Micro AI-For-Mobility – Research Platform for AI-Based Control Methods

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***Abstract*— The AI for Micro Mobility (µAFM) is the new research platform for investigation of novel active and passive electronic bicycle assistance control methods within the Department of Vehicle System Dynamics at the German Aerospace Center (DLR). Autonomous driving and artificial intelligence offer completely new possibilities for control systems. However, no studies have yet investigated the holistic approach, from the perception sensors to the control algorithms, with the aim of protecting vulnerable road users, particularly in the context of bicycles. The objective of our research is to contribute to this field of study. To this end, we equipped a production electric serial hybrid power train bicycle with a set of state-of-the-art sensors and computational hardware. The hardware and software integration of the various sensors as well as the network architecture is presented. Paving the path for further research in this field. Concluding, two real-word experiments are conducted to validate and investigate the performance of the setup for further control algorithms studies.**

***Keywords*— AI-based control methods, e-bike research platform, bicycle assistant systems, robotic bicycle, electro-mobility, micro mobility platform**

I. Introduction

Global warming, a pressuring issue of our times, has catalyzed numerous international conferences and agreements with the goal to reduce greenhouse gases. The latest agreement aims to decrease emissions drastically [1]. However, emissions from the transport sector are steadily increasing [2]. To keep up with the agreed targets, the European Union needs to reduce an estimated 60% of greenhouse gases in the transportation sector. One way is the diversification of the transport systems landscape [1]. Electric bicycles can be beneficial in this context, especially regarding commercial delivery of goods in urban regions, since they have up to ten times lower lifecycle emissions than commercial vehicles [2], [3]. In addition, they increase the radius of activity in comparison to conventional bicycles [4]. Therefore, governments around the world are subsidising electrical bicycles and vehicles as well as its infrastructure [5], [6]. This is one of the reasons why electric bicycles are currently leading the market in sales figures, and are constantly rising in sales with an annual grow rate up to 10 % [7].

Complementary, the increasing numbers of electric bicycles participating in traffic lead to more severe accidents and higher hospitalization rates [8]. Notably, two-thirds of the accidents are single bicycle accidents and 26% are bicycle-vehicle collisions [8]. On the contrary, electric bicycles cause three times more pedestrian accidents and lead to twice the number of fatalities than conventional bicycles [9], [4]. This alarming trend emphasizes the need to improve driver safety. This can be achieved by supporting the cyclist in the main driving tasks as stated in [10]. Contemporary works roughly distinguish between perception tasks and control related tasks. The perception focuses on the integration of various sensors, mostly to detect hazardous situations, while control mainly considers the optimization of the power train, vehicle stabilization and path planning.

For instance, the authors of [11] enhance driver safety by utilizing a LiDAR sensor to scan the surrounding area and alert the driver in dangerous situations through an acoustic signal. The authors of [13] developed a novel radar specifically for bicycle application, with a broad near detection area. Degen et al. [14] use a radar for object detection together with a camera and an inertial measurement unit (IMU) for sensor fusion to inform the driver in emergency conditions on a mobile device. Meanwhile, [15] analyses the ground via camera images to create a terrain profile for possible path planning algorithms.

On the control side, [16] investigates different vehicle model depths for motion planning and control algorithms together with experimental validation of the controllers. The authors of [17], [18] derive equations for steering stabilization and implement them on a bicycle robot. Other related work refrain from testing on a real-world platform.

Fig. 1 contextualizes this work within the broader context of current research in the field. In contrast to other research platforms, which either concentrate on perception [11], [13], [14], [15] or control [16], [17], [18] and exclude the combination of both systems. Our approach is characterized by an *integrated assistance system.* That combines sophisticated perception sensors, vehicle state sensors and bicycle control in a single platform. This enables the active and passive protection of vulnerable road users and the research for advanced control algorithms in combination with the serial hybrid powertrain. Furthermore, the perception sensors follow a scalable design of the hardware and software for potential future application within the departments research vehicle fleet [19].

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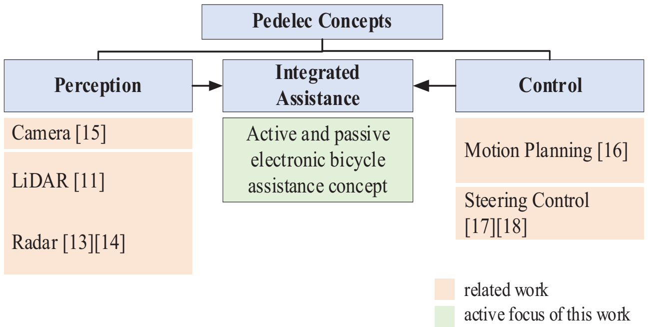

Fig. 1. Categorization of this work wihin the research field.

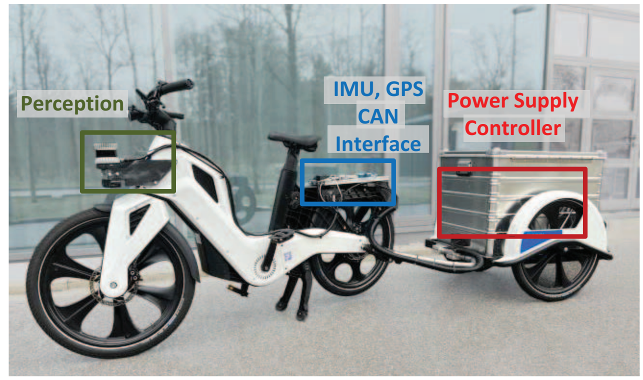

Fig. 2: The µAFM research plattform and the corresponding installation locations for sensors, controllers and power supply.

The main contributions of this work are:

- Design of a novel comprehensive integrated assistance system for bicycle application. Further, we present an overview of the sensor and actuator network together with power train architecture. Following this framework, we provide an in-depth analysis of the real time middleware software, including the design of the CAN driver, the radar driver, the system integration of the sensors and the overall software architecture.
- Validation of the platform, with a particular focus on the quality of the perception sensors, vehicle state and powertrain signals. The intention is to create a platform for further AI-based software research. So, a detailed analysis of test drive scenarios for data collection with the full sensor and actuator setup is carried out, which can be used for further development of AI-based control algorithms. It should be noted that this is not a production-oriented development, as the hardware has been optimized for performance to accommodate the latest algorithms and not on cost efficiency.

II. Vehicle Architecture

The necessity for an experimental carrier has been identified as a key requirement for the introduced investigation of the novel *integrated assistance system* approach. The proposed solution is a production electric cargo bicycle with a serial hybrid power train, which will support the additional load required for the research equipment and enable a high degree of manipulation for the control algorithms in the power train. We equipped it with a set of state-of-the-art sensors and computational hardware. In a holistic approach we designed the hardware according to our requirements, for later application within our research vehicle fleet. This section presents an overview of the vehicle setup, its network architecture and the unique power train functionality.

A. Vehicle Overview

Fig. 2 shows the developed µAFM research platform with the corresponding installation locations for sensors, controllers and power supply.

The extensive use of modular profiles on the front and rear carrier allows high flexibility and modularity in extending the existing setup together with cross-fleet sharing of the sensors and the associated software.

The front carrier of the presented hardware setup contains the following perception sensors for the environmental scene analysis:

- High-resolution LiDAR with 64-vertical and up to 2048 horizontal layers and a 360° field of view.
- 77 GHz radar sensor with digital-forming scanning antenna that offers two different types of data. First, it provides Radar Data Images (RDI), e.g. raw data detection points of the radar with a resolution of max. 1104 detections per scan and a latency of < 35 ms. Second, it provides an object list containing the processed RDI data with a multitrack and multitarget Kalman filter.
- Stereo camera with 2.1 mm lenses and a field of view of 92°. In addition to the RGB-channels, it delivers a depth image of the scenery in a range up to 20 m coupled with a three-dimensional AI-based object detection.

Besides the aforementioned perception sensors, the platform is equipped with measurements units for navigation, vehicle state monitoring and low-level control interaction of the power train. The following instruments are mounted on the rear carrier:

- Intelligent 9-axis absolute orientations sensor with integrated sensor fusion that provides the orientation of the device [20].
- Global navigation satellite system (GNSS) sensor with global positioning system (GPS) receiver operating at an update rate of 5 Hz and an accuracy of 2.5 m. The unit provides a second velocity signal and positioning signals for simultaneous localization and mapping (SLAM) algorithms.
- Controller area network (CAN) interface for high speed data transfer with up to 1 Mbit/s bandwidth.

The trailer module completes the overview of the sensor hardware. It contains the power supply of the research equipment and also contains the main control unit. The real-time capable Linux-based computing platform contains an advanced graphical processor unit (GPU) and adequate storage capacity for AI-driven methods.

B. Network Architecture

After introducing the physical modification and sensor integration in the previous chapter, the following section focuses on the underlying network depicted in Fig. 3. The illustration provides a comprehensive overview of the network architecture. It highlights the communication protocols designed to ensure robust real time data exchange that facilitates the communication lines between the sensors, the actuators and the main control unit.

The network architecture is designed for real-time communication, on the basis of data distribution service (DDS). DDS is a middleware that facilitates efficient distribution of data in a distributed system [21]. In the µAFM, it ensures the real-time communication via Ethernet for the LiDAR and the radar sensor. Complemented by USB-C for rapid image data processing, regarding the stereo camera and USB-A for GPS and IMU, ensuring precise navigation input. Finally, the CAN interface enables high-speed communication with the power train control and human machine interface (HMI) control bus.

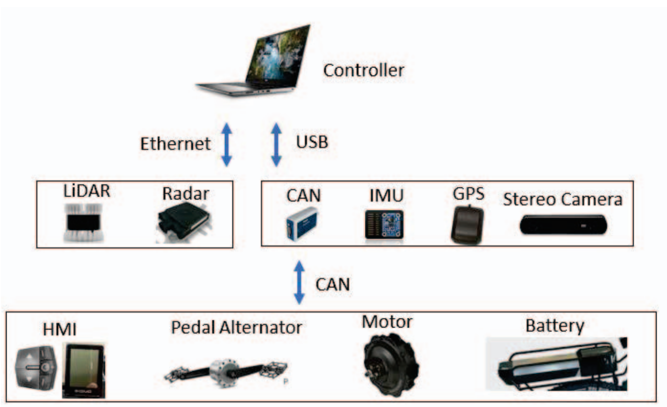

Fig. 3: Overview of the µAFM network architecture.

C. Power Train Functionality

The µAFM is equipped with a unique serial hybrid system, referred to as "Bike by wire" [22]. The pedals are mechanically decoupled from the drive train, i.e. there is no physical connection (e.g. a chain) between the pedals and the motor. The alternator is connected to the pedals and constantly induces a resistance on the pedal while simultaneously absorbing the human pedaling power [23]. This increases the freedom of control interventions, from the simulation of a continuous variable transmission system over the adaptation of the pedal feedback up to the separate control of engine and alternator. This provides a smooth transition between a *pedal-assist* electric cycle, also called *pedelec*, that is characterized by an electric motor that assists the driver while pedaling and a *power-on-demand* electric bicycle where the bicycle has an electric motor activated by a throttle [7].

III. Software Architecture

As the µAFM is equipped with a diverse set of sensors, a suitable software stack is needed to meet our requirements. We defined them as followed:

- Real-time computing to enabling advanced control algorithms.
- Simple sensor system integration with a broad use of open source software.
- Straightforward coordinate transformation of the sensor data, to enable sensor fusion and data processing from a diverse set of sensor inputs.
- Modularity and scalability so that the algorithms can be reused on comparable mobility platforms.

Due to the requirements, the open source software library Robot Operating System 2 (ROS2) was chosen. It is a state-of-the-art middleware platform for robotic and autonomous driving-systems. ROS2 is efficient and robust in handling data processing and communication tasks in comparison with other systems and broadly used in research [24]. Furthermore, the middleware platform is based on a publisher/subscriber structure. In contrast to ROS1, ROS2 uses DDS for communication to improve its real time capabilities. A ROS2 network consists of multiple nodes, which can publish and subscribe to topics for data exchange between the nodes. A node is a modular functional unit like e.g. a sensor driver or an algorithm for processing and fusing sensor data. In the following, the developed sensor drivers are explained in detail and the necessary coordinate transformation for the sensor integration is introduced. The open source ecosystem offers a variety of software packages for robot control, autonomous driving and development of AI applications [25], [26], [27], [28], [29] to advance the development and deployment of intelligent and autonomous systems. Together with the sensor and computing hardware, the software architecture based on ROS2 enables the use of a wide range of AI-based control algorithms. Several studies have already shown that a comparable setup is suitable for this purpose [30], [31].

A. Sensor Drivers

Due to its extensive open-source community, many sensor drivers and algorithms are freely available for ROS2. For a subset of our sensors, including the stereo camera [29], the LiDAR [32], the IMU [33] and the GPS sensor [34], drivers are available. Nevertheless, our project demands further custom software development for the CAN and radar driver to achieve full operational integration.

The CAN driver is built on the socketCAN API. This enables the driver to be hardware independent and support all major CAN chipsets and bus types. The socketCAN API also allows the programmers easy access to the CAN sockets on a Linux system [35], [36]. The driver comprises two ROS Nodes, (cf. Fig. 4). The first node accesses the socketCAN API, reads the data and converts it into a ROS messages. The second node processes the generated ROS message and decodes it according to the CAN data description format (dbc). The CAN messages are then published as custom ROS messages. In order to adjust this driver to a new CAN-Bus, solely the parser node has to be adapted to the new *.dbc- file format.

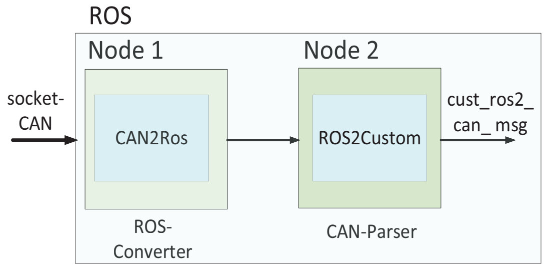

Fig. 4: CAN driver ROS node and message structure.

In contrast to the CAN driver, there is no preliminary work for the radar available. Therefore, a custom driver was developed. The radar driver reads the raw ethernet byte stream, processes it and integrates it into the ROS2 environment. Fig. 5 visualizes the data processing by the radar driver. It is separated into three functional steps represented by the nodes. It starts with byte stream decoding and conversion into ROS2 messages. This stage is running on a separate thread to avoid latency delays caused by the sensor input. It is followed by a filtering stage, where invalid data and data with high signal to noise ratio is dropped. The last part consists of the data preparation for the visualization of the radar output. It is either converted into 3D object marker arrays or ROS2 point cloud format in terms of the raw reflection for later use in RViz [37] visualization software.

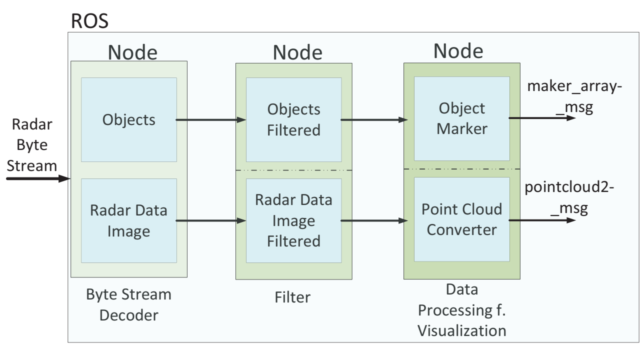

Fig. 5: Radar driver ROS node and message structure.

Furthermore, the inclusion of the correct time frames and clocking systems play an important role for both drivers, enabling a real-time and time-synchronous system. On the one hand, a timestamp is generated by reading the received CAN-Bus message and integrated into the *cust_ros2can_msg* message. On the other hand, the radar already provides timestamps at the scan of the RDI data and after the processed objected list. These timestamps are included into the ROS2 messages. This provides the basis for further time synchronisation using the precision time protocol (PTP). This standard provides a protocol that enables precise synchronisation of clocks in measurement and control systems [38].

B. Coordinate Transformation

Fusing data from many different sensors with different coordinate systems (IMU, GPS, LiDAR, stereo-camera, radar) while focusing precisely on the executing frame is a crucial task in a robotic system [39]. We are using the integrated *tf*-library in ROS2 to transform all sensor data according to the autosar standard [40] to the center of gravity of our bicycle (*base_link*) as seen in Fig. 6.

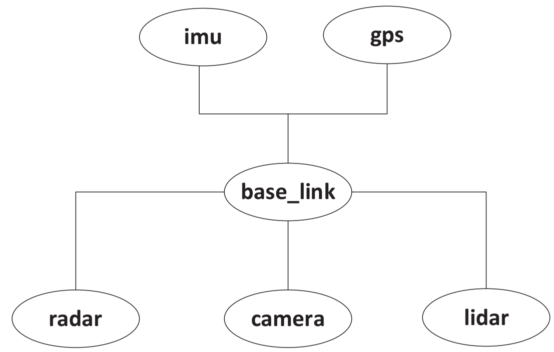

Fig. 6: Coordinate transformation structure of the µAFM.

IV. Results

For the experimental validation of the full equipped µAFM setup, two test-drives are conducted. First a static test validating the perception sensors according to the following criteria:

- The coherent coordinate transformation of all sensors, achieved by a qualitative analysis of the perception data.
- The functionality of the developed radar driver, with respect to the point cloud and object detection.
- The detectability of critical urban objects in front of the bicycle driver.

Further, a dynamic test is carried out with the objective to analyse the capabilities of the power train performance regarding the driver-vehicle interaction and the power train observability.

A. Static Test: Perception Sensors

For this experiment, the µAFM is positioned in front of our laboratory and orientated towards the surrounding road network. Two test objects, a pedestrian and a passenger vehicle moved across the µAFM field of view. The results are analysed using the visualization in RViz. Fig. 7, exemplarily shows the results from this experiment. The main panels illustrate the LiDAR and radar data in a 3D point cloud visualization together with the object detection of the stereo camera. It shows the radar driver capability to detect and render pedestrians as well as road vehicles. Additionally, this demonstrates the high resolution of the laser sensor, whereas the radar detects the object with less rendering precision. Moreover, a deviation of the camera detection is seen. This derives from the deep view of the camera, which provides decreased resolution on the edges of the field of view. The images on the right top corners show the two-dimensional view of the camera, correlating the sensor data above with real-world visual information in the same time instance. This cross-validation confirms the overall sensor integration, including the coordinate transformation since all sensor data is congruent.

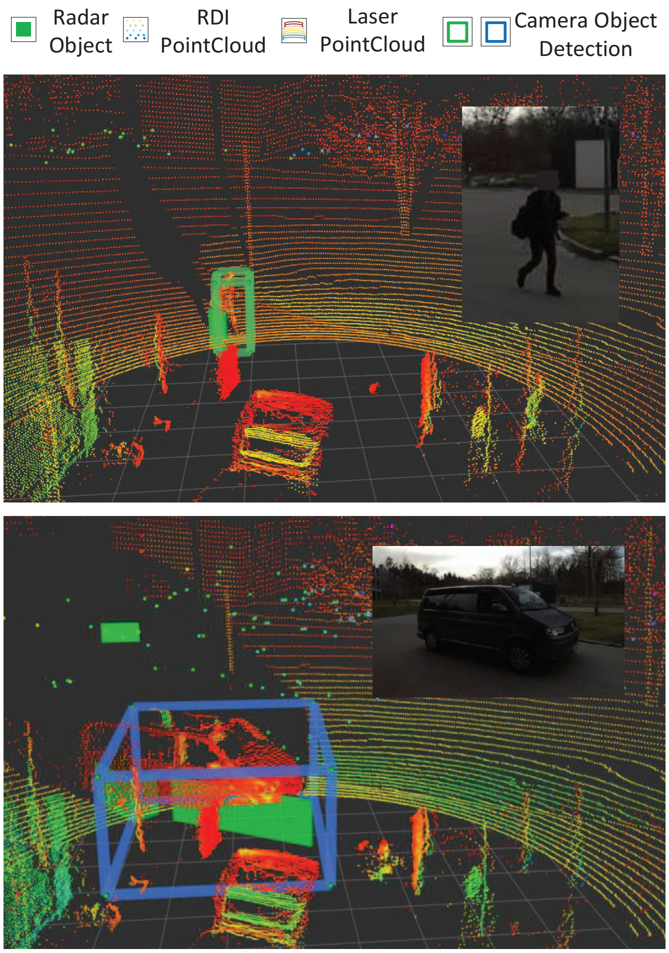

Fig. 7: Perception sensor test result with a pedestrian and a passenger vehicle.

B. *Dynamic Test: Vehicle State and Power Train Test*

For the second experiment, we chose a short track on our research campus, starting at our laboratory passing administration buildings and returning to the starting point. In preparation for the test drive, we visualize the GPS data from the vehicle with a ROS2 web bridge [41] and an open source interactive map[1], [42], to obtain a better understanding of the test conditions. In Fig 8, the GPS data of the experiment are visualized. The signal is a few times off the road. The reason for this is the GPS positioning variance of 2.5 m.

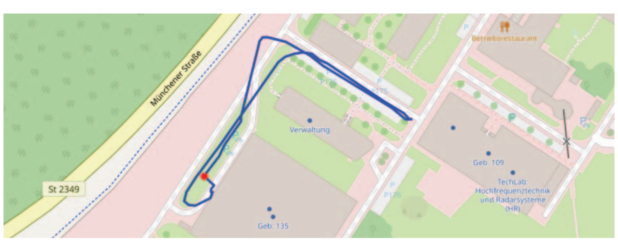

Fig. 8: GPS-position of the experiment.

Complementary, Fig. 9 provides a comprehensive overview of the multi-modal sensor and actuator output of the experiment. One can observe high ripples in the inertia measurement unit coupled with synchronized spikes in the motor torque, human torque and battery current around the time of 60 seconds. These oscillations stem from the active pedaling of the driver.

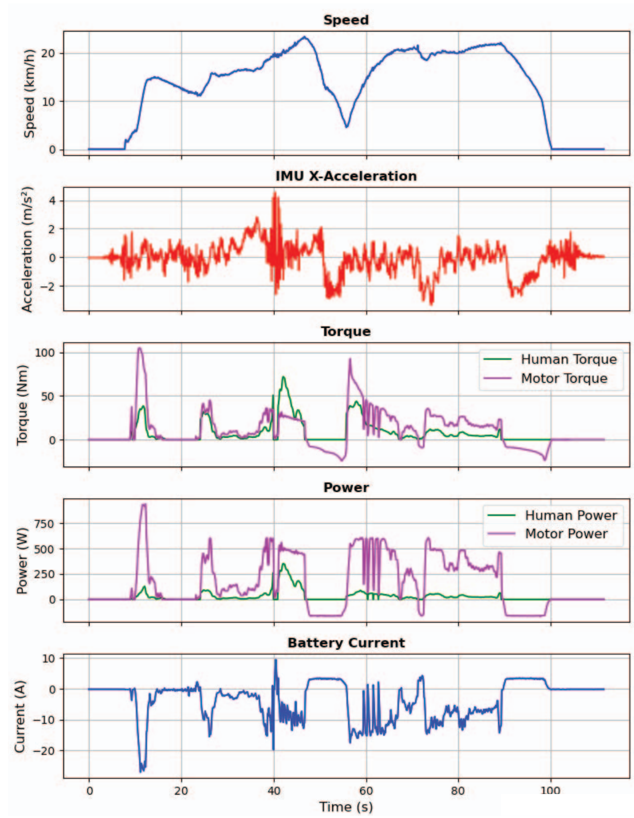

Fig. 9: Multi-modal sensor and actuator output of the dynamic experiment with the µAFM.

Moreover, the graph shows that the human power exceeds the motor power, resulting in a positive system battery current (charging). In addition, the battery is charged through recuperation during deceleration intervals, observable around 50-55 s and 90–95 s of the experiment. Completing the observation in Fig. 9, one can see that speed, acceleration and power train data is recorded time synchronous. This is essential in such a multi-modal system, involving multiple sensors and actuators, to ensure that all parts operate in alignment.

We can summarize that this time synchronized dataset enables a detailed examination of the vehicle performance regarding sensor sensitivity and observability of the power train. In alignment with the GPS-tracked route this allows a quantitative validation and implementation of further control algorithm research.

V. CONCLUSION AND OUTLOOK

This paper presents the µAFM, a novel holistic approach to the development of an integrated bicycle assistance research platform, which combines perception sensors and bicycle control. A commercial hybrid electric bicycle is equipped with state-of-the-art sensors and interfaces for low-level power train control, creating an advanced platform for AI-based control

[1] www.openstreetmap.org/

algorithms. ROS2 is utilized for real-time computing, straightforward sensor integration and sophisticated control algorithm development, for our platform.

Additionally, a comprehensive insight into the developed CAN and radar driver in ROS2 is provided. Two real-world test drives showcasing the platform capabilities to accurately detect and process environmental data while effectively managing vehicle state and power train performance concluding in a successful implementation of the hard- and software integration.

This work paves the way for further on-field experiments, simulations in integrated assistance control research. Further work will focus on the development of control algorithms for safety critical applications. Moreover, it is planned to utilize the platform to analyze end-to-end latency, since it is a critical factor in the development of real-time control systems and is crucial to their performance and reliability.

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