ABSOLUT - An Automated Shuttle Bus between Leipzig Exhibition Area and BMW-Terminal

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Abstract

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The article provides an overview on the system architecture employed and focuses on the automated driving system based on the Robot Operating System and the Automotive Data and Time-Triggered Framework. To ensure reliable operation in diverse conditions a redundant sensor concept with GNSS, LiDaR, Camera and Radar is introduced. Furthermore the article discusses the shuttles localization and state estimation system. As the route contains a high variability of driving environments a combined GNSS/INS/LiDaR fusion system with additional failure detection module is employed. To approve the shuttle for driving in public traffic a stepwise process is defined in close collaboration with regulatory agencies.
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Index Terms—Autonomous vehicles, Public transport, Intelligent Transportation Systems, Localization, State Estimation

I. INTRODUCTION

A. Motivation

In Europe and Germany public transportation operators (PTOs) like the Leipzig transportation service company (LVB) face similar challenges in providing a comprehensive but cost-efficient public transport, especially outside of metropolitan areas in sub-urban and rural environments.

The industrial area in the north-east of Leipzig accommodates production plants and offices with up to 35,000 workers commuting into the area every day. This produces a very inhomogeneous volume of traffic throughout the day with large peaks in the morning and afternoon but quiet phases in between. Further, the Leipzig exhibition area yields another unsteady flow of traffic around the time of events. This inhomogeneous volume of potential passengers and the increasing shortage of staff and bus drivers makes it not economically viable to operate with regular sized buses with sufficient frequency. Hence, the LVB is highly encouraged to explore other modes of on-demand transportation services with increasing levels of automation.

In order to demonstrate the state-of-the-art in automated driving technology, uncover potentially unknown obstacles and to probe customer acceptance, the project ABSOLUT started in January 2019 to develop and operate an automated and on-demand shuttle-bus service on a 15 km test route between the train and tramway station at the Leipzig trade fair and the BMW Factory plant. Fig. 1 shows the shuttle during operation in front of the main trade fair building.

The project followed a holistic approach by not only focusing on the vehicle and the automated driving system (ADS) itself but also on integration into existing public transport infrastructure. In any case, the development of the ADS, with a special focus on the localization and state estimation system, proved to be the most challenging part of the project. The following section covers the unique characteristics of the shuttle’s operational design domain (ODD) compared to previous projects with similar ambitions.

B. Related Work

The automation of road vehicles in open spaces (e.g. [39]) and urban areas (e.g. [21], [8], [20]) has been a highly contested field of research in industry and academia for over a decade. Unfortunately most state-of-the-art ADS still lack robustness for an automated operation without any human supervision on public roads [44].

Compared to passenger vehicles, the public transportation sector offers different constraints for automated driving in the form of well defined ODDs, a tolerable higher system cost per vehicle, generally lower driving dynamics and shorter maintenance intervals. Over the last several years, many projects have emerged with the goal of implementing automated shuttle services on small circuits of open roads or closed business premises in Europe ([15], [45], [31], [41]) and worldwide [9]. Compared to these ABSOLUT differs in the following aspects and provides the subsequent challenges:

- With driving speeds of up to 70 km h$^{-1}$ in dense mixed traffic with up to 100 km h$^{-1}$ the ODD grows significantly and for the first time presents a practicable supplement to conventional buses in sub-urban use cases.
- The driving environments along the route contain significantly more variability (e.g. parking lots vs. multi-lane...
roads; narrow vs. open spaces) and infrastructure (traffic lights with public transport specific signalling, railway crossings, bus stops partly on open roads).

- Shared open spaces with vulnerable road users (VRUs) demanding 360° environment perception
- Safe and reliable entry of bus stops with minimal distance to the curbside even on country roads and underpasses and tunnels which disturb Global Navigation Satellite System (GNSS) and Long Term Evolution (LTE) reception require accurate and reliable vehicle localization

The goal of this article is to provide technological details of the concept for environment perception and the ADS in particular as well as sharing some lessons learned on the way to automated and scalable on-demand shuttle services in suburban regions. Section I-C gives an overview of the subsequent parts of the paper.

C. Outline of the paper

The article is divided into 4 parts. Section II describes the individual components of the vehicle and the additional hardware. The core parts of the ADS environment perception, state estimation and planning are covered in Section III. In part IV we outline the additional infrastructure installations on the test route. Section V illustrates some key aspects regarding shuttle operation which includes legal challenges as well as the integration into the public transportation service network. Section VI concludes the article with our key findings and an outlook on subsequent projects.

II. VEHICLE

The vehicle employed in ABSOLUT needs to meet the following requirements:

- Emission-free propulsion

Fig. 1: The ABSOLUT e-Crafter at trade fair Leipzig

Fig. 2: Architecture of the DbW-system and low-level control unit
• Sufficient size to transport 4 to 6 passengers close to individual demand
• Capable of operating at velocities up to \(70 \text{ km h}^{-1}\)

With the beginning of the project no suitable automated shuttle bus solution was commercially available. The development of a complete vehicle from scratch was quickly neglected due to the tight schedule of the project as well as concerns regarding the license for the operation on open roads. Hence, we chose to purchase a standard Volkswagen e-Crafter as the base platform which afterwards was retrofitted with a Drive-by-Wire (DbW) system, sensors, computing and peripheral hardware, as well as interior equipment to seat and transport passengers. Fig. 1 shows the completed vehicle including all extensions. Table I in the appendix lists the core technical details of the base vehicle. The following sections cover the DbW system and the sensors in more detail.

A. Drive-by-Wire system

A DbW system for steering, acceleration and braking via electronic commands is essential for any automated vehicle. Since the standard e-Crafter does not contain a DbW interface off-the-shelf, a retrofitted solution had to be installed. Regardless of the actual implementation the system needs to fulfill the requirements defined by ECE R 79 [25] for steering and ECE R 13H [24] for braking performance.

Fig. 2 shows the architecture of the DbW system consisting of the Bozio DbW ECU with sensors and actuators on the left and the low-level control unit on the right. In order to facilitate the approval process, the vehicle is controlled using the conventional mechanical interfaces, i.e. the steering wheel, throttle and brake pedal. By retaining the conventional interface the vehicle’s basic regulatory approval for manual operation remains valid. With respect to the functional safety of the system, the actuators and sensors for steering and braking as well as the software modules in the DbW ECU are carried out redundantly (Fig. 2 - left side).

According to current regulations, any automated operation in public traffic requires a human safety driver, who constantly monitors the system’s state and intervenes in case of any ADS failure. This intervention can be performed at any time by tapping the brake pedal or taking over the steering wheel (see also V).

In order to apply prototypical ADS functions without functional safety approval an ISO 26262 compliant security layer is implemented. The low-level control unit (Fig. 2 - right side) meets these requirements and isolates errors on the high-level side by:

- limiting steering, acceleration and braking requests from the ADS with vehicle specific data e.g. a velocity-dependent steering torque limiter
- electrically isolating the base vehicle CAN-bus communication from the ADS when driving in manual mode

With the DbW system in place the ADS can control the shuttle based on the information about the vehicle environment gathered by the sensor system, which is consequently covered in the next section.

B. Sensors

The e-Crafter is equipped with several sensors for 360° environment perception. Further, it contains an On-Board-Unit (OBU) for Vehicle-to-Infrastructure (V2I) communication (as described in section IV). Generally the main purposes of the sensors described in this section are the detection and classification of dynamic obstacles and other road users as well as the localization of the vehicle absolutely and relatively within its driving lane.

The choice of sensors, their positioning and the integration into the vehicle body followed several design principles:

- **Redundancy**: All relevant areas around the vehicle must be fully covered complementary with at least two independent sensors, ideally with different physical principles (e.g. camera and radar) in order to operate in any lighting conditions (day or night) as well as in bad weather.
- **Dynamic Range**: The perception system must cover ranges from 1 m e.g. while driving on parking lots with VRUs as well as up to 200 m when driving with speeds of \(70 \text{ km h}^{-1}\).
- **Weather resistant integration for year-round operation**: Provide suitable protection for sensors when operating in harsh conditions. This includes for example heating units for the camera housings to prevent fogging on the lenses.

The sensors are listed in Table III and their respective location on the vehicle is illustrated in Fig. 3. As the Figure depicts, the vehicle is equipped with 9 cameras (C1 - C9), 9 LiDaR (L1 - L9) and 5 radar (R1 - R5) sensors for environment perception as well as a three antenna Realtime Kinematic (RTK) GNSS System (A1 - A3) assisted by an independent Inertial Measurement Unit (IMU) (H) for state estimation. The resulting sensor setup was deliberately over-sized regarding quantity, resolution and field-of-view. A reduction in the number of sensors while maintaining a sufficient level of accuracy and safety is part of ongoing research (see VI-A1).

Fig. 4 shows the resulting sensor coverage of the vehicle’s environment grouped by the level of redundancy in ideal weather conditions. For adverse weather conditions like rain and snow a model was implemented according to [12] and [14] to evaluate the effect on range and field of view. Combined with an environmental simulation (see section V) we optimized the sensor setup for sufficient coverage of all relevant areas along the route in various weather conditions.

C. Additional Hardware

All computational hardware for communication and data processing is stored inside a rack-like housing vertically mounted in the rear left of the vehicle (IT-Rack in Fig. 3). In order to further protect sensitive hardware from impacts and shocks they are mounted onto shock and vibration absorbing sockets. Additionally the main components are listed in Table II in the appendix. With sensors and hardware in place the next section covers their functional interaction and the ADS.

III. AUTOMATED DRIVING SOFTWARE

The software components for the automated driving system were jointly developed by three partners from industry
and academia. Fig. 5 illustrates the architecture of the ADS with its core components and their distribution to separate machines. The Localization PC holds the functionality for global positioning and vehicle state estimation (section III-A). It provides the fused state to the Nvidia Drive and the HAD PC. The former computes the environment model, called local dynamic map (LDM) (section III-B), based on this state and the objects provided by the detection modules. The HAD PC uses the information from LDM and the vehicle state to derive a reasonable driving maneuver and plan a trajectory (section III-C). Localization system and LDM use the Robot Operating System (ROS) as middleware and communication layer. Both computers are connected with 10 Gigabit Ethernet forming a distributed system. The planning and control modules are implemented in the Automotive Data and Time triggered Framework 2 (ADTF2). Data exchange with the LDM is established using a communication bridge based on flatbuffers\textsuperscript{1} for serialization and ZeroMQ\textsuperscript{2} for transmission. All modules use the GNSS system as a common time source for synchronization. The subsequent sections outline the localization system as well as the LDM and the planning and control modules.

A. Localization & State Estimation

Accurate and reliable localization and state estimation is of significant importance for automated vehicles especially when driving in dense traffic or in close proximity to VRUs [18], [38]. Additionally, as introduced in I-B, the route contains sections without sufficient GNSS reception and a mix of areas which are rich (parking lot, exhibition area) or very poor of features for LiDaR-based localization which adds additional complexity to the task.

The vehicles state $x^E$ is defined by (1), where $x, y, z$ describe the vehicle position, $\theta_z$ the yaw angle, $\delta$ the steering wheel angle, $\dot{x}$ the longitudinal speed, $\theta_z$ the yaw rate and $\ddot{x}$, $\dot{y}$ and $\theta_z$ the longitudinal, lateral and yaw accelerations.

The position and the yaw angle are in the earth-fixed $ECEF$-$\mathbb{R}^3$-system, whereas the other quantities are given in vehicle coordinates according to SAE J670 [3]. In addition to the values for motion on a road surface the state contains the altitude $z$ for operating on routes with bridges and underpasses where both paths can be driven.

$$x^E = [x, y, z, \theta_z, \dot{x}, \theta_z, \ddot{x}, \dot{y}, \theta_z, \delta]^T \quad (1)$$

Whilst Stephenson [38] demands a 2D accuracy of 0.05 m with a pose update frequency of 500 Hz for automated vehicles these values apply for a maximal velocity of 250 km h\(^{-1}\). Taking into account the vehicles maximum speed of 70 km h\(^{-1}\) on the route and the dimensions of the roads, the requirements in \textit{ABSOLUT} can be formulated less severe. Employing the geometric approach suggested by Reid et. al [30] together with several hundred test kilometres on the route an accuracy requirement of 0.1 m lateral and 1° angular with 100 Hz update frequency has proven to be suitable for this use case.

Fig. 6 illustrates the architecture of the localization system mainly relying on GNSS, IMU and LiDaR data. The global pose is primarily derived from a three-antenna RTK-GNSS System [10]. A RTK reference station is installed on the rooftop of the Leipzig trade fair area in order to provide the vehicle with correction data. In case of an outage of the reference station we employ \textit{SAPOS} [42] or \textit{Axio-Net} [11] correction services as a fallback.

Unfortunately GNSS is prone to jumps due to non-line-of-sight or multi-path errors for example when passing bridges. Hence the GNSS solution is fused with the solution of a LiDaR based absolute localization system. We make use of three different approaches: a localization using a dense global point cloud map and the Normal Distribution Transform (NDT) for registration [1], a map of pole like features with global reference and a particle filter for pose estimation proposed by Zhang et al. [46] and a \textit{FAST-LIO} based re-localization module [43]. The pointcloud maps of the route are generated by \textit{LIO-SAM} [36]. An evaluation and comparison of these approaches in terms of usability and accuracy for our use-case is still ongoing.

The global pose is fused with data from an IMU, vehicle odometry and LiDaR based odometry [35] in local map-coordinates. The fusion is done using an Extended Kalman\footnote{https://github.com/google/flatbuffers}
Filter (EKF) provided in the robot localization package [22] (State Estimation System in Fig. 6). The overall stability of the fused state highly depends on the quality of the input signals including the correct allocation of their measurement covariances. As GNSS suffers from errors with insufficient sky view and the LiDaR Localizers are challenged in open areas without features this requirement cannot always be met resulting in jumps or oscillating movement in the fused state. Consequently the measurements of the GNSS $z_{GNSS}$, LiDaR Odometry $z_{LO}$ and absolute LiDaR localization $z_{LA}$ need to be monitored for errors. As Fig. 6 depicts the signals are not fed directly into the filter but through an Outlier Gateway. The Outlier Gateway consists of a Failure Detection and Exclusion System (FDE), and an EKF-based reference estimator. Fundamentally the gateway compares the relative movement of the vehicle between consecutive measurements $z_i$ ($i \in \{GNSS, LO, LA\}$) to the relative movement of the reference estimator. If the lateral, longitudinal or angular deviation exceeds a threshold value an error is detected and the covariance of the respective input is inflated. The subsystems are covered in more detail subsequently.

1) Reference Estimator: The short-term reference estimator uses vehicle speed $v$, lateral $a_y$ and longitudinal accelerations $a_x$ as well as the yawrate $\omega$ (Vehicle IMU in Fig. 6) as inputs to calculate a reference state $\tilde{x}_{ref}$ and is based on the assumption that these inputs are insensitive to faults caused by the environment. Motion prediction is done employing the Constant Turnrate Velocity (CTRV) Model (2) [34]. The reference estimator does not include absolute pose measurements and is limited to short-term estimation consequently. As only the 2D pose quantities of the measurements under test are monitored (6), the prediction in (2) omits some values. For the reference inputs a static measurement covariance is assumed and determined empirically on various test drives.

$$
\begin{align*}
\tilde{x}_{ref,k} =
\begin{bmatrix}
x_{k-1} + \frac{v}{\omega} (\sin(a) - \sin(\theta_{z,k-1})) \\
y_{k-1} + \frac{v}{\omega} (-\cos(a) + \cos(\theta_{z,k-1})) \\
0 \\
\theta_{z,k-1} + \omega \Delta t \\
v \\
\omega \\
a_x \\
a_y \\
0 \\
0
\end{bmatrix}
\end{align*}
$$

(2)

with:

$$
a = \omega \Delta t + \theta_{z,k-1}
$$

(3)

2) FDE System: As stated before FDE monitors the relative 2D movement $du, dv, d\theta_z$ in vehicle coordinates of the signals under test $z_i$ and the reference state $\tilde{x}_{ref}$ between consecutive measurements. Fig. 7 depicts the relative coordinates of two vehicle states. For this purpose the vectors of the reference state and the measurements are reduced to 2D poses as depicted below (4, 6). The differential reference movement $\Delta \tilde{p}_{ref,k}$ is defined by (5) with $\mathbf{R}_i$ being the planar rotation to vehicle coordinates.
The differential input movement $\Delta z_{i,k}$ is calculated by (7).

$$\Delta z_{i,k} = R_{i,k-1} (z_{i,k} - z_{i,k-1})$$

The unfused state $\mathbf{p}_{ref}$ is derived from the ego-system $\mathbb{E}$, the local odometry $\mathbb{LO,LA}$ and the LiDAR odometry $\mathbb{LiDAR}$.

$$\mathbf{p}_{ref} = \begin{bmatrix} x^E_j \end{bmatrix}_{j \in \{1,2,4\}} = \begin{bmatrix} x & y & \theta_z \end{bmatrix}^T$$

$$\Delta \mathbf{p}_{ref,k} = R_{ref,k-1} (\hat{\mathbf{p}}_{ref,k} - \hat{\mathbf{p}}_{ref,k-1})$$

$$\hat{\mathbf{p}}_{ref,k} = \begin{bmatrix} du & dv & d\theta_z \end{bmatrix}^T$$

$$\mathbf{c}_i = \begin{bmatrix} d_{u_{\text{max}}} & d_{v_{\text{max}}} & d_{\theta_{\text{max}}} \end{bmatrix}^T$$

$$\delta_{i,k} = \Delta z_{i,k} - \Delta \hat{\mathbf{p}}_{ref,k}$$

$$\mathbf{\Sigma}_i = \mathbf{\Sigma}_i \cdot 10^b$$

$$b = \begin{cases} e_{\text{max}} \cdot \left(1 - \frac{d_{t_{\text{error}}}}{t_{\text{rec}}} \right), & \text{if } \delta_{i,k} \geq \mathbf{c}_i \\ 0, & \text{otherwise} \end{cases}$$

In case of an error the corresponding measurement covariance $\mathbf{\Sigma}_i$ gets inflated to $\hat{\mathbf{\Sigma}}_i$ according to (10, 11) with $e_{\text{max}}$ being a tunable maximum penalty exponent, $d_{t_{\text{error}}}$ the time since the last error was detected and $t_{\text{rec}}$ a tunable recovery time. After $t_{\text{rec}}$ the input is fused with its original covariance again.

The fused state serves as the base for lateral and longitudinal vehicle control within the map as well as for correct assignment and determination of surrounding traffic objects. This process is executed by the perception system covered in the next section.

**B. Environmental Perception**

As mentioned in Section II-B the main purpose of the sensors is the detection of dynamic obstacles and other road users. The Continental ARS430 radars (R1 - R5 in Fig. 3) as well as the Ibeo LUX LiDaRs (L1 - L6 in Fig. 3) already provide detected objects including position, classification, moving speed and direction of movement.

For the detection of the objects based on the cameras, Nvidia DriveNet [27] was used. This neural network has been trained for a wide range of traffic scenes in Europe and the U.S. and is able to recognize dynamic objects such as vehicles, cyclists,
and pedestrians as well as road infrastructure such as traffic lights and traffic signs.

The general pipeline of object data fusion is illustrated in Fig. 8. As shown, all sensor object data is converted to a common representation and is augmented and verified with vehicle dynamic data. To associate and match the objects from different sources as well as to integrate new objects into the environment model the Gower’s Distance [13] is used. This metric determines the similarity between two object hypotheses $o_i$ and $o_j$ with $p$ features by calculating the mean distance the partial dissimilarities $s_{i,j}$ (12). Only objects below a similarity threshold to existing ones are added to the object list and forwarded to the environmental model. A strength of the Gower’s Distance is the capability to process mixed data with quantitative and categorical variables. The partial dissimilarities $s_{k,quant}$ for quantitative features like the orientation, dimension and position of the objects are calculated using (13) where $o_{i,j,k}$ is the feature $k$ of $o_{i,j}$ and $R_k$ is the range of the feature over all present object hypotheses. In contrast to that $s_{k,cat}$ for categorical features like the object class is defined by (14) resulting in 1 if the features are identical and 0 otherwise. Objects are fused by a Kalman Filter afterwards in order to reduce noise and false detections.

$$d_G(o_i, o_j) = 1 - \left[ \frac{1}{p} \sum_{k=1}^{p} s_k(o_i, o_j) \right] ; \quad d_G \in [0; 1]$$  

$$s_{k,quant} = 1 - \frac{o_{i,k} - o_{j,k}}{R_k}$$  

$$s_{k,cat} = \begin{cases} 1, & \text{if } o_{i,k} = o_{j,k} \\ 0, & \text{otherwise} \end{cases}$$

The environmental model is facilitated in the form of a LDM according to [6] and [17]. It maintains information on objects influencing or influenced by road traffic and contains all fused objects with their respective position, dimension and motion vector as well as a probabilistic lane assignment of the objects. The model is based on a high definition (HD) map, stored in ASAM OpenDrive 1.5 format [37], which contains all semantic information like right of way rules, traffic light signals with their current state as well as all other traffic infrastructure elements. The LDM can then be queried to provide the required information for the path planning modules of the ADS.

Although the HD map acted as the primary source of information for driving lanes, lane markings and bus stops, a lane detection module based on the image of the front camera (C1 in Fig. 3) is implemented to aid the lateral localization in the current driving lane. The module uses Nvidia LaneNet [26] with extensions for temporal reasoning and lane tracking to smooth jittering lane positions. Both the lanes from the map as well as the lane detections are stored as lists of 2D points where a B-spline (several piece-wise cubic polynomials) is estimated by regression. Because outliers in the image based lane detection are quite common, a robust RANSAC-based estimator is used to estimate the correct B-spline model. These models are then fused with respective weights based on their expected quality.

By providing reliable information about surrounding traffic objects and their dynamic state the perception system represents the base for the planning components covered in the subsequent section.

![Fig. 8: Object fusion pipeline](image-url)
entire route with respect to factors such as travel time, ride comfort and task fulfillment. The global approach on this layer leads to planning horizons of individual strategic decisions ranging from minutes up to several hours.

2) Tactical Planning: The tactical planning layer generates optimal driving maneuver requests based on the given strategic route. A constant comparison of current driving states and actual target states (e.g. target speed, target lane) with a subsequent adaptation leads to a short-term optimization of the vehicle behavior w.r.t to the chosen target states and dynamic as well as static objects in the environment. The planning horizon in this layer is roughly equal to the atomic driving maneuvers that are planned which usually take several seconds.

3) Local Planning and Control: The driving maneuvers previously selected at the tactical planning level are realized by a local path planner. The path planner performs motion planning for both the longitudinal and lateral motion of the vehicle, considering the kinematics of the vehicle. Furthermore, dynamic and static objects are incorporated in the planning. The planning is performed periodically, so that the path can be rapidly adapted to new conditions. Steering the vehicle autonomously along this planned path while respecting the dynamic limits of the vehicle is a task of the control system. In ABSOLUT, a model predictive control approach as outlined in [32] is used to solve this path-following problem. Furthermore, an adaptive cruise control (ACC) controller as described in [33] is used to follow dynamic objects.

While the preceding paragraphs cover the ADS and the equipment of the shuttle, the next section introduces the installations on the roadside and the V2I hardware.

IV. INFRASTRUCTURE

The test route contains a total of 11 junctions as well as a railway crossing. Because the computer vision based traffic light detection still lacks robustness, especially due to the public transportation specific signalling, the ADS heavily relies on V2I communication in order to determine the current status of the traffic lights. Hence all traffic lights were retrofitted with Roadside Units (RSU) to communicate with the shuttles OBU. The communication is based on the ETSI C-ITS G5 (WLAN 802.11p) standard by the exchange of MAP and SPAT messages [5], [7], [4]. With potential driving speeds up to $70 \text{km} \cdot \text{h}^{-1}$ a signal range of $150 \text{m}$ was intended to guarantee comfortable stopping at junctions ($< 2 \text{m}^2 / \text{s}^2$) even with standing passengers. To evaluate the performance of the RSUs the signal ranges and quality were monitored on numerous test runs along the route. Fig. 9 shows an example of the signal range which was recorded at a signalled junction at the exhibition area. The color in the heat map depicts the amount of valid SPAT and MAP messages at this location (descending from red to blue). As shown, our requirements of a $150 \text{m}$ signal range could be satisfied. The quality of the signals showed to be sensitive against the positioning and orientation of the RSU antennas depending on the surrounding terrain, thus the RSUs had to be calibrated iteratively.

Fig. 9: Range of detected SPAT messages for a RSU at the Exhibition Area; shuttle trajectory (red); location of the RSU (purple sign); received signals (green); Background: Thunderforest Mobile-Atlas ©OSM

As the preceding sections introduced the vehicle and infrastructure setup and the ADS the following paragraphs share our approach to the legal approval of the shuttle.

V. VALIDATION AND LEGAL APPROVAL

Due to the tight schedule of the project the development of vehicle and ADS had to be significantly parallelized. For the development and validation of the functions for environmental perception, the availability of realistic data from the various sensors is of utmost importance.

Therefore, several test vehicles were equipped in order to collect data on the route from early on in the project. As represented in Table IV a we employed four standard passenger cars apart from the final EZ10 and the e-Crafter for distinct sensor analysis. Especially the two vehicles equipped with a multi-sensor rooftop-box (Table IV line 3) provided valuable insights on the sensor performance.

Real world testing is accompanied by a simulation model of the route using IPG CarMaker software [16]. It serves for the evaluation of the vehicles driving performance and energy consumption and the validation of the sensor setup in terms of sensor coverage, field of view and detection ranges along the test route.

Fig. 10 illustrates the simulation environment with the upper image showing a junction on the route in Leipzig and the lower image showing the corresponding part in the simulation model. Additionally, a traffic simulation based on SUMO [19] was implemented in order to calculate circulation times for the on-demand operation of the shuttle bus under varying traffic density.

With a standard commercially available VW e-Crafter as the base vehicle, operating the automated bus on open roads
legally required the approval of any significant modification to the vehicle. All additional hardware i.e. the DbW-system, the sensors as well as computers and peripheral components had to pass an electromagnetic compatibility test specified by UN ECE R10 [23]. For the approval of the DbW-system as well as the ADS itself we collaborated closely with regulatory authorities to define an incremental validation and approval approach following the development process of the project. This resulted in multiple approval phases slowly increasing the capability of the ADS from simple path-following to interacting with other traffic participants, crossing junctions and entering bus-stops. Following this approach, the shuttle was awarded a testing license which allows operation of the vehicle manually everywhere while driving in automated mode is strictly tied to the ODD along the route. With the new law on automated driving in Germany taking effect in 2021 [2] which introduces the concept of an ODD specific license for automated vehicles, we believe in the practicability of the incremental approval approach especially for research projects.

According to current regulations a human safety driver is mandatory for any automated operation in public traffic. He or she must be able to take over control at any time to prevent potentially hazardous behaviour. The safety drivers were conventional bus drivers by the LVB which took part in a training for the automated shuttle. During qualification, they were faced with synthetically induced errors in the ADS e.g. a drift in the localization or failing sensors in order to refine their judgement of when to intervene.

VI. CONCLUSION

In autumn 2022 the project ended with four weeks of on-demand pilot operation with passengers on the route. This period as well as the development process provided numerous insights regarding user acceptance, technological challenges and future strategies for the implementation of automated shuttles into the operating regime of PTOs. In this section we want to discuss our key conclusions. In the authors opinion the main contributions of ABSOLUT are:

- A working Cooperative Intelligent Transport Systems (C-ITS) application for automated passing of junctions and railway crossings
- A general concept of approving an automated bus shuttle on public roads in Germany
- An example vehicle configuration and lessons learned for the operation of highly automated vehicles regarding vehicle environment, maximum velocities, diversity of scenarios and road users as well as regarding the integration into an existing public transport infrastructure

A. Lessons learned and ongoing Challenges

From May 2021 until the end of November 2022, the shuttle drove approx. 6000 km with an estimated 3000 km of operation in automated driving mode. During the final project phase the safety driver had to intervene 2 to 3 times per 15 km lap on average, which forms a solid basis for future work and research. With the goal to reduce the number of interventions we see the following challenges.

1) Sensors and Hardware: As stated in II-B the sensor setup is deliberately oversized. While enabling 360° environment perception this leads to immense system costs and a high demand for the input bandwidth of the ADS. Its computational resources are currently insufficient to process the data of all sensors in full resolution simultaneously. Thus prices for sensors and hardware are about to sink in the future a challenge still lies in the appropriate choice of sensors for a certain route without loss of generality for other use cases.

2) Automated Driving System: The automated e-Crafter is currently capable of operating safely at speeds up to 60 km h^{-1} in real traffic with pedestrians, cyclists and cross traffic. However a big challenge still lies in the robustness the localization system with a certain emphasis on sections where environment parameters change rapidly (for instance when crossing a bridge) and thus the covariances of GNSS and LiDaR localizers alternate as well.

A further problem in the cooperation of multiple institutions is a missing standard for the interpretation of high definition maps. Despite using the common OpenDrive format, we encountered numerous issues in the interchange between map providers and users.

B. Future Work

Several technological challenges remain on the way to scalable on-demand automated shuttle services. Specifically, in future projects we want to address the following topics:

- increased reliability and accuracy of the localization and state estimation system to reliably cover mixed traffic

![Fig. 10: Modelling the route in CarMaker - example junction; Google Earth image (top); CarMaker road model (bottom)](image)
environments by improving the LiDaR-based localization module, by adding an integrity monitoring layer to the *Outlier Gateway* and by adding a fallback localization strategy based on local road features

- enhanced object detection and fusion for safe operation in close proximity to VRUs

While the current release of the V2X-Interface only supports a binary decision based on the current state of the traffic light the integration of a *Green Light Optimized Speed Advisory System* according to [28], [40] is planned for future work and subsequent projects. Further, for a truly economically viable automated shuttle bus solution, the vehicle has to be able to drive reliable and safe without the constant supervision of an on-board safety driver. German and European law suggests the transfer of the supervisory task to a remote operator, who can monitor several vehicles at the same time and only intervenes when a vehicle reports a problem [29]. However, next to regulatory uncertainties, technological questions regarding the design and safety of the interface between vehicle and remote systems when a vehicle reports a problem [29]. However, next to regulatory uncertainties, technological questions regarding the design and safety of the interface between vehicle and remote systems when a vehicle reports a problem [29]. However, next to regulatory uncertainties, technological questions regarding the design and safety of the interface between vehicle and remote systems when a vehicle reports a problem [29]. However, next to regulatory uncertainties, technological questions regarding the design and safety of the interface between vehicle and remote systems when a vehicle reports a problem [29]. However, next to regulatory uncertainties, technological questions regarding the design and safety of the interface between vehicle and remote systems when a vehicle reports a problem [29].

**APPENDIX**

**TABLE I: Specification of the Volkswagen e-Crafter**

<table>
<thead>
<tr>
<th>General</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>2502 kg</td>
<td></td>
</tr>
<tr>
<td>Size ($L \times W \times H$):</td>
<td>5986 mm×2427 mm×2590 mm</td>
<td></td>
</tr>
<tr>
<td>Wheelbase</td>
<td>3665 mm</td>
<td></td>
</tr>
<tr>
<td>Passenger seats:</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

**Powertrain & Battery**

| Power                      | 100 kW |       |
| Speed:                    | max. 90 km h$^{-1}$ |       |
| Battery Capacity:         | 31.7 kJ h$^{-1}$ |       |
| Range:                   | approx. 115 km (combined) |       |

**TABLE II: Hardware (extract)**

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Model</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nvidia</td>
<td>DRIVE AGX Pegasus</td>
<td>Perception</td>
</tr>
<tr>
<td>Neousys Techn.</td>
<td>Nuvo-8208GC</td>
<td>HAD PC</td>
</tr>
<tr>
<td>Neousys Techn.</td>
<td>Nuvo-7100VTC</td>
<td>Localization PC</td>
</tr>
<tr>
<td>Neousys Techn.</td>
<td>Nuvo-7100VTC</td>
<td>Maintenance PC</td>
</tr>
<tr>
<td>Cohda Wireless</td>
<td>MK5 OBU</td>
<td>V2X interface</td>
</tr>
<tr>
<td>TDT</td>
<td>G3000-LW-ELW</td>
<td>LTE Router</td>
</tr>
<tr>
<td>Würth Elektronik</td>
<td>WE-CABIN Display i7</td>
<td>Safety Driver interface</td>
</tr>
<tr>
<td>Kienzle Argo</td>
<td>UDT AT Pro</td>
<td>accident data recorder</td>
</tr>
</tbody>
</table>

**TABLE III: Additional sensors in the VW e-Crafter**

<table>
<thead>
<tr>
<th>Category</th>
<th>Type</th>
<th>No. in Fig. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTK-GNSS</td>
<td>ANavS MSRTK</td>
<td>A1 - A3</td>
</tr>
<tr>
<td>IMU-AHRS</td>
<td>Xsens MTi 630</td>
<td>H</td>
</tr>
<tr>
<td>LiDaR</td>
<td>Ouster OS2 64</td>
<td>L7</td>
</tr>
<tr>
<td>LiDaR</td>
<td>Ouster OS1 64</td>
<td>L8</td>
</tr>
<tr>
<td>LiDaR</td>
<td>Velodyne VLP-16</td>
<td>L9</td>
</tr>
<tr>
<td>LiDaR</td>
<td>Ibeo Lux 4L</td>
<td>L1 - L6</td>
</tr>
<tr>
<td>Camera</td>
<td>Sekonix SF3323-10X</td>
<td>L1 - R5</td>
</tr>
<tr>
<td>Camera</td>
<td>Sekonix SF3323-10X</td>
<td>C1</td>
</tr>
<tr>
<td>Camera</td>
<td>Sekonix SF3323-10X</td>
<td>C2, C3, C8</td>
</tr>
<tr>
<td>Camera</td>
<td>Sekonix SF3323-10X</td>
<td>C4 - C7</td>
</tr>
<tr>
<td>Camera</td>
<td>Flir ADR 60°</td>
<td>C9</td>
</tr>
<tr>
<td>Multi-Purpose</td>
<td>Panorama</td>
<td>MiMo1,</td>
</tr>
<tr>
<td></td>
<td>LGMQM4-7-38-</td>
<td>MiMo2</td>
</tr>
<tr>
<td></td>
<td>24-58</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE IV: Test Vehicles in ABSOLUT**

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Equipment</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skoda Octavia</td>
<td>RTK-GNSS,</td>
<td>LTE quality monitoring, RTK-GNSS-Localisation continuous operation test</td>
</tr>
<tr>
<td>BMW i3</td>
<td>V2X OBU</td>
<td>Car to Traffic Light communication testing</td>
</tr>
<tr>
<td>Audi A6 &amp; Mercedes Benz E-Class</td>
<td>RoofTop-Box with three Cameras, 360° and LiDaR, IMU and RTK-GNSS</td>
<td>Data acquisition for offline Localisation, SLAM, object detection and Computer Vision development</td>
</tr>
<tr>
<td>EasyMile EZ10</td>
<td>full setup (see II-II-B)</td>
<td>automated driving at lower speed</td>
</tr>
<tr>
<td>Volkswagen eCrafter</td>
<td>full setup (see II-II-B)</td>
<td>automated driving at higher speed</td>
</tr>
</tbody>
</table>

**REFERENCES**


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Marcel Graef holds an M.Sc. in Media Informatics from HTWK Leipzig University. He specialized in image processing during his studies and collaborated with Fraunhofer Institute for Digital Media Technology (IDMT). At Sedenius Engineering GmbH, he played a key role in virtual testing projects for automotive sensors and autonomous driving. As the CTO since 2019, he shapes the company’s technological strategy and R&D department. His research focuses on intelligent Autonomous Vehicles and systems for people and goods, showcasing his dedication to advancing safe and efficient mobility solutions.

Marcus Pelz received the M.Sc. degree in mathematics from Chemnitz University of Technology, Chemnitz, Germany in 2017. Since 2018 he is at IAV GmbH, where his focus is on the development of self-driving systems and cooperative driver assistance systems for applications in modern mobility solutions. Currently, he is Team Manager for intelligent driving functions development at IAV GmbH.

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