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Development of Positioning Methods for ATO in a Scaled Model Environment

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Abstract

The desire for greener transport requires a shift of transportation to rail-based systems. Automation and digitalisation are being used to make rail transport competitive in intermodal transport. Initial automation projects on closed systems such as metros show the potential of automatic train operation (ATO). As more complex systems for automatic train operation are developed and integrated, the need for testing and development opportunities are increasing. Virtual pre-development and subsequent verification on the real field is a well-established process, and the limited availability of field environments for rail vehicles makes the use of scaled models for verification an appropriate solution. In response to the growing demand for efficient, safe, and sustainable rail transportation systems, this research addresses challenges in real-world implementation by utilizing scaled models. By introducing these innovations within scaled models, the research creates a controlled environment for testing and refining ATO systems, components and functions. This ensures robustness and reliability, facilitating the transition to full-scale deployment. In summary, the paper contributes to the evolution of ATO functions, presenting novel features within scaled models that showcase the effectiveness and feasibility of camera-based positioning in enhancing overall automatic train operation capabilities.

Keywords: ATO, automatic train operation, scaled model development, scaled technology, camera-based localization, ultrasonic-based localization

1 Introduction

The climate policy framework for the upcoming decades necessitates a transition in traffic volumes from road transport to more eco-friendly alternatives, with rail emerging as a preferred solution [1]. To establish a competitive rail-based substitute for road transport, it is essential to investigate the existing drawbacks of rail transport in both passenger and freight domains.

As per [2], common issues in passenger rail transport encompass crowding; organization of the rail system; financial cost; low number of trains; delays; train route, boarding and exiting the train as well as luggage transportation and safety issues.

In the field of rail freight transport, a significant differentiation exists between full train and single wagonload transport. Full train transport is primarily used to transport large quantities of general or bulk cargo with identical origins and destinations. On the other hand, single wagonload transport involves trains transporting various load types, with each wagon having unique origins and destinations. Single wagonload transport is a competitor to road transport, but faces challenges such as reduced last mile flexibility, unpredictability and high costs. Shunting process costs constitute a significant portion of total single wagonload transport expenses, providing no direct value addition. [3]. Therefore, optimizing rail freight transport holds potential through advancing shunting processes. Automation and digitalization are perceived as catalysts for enhancing predictability, positively influencing both passenger and freight transport, and subsequently improving the performance and economic efficiency of railway systems [4],[5].

Building on this anticipation, various successful automation projects in passenger and freight transport have already been executed. In addition, digitalisation is a topic that is becoming increasingly important. By collecting and providing data on procedures, processes, communication and interfaces, direct improvements in passenger transport are ensured through a reliable flow of information to passengers. The generation of data also offers a wide range of use cases for operational and technical optimisation.

Examples for further digitalization from shunting operations include the projects ASaG camera bridge [6], the digital automatic coupling [7] and the AmaBPro automatic brake test [8]. Until now, data has been collected manually or semi-automatically and sometimes physically transferred on paper. Automatic data collection and processing offers significant added value in rail transport. This paper shows the potentials of camera-based positioning demonstrated for a scaled model automated shunting locomotive.

1.1 Basics of Automatic Train Operation

As previously stated, several automation projects are already operating successfully. The grade of automation (GoA) [9] defines the ascending takeover of tasks by an automated system, ranging from on-sight driving operation GoA0 to unattended operation GoA4. To investigate the impact on systems currently in development, the operating conditions of some example systems are described below. The first GoA4 system was already operational in Kobe, Japan in 1981 [10] and represents an enclosed system. Subsequently, the underground railways in European cities became increasingly automated. A significant milestone was the launch of the U2 and U3 underground lines in Nuremberg, which were the first to ensure mixed operation with automated and non-automated lines since 2008 [11]. The system is primarily closed and free of intersections, with only a few well-defined interfaces to the external environment. This allows for the automation of subways by monitoring the infrastructure at critical locations.

The S-Bahn in Hamburg demonstrates a further step in the automation of rail vehicles by showcasing ATO over ETCS. Passenger operation is conducted using GoA2 (automated operation with driver monitoring), while depot operation is performed according to GoA4 (fully automated).[12].

Rio Tinto uses advanced automated rail vehicles in Australia for its auto haul project. Automation is backed up by radio remote control. Safety measures include additional safeguards for crucial areas such as level crossings and inhabited zones. The primary risk along the route is potential collisions with wild or grazing animals. The train is equipped to detect impacts on the locomotive, providing supervisors with data for impact evaluation. Based on this information, the supervisor can make a remote decision on whether to continue or halt the journey. [13].

The mentioned systems are located in secure environments and operate in fully automated mode when the risk of human or economic harm is low. To expand the deployment of automated rail systems to more challenging applications, effective solutions must be developed to address critical scenarios. The following process explains this development.

1.2 Development of ATO Systems

The examples demonstrate the varied applications of automation in railroad systems. These applications can be classified as either mainline or on-sight operations in the field of railroad technology. The work in this paper describes the implementation of scaled ATO functions and camera-based localisation in connection with the application area "driving on sight".

The "driving-on-sight" category encompasses intricate operations like depot trains, shunting, approaching stops, or navigating mixed tram and road traffic. The relatively low speeds involved allow for monitoring the stopping distance directly from the vehicle. When automating the vehicle, there's a need to substitute the driver's visual, acoustic, and sensory perception with an automated system. This transition is achieved by integrating data from various sensors. Depending on the specific application, color cameras, infrared cameras, LiDAR, radar, or ultrasonic sensors are employed to replicate and enhance the driver's visual capabilities. [14].

Furthermore, precise positioning of the locomotive in the track plan is crucial to differentiate between obstacles within the clearance gauge and objects detected by the environment detection system. As the installed balises do not offer the required accuracy, positioning systems that incorporate GPS/GNSS, IMU, and odometry sensors are utilised. In the context of this work, the possibility of expanding these sensors by integrating camera systems is being investigated.

In addition, the option of using camera systems to automate other previously manual monitoring activities is thus made possible, such as the detection of false runners during shunting operations in marshalling yards, or the automatic detection and digitization of parking positions of vehicles in the depot.

1.3 Usage of Scaled Models

Scaled models are widely used in scientific and engineering applications, particularly in the study of airflow in wind tunnels. Testing full-scale objects such as airplanes [15] or buildings [16] can be economically impractical, so a cost-effective approach involves scaling down both the wind tunnel (test site) and the test object until a satisfactory balance between cost and knowledge gain is achieved. To apply the findings to real-world scenarios, measurement results obtained from scaled models are adjusted using physical correlations, such as the Reynolds number. Scaled models also play a crucial role in validating simulation approaches in various contexts.

Scaled models are commonly used in railway applications. For instance, Reference [17] shows the use of a scaled vehicle with a 5-inch track gauge to validate dynamic simulations. The “Eisenbahnbetrieblabor”, which is the railway operations laboratory at TU Dresden, provides an H0 gauge (16.5 mm) model layout for teaching and research, with a particular focus on safety technology and signal box technology. This facility offers the opportunity to establish connections with real systems, such as the Dresden suburban railway [18]. Additionally, RWTH Aachen University operates an H0-scale environment that incorporates various realistic signal box technologies. This setup enables the simulation of actual switch towers, various safety technologies including ETCS simulation, and an extensive track network to explore solutions for dispatch optimization [19].

The university of applied science Nuremberg has a scaled test field in G gauge (45 mm) in order to pre-validate the development of components and functions for automatic train operation in the model quickly and cost-effectively [20]. The experiments shown below were carried out there.

1.4 Areas of Application for Camera-Based Positioning

In areas where GPS availability is low or in buildings, alternative technologies must be used for positioning applications. Time-of-flight-based systems that use ultrasound or electromagnetic signals can be a solution for this. With the increasing availability of computing power and the integration of new algorithms or AI methods, cameras offer the possibility of being used in positioning systems, with higher resolutions.

Applications in buildings are typically storage facilities or machine halls, where both people and industrial trucks are present. To minimize the risk of accidents in mixed operation areas, it may be beneficial to track and monitor the positions of both parties involved. Reference [21] discusses the advancement of a camera-based tracking system for locating industrial trucks. Low-cost camera-based positioning systems can achieve pallet-accurate precision with a resolution that is sufficient. The developed system and software components achieve latencies below 60 ms and a 25 Hz sampling rate. However, position data alone cannot move the pallet, and an automated system requires additional sensor data.

[22] shows the improvement of classical vehicle localization by adding camera-based data generated on landmarks. Therefore, cameras in ATO systems for surrounding surveillance could be utilized to identify landmarks and enhance localization accuracy.

Another approach of camera-based localisation is published in [22]. through the use of a stereo camera to position a drone within rooms. For this purpose, the drone's area of operation is first measured in the form of images and stored as a "map". To operate the drone, the currently detected camera image is compared with the stored images to estimate the actual position.

The literature describes numerous applications of camera-based systems. These include external systems, which capture the object from a third-person perspective, and first-person camera systems used to measure the object. Both types of systems offer solutions to existing problems and optimization projects, which are the main focus of current developments in ATO functions. This work aims to perform a basic verification of camera-based methods for use in the railway sector by externally positioning a locomotive in a shunting yard area. The camera-based positioning system will be developed as scaled model to be used and compared with the existing ultrasound-based positioning system of the scaled ATO system for shunting activities described below.

2 Scaled Model Development for ATO

In order to investigate new technologies for Automatic Train Operation (ATO) functions within the scale model, an appropriate test area [20] and a demonstrator vehicle have been developed. Utilising lessons learned from a parallel project [23] where the automation of a shunting locomotive was underway, adaptations to both the testbed and the demonstrator were be mandated to harmonise with the requirements inherent to automated shunting operations. This careful calibration is intended to increase the methodological robustness and comparability of results within the overall scientific investigation.

2.1 Test environment and demonstrator locomotive

The test area, illustrated in Figure 1, is built on a u-shaped plate with external dimensions of 6.2 m x 3.6 m, constrained by the room size. It includes approximately 34 m of track length, consisting of 17 switches and two three-way switches, with a track gauge of 45 mm. The test area is composed of a track harp for arrival tracks, a hump with two parallel tracks, and a dead-end track used for switching between the tracks.

Figure 1: Scaled test environment, track plan and sensor positions

Primarily designed to research ATO topics with a focus on positioning, shunting order generation and environmental detection, this setup also offers a wide range of rail vehicles for testing, including flat wagons, container wagons, timber wagons, and vehicle transporters.

To enable automated driving, it is necessary to position appropriate sensors, analyze data, and control actuators. Sensor data primarily provides information for environment detection and localization. Due to the high computing power required for analysing environmental data, a Raspberry Pi is considered a suitable solution due to its ample interfaces. Figure 2 shows the structure of the demonstrator vehicles. The central unit is a Raspberry Pi 4B 8GB (a). The two mobile Marvelmind ultrasonic beacons (b) on each of the demonstrators are used for the positioning functions described in the paper. In addition, two Arduinos, ultrasonic sensors, cameras, incremental encoders, a tensile force meter (blue demonstrator) and a LiDAR (blue demonstrator) are installed per locomotive to implement the highly automated driving functions, but these are not discussed further in this paper due to their lack of relevance for the positioning systems.

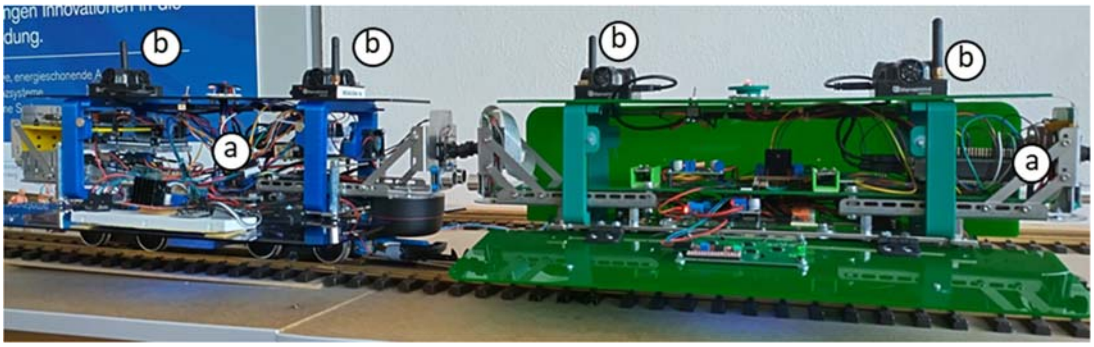


Figure 2: Demonstrator locomotives, with Raspberry Pi and mobile beacons highlighted

The highly automated system receives shunting orders containing route data, permitted speeds and information about operational obstacles such as wagons. The LiDAR sensor is used to record environmental data and check for obstacles by means of data fusion with the position and route data. High-precision, reliable localisation with an ideally high sampling rate is necessary for precise differentiation between obstacles and objects outside the clearance gauge. As part of the localisation process, the recorded raw data is projected orthogonally onto the route in order to eliminate lateral deviations. It is also possible to refine the measured points via sensor fusion with the odometry data using a Kalman filter. In the following, however, only the original data from the various localisation systems will be used. The possibilities of the originally existing ultrasound-based localisation are compared with a newly implemented camera-based localisation method and finally analysed.

As a reference value for the track plan, the lab was measured using a 3D scanner with a point cloud of 14 million points. The points of the track plan were extracted manually from the scan by identifying the centre of the track. The measured track plan is therefore subject to distortions due to the scanning procedure and the manual identification of the track centres. This fact must be considered when evaluating the various localisation systems in relation to the track or route data.

2.2 Ultrasonic-based positioning system

For the implementation of the localisation, an industrially available product was used in the first phase in order to provide a basis for the development of ATO functions. The *Marvelmind Indoor Positioning System* (IPS) consists of ultrasonic transmitters and a modem for radio communication between the components. The ultrasonic system is based on the time-of-flight measurement of an acoustic signal and, in the scaled model, serves as a synergetic replacement for GPS systems, which are based on the time-of-flight measurement of radio signals received from satellites. In order to compare the results of the scaled model and the real world, it is necessary to discuss the differences between the two technologies. Although the measurement principle is analogue, the different propagation speed of the respective transmission medium, air (approx. 340 m/s) compared to electromagnetic waves ($2.98*10^8$ m/s), leads to significant differences in the mode of operation. By their very nature, both systems react to shadows with reduced localisation accuracy and reliability. Due to the small space of reverberant walls compared to the speed of sound, measurements in the wall area are affected by reflections and doubling, which degrade the signal quality and need to be filtered out by the system or in post-processing. It is expected that there will be sufficient similarity between the scaled technology and the real technology to allow further development and testing.

The IPS was tested using three stationary beacons positioned 1.7m above the wall panel and two mobile beacons (hedges) on the demonstrator, as seen in the Figures 1 and 2. The hedges are equipped with integrated IMUs, which interpolate the position between the actual ultrasonic data points (with 16 Hz) up to 100 Hz. The measuring system is calibrated according to the operating instructions for the application and operated with the 100 Hz IMU protocol. The system reads the data through the beacons on the USB interface of the Raspberry Pi. For the data reading process the IPS's raw data is pre-filtered for package loss, plausibility (measuring point within the room) and consistency (measuring point in relation to the previous measuring point in relation to speed). This pre-sorting reduces the average sampling rate to approximately 85 Hz.

To check the IPS, position data is analysed both when the vehicle is stationary and during repeated journeys along a defined route. The results of this procedure are presented in Chapter 3 and compared with the camera-based system developed in the next section. Difficulties of the ultrasound-based system regarding unexpected jumps between two measured points and problems with shadowing and reflections gave the impulse to investigate visual localisation methods.

2.3 Implementing a camera-based positioning system

The literature examples have shown that there are a large number of use cases for camera-based localisation algorithms and sensor technology. For the implementation of camera-based localisation in the scaled system, external monitoring or detection of the object to be located is chosen, which involves equipping the corresponding railway infrastructure with cameras on lamp posts, for example. In order to set up a visual network in larger areas such as marshalling yards or depots, it is necessary to use and merge several cameras.

To be able to investigate these effects, the laboratory is equipped with two webcams *Conceptronic AMDIS08B* on the ceiling, as shown in Figure 1 (red). The cameras are wide-angle 4K cameras with a maximum frame rate of 30 Hz. The wide angle is required to cover as large an area as possible and is accompanied by corresponding lens distortion. By using the camera parameters and the distance to the coordinate plane, a size of approximately 1,5 mm x 1,5 mm can be calculated for a pixel on the measurement plane. This provides sufficient resolution and sampling rate on the camera side for use in a highly automated system, but direct replacement of the ultrasound-based system is not the focus of this step in exploring the possibilities. More interesting are the methods and algorithms required to extract position data from the cameras. For a cost-effective investigation on the scaled model, the laboratory is also not equipped with a powerful PC. Existing *MATLAB* toolboxes are used for a quick and straightforward validation of possibilities and to demonstrate the necessary processes. It is accepted that real-time capability may not be achievable in the proof-of-concept step under certain circumstances.

At the beginning of the work, the steps are identified to perform camera-based localization with more than one camera. These are illustrated in Figure 3.

Figure 3: Process of camera based-positioning

Fundamentally, coordinate systems in projective geometry of cameras are described based on the pinhole camera model. In this context, extrinsic and intrinsic parameters underlie the transformation between camera coordinate system, image coordinate system, and world coordinate system. The intrinsic parameters describe internal camera parameters, typically known from manufacturer specifications. The extrinsic parameters describe the position and orientation of the camera in space. For this, it is necessary to perform a camera calibration.

The *MATLAB Toolbox Stereo Camera Calibrator* is used for the calibration process. With this tool, it is possible to calibrate both cameras in a single run. For the calibration process, a checkerboard pattern is captured in 25 different positions at the height of the track plate. The calibrator detects the chessboard pattern and displays the coordinate system as shown in Figure 4. The calibration process then generates the desired parameters, which are stored in a *stereoParameter-object*, to compensate for the distorting effects of the lens.

Figure 4: Detected checkerboard

For the fusion of camera images, temporal synchronization is essential to avoid undesired effects or ambiguous positions during the transition between two cameras. Each camera has a USB interface to the PC, which consequently needs to be read in parallel. The *MATLAB Toolbox Parallel Computing* is used to create two workers that can independently process the incoming data stream in synchronization.

Furthermore, the images are fused together. In the literature, various image stitching methods are available, distinguishing between direct and feature-based approaches [24]. For the fusion of high-resolution images, feature-based algorithms are the suitable choice due to their lower computational cost. *MATLAB* provides algorithms such as SURF, BRISK, SIFT, and FAST, among others. A preliminary investigation has shown that the SURF algorithm, for the described application, yields the highest number of features in relation to time. In the state of the art, it is common practice to filter the found features using a RANSAC algorithm to eliminate outliers and ensure reliable image stitching. This process is also carried out using the *estimateEssentialMatrix* function implemented in MATLAB.

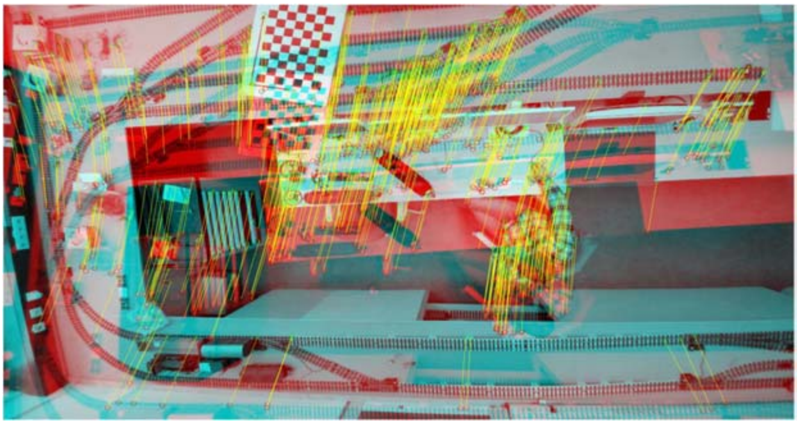
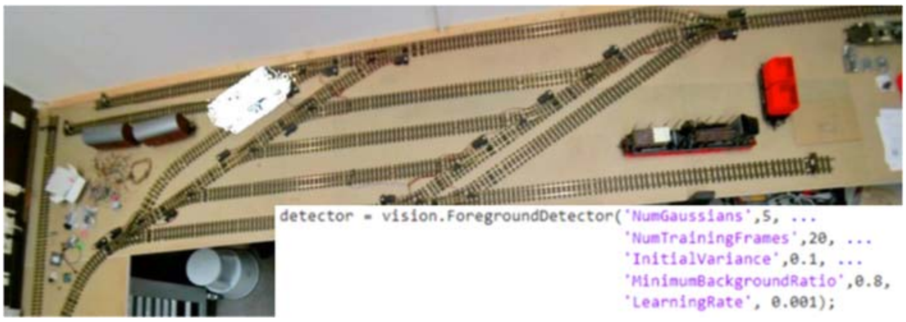


Figure 5: Feature detection with SURF, after RANSAC filtering

Figure 5 displays the filtered, matched features. It is evident that, after the filtering process, only nearly parallel lines between the feature points are found. Numerous features are detected on irregular objects, while on homogeneous structures such as tracks, few features can be clearly identified. This effect must be taken into account when discussing the transfer of the scaled application into the real environment.

The next step is object detection in the image. For a general assessment of how precisely and reliably camera-based localization can be performed, a relatively simple method is desired. The *MATLAB Computer Vision Toolbox* offers various methods and algorithms for this purpose. Traditional segmentation methods and deep learning methods are available. Object detection algorithms that utilize background subtraction for object segmentation require minimal computational effort and are quick and easy to implement [25]. As a result, a background detector is employed for implementing locomotive detection in the fused image. It should be noted that the background detector requires a static environment apart from the object to be detected. In the laboratory environment, this condition can be considered given, while a more elaborate alternative must be chosen for use in a real and dynamic environment. Figure 6 shows the results from the use of the *ForegroundDetector*. This allows for determining the position of the locomotive based on the centroid of the point cloud in the image. It should be considered that the perspective from which the locomotive is depicted changes, causing the centroid of the point cloud to not necessarily correspond to the geometric centroid of the locomotive, depending on its position on the track layout.



```
detector = vision.ForegroundDetector('NumGaussians',5, ...
                                      'NumTrainingFrames',20, ...
                                      'InitialVariance',0.1, ...
                                      'MinimumBackgroundRatio',0.8,
                                      'LearningRate', 0.001);
```

Figure 6: Detection result and used Foreground Detector parameters

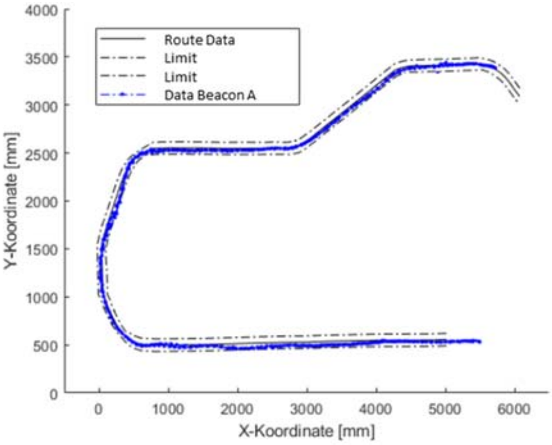
In conclusion, the pixel coordinates need to be transformed into world coordinates, for which the insights from the calibration process in the first step are utilized. By establishing a reference coordinate system, the measurement data are transformed into the same coordinate system output by the ultrasound system. This allows for comparing various localization approaches in the next step.

3 Results

The analysis of the localization systems, maximum deviations are considered, as they are crucial for the reliability of highly automated systems. For stationary measurements, the deviation from the mean average over 100 measurement points is calculated. To assess the deviation during motion, track plan data from the 3D scan are used. Deviations in the longitudinal direction cannot be captured with this methodology, as it is not possible to relate the actual value and the measured value during motion. Consequently, only the lateral deviation is considered, which is eliminated in the subsequent localization process through orthogonal projection.

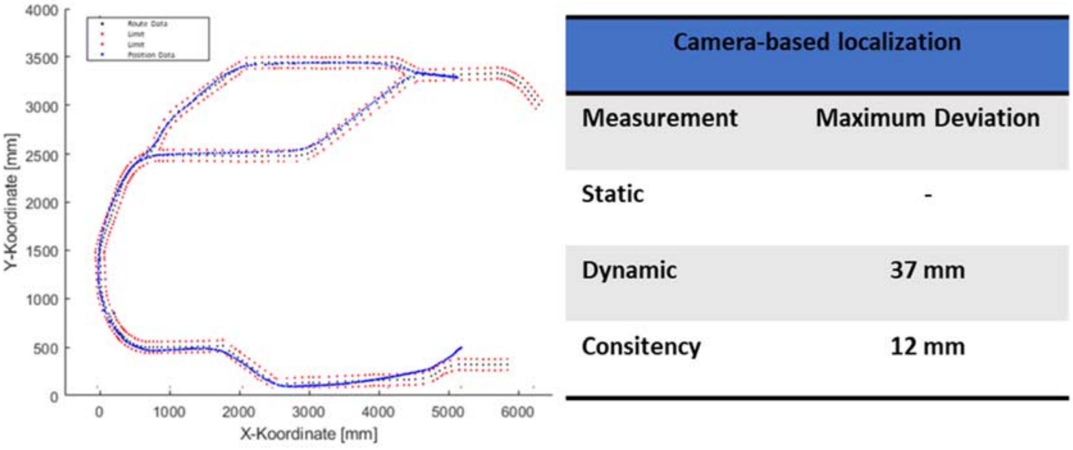
The results for the ultrasonic-based system are shown in Figure 7. The deviation from the track plan and the consistency may be due to a possible distortion when manually entering the coordinates of the stationary beacons. Considering the scaling factor of 1:32, a maximum deviation of 1.92m or 0.48m can be extrapolated. Values under 3 m are comparable to GPS systems with live post-processing. It can be inferred that replacing the GPS system with an ultrasound-based system in the scaled model is a sufficient adaptation.

Figure 8 views the results for the camera-based system. While there is no static deviation in stationary images the dynamic deviation improves to a maximum of 37mm and the consistency deviation is also lowered to 12mm. The area on the lower right sight is excluded from the deviation calculation because of issues with the camera calibration.



Ultrasonic-based localization	
Measurement	**Maximum Deviation**
Static	**3 mm**
Dynamic	**60 mm**
Consitency	**15 mm**

Figure 7: Visualization of dynamic measurement data and deviation for the ultrasonic system



Camera-based localization	
Measurement	**Maximum Deviation**
Static	-
Dynamic	**37 mm**
Consitency	**12 mm**

Figure 8: Visualization of dynamic measurement data and deviation for the camera system

4 Conclusions and Contributions

The experiments conducted on the scaled model clearly demonstrate the superior performance of camera-based localisation systems in terms of both error and reliability. However, the feasibility study conducted on the chosen optical localisation method reveals a limitation in achieving real-time capability due to the current hardware configuration. In order to bridge this gap and improve the practical usability in real-world scenarios, a customised implementation tailored to specific application requirements is imperative.

These findings underline the promise of integrating camera-based localisation systems with automatic train operation systems. However, realising this potential depends on overcoming challenges related to latencies, calibration methods and achievable sampling rates to ensure seamless integration with conventional and widely used localisation systems.

As highlighted in the introductory remarks, the use of camera systems extends beyond mere localisation applications, offering significant potential for automated and AI-based data collection. This versatility not only broadens the range of applications, but also enables the generation of added value from the sensor system in different contexts. This multifaceted utility promises to significantly reduce the workload of overworked personnel in the future, establishing camera systems as integral components in the advancement of automation and data-driven decision-making processes for railway systems.

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