on the necessity and reliability of the amount and variation of test cases for a particular use-case. These different scenarios lay outs, stored in a database for scenario reconstruction purposes in order to retest exactly the same test case, serve as the test basis to be carried out in the LAB.

4.3 Digital twins

Monitoring physical processes and product life-cycles using sensor data from real world and mathematical models of high level of adequacy replacing the systems behaviour is known from optimizing production processes. A digital twin can replicate living or non-living entities in all situations, at all stages of life cycle including emergencies with a big accuracy. Benefits are given in quick simulations of event evolutions in order to find errors and most effective operation modes. (El Saddik, 2018; Shabelnikov & Olgeyzer, 2020)
For the automation of shunting yards photorealistic models are used for process monitoring (Shabelnikov & Olgeyzer, 2020). A schematic 3D example developed at IFZN is shown in Figure 12.

Figure 12: 3D visualization of a schematic shunting yard (IFZN)

The 3D visualization enables augmented reality, in order to simulate scenarios for the evaluation of the process automation. Thereby, both infrastructural and locomotive components can be addressed. When automating the vehicle itself, simulated models of the systems involved are required.

4.3.1 Vehicle model

The testing method presented focuses on the automation of a shunting locomotive. The driving command set in the high-level is based on realistic perception. Therefore, the motion of the vehicle in the LAB is required to be also as realistic as possible. Since railway vehicles are track guided, initially a simple model of kinematics is considered sufficient. In a more detailed approach also pitch, yaw and roll are described within a kinematic model. Initially, the vehicle model is described by masses M_i, Forces F_i due to gravity, power (traction) as well as resistances (drag) and friction components μ.

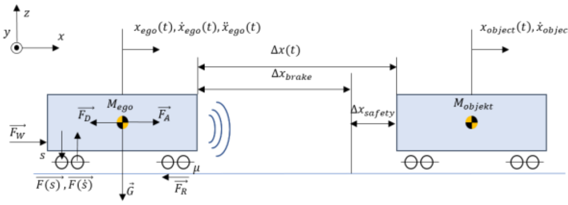

Figure 13: Parameters of a kinematic model of a railway vehicle

4.3.2 Sensor models

Optical systems such as cameras are specified by resolutions and characteristic lenses. Therefore, the framework Unreal® provides a huge variety of parameter adjustments. Depending on the camera system used within the sensor architecture of the automated system these must be customized.
Representing a laser scanner in form of a simulated model requires the exact scan pattern,

including the two-dimensional FoV in horizontal and vertical expansion and knowledge about the characteristic interfaces. The geometrical beam extension is replicated using ray tracing technology. Each ray either hits an object or is terminated after a certain threshold in a performance matter. The coordinates of collision between a ray and a surface is transformed from the global into the ego coordinate system and wrapped into the supplier characteristic UDP stream. Initially developed porotypes of the digital sensor models derive a simple dataset for camera and laser scanner, as visualized in Figure 14.

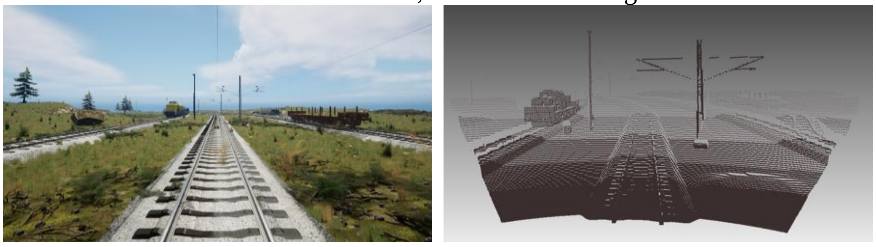

Figure 14:Idealized sensor data for camera (left) and laser scanner (right) derived from the Simulation-LAB

For a more realistic dataset, various measurements are investigated in order to recreate typical disturbances such as Gaussian noise and others. A further focus lies on the photorealistic scene rendering for a meaningful camera data stream.

4.4 Experience and first results

Considering the performance of the simulation framework in terms of computing and photorealism, the Unreal® Engine 5, released in April 2022 has been selected as a result of a determining feasibility study. Compared to the official documentation, community support, off the shelf plugins and module solutions available for version No. 4, there are still few information available.

In a second step developments focused on the creation of a simple simulation environment for demonstration purposes and approach evaluation. Reconstructed railway specific elements were successfully rendered within the simulation environment and a photorealistic scenery has been created. A model of the loco has been integrated into the simulation environment. The movement of the locomotive was defined to follow a specific track. The speed of the loco has been remotely controlled from a second computer. Therefore, the UDP sockets and protocols have been defined. A simple model of a laser sensor was developed and installed in the simulation environment at the front of the locomotive. The data has been streamed to a LINUX-based point cloud visualization instance in the Robot Operating System (ROS). The visualization of the data received from the simulation environment is shown in Figure 14. However, computing performance and rendering time of the simulation environment is not optimized yet. Hence, emulating sensor data at characteristic frame rates of 10Hz to 20Hz is not achieved yet.

In the recent third step of the development process the scenery is laid out according to the real field in Munich. This is required when testing the mapping and correction algorithms of the SUT`s localization system. Therefore, a spline has been defined along measured GPS positions, shown in Figure 15. The spline has been used to automatically create the virtual rail track and to guide the vehicle during virtual test drives. Thereby, sending the position (longitudinal and lateral) has been successfully demonstrated.

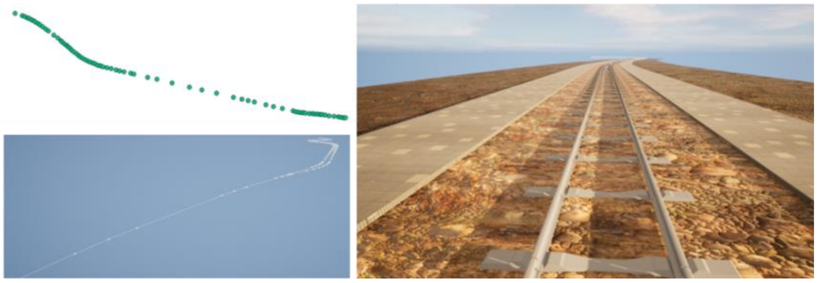

Figure 15: Reconstruction of a specific rail track using GPS coordinates (left, above) in the simulation environment (spline left, below, track right)

According to a certain test scenario setup, transferred from MATLAB Simulink using JavaScript Object Notation (JSON), related objects of the layers two to four of the six-layer model introduced in Chapter 4.2, have been imported from a database and located in the scenery.

5 Outlook

In this work a holistic virtual testing approach for highly automated sensor-based driving decision making of railway applications is proposed. Simulated sensor data is forwarded in a closed-loop to the system under test. Decisions are translated to control a simulated vehicle through the virtual environment. The aim is to represent tests in the field by virtual test drives. Therefore, digitally executed test cases are recreated in the field. The comparison of both test results is used to improve the LAB quality.

Ongoing developments focus on realistic sensor models and the real time data transmission to the SUT. Furthermore, the vehicle kinetics and kinematics are empirically derived and assigned to the simulated vehicle movement in order to close the loop based on a driving decision done by the SUT. A digitally reproduced model of the entire shunting yard in Munich North is aspired. On this basis, various scenarios can be built in the simulation environment. In addition, an observation instance is developed to automatically verify and evaluate test results.

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