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The Key to Automating On-Sight Railway Operations

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***Keywords*— Virtual Environment, Sensor Data Simulation, Closed Loop Testing, Virtual Validation, Automated Driving System**

***Abstract*— The success of automation initiatives in the rail sector hinges on selecting the appropriate tools for development, testing and authorization processes. Automated systems should be proven to be trustworthy and safe in every possible situation before they are brought to market. This manuscript uses a railway shunting yard as an example to illustrate how digital twin techniques can overcome challenges. It demonstrates localization-data-based environment virtualization for realistic and coherent perception data emulation across navigation systems, optical cameras, laser ranging systems and vehicle velocity. This progress reduces the reliance on real data recordings for the development of automated driving stacks.**

This article presents a comprehensive, domain-specific approach to developing and independently testing automated driving functions against functional requirements. Within a fully virtual, closed-loop laboratory setup, it highlights the advantages of flexible scenario design for effective and efficient development. In addition, a test run observer module is introduced, enabling successive test sequences while automatically detecting collisions and incorrect driving decisions. The study also provides an outlook on integrating AI-based algorithms and on transferring validated functions back to real-world operations.

I. Introduction

AUTOMATION is increasingly viewed as an innovative path for overcoming the challenges of manifold railway services [1] but progress is slow. Enhanced by staff shortages and demand for optimal processes, vehicle automation through driver assistance and driverless operation is pursued as a solution approach, such as demonstrated for metros [2], shunting [3] and also branch lines and trams [4]. The motivation for automation is strengthened by advantages seen in flexibility, faster and optimal operations, lower costs, higher safety level, better energy efficiency [2] and enrichment of the work of the staff.

This study presents a development approach for on-sight operation (OSO) of rail transportation systems, specifically the automation of shunting locomotives in a shunting yard because this is the most labor-intensive but not value-adding process in rail freight transport. The concept itself can be transferred to use cases with higher degrees of freedom such as tram lines and other guided vehicles.

Compared to more complex systems, such as those used for road vehicles, aircraft, or spacecraft, the automation of locomotive movements in a shunting yard may seem trivial, but it poses challenges, particularly in terms of terrain accessibility and safety criticality for execution of certification tests. Furthermore, suitable test areas are unavailable as most driving path observation methods rely on digital maps, meaning operation is only possible on certain sections of track.

Recent investigations in railway OSO automation culminate in the “digital shunting yard” in Munich, Germany, which also considers the roll out of a GoA4 locomotive in future [5]. Currently, neither standards nor empirical values exist for hardware selection or software architecture design, i.e. the automated driving stack (ADS). Related research mainly focusses on the sub modules for obstacle detection and classification [6], [7], [8] but an end-to-end signal pipeline (sense-plan-act) and the according test bench are not presented yet. Furthermore, there are no generally applicable licensing guidelines in either the railway or road transport sectors, particularly since it appears to be difficult or impossible to provide proof.

This paper presents system virtualizations in a co-simulation setup for a methodical approach to address these existing gaps. Starting with a basic description of the tasks to be automated and the challenges inherent in the example system, the requirements and scope of a tool framework for the entire development and early-stage test process of the automation is presented.

II. Motivation of System Virtualization

Single wagonload rail freight transport is currently facing major economic challenges, particularly in Germany [9]. Let the example topology be designed as a hump shunting yard, in which shunting locomotives approach groups of parked wagons. Once detected and slowly attached to them, the wagons can be pushed over the hump, rolling by gravitation and sorted into new train directions in the classification tracks. The locomotive returns to the dead-end track, where the process starts over for the next wagons. [10]

The objective of different interest groups is to automate these movements [11] which are performed without any train protection system, thus called as on-sight operation.

One vision of initiated, automated OSO envisages a land-based component from which a driving order is to be sent to the vehicle. An appropriate on-board driving decision can then be made based on perception systems for observing the surroundings, geo-localization systems for estimating position and real-time data on vehicle parameters. Sophisticated ADS rely on sensor data fusion algorithms for redundant and stable decisions, especially under uncertain conditions. A geolocation system accompanied by a digital map of the area is used to

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determine the vehicle's trajectory. [12]

Similar to other shielded areas, e.g. space exploration, here the economic necessity of continuous operation prevents regular access to the real physical test site. In addition to a functioning locomotive and its operating costs, there are other factors in the field, such as closed test tracks, test managers, shunting attendants and train drivers, who are not only financially unavailable, but also lack capacity noting that the number of tests is a multiple of thousands of possible critical situations. Moreover, for regulatory reasons, difficulties arise when the first sensor data is recorded, both to verify the sensor selection and to develop the initial algorithms and system architectures on which the automated system will later be based. Furthermore, the recording of scenes that harbor high risks of property damage and personal injury is strictly prohibited. However, in order to troubleshoot the algorithms and identify edge cases, it is essential to use sensor data whose georeferencing matches the digital map. To ensure sufficient diversity of testing and accessibility at an early stage, the physical test site should be replaced with a simulation.

Computer science entered the field of simulation engineering in the second half of the 20th century [13], evolving to encompass virtual representations of complex systems and architectures, including those in the railway sector [14]. Today, research into system virtualization is widespread in the automation of robotic applications, with the aim of providing a detailed representation of characteristics. Following the argumentation of Kritzinger et al. [15], a Digital Model (DM) of a physical test site, here the shunting yard, can be recreated by a physically and visually realistic environment rendering. This approach based on physics engines (PE) is demonstrated for instance in the automotive [16] [17], aerial vehicle [18] and the railway domain [10], [19]. Virtual end-of-line testing of automated systems has been established in recent years, as part of the PEGASUS project [20], and has also been suggested for the railway sector by Greiner-Fuchs et al. [21]. According to Aheleroff et al., the overall virtualization of the closed loop setup [19] turns the DM into a 'Digital Twin Predictive' (DTp), a virtual replication of all systems involved without any linkage to a physical property, but real time communication in the co-simulated cyber space [22].

Compared to systems with higher manoeuvrability, rail vehicles are laterally guided which simplifies control but also prevents them from swerving in front of obstacles. Hence, precise obstacle localization is mandatory. Therefore, automated driving systems can rely on geographic and topologic information, to map their position and thus observe their driving gauge for collision course with any obstacles [12]. This introduces a new, yet fundamental, requirement for system virtualization. The DM of the shunting yard must stick to the exact GNSS coordinates and rail topology of the physical field and accordingly provide an interface for localization sensor modelling, to make the automated system think to be in the physical yard.

Summarized, virtual simulation enables the accessibility of coherent data within the test and development process of automated and autonomous systems. For this purpose, the approach demonstrated in [10] is modified and rolled out to the entire arrival track section of an example shunting yard in Germany using publicly accessible geo-information.

III. Setup of the Co-simulated Cyber Space

To exploit the advantages of virtualization throughout the entire process chain, each subsystem involved is modelled to a DM. The distribution of the single models to stand alone computing instances is chosen in terms of flexibility in coworking and transparent fault allocation. According to an architecture proposed in [10], the DTp is set up in a closed loop as follows in **Fig.** ***1***. Instance (a) defines the operational design domain (ODD) [23] – corresponding test scenario description. This description refers to the expertise and knowledge of people, involved in the daily processes that are to be automated.

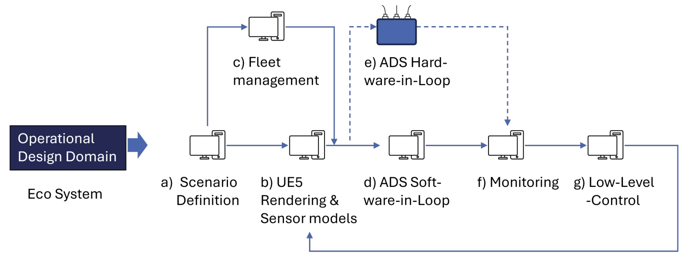

Fig. 1. Co-simulated closed loop setup

The scenario description reaches from regular daily situations to highly complex edge cases, with a high potential of risk and danger. [24]

For this explicit use case, the scenario variation is methodically structured along the 6-Layer model of situation design [10], **Fig.** ***2***.

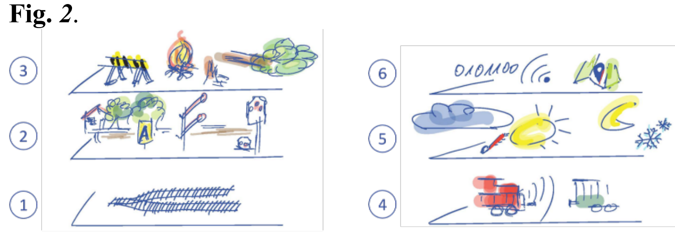

Fig. 2. 6-Layer Scenario design model [10]

In order to create a virtual model of the example shunting yard, layer 1 (rail topology) as well as layer 2 (steady objects and infrastructural components) are related to the actual layout of the physical property. Therefore, pictures and geoinformation of the arrival tracks is gathered from public platforms. The height and inclination data are provided by the state administration [25] and are used to draft the topology of the area within the PE. The rail track geometry is obtained from BRouter [26] together with additional open map data, exported as CSV files. These data are transformed into splines in the PE and combined with the corresponding height map to generate the digital terrain model. The Universal Transverse Mercator (UTM) zone is represented as a three-dimensional rectangular coordinate system, which defines the virtual dimensions of the environment. This setup enables a virtual positioning sensor to emulate the real-world GNSS data as it moves through the simulation. Depending on the required fidelity of landmarks

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such as poles or buildings, other scenario elements from the real yard should be included within this mapping process.

The layers three to six can be designed flexibly. The final scenario description is defined in the form of a standardized JavaScript Object Notation (JSON) file, which is based on a proposed open standard [27]. The description file is forwarded to the PE (b). Following this procedure, a scenario can be stored and reproduced for comparative test runs.

The fleet management system (c) is modelled on a real control centre (CC). It is designed as a graphical user interface providing an abstract overview of the existing tracks in the drivable area. The interface enables the definition of a switch setting to adjust the route for the locomotive.

The CC handles the communication protocols with the mobile component, i.e. the vehicle. It prompts the shunting order described in the scenario description (i.e. attach, drive, emergency stop, etc., as well as the actual position plus the targeted track, layer six) to the Autonomous Driving Stack (ADS) (d or e) and thus initiates a virtual test run.

Together with the DM of the shunting yard (b), the CC simulates the land-based component (locally stationary) of the automated system. This DM is a precise representation of the entire arrival track harp of the example shunting yard, as shown in **Fig. *3***. The linkage to the CC allows the virtual point setting and communicates the starting position of the simulation according to the scenario description, i.e. activating a certain track spline.

Fig. 3. DM of the example shunting yard arrival tracks in PE showing an explicit situation

The layer 3 to 5 elements of the scenario description JSON file are then successively spawned as actors along the selected driving path on that map.

The vehicle itself is spawned as the main playable character. Similar to a real locomotive moving along a track, the virtual vehicle is guided along the activated spline. Digital perception sensor models are integrated to the PE and virtually mounted at the front of the vehicle. The simulated GNSS sensor is variably attached to the centre of the vehicle and continuously emulates its position. The sensor models emulate the physical sensor data streams, for each sensor required on the real-world system. The data, visualized for Light Detection and Ranging (LiDAR), Red-Green-Blue (RGB) camera, odometry and UTM positioning in **Fig. *4***, is then forwarded via User Datagram Protocols (UDP) to the ADS.

For independent safety argumentation the ADS can be integrated and treated as a black box system under test. Thereby, the ADS can either run on laboratory computing units (software in the loop, SiL) or the final in-field hardware (hardware in the loop, HiL). However, the driving decision of the ADS is forwarded to a vehicle kinematics model (g, MATLAB Simulink), which in turn controls the velocity of the vehicle through the simulated environment (b) and hence turns this DM composition into a DTp.

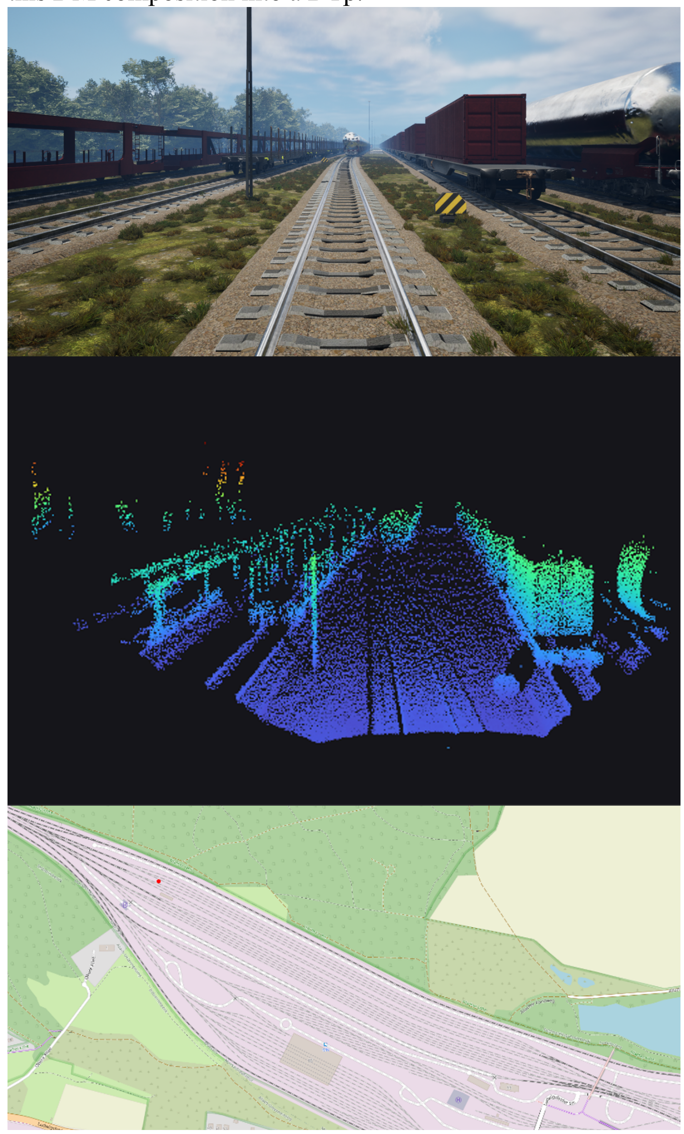

Fig. 4. PE Emulated sensor data of RGB camera (top), LiDAR (mid), GNSS (red dot, bottom), visualized using foxglove studio and Open Street Maps.

IV. Testing the Automated Driving Stack

Although end-of-line testing would require a large test catalogue, even simple function developments can consider multiple test cases in the early stages. Minor changes to the ADS software may necessitate retesting all passed test cases to ensure that the changes do not affect other subsystems and earlier developments. To this end, the closed-loop setup enables automated testing of any pre-defined cases.

Each test case definition implies an expected system behaviour. The corresponding evaluation criteria must be derived specifically for each use case. Whether a test case passes or fails

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depends on several aspects, as shown in **Fig. *5*** [28]. Thereby, the influence of each object within the domain-specific scenario description (6-Layer Model) expands the test case diversity. The applicable legislation and risk assessments define the boundary conditions against the background of safety, while the technical requirements define the minimum quality of service.

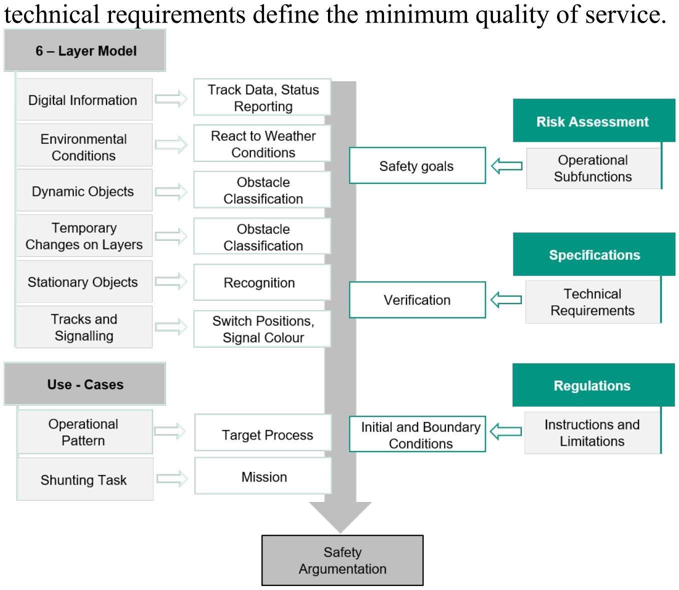

Fig. 5. Methodical approach of defining pass fail criteria in order to contribute a safety argumentation, leaned on [28]

These attributes are developed to the evaluation criteria for scenario-based testing of highly automated railway driving-decision systems [29]. Their mathematical description is modelled in the PE as a collision observer model (COM), running parallelly to the postulated test runs as described [28]. During simulation, the COM model detects failed test runs. This automated test observation allows unsupervised testing for a sequence of test cases. The output of the COM serves as driving test report and thus can contribute a safety argumentation.

V. Results and Discussion

Addressing the central research questions of this study, two key objectives were achieved. An independently developed rudimental ADS (automated driving and control unit, ADCU [12]) was integrated into the presented test bench. Thereby, the closed loop was set up and put into operation successfully. The ADS received GNSS and LiDAR point clouds and returned the target velocity to the vehicle model. The ADCU's main focus was obstacle detection from LiDAR point clouds. The clustering algorithm was tested in a scenario involving an approach to a container wagon. This experiment demonstrated that virtual closed-loop testing can be used for railway applications.

The second achievement is the development of an experimental but full ADS. To the authors' knowledge, it is the first software stack with a complex raw sensor data processing for OSO in the railway domain [30]. The software stack was tested for about 100 hours real operation time (locomotive moving). The maximum velocity of the simulated vehicle was limited to 15 km/h. The test scenario description was chosen to the randomized localization of different wagons on 14 tracks, as pictured in **Fig. *3***., no further disturbances, only the regular service including the original signalling at good weather conditions during summertime afternoon.

The test runs showed confident detection of freight container wagons, appropriate driving decision prompting and a correct scenario handling in most cases. A two-storey car transporter was repeatedly not recognised in time with the selected sensor settings, which led to collisions. This is a critical test scenario, since the front face of these and other so called flat wagons without any load is very small, but still must be detected on time to prevent collisions. This test case is reminiscent of a fatal accident that occurred in 1999/2000, when a radar-based automation system was tested and failed.

The automatic setup of scenarios and the initiation of test cases was tested alongside the COM. The test capacity resulting from the time savings enabled rapid improvements in the development of the system under test. An optimized object clustering for instance stabilized the detection of critical wagon types.

Despite the breakthrough in developing a full ADS for railway application, there is still a lack of transfer from virtual testing and development back to the real world. This domain gap is widely discussed and not limited to the railway sector [31]. The quality of the sensor models was evaluated using pre-trained computer vision models and further standard methods adapted from the automotive domain. The results showed a promising analogy to analyses on real world data. [32], [33], [34].

The full ADS has not yet been applied to real-world applications. Thus, the influence of the domain gap on the quality of the driving stack development cannot yet be assessed.

VI. Implicated Strategy for Automation Management

Depending on the specific use case and data accessibility, subsystems of varying scope may be required for simulation. It is therefore important to identify all the subsystems involved in the automation process during the initial project stages and analyse the need for their virtualisation or their integrability at a later stage. Although competencies in standards, service, ADS development and simulation are mostly distributed among different groups, effective progress requires close collaboration between them. Many development teams have to work on the project simultaneously. Therefore, the interfaces, variables and protocols between the subsystems must be defined precisely. The simulations are extremely computationally intensive and may need to be run on distributed systems. Maintaining the server infrastructure and providing workplaces for software engineers is not something that should be underestimated.

It is helpful to check whether any of the individual simulation modules are already available and can be integrated into the closed-loop setup. One example is a vehicle kinematics model, for which extensive measurement runs would otherwise be required. The same applies to sensor models, which are already available for certain devices.

The test scenario design can be processed using various models and taxonomies. However, it is important to identify a relevant and efficient sequence of tests so that a measure for safe operation can be determined within a finite test scope. This also means that the test developers must be independent of the ADS development team. They provide appropriate test cases for each stage of development, so they must be closely involved in the process.

Once the system has been declared functional in the virtual closed-loop setup, it is advisable to transfer the development process to reality submodule by submodule. For instance, sensor models can be replaced by real word data while keeping other subsystems simulated. The final step is to correct the uncertainties in vehicle kinematics modelling within a vehicle in the loop and metaverse test. To this end, all systems operate on the target hardware within the target vehicle in the target field. Metaverse testing means, obstacles such as humans are augmented in real-time into the real data stream before involving real humans.

This approach also highlights the need for new competencies in simulation engineering, data management and scenario design, indicating a potential shift in workforce qualifications and training requirements.

Although the concept was demonstrated for a shunting yard, it can be transferred to other guided transport systems, such as trams and branch lines.

VII. Outlook –DMs as a Virtual School Bench for Automated Systems

The ADS development process involves a wide range of stakeholders, including authorities, licensing agencies, operators, investors, manufacturers and others. First, standards must be created in broad-based consortia that make the approval process for automated OSO systems transparent and accessible.

The results presented demonstrate how virtual models can speed up and reduce the cost and risk of developing automated driving functions by replacing scarce and expensive field tests with reproducible, closed-loop simulations. This accelerates development cycles, makes more efficient use of resources and enables the systematic testing of edge cases and safety-critical scenarios before deployment in the field. As described here, the virtualization of the rail environment is a strategic first step in virtual engineering supporting the automation strategy of railway vehicles. Using the example of a shunting yard, the approach demonstrated that sensor data for GNSS, LiDAR, cameras, and odometry can be emulated consistently within a physics-based simulation, thereby reducing dependence on costly and limited field trials. The integration of automated scenario generation and a collision observer enabled systematic testing of functional requirements and edge cases, contributing to faster development cycles and stronger safety arguments.

In addition to the sensors described methods for emulating synthetic sensor data for ultrasonic and radar systems as well as infrared cameras can become relevant in future, to fulfil redundant specifications such as multi-sensor perceptions.

Complex algorithms such as convolutional neural networks diffuse more and more into systems of everyday life and hold a huge potential, for instance in object detection and classification [35]. Yet there is neither a common approach of understanding the decisions of such a system nor a methodical description of a minimum variety of training data required. Using the presented virtual environment, the authors are researching on different techniques of training and explaining artificial intelligences (XAI) to monitor the decisions (classifications) of neural networks. The overall aim is to find an argumentative basis to integrate complex algorithms into authority proven devices. These investigations are considered within the postulated testing process as formulated in **Fig. *6***.

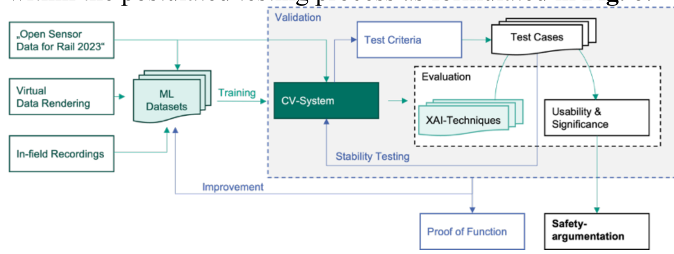

Fig. 6. Safety argumentation of deep learning-based object classification in the railway domain using XAI techniques and ODD specific test cases

Trained Computer vision models (CV-Systems) are embedded into the ADS under test. There are some domain specific training data sets available, the data base for the railway sector is low, the "Open Sensor Data for Rail 2023" [36] is a beginning, but the recording and preparation time beforehand is cumbersome and error-prone [37]. Programmes such as RailSim [6] offer virtual training data in an attempt to provide a replacement strategy, but they may be too generic for specific use cases. In order to create an ODD specific training data set, an additional module was integrated into the PE to rapidly create appropriate virtual ground truth data [34]. Having the scenario describing JSON file and the rendered sensor data, use case specific labelled virtual training data can be created. That turns the DTp into a playground where machine learning models can learn from. The COM of the test cases downstream are extended by the XAI techniques to measure which training data is useful, and which not.

With an increased fidelity of the virtual environment, the overall aim is to train the ADS within a virtual laboratory environment for in-field service. This approach is already demonstrated for RGB-image based signal detection [38] and RGB-image based reinforcement learning for driving decision making [39]. In a next step multimodal CV-Systems will be investigated.

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