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Level 4 commercial autonomous vehicle control system transition to an open-source solution

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Abstract. This paper introduces a novel approach for transferring the entire set of low-level control systems from one robot bus, i.e., an autonomous vehicle (AV) shuttle, to another with distinct electronics and mechanical specifications. The research entails a series of experiments to assess the reliability and safety of the AV shuttle after integrating the critical control systems responsible for steering, accelerating, and braking into the target shuttle. The ultimate goal is to meet the necessary requirements for registering the target AV shuttle as a legal vehicle on the roads in Estonia. Consequently, several crucial tests of the shuttle's low-level control system were conducted, e.g., intentionally disconnecting different subsystems to simulate sudden failures and evaluate whether the shuttle responds in accordance with the appropriate protocols. As a case study, the upgraded autonomous shuttle was tested on the streets of Tallinn. The most relevant findings are introduced in the second part of this paper. The outcomes of the study demonstrate the feasibility of seamlessly transferring low-level control systems between various models of autonomous shuttles, eliminating the risk of encountering safety or reliability issues.

Keywords: cyber-physical system, autonomous vehicle, robot bus, low-level control, open-source software.

1. INTRODUCTION

The advancement of automated vehicles (AVs) has recently sparked hopes for a future with fully driverless transportation, boasting improved efficiency, enhanced traffic safety, and energy conservation. The concept of AVs has a rich history, with one of the earliest notable examples dating back to the 1950s when General Motors pioneered an automation system embedded alongside roads, as the technology then did not permit integration within the vehicles. Nevertheless, this marked a significant step towards envisioning autonomous driving [1].

The actual realization of AVs began to materialize in the new millennium. In 1998, the ARGO vehicle achieved a remarkable feat by successfully completing a driving test spanning over 2000 km on an Italian highway, signaling the dawn of driverless vehicle history [2]. The contemporary definition of AVs revolves around their reliance on sensors to perceive their surroundings and computer technologies to make informed decisions. This definition was first practically demonstrated during the DARPA Grand and Urban Challenges competition held between 2005 and 2007 [3].

Following the 2010s, there was a surge in the development of AVs, with numerous companies and research groups investing substantial resources into creating commercialized technologies and experimental platforms [4,5]. The blossoming interest in AVs has set the stage for their potential widespread adoption and integration in various industries in the near future.

Among commercialized technologies, the advanced driver assistance system (ADAS) stands out as one of the most successful and widely adopted technologies in commercial vehicles. Its primary function is to offer basic

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Fig. 1. The TalTech iseAuto (left) and Navya Evo (right) autonomous shuttles. Photo by Heiko Pikner.

assisted features, such as distance control, lane keeping, and collision warning. ADAS represents a significant research direction focused on object perception to enable intelligent decision-making. Over the years, advancements in the sensor industry and computing power have driven remarkable progress in corresponding techniques.

Two key technologies that have contributed to the success of ADAS are light detection and ranging (LiDAR) sensors and computer vision. These technologies allow vehicles to overcome weather limitations and achieve precise detection and classification of objects, enhancing overall safety and performance.

While the industry has mostly relied on mature technologies, the research community has shown considerable interest in experimental autonomous driving platforms. Examples like [6] and [7] involve testing autonomous driving algorithms in vehicles for civilian usage. Developing low-speed AV shuttles, also known as robot buses, further seeks to explore the practical potential of autonomous vehicles in real-world scenarios. The deployment of such real-traffic AV shuttles could potentially reshape human transportation habits. One notable AV shuttle is the iseAuto shuttle (depicted as the left one in Fig. 1), designed and developed by the autonomous vehicles research group at TalTech, Estonia [8,9]. The iseAuto shuttle represents a significant step forward in the autonomous driving domain, and its success could pave the way for further advancements in the field.

The emphasis on reliability and safety has been paramount in developing autonomous vehicles since their conception in research communities. Unlike human drivers who rely on their sentient brains as sensors and computers to perceive the environment and make decisions, AVs require cutting-edge technology to replicate these functions. In traditional driving, the physical control of the steering wheel, brakes, and throttle by human hands and feet ensures the vehicle's safety. However, for autonomous vehicles, extensive research has centered around the perception-decision aspect, aiming to attain a comprehensive understanding of the environment and flawless decision-making capabilities. Nevertheless, some perspectives argue that the low-level control systems hold greater significance for AV safety than the perception-decision stage. The precise and fail-safe execution of critical steering, speed, and brake controls in AVs leaves little room for mistakes. Therefore, it is imperative to subject the AV's low-level control system to rigorous failure-proof and accuracy tests before deploying these vehicles into real traffic.

By prioritizing safety at both the perception-decision stage and the low-level control systems, researchers and developers endeavor to instill the highest levels of confidence in AV technology, ensuring its seamless integration into real-world transportation scenarios.

An often chosen platform for testing autonomous driving is commercial vehicles due to their well-tested suspension, car frame, and other mechanical components. However, adapting these vehicles for autonomy requires significant electronic modifications to enable computer operation. For instance, in their research, Wei et al. [10] integrated multiple actuation/electronic control modules into a Cadillac SRX to achieve full autonomous capabilities for brake, throttle, steering, and transmission shifting systems.

Regarding low-speed AV shuttles, the controlling systems differ as they lack traditional components, such as steering wheels and brake/throttle paddles. Instead, manual control relies heavily on joystick controllers, while telecontrol utilizes simulated steering wheels. Consequently, the entire low-level control system must be extensively customized for each vehicle.

A significant contribution of their work is the successful transfer of the low-level control system from the TalTech iseAuto AV shuttle [11] to the Navya Evo AV shuttle (depicted as the right one in Fig. 1). The Navya AV shuttle, a mature French-made self-driving product in the market, had previous piloting experience on Estonian roads [12]. However, by the end of the pilot, the vehicle's software was outdated, and the contract with the manufacturer had concluded. Despite these challenges, reliability and performance testing of the Navya AV shuttle demonstrated the feasibility of migrating iseAuto's low-level control system to another type of AV shuttle with different hardware specifications. This achievement opens up possibilities for using proven autonomous technologies in various AV models, enhancing their safety and efficiency.

2. TRANSITION OF THE LOW-LEVEL CONTROL SYSTEM

In our research and development efforts, we have successfully constructed two autonomous vehicles, namely a full-scale AV shuttle – iseAuto [13] – and a warehouse logistic robot – BoxBot [14]. As we continue to progress, our team now focuses on transferring our advanced low-level control system to an open-source platform, ensuring its adaptability to various types of autonomous vehicles. This step aims to foster collaboration and innovation within the autonomous vehicle community, as a universal and modular low-level control solution can greatly facilitate the promotion and widespread deployment of autonomous technologies.

By making our low-level control system open-source, we enable other researchers, developers, and manufacturers to leverage our expertise and integrate our proven technology into their AV projects. The versatility of this solution ensures seamless integration into different vehicle models, reducing the development time and resources required for implementing autonomous functionalities. Such accessibility can accelerate the overall advancement of autonomous technology and pave the way for a safer and more efficient future of transportation.

To validate the effectiveness and compatibility of our low-level control system in different vehicles, we conducted a series of comprehensive tests and experiments on the Navya shuttle. The Navya shuttle serves as an excellent testbed for evaluating the adaptability and robustness of our control system. Through these rigorous assessments, we ensure that the transferred solution meets the highest standards of safety, reliability, and performance, laying the groundwork for its real-world implementation.

Our vision is to contribute significantly to the growth of the autonomous vehicle ecosystem by fostering collaboration and knowledge-sharing across the industry. By making our low-level control system openly accessible, we aspire to catalyze advancements in autonomous technology, fueling its widespread adoption and transforming the way we experience transportation in the modern world. Prior to any modifications, the self-driving shuttle Navya had the capability to autonomously traverse a predefined route. However, this required an expensive and time-consuming analysis and assessment process. The shuttle's supplier was responsible for recording and editing the 3D LiDAR map and driving path using their own proprietary models and software [15]. Consequently, implementing the shuttle on a new route or making changes to existing routes necessitated the presence of a specialized team from the vehicle manufacturer.

The process of converting the existing self-driving shuttle into an open-source solution comprises several design stages. As of now, the vehicle manufacturer has not disclosed any details about the performance and technical solutions of the vehicle. The original shuttle, which was operated through a joystick, lacked the capability for autonomous driving.

The initial phase entails examining and charting the current low-level architecture. The primary focus is on identifying the original control computers and their data connections to the vehicle's low-level systems. Communication with the low-level vehicle system is facilitated through the use of the controller area network (CAN), a well-established multi-master broadcast serial bus communication protocol employed for linking electronic control units (ECUs) in automotive applications [16]. Moreover, the vehicle is equipped with an ethernet network that allows the two control computers to communicate not only with each other but also with higher-level sensors like LiDAR sensors.

In the second stage, the focus shifts to logging the CAN messages from all three identified networks. Each message possesses a distinctive CAN ID for easy identification. To determine the CAN network speeds, various

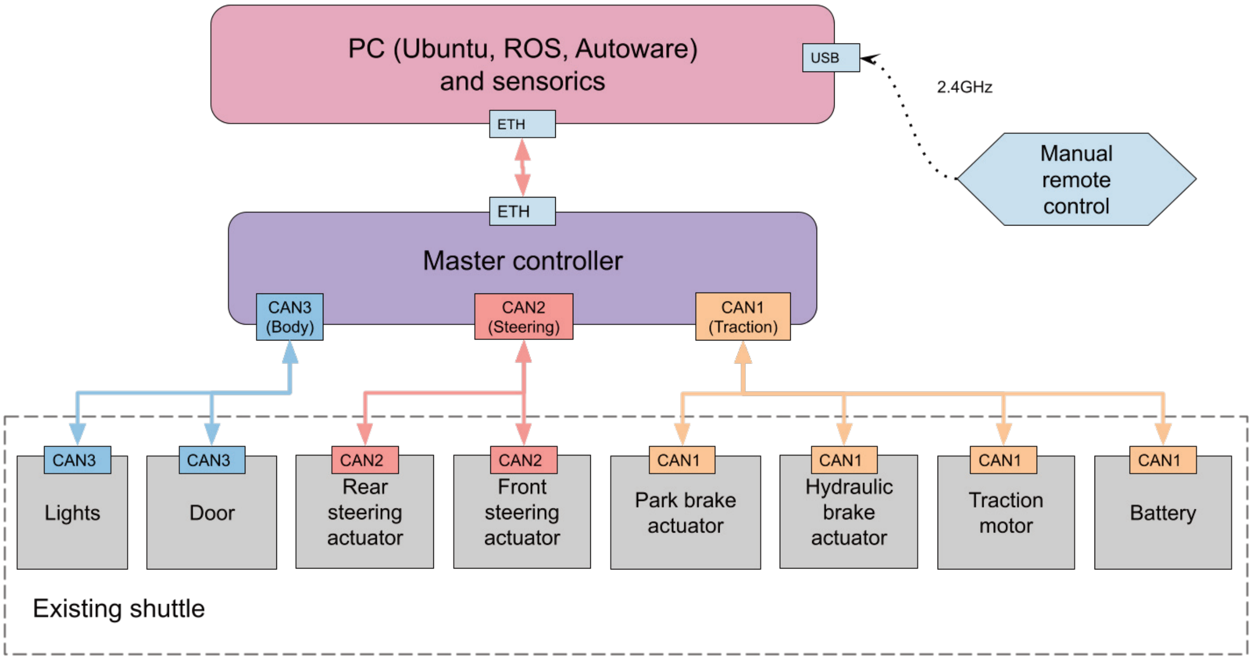

Fig. 2. Updated hardware architecture for the shuttle.

standard settings were experimented with. A custom-built gateway controller was employed separately to discern the direction of packets. For instance, the mapping of packets sent by the original control computer for each CAN network was accomplished through this process.

In the third phase, the main objective is to identify the data within the data field of the CAN packets. The SavvyCAN DBC files serve as repositories for definitions of how the data are formatted on the bus. By processing the raw data, it becomes possible to extract various parameters, such as RPM, odometer readings, and more [17]. To determine important parameters, adjustments were made using the existing joystick or touchscreen, while monitoring the changes in the CAN packets transmitted by the original control computer. The existing data, including specified ranges like the minimum and maximum steering angle, speed, and other signals, were thoroughly documented.

Moreover, it is essential to find feedback for each crucial signal, enabling the utilization of a regulator such as the proportional integral derivative controller (PID), which facilitates monitoring the execution of commands. This ensures that the control system can function effectively by providing necessary feedback and verification.

In the final step, the process involves establishing bidirectional communication for all the necessary messages required to control the shuttle, as illustrated in Fig. 2. To accomplish this, an existing in-house developed master controller [13] is utilized as the central control unit. To facilitate the integration of new vehicle-specific messages, additional software layers are added to the master controller.

Three distinct CAN buses are identified and connected to the master controller: CAN1 for traction and battery, CAN2 for steering, and CAN3 for body-related systems. Furthermore, a new control computer equipped with open-source software (Ubuntu, ROS, Autoware) is introduced into the system. To interconnect this new control computer with the existing lidars, cameras, and a mobile internet access point, a novel ethernet network is established.

Once these modifications are implemented, the self-driving shuttle becomes operational and capable of driving. The subsequent focus lies in fine-tuning and testing the vehicle to achieve autonomous driving capabilities.

3. EXPERIMENTS

Creating a safe and dependable solution necessitates conducting numerous experiments. The initial step involves integrating steering system control signals into the master controller. During this stage, it is imperative to determine the range of control and feedback signals. To facilitate further analysis, data logging is carried out to capture relevant information. For instance, Fig. 3 illustrates how the control signal sent by the original control computer considers the movement speed of the steering system. The vehicle possesses both front and rear axles,

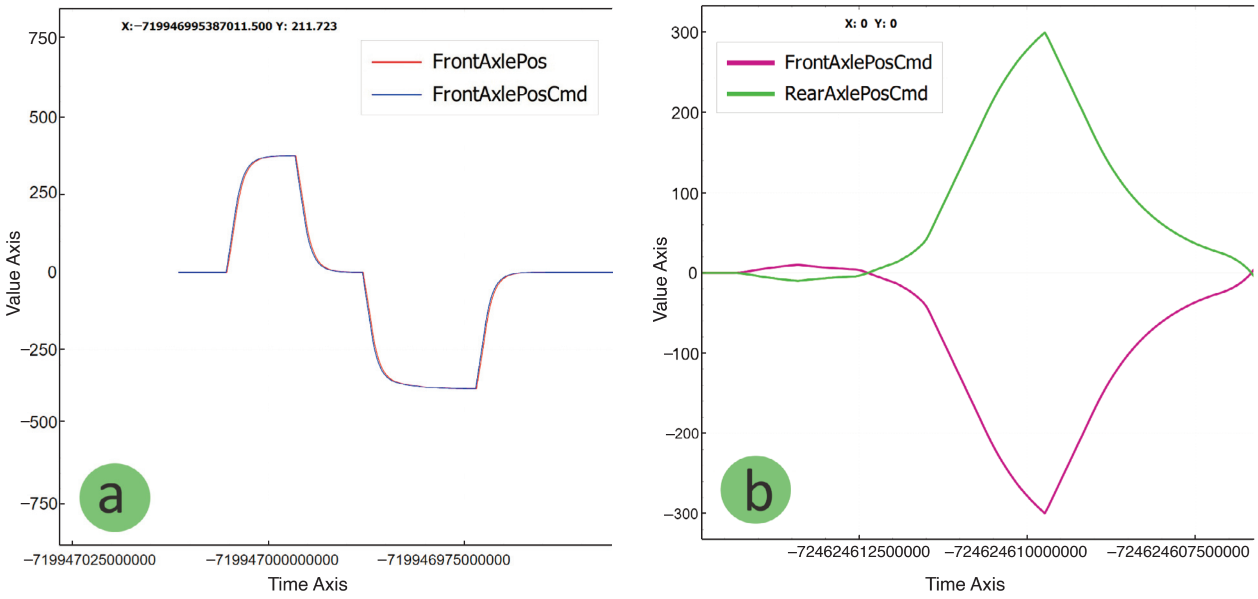

Fig. 3. Steering signals with the original control system: (a) relationship between position and feedback signals, (b) relationship between front and rear axle signals.

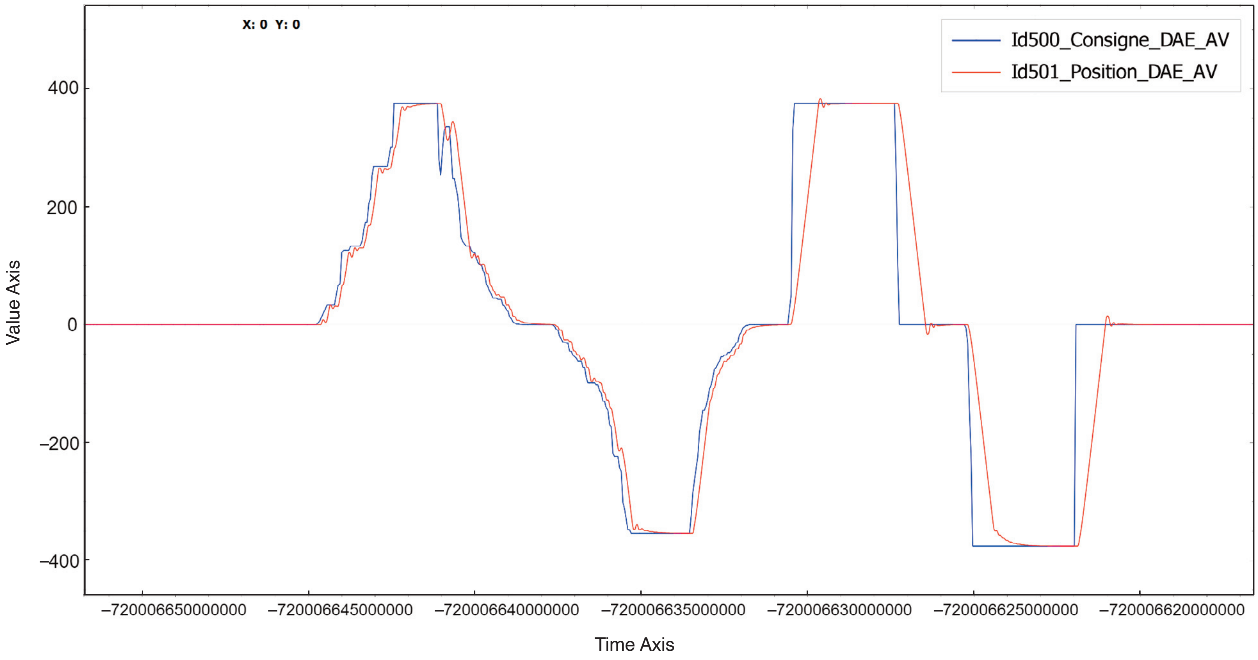

Fig. 4. A custom master controller sends out steering signals. Slow and high-speed movements are requested.

and their turning capabilities are taken into account. Notably, the values of the rear and front axle control signals differ in sign.

Moreover, an innovative approach is devised to enable independent control of the front and rear axles, a feature expected to be beneficial in various future experiments. Figure 4 showcases the steering signals transmitted by the master controller. Experiments were conducted to measure the speed at which the axle could mimic changes in the control signal. As anticipated, the maximum axis

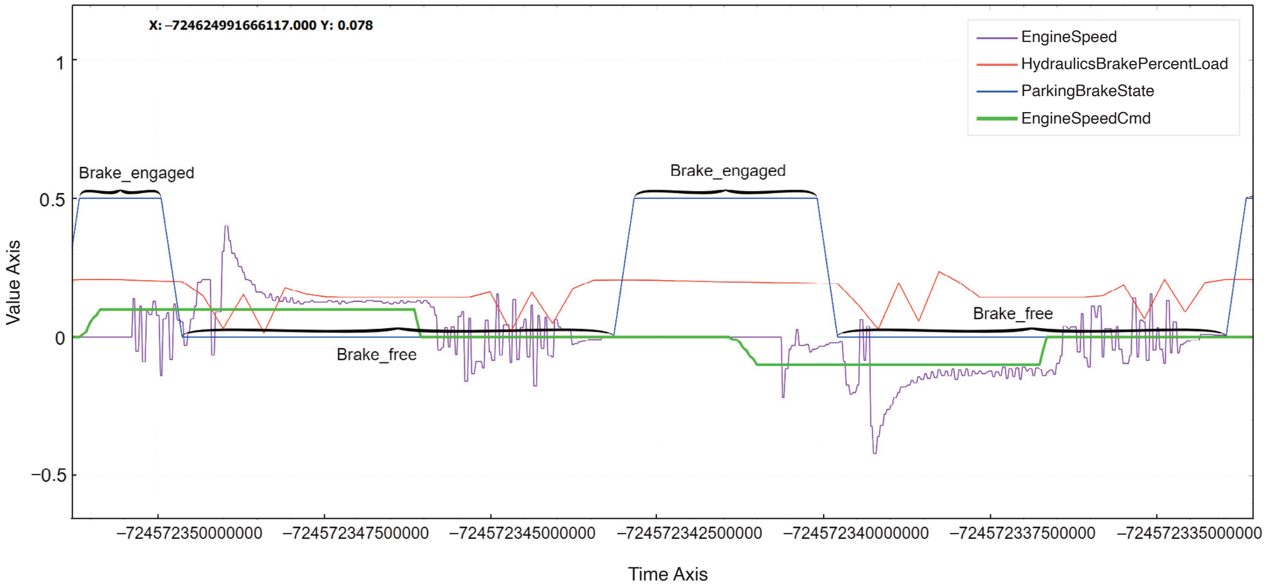

Fig. 5. Engine speed request sent out by the original control system activates the hydraulic brake and handbrake.

movement speed remains constant, and when reached, the actual position of the axle lags behind the required position.

The steering signal processing in the master controller follows a straightforward approach. The desired steering angle is conveyed through a user datagram protocol (UDP) packet from ROS, where it is converted from radians to degrees. Subsequently, a vehicle-specific CAN packet is generated based on this information. Moreover, the position signals of both axles are forwarded to ROS as feedback, completing the steering signal processing loop.

Moving on to the next step, the focus is on implementing the traction motor speed and control signals. The traction motor ECU awaits a status signal, which can either be in "use" or "standby" mode. However, managing the speed of the traction motor and braking presents a more intricate challenge. The vehicle features both a hydraulic brake and an electric handbrake that engages when the shuttle comes to a stop, as depicted in Fig. 5.

Upon scrutinizing the packets and analyzing the logs, it becomes evident that the corresponding ECU governs the brakes by utilizing the engine speed signal. As a result, inverting the engine speed signal causes the vehicle to move in reverse. When the engine speed signal reaches zero, the hydraulic brakes are engaged first, and as the shuttle comes to a stop, the handbrake is also applied to ensure a complete halt.

The speed signal processing within the master controller is relatively simpler compared to the steering signal. The desired speed signal is encapsulated in a UDP packet sent by ROS, which is then used to form a vehicle-specific CAN packet. Similarly, the traction motor control signal, represented by a one-byte flag, is processed in a manner similar to the iseAuto gear signal.

The engine speed request is transmitted by the master controller. As anticipated, the traction motor's speed adheres to the input signal. Additionally, the master controller forwards the speed feedback signals to ROS, enabling basic telemetry and speed regulation functionalities.

The autonomous shuttle underwent an extensive two-month testing phase within a specific district of the city, following a prescribed 1.1-kilometer route illustrated in Fig. 6. Subsequently, we harnessed a PostgreSQL database to meticulously record crucial data from the autonomous shuttle, which is structurally depicted in Fig. 8. These data empower us to conduct a thorough analysis of the shuttle's performance and behavior during the testing phase.

PostgreSQL, recognized as the world's leading open-source database management system (DBMS), provides comprehensive support for an array of structured query language (SQL) transactions, concurrent control mechanisms, and contemporary features. These include intricate query capabilities, trigger functionalities, view creation, transactional reliability, and the flexibility to integrate data type extensions, functions, operators, and procedural languages [18]. The database is organized into two distinct sections: the first segment houses higher-level data, encompassing sensor data, localization parameters, trajectory planning, and tracking parameters. In contrast, the second section manages vehicle status data at a lower

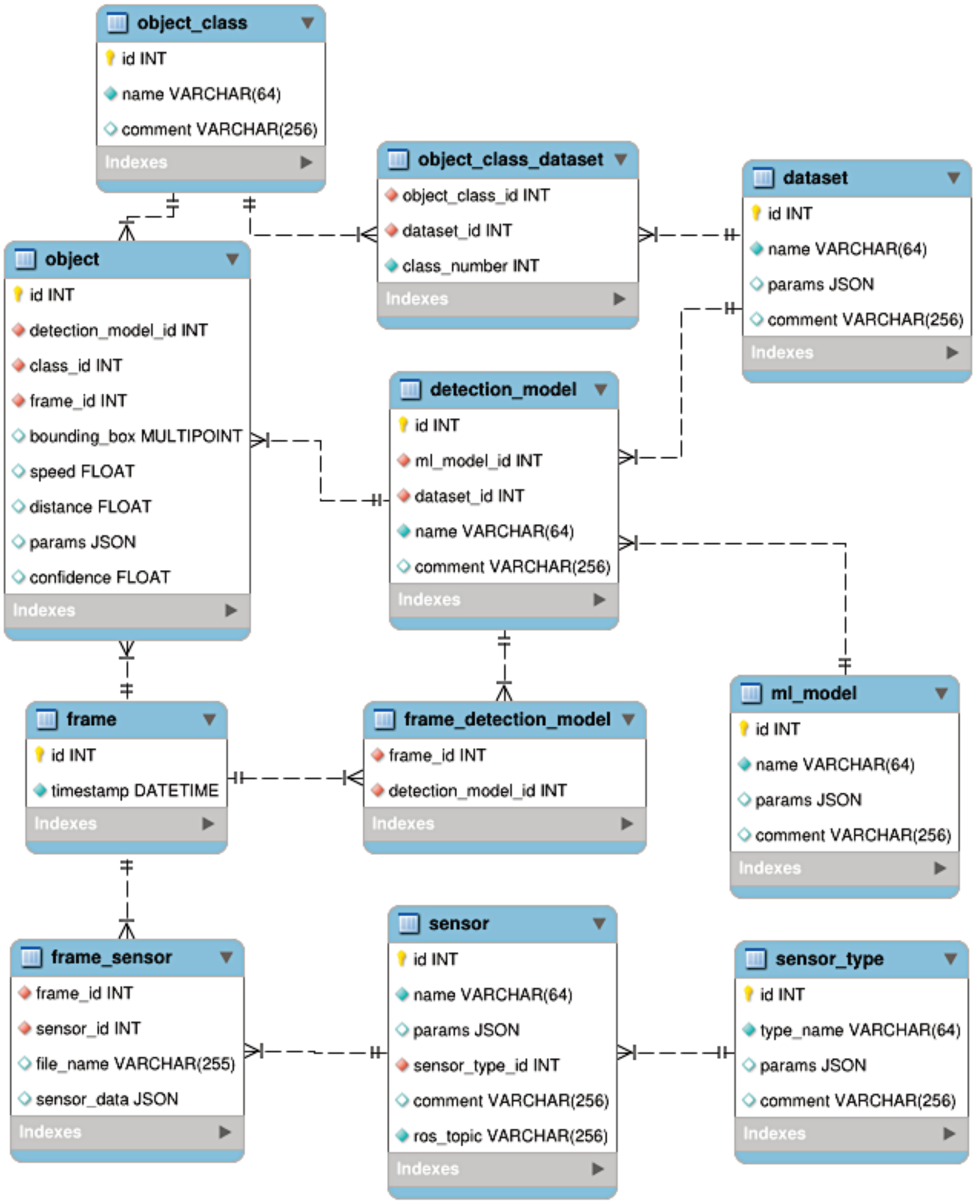

Fig. 6. System logging SQL database schema.

level, covering variables such as velocity, steering angle, door and light status, as well as brake and emergency brake status. As depicted in Fig. 8, the blue line represents GNSS (global navigation satellite system) data retrieved from the database, illustrating the trajectory path followed during the experiments on the designated route.

During our experimental evaluation of the master controller, we aimed to thoroughly assess its performance within the context of the autonomous shuttle. To do so, we conducted a comparative analysis using two different software systems: the original software, which came with the shuttle, and a custom software solution specifically designed for this study. These tests were carried out along a defined section of the shuttle's route, and throughout the experiment, we diligently recorded the steering data, as exemplified in Fig. 7.

The results, as depicted in Fig. 7, tell an intriguing story. They reveal that the steering angle achieved with our custom master controller consistently outperforms the steering provided by the original software. This enhanced performance is characterized by a smoother trajectory, implying greater precision and control over the shuttle's movements.

In conclusion, our evaluation strongly suggests that the custom master controller has the potential to sig-

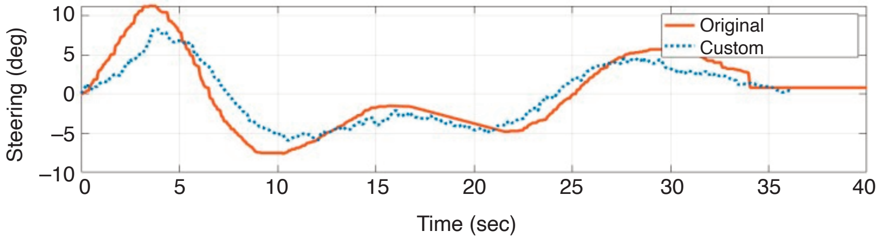

Fig. 7. Steering angle of the original software and with custom controller.

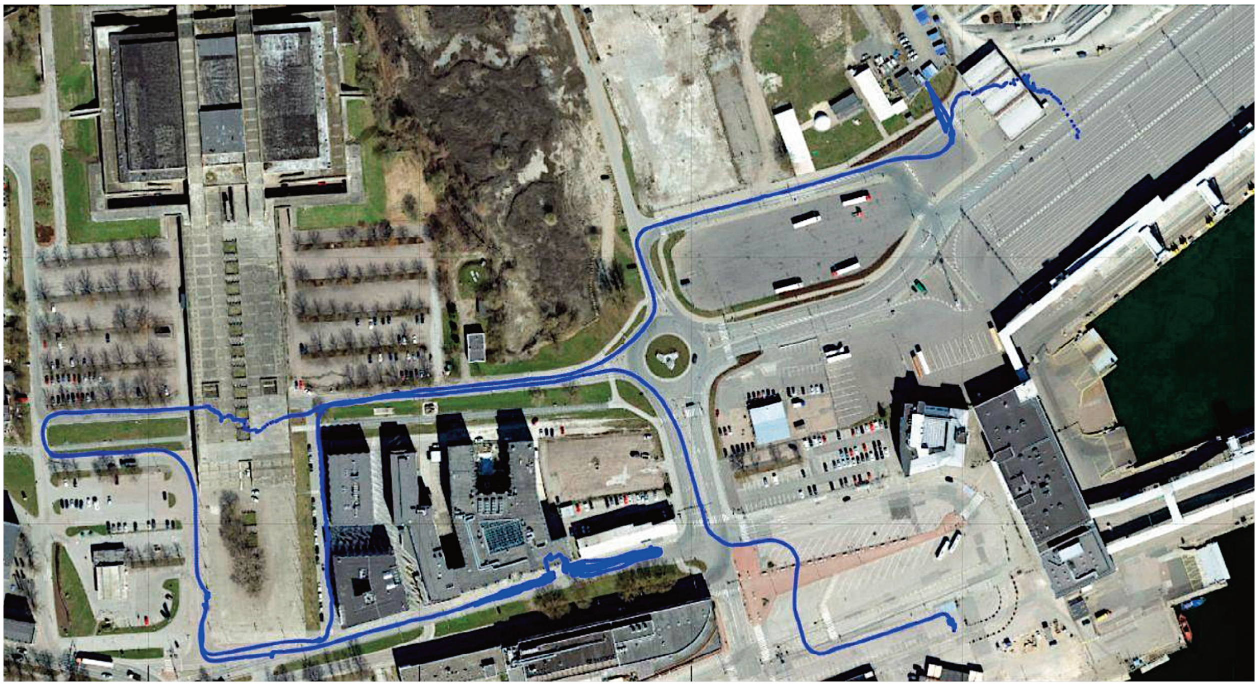

Fig. 8. Designated route that extended for a distance of 1.1 kilometers recorded in the database.

nificantly enhance the autonomous shuttle's steering performance compared to its original software counterpart. This finding highlights the importance of software optimization in achieving smoother and more reliable autonomous vehicle operations, which ultimately contribute to the advancement of autonomous transportation technologies. Further research and testing could provide valuable insights for refining and fine-tuning the custom software for even greater improvements in steering and overall autonomous vehicle performance.

4. RESULTS AND DISCUSSION

The new control system successfully completed all initial tests, conducted meticulously to ensure the shuttle's safety. The testing process adhered to a well-structured plan. First, the electronic control modules were tested individually on a testing bench while closely monitoring their performance. The analyzed results proved beneficial in fine-tuning data and refining the modules' operations. Next, the ECU was mounted on the shuttle, and further tests were conducted while the vehicle was lifted from the ground. This step allowed for additional scrutiny to verify the system's functionality under practical conditions.

Lastly, the driving tests of the shuttle were carried out on an empty street to identify any critical bugs and enhance the software's performance. This real-world testing enabled the team to rectify any issues and make necessary improvements to ensure the system's optimal functioning.

During the testing and debugging phase, a safety-critical bug was detected and promptly addressed in the master controller software. The issue arose from the incorrect processing of speed command packets, leading to a sudden application of the shuttle's brakes. This behavior posed a significant safety risk to the passengers. Fortunately, the bug was swiftly rectified, ensuring that such abrupt braking incidents no longer occur, thereby enhancing the overall safety and reliability of the shuttle's control system.

To register the autonomous shuttle as a legal vehicle in Estonia, specific tests are mandated, which include verifying the reliability of the shuttle's control system by temporarily disconnecting certain system components. These requirements were taken into account during the development of the updated safety concept. Each module within the system serves a safety-related function.

For instance, the AI computer plays a crucial role in processing lidar and camera data, allowing it to execute smooth braking maneuvers when deemed safe and with sufficient distance. The master controller, in this safety concept, primarily acts as a gateway. It possesses the capability to deactivate all control packets transmitted across the three CAN networks if there is a loss of databus connection. This precautionary measure enables the low-level vehicle hardware to detect the issue and promptly execute emergency brakes, which involve shutting down the traction motor power, thereby ensuring a secure and controlled braking procedure.

In addition to initiating regular brakes and applying the handbrake, the AI computer is programmed to detect the absence of feedback packets. In such a situation, it immediately halts active driving actions to ensure safety and prevent any potential risks or hazards. The new master controller has three CAN connections and an ethernet connection linked to the main computer. Through testing, it was discovered that each connection plays a critical role in the safe operation of the shuttle. If the traction CAN1 is disconnected, the vehicle immediately engages in emergency braking and initiates a shutdown of the high-voltage system. Disconnection of the steering CAN2 causes the steering mechanism to cease functioning, leading to the loss of position feedback packets. Subsequently, the system shuts down as a precautionary measure.

When the body CAN3 is disconnected, both interior and exterior lights are deactivated, and the automatic doors cease to operate. However, a dedicated switch is available to cut off the power, allowing for manual opening of the doors. Lastly, if the ethernet connection between the master controller and the new control computer is severed, all control packets vanish from the three CAN networks. As a safety measure, the shuttle engages emergency brakes and comes to a complete stop. These safety protocols ensure that any potential disruptions or disconnections are promptly detected and managed, safeguarding the passengers and the vehicle's overall operation.

The functionality of the emergency stop buttons was individually tested using the control signal generated by the new master controller. The outcome demonstrated that the vehicle came to an immediate halt, as expected, aligning with the safety concept outlined previously. Nevertheless, further tests are necessary to assess the braking force and ensure it meets the stipulated requirements. These additional tests will provide a comprehensive evaluation of the shuttle's braking capabilities and validate its compliance with safety standards.

5. CONCLUSIONS

The process of transforming the existing self-driving shuttle into an open-source solution entails several crucial design steps. Firstly, the team maps the existing low-level architecture, identifying control computers and data connections to low-level vehicle systems, particularly using the controller area network (CAN) protocol.

Secondly, they log and analyze the CAN messages to extract essential data, creating a comprehensive understanding of the shuttle's functioning. Based on these data, a new solution is developed and implemented.

To ensure the safety and reliability of the new solution, rigorous experiments and tests are conducted on both low-level and high-level components. Critical tests involve deliberately disconnecting various system components to verify the system's resilience and ability to respond to faults appropriately.

In low-level tests, the focus is on assessing whether life-critical actuators precisely follow the intended movement patterns and if the selected action plan is triggered accurately when artificial faults are introduced.

The successful outcome of these experiments and tests culminated in creation of the new parallel-built shuttle, TalTech iseAuto 2.0. The insights and knowledge gained from this work contribute to the future efforts of making the shuttle street-legal in the shortest possible time, while ensuring its compliance with safety standards and regulations. The new shuttle is based on the Estonian first self-driving shuttle ISEAUTO, but has an updated low-level control system as well as a higher-level autonomous driving software stack – Autoware.Universe.

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Tase 4 autonoomse sõiduki juhtsüsteemi ümberkujundamine vabavaralisele lahendusele

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Uurimistöö tutvustab uudset lähenemisviisi avatud lähtekoodiga madala taseme juhtsüsteemi ülekandmiseks ühelt erinevate parameetritega autonoomselt sõidukilt teisele. Töö jagunes mitmeks etapiks. Esiteks kaardistati olemasolev lahendus ja leiti andmesiinid. Andmesiinidel liikuvad paketid salvestati ja neist eraldati olulised juhtsignaalid. Peale seda oli võimalik need signaalid taasluua, kasutades vabavaralist lahendust. Töökindluse ja ohutuse hindamiseks korraldati mitu katset erinevate alamsüsteemide rikete simuleerimiseks ja tulemuste mõõtmiseks. Pilootprojekti raames testiti modifitseeritud autonoomset sõidukit Tallinna tänavatel. Uuringu tulemused näitasid, et madala taseme juhtsüsteemide ülekandmine erinevate autonoomsete sõidukite vahel on teostatav. Tulemusi kasutati TalTechi uue iseAuto v2.0 arenduseks, kus võeti arvesse eksperimendi tulemusi ja saadud kogemusi madala taseme süsteemide testimisel linnatänavatel.