Automated Coupling of Freight Wagons using a Road-rail Vehicle and Innovative Communication and Positioning Technologies

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***Abstract*—The focus of this work is the development of a comprehensive system for the automation of shunting processes in marshalling yards, based on an electrically driven dual-mode (Road-rail) vehicle as an autonomous shunting vehicle (ASV) and a highly available localization and communication system. Possible areas of application are shunting locations where a low volume of traffic does not justify large shunting yards. In addition, individual subsystems can also be used across different modes of transport, as key innovation pillars - secure communication and reliable localization - are also essential prerequisites for highly automated driving in road transport. The associated research project AZubiG lays the foundation for electromobile logistics in rail freight transport. AZubiG enables automatic and highly flexible 24/7 operation in shunting and rail operations. This strengthens the competitiveness of rail transport by improving the “last mile” and exploiting its ecological and economic advantages. The main requirements were a system architecture for reliable localization and secure communication, system design, implementation and integration of the electronic components for the implementation of automated shunting operations. In functional terms, this affects the shunting vehicle on the one hand and the freight car itself during the coupling process on the other. In specific terms, the design of the components of the positioning system based on a radio sensor network (WSN) consisting of permanently installed anchors and mobile tags is explained in this context. The TDoA (Time Difference of Arrival) method proved to be suitable for dynamic deployment scenarios. However, this requires highly synchronized infrastructure points, which are usually implemented using wired solutions. In the railroad sector, cabling of this type is difficult to implement, as infrastructure points are required on both sides of tracks and subsequent cabling is therefore not feasible or economical. For this reason, a concept was developed that is completely wirelessly synchronized and uses ultrawideband (UWB) runtime signals between the anchors in order to synchronize them with each other continuously. In the end, the work presents laboratory and field tests of varying granularity (railway laboratory, railway research hall, research operating yard) and their evaluations in terms of feasibility of an autonomous shunting vehicle.**

Keywords- Railway; automated shunting; marshalling yard; shunting yard; automation; intelligent transport systems; autonomous shunting vehicle (ASV); UWB; TDoA

I. INTRODUCTION

Today's transportation systems face a multitude of complex social, economic, environmental and technological challenges. While innovative and disruptive technologies, such as the use of Unmanned Aerial Vehicles (UAVs) in transportation, are opening up new opportunities, historically evolved transport infrastructures continue to be of central importance. An outstanding example of this is rail transport, whose roots go back to the early 19th century. A significant milestone was the commissioning of the first steam locomotive with 36 attached wagons for public rail transport between Stockton and Darlington in 1825 - an event that laid the foundations for the modern rail industry and continues to shape global passenger and freight transport today [1], [5]. While rail freight transport makes an important contribution to sustainable mobility thanks to its high energy efficiency and comparatively low emissions, many processes still face considerable challenges. Particularly in the areas of shunting and train composition, numerous procedures are still characterized by manual processes that are both time-consuming and inefficient. The digitalization and automation of these workflows offer enormous potential for optimizing logistics chains, increasing transport capacities and reducing operating costs. The increased use of modern technologies such as artificial intelligence, automated coupling systems and digital control systems could help to make rail freight transport more efficient, economical and environmentally friendly. In this regard, the Section II of the article examines the current status of shunting in a marshalling yard and discusses the shortcomings of current shunting systems. Building on this, Section III introduces the autonomous shunting vehicle (ASV) and explains the components relevant for automation, as shown in Fig. 1. In addition, Section IV takes a closer look at concepts for secure, high-availability localization and communication. The article concludes with a discussion of current laboratory and field tests in a railroad research depot (City of Dresden, marshalling yard, Germany) in Section V and further work in Section VI.

II. STATE OF ART - AUTOMATION OF SHUNTING PROCESSES IN MARSHALLING YARDS

As highlighted in [2], [3], current shunting systems face significant limitations that hinder their efficiency and

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adaptability. This is particularly critical given the increasing demand for freight transport, with rail freight playing a crucial role as a low-emission alternative. Additionally, the ongoing digitalization of rail transport and the integration of smart freight wagons exert growing pressure on shunting yard systems to incorporate digital solutions. The presence of media discontinuities within these systems would compromise the feasibility of an end-to-end digital transport chain.

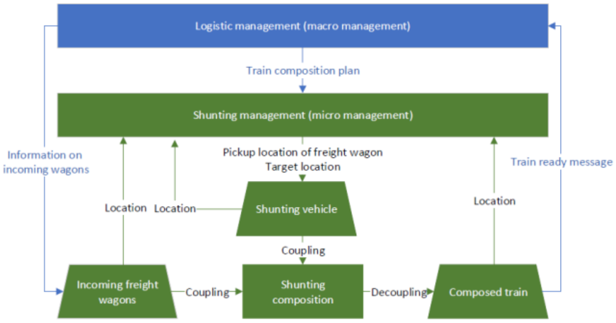


Figure 1. Abstraction of the automated shunting process [2].

A. *Overview of relevant components for shunting*

We have the following components for shunting in this order:

- Shunting management process
- Localization especially multisensor data fusion of Realtime Kinematic Satellite based localization (RTK GNSS), Inertial Navigation System (INS) and Wireless Sensor Network (WSN) for seamless localization in-/outdoor
- Communication Systems especially leaky coaxial cables
- Obstacle and railtrack detection by AI-camera
- Digital Automated coupling
- Smart infrastructure and onboard systems
- Human machine interface
- Safety and security concept
- …

In the following, we will focus on the explanation of components for understanding and specifically on scientific and technical innovations. The systematic shunting process with its individual stages is shown below. In this regard, the coupling process requires a particularly high degree of accuracy in the position and alignment of the ASV

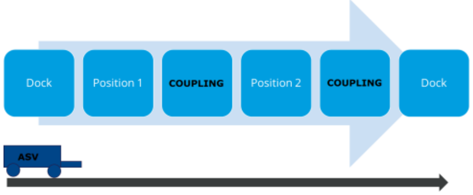


Figure 2. Shunting process

B. *Introduction of Wireless Sensor Networks for Positioning and Navigation*

In order to realize an autonomous coupling process indoor and outdoor in freight yards, a WSN is adapted for positioning in combination with RTK GNSS and an INS combined in an Onboard Unit (OBU) [6]. The technical basis for this was the recent increase in miniaturization and the progressive development of microsystems technology for the construction of highly complex sensor nodes, which are combined as individual systems in an infrastructure-free and self-configuring WSN based on Ultrawideband (UWB).

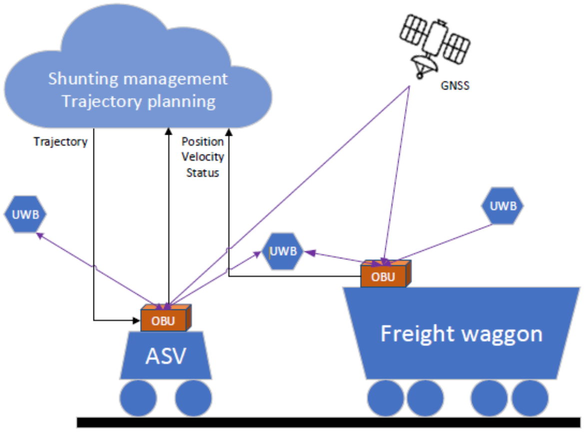
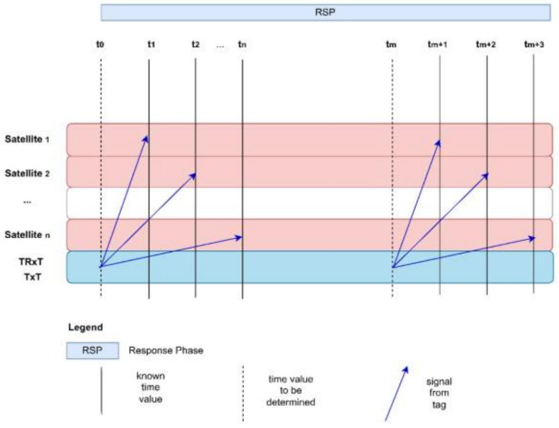


Figure 3. System overview for the ASV and freight wagon technologies required for an autonomous coupling process [2]

In this context, the focus in the following will be on positioning and navigation with radio sensor networks and not on RTK-GNSS (a sufficiently well-known and established method). In generally broadband radio systems can be used for providing distance relations in the form of distance and angle measurements in corresponding real-time performance e.g. on the basis of the licensed ultra-wideband spectrum (UWB). Within a WSN typically with at least four permanently installed anchor nodes, an ASV equipped with a tag can autonomously run a corresponding necessary trajectory to the track and then to the wagon. The anchor nodes are statically attached in pairs to appropriate infrastructure in buildings or outside in the marshalling yard, e.g. to lanterns (see Figure 4). A total of 6 indoor anchors and 12 mobile outdoor anchors were used for the test area. These are PoE-capable and time-synchronized to a central unit.

Figure 4. One of six installed UWB indoor Anchors in the test area

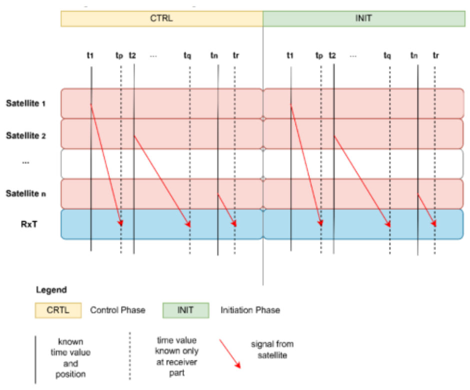
In principle, the tags fitted to vehicles can also change their role to an anchor under appropriate boundary conditions, such as when a vehicle is stationary. nodes can be integrated, for example, in the clothing of forest workers or directly on mobile devices such as drones, chainsaws. Operationally and algorithmically, static and mobile nodes can switch properties [2]. The shunting vehicle can move freely and must therefore be located freely in 2-dimensional space regardless of track layouts and environments. The accuracy and the update interval should therefore be as high as possible. During rerailing, it is necessary to localize in the cm range. The control system runs on the shunting vehicle itself and therefore the position must also be available on the vehicle itself. A direct calculation of the position on the vehicle would be useful so that external influences and interference can be excluded and the fusion of wireless localization with intertial sensors etc. can be carried out with very low latency. The up-link time-difference-of-arrival method is used to localize the wagons, while the shunting vehicle is to be located using the down-link time-difference-of-arrival method. Both methods are described in more detail below. With UL-TdoA (see Figure 5: Uplink TdoA in CoreZone Specification), a tag (usually battery-operated) sends a message via UWB, which is received by the infrastructure. A single packet is sufficient for localization, which makes the implementation very energy-efficient. The position is then determined by algorithms in the server, which evaluate the runtime differences in the installed satellites (infrastructure on the site, which is permanently installed and whose positions do not change). The position calculation itself therefore takes place centrally and can be saved directly on the server.



Transactions	Interface to upper layer
t0: TxT / TRxT sends message. t1: Satellite 1 (noted S1) receives message. t2: Satellite 2 (noted S2) receives message. tn: Satellite n (noted Sn) receives message.	S1: I received the message back from tag at t1. S2: I received it at t2. Sn: I received it at tn.

Figure 5. Uplink TdoA in CoreZone Specification

With the DL-Tdoa method, on the other hand (see Figure 6: DL-TdoA in CoreZone Specification), the individual components of the infrastructure send their own signals permanently (every 125ms) with additional information on position and time synchronization. These signals are used among each other to keep the entire network time-synchronized on a UWB basis. At the same time, by receiving these signals at an end point, the own position can be calculated using the runtime differences. However, this process requires more energy, as a UWB transceiver in the receiver module has an increased energy requirement and the reception of such messages must be permanently guaranteed. The shunting vehicle provides a receiver with sufficient energy, as the energy required to move a wagon or the vehicle itself is much higher and the vehicle must therefore generally be charged regularly. The onboard calculation can therefore be carried out centrally on the vehicle and made available in combination with inertial sensors without high latencies.



Transactions	Interface to upper layer
t1: Satellite 1 (noted S1) sends message tp: RxT receives message t2: Satellite 2 (noted S2) sends message tq: RxT receives message tn: Satellite n (noted Sn) sends message tr: RxT receives message	none

Figure 6. Downlink TdoA in CoreZone Specification

This technique enables energy-efficient, highly dynamic and flexible 2D positioning of the shunting vehicle in appropriately equipped areas of marshalling yards and buildings. In this context a special feature is realized, the challenge of seamlessly locating the ASV from indoors to outdoors and vice versa. These areas are as shown in the following Figure 7, for example roll-up doors.

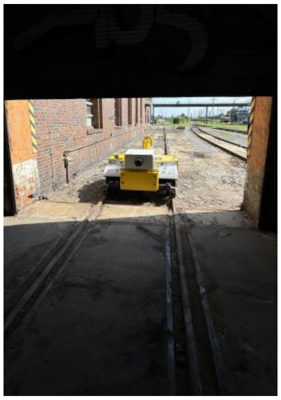


Figure 7. indoor/outdoor transition

III. AUTONOMOUS SHUNTING VEHICLE (ASV)

In generally, the shunting process with an ASV is illustrated in the following subtasks (see Figure 8). First, a preliminary positioning of the ASV is initialized on the basis of existing positioning signals. This is already based on integrity approaches based on technologies such as GNSS, LCX, WSN), some of which are independent of each other. In this phase, an operator also specifies a destination point for rerailing on the track plan and a travel trajectory is then computed. The ASV then travels autonomously along this trajectory to the destination point and a new phase of fine positioning on the track begins.

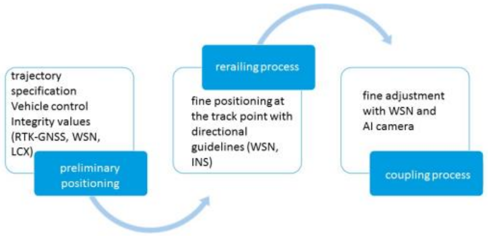


Figure 8. Shunting process scheme

This is essential so that the rerailing process can be realized. A very precise angle-based alignment in +/- 1 angle accuracy of the ASV is absolutely necessary here. This is achieved through the combination of INS and an AI-supported camera that recognizes the tracks. Once again it is made clear that in this context it is not the absolute position accuracy on the track that is relevant but only the exact orientation of the ASV at a track point. Once the ASV has rerailed, the coupling process can begin.

A. *Technologies Used on ASV*

The two-way vehicle used is a vehicle with so-called tank steering, i.e., no axle is steered. Steering movements are achieved by speed differences between the left and right wheels, which also enables the vehicle to turn on the vertical axis. According to a literature search, it was found that a Stanley controller [8] can be used for these vehicles under certain conditions [9] (see Figure 10).

Figure 9. ASV side view

To control the vehicle, the Stanley controller had to be integrated into the vehicle in such a way that it can control the vehicle in accordance with the tractor specifications. Due to the system, this was realized via the technology of the control unit, specifically the radio remote control (FFB), which an operator uses to send driving commands to the vehicle (see Figure 9). The receiver unit of this FFB on the vehicle converts the specified control commands into signals on the vehicle bus (CAN bus). It is at this point that a CAN gateway is installed, which reads the CAN bus coming from the receiver unit and transmits a modified bus with the same messages to the vehicle. This allows the control commands for steering and driving to be manipulated or specified by a controller.

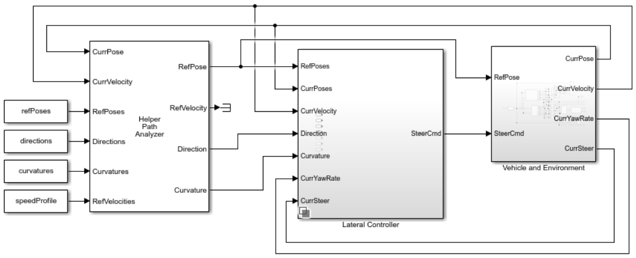


Figure 10. Simulation model of the control loop consisting of Stanley controller and kinematic vehicle model of a tank steering system.

The control center sends the desired movement trajectory via WLAN. This data must be received and processed so that it can finally be used by the controller to control the vehicle. Real-time capable hardware and software was used for this purpose. Specifically, this involves a CarPC “Mexcom VTC7230-BK”, which receives the data from the railroad area via a standard wireless LAN (WLAN). In addition, the CarPC runs software that processes the data received from the control center and makes it available to the real-time capable prototype control unit “dSpace MicroAutoBox II” (MABX) via a UDP Ethernet connection. A CAN gateway was implemented on the MABX. In addition, the Stanley controller runs on the MABX so that it can manipulate the control signals on the CAN directly in order to keep the latency times as low as possible. The laboratory tests and the tests in the railroad environment were successful in terms of real-time capability and control of the ASV (see Figure 11).

Figure 11 ASV integrated hardware for autonomous driving

B. Technical Realizing of the Rerailing Procedure

The system interfaces for communication, localization and control were used to create a corresponding configuration and control interface for a control center.

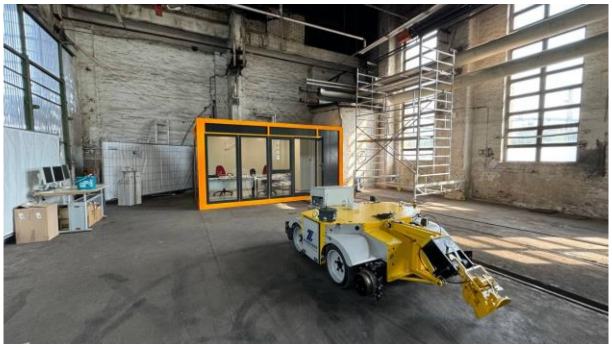


Figure 12. Operation control center and ASV

In addition to entering the basic information and parameters for the shunting area, other areas such as the single-track area were also implemented for driving operations. This area is specially designed (like a railroad crossing) so that the vehicle can drive into it in road mode and then access the track. In addition to the rerailing points, there are other important points for the operation of a vehicle, e.g. the shelter or the loading point. Everything the operator needs to enter such points was also implemented in the control center and tested using the defined test sites in Dresden and Wustermark. Once the system has the basic information for route planning, it implements the path planning using the implemented controller so that destination points can be approached.

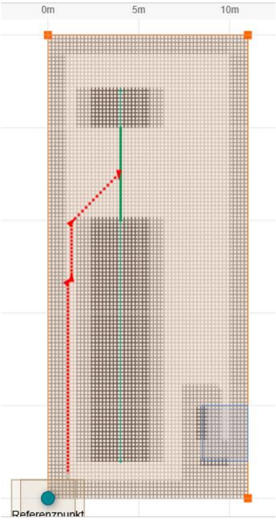


Figure 13. Control Center dashboard with trajectory computing

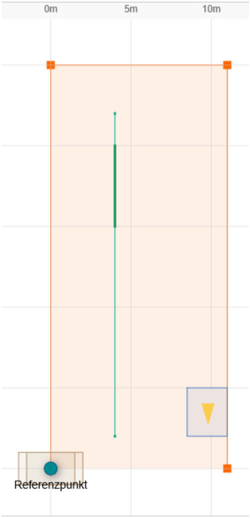


Figure 14. Control Center dashboard with ASV position and heading (MAP view)

The red arrows in Figure 13 clearly show that the path is planned towards the middle of the rerailing area, and that the vehicle on this area should already have the same longitudinal alignment as the track (green) itself. The heading points in the direction of the wagon. The system has automatically defined all dark shaded areas as passable from the data entered and has planned the path only in the passable areas, thus providing the prerequisites for executing complex driving maneuvers. Typical destination points are the rerailing point and the loading station; in rail mode, the wagon. As soon as the ASV is connected to the system, a valid position and an initial heading are automatically determined. Position and direction are indicated by an arrow - similar to navigation systems (see Figure 14). From the system's point of view, there are three main steps in a driving process. Driving in road mode, rerailing and driving in rail mode. Different algorithms are required in all three steps. When driving on the track, for example, no real path planning is required, as the vehicle cannot leave the track and therefore has perfect longitudinal guidance. However, the speed is important in this step, e.g. to carry out a successful coupling process without moving the wagon far beyond the shunting position. The ASV also reacts differently in rail mode than in road mode and also moves a significant load when a wagon is coupled. This changes the braking distances in particular and the speed controller has a significantly longer distance to travel before coming to a standstill.

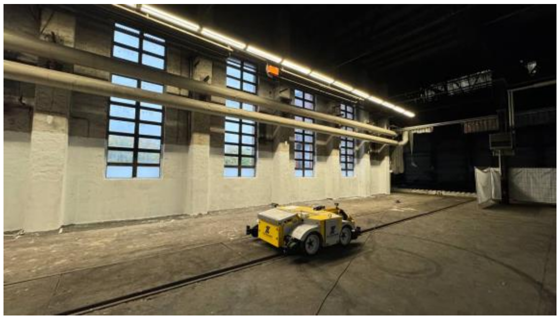


Figure 15. Finished ASV indoor rerailing process

However, it is technically irrelevant on the system side whether a shunting operation is aborted in the middle or not. The system only needs to ensure that the ASV can still safely leave the track. The system can check this via the positions and the map data and then abort the operation if the ASV has taken up a safe position. It is precisely this check that takes place in all steps of a shunting process. If, for example, the selected wagon fails during the operation, e.g. during rerailing, the process would be aborted after rerailing, as there would then be no target position for the next step. In principle, the system always performs the same steps:

- Find the best rerailing position for the operation
- Guide the ASV to the rerailing position
- Rerail (in the correct direction)
- Drive to the wagon and couple
- Check/wait that the path to the next shunting position is clear
- Drive with the wagon to the next shunting position

- Repeat the two previous steps until the destination position of the wagon is reached
- Uncouple
- Drive to the rerailing point
- Rerail

Once the process is complete, the ASV is available for the next process (see Figure 15). If another operation is stored in the system for the vehicle, it is started. The system can operate several ASVs in parallel. When coupling a wagon, in principle only the coupling of the wagon is driven against. This then engages and locks automatically. The vehicle is then steered to the target position with the coupled wagon. Automatic uncoupling then takes place by pneumatically opening the coupling (see Figure 16)

Figure 16. Coupling process

IV. HIGHLY AVAILABLE LOCALIZATION AND COMMUNICATION SYSTEM

For the goal of autonomous shunting, a system concept “integrity of localization and communication” was developed, see Fig. 17. A distinction is made between statistical integrity and systematic integrity. In the case of statistical integrity, the sensor measurement data is evaluated on the basis of the available sensor measurement values; this procedure is used to evaluate the UWB and Bluetooth Low Energy (BLE) data. A quality factor (DQF, Distance Quality Factor) returns an evaluation of the current measured value and can be integrated into the calculation. RAIM (Receiver Autonomous Integrity Monitoring) can be integrated into the satellite position data determined. This procedure can intervene to support the acquisition of measured values and sort out faulty satellite data before a position is calculated. In systematic integrity monitoring, all available information from the systems used is used and merged into a position solution.

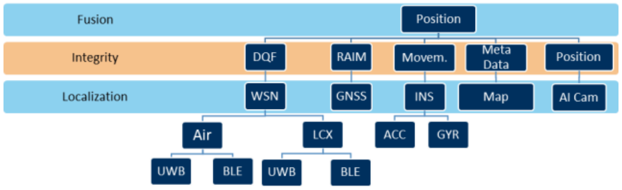


Figure 17. Concept Integrity Localization

If the overall solution deviates significantly from the solutions of the individual systems, as in the case of a threshold-based deviation of the ASV position of 10% for three seconds in the longitudinal and lateral directions, a warning can be sent to the control system of the ASV in order to initiate emergency braking of the freight wagon. In order to ensure the permanent transmission of a position to the central control component of the UAV, the development of a redundant communication infrastructure is proposed. The system concept provides for the transmission of data via the UWB (IEEE802.15.4z) and BLE (IEEE802.15.1) radio standards used for positioning. In the event of interference via the air interface, the use of other transmission media is planned. In the approach investigated, leaky waveguides and slitted coaxial antennas were used.

Figure 18 shows the basic use of LCX for locating and transmitting information.

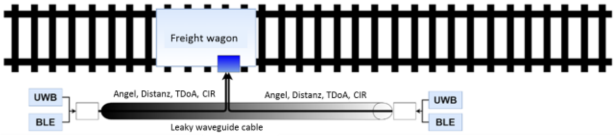


Figure 18. Basic use of leaky waveguide cable for localization and information transmission

Initial investigations with leaky waveguides (LCX) as a communication medium under laboratory and test side conditions have shown that this medium is suitable as a redundancy system for the transmission of communication data (Figures 19 and 20).

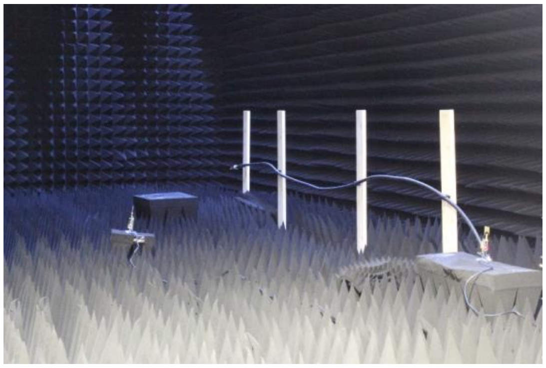


Figure 19. Laboratory tests on the use of leaky waveguide cables for localization and information transmission

Figure 20. Real-world test investigations into the use of leaky waveguide cables for localization and information transmission in the rail sector

The methods developed for multisensor-based integrity monitoring were combined on the basis of the individual algorithms tested in the conceptual phase on the basis of synthetic data. In this context, the radio channel in particular was implemented using software with regard to a “control loop” for integrity monitoring (see Figure 21) based on the above-mentioned radio parameters.

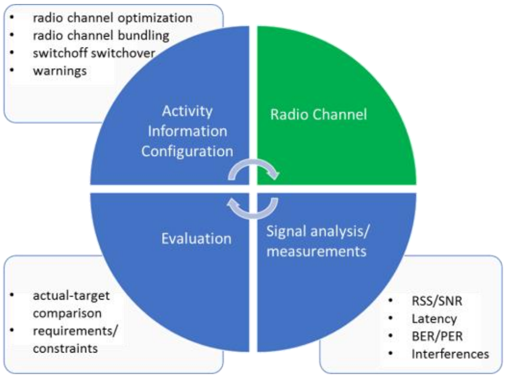


Figure 21. Representation of the “control loop” of integrity monitoring for radio communication [4]

V. LABORATORY BASED AND FIELD TESTS IN RAILROAD RESEARCH DEPOT

The following approach has proven itself scientifically and practically as a way of finding objectives. First, computer-aided simulative investigations with modeling and simulation. Secondly, laboratory-based tests of selected promising components (e.g. UWB radio sensor network, LCX cable). Thirdly, after systematic laboratory tests, the transfer to the real test environment, in this case the Railroad Research Depot takes place. In the following, individual results that are considered important are shown. Figure 22 shows a simulative evaluation of the distance estimates of the UWB radio system actually used on the basis of a multipath-free and a multipath-strong 3D modeled railroad operating area. It is clearly visible that a good position estimate can be derived despite the strong multipath propagation [7].

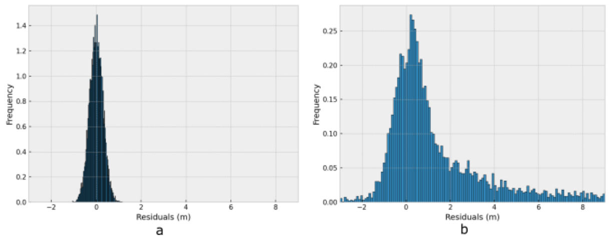


Figure 22. UWB distance estimates. a) free space propagation, b) strong multipath influence

Furthermore, the possible use of an LCX cable was also investigated, which was initially evaluated in the laboratory (multipath-free room) under best-case conditions (see Figure 19). The results are shown below in Figure 23.

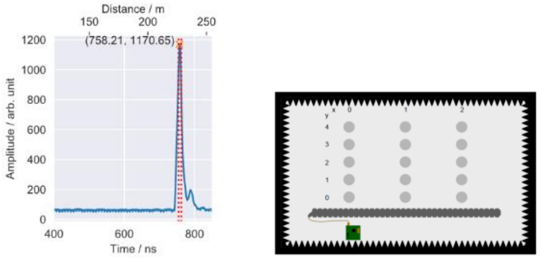


Figure 23. Measurement result of the channel impulse response at point 2-2 (marked in red) for determining the position along an LCX in a multipath-free room

VI. CONCLUSION AND FURTHER WORK

In In this work, we have shown the implementation of an automatic shunting system with an ASV and dealt with the most important system components for the realization, in particular with the implemented system concepts and components for localization and communication based on radio sensor networks and leaky waveguides cables. It can be stated that the complexity of autonomous navigation of ASVs in densely occupied marshalling yards was underestimated. For this reason, ongoing research and development work is focusing on evaluating and fine-tuning the system components for control, communication and localization. This will focus in particular on improving the object recognition of the rails to initialize the rerailing process using AI-supported image processing, as this has so far proven difficult for different marshalling yard environments.

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