A SELF-DRIVING CYCLE RICKSHAW FOR AUTONOMOUS URBAN PASSENGER AND FREIGHT TRANSPORT

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ABSTRACT

This paper presents the implementation and potential use-cases of a new innovative development of a fully connected and automated three-wheeled cycle rickshaw. The rickshaw is used for transporting passengers or logistics parcels or a combination of both. For this purpose, the rickshaw is equipped with an electric power train system including a lithium accumulator as well as actuators for breaking, propulsion and the steering of the front wheel. The environmental sensing is currently realized via three LiDAR sensors mounted at the roof of the rickshaw observing the 360-degree surrounding of the vehicle. Equipped with a state-of-the-art on-board unit for V2X-communication and remote-control access in cases of overstress situations for the trajectory planning and self-driving functionality the rickshaw represents a fully equipped connected and automated vehicle for urban road traffic.

The rickshaw shows a substantial potential to increase the productivity, reliability and flexibility of logistics and transport services. A higher degree of automation in logistics and freight transport – within this prototypical implementation realized by the self-driving functionality – allows for a more cost-efficient operation of logistics fleets and businesses. Additionally, less weight due to the absence of a driver and light-weight components also leads to a reduced energy consumption.

The developed self-driving rickshaw gives the opportunity to automatize first- and last-mile logistics services as well as passenger transport with reduced costs.

Keywords: *Rickshaw, Automated Vehicle, Passenger Transport, Freight Transport*

1. MOTIVATION AND INTRODUCTION

With increasing investments in public transport, reviving long distance bus services and the intensified need for city logistics due to ever-growing e-commerce market shares, the demand for professional drivers is continuously growing. In contrast to that we see a reduced availability of vehicle personnel like professional bus drivers and truck drivers as well as a generally low availability of potential new personnel with a truck or bus driving license. This comes often hand in hand with a reduced willingness of citizens to work as professional drivers for often comparably low salaries despite the difficult working conditions. In addition to that, in several countries the situation might even intensify due to an above-industry-average age of professional drivers and therefore high expected retirement shares in the upcoming decade (for Germany see [1]).

One solution for the driver shortage definitely lies in the field of vehicle automatization. A low level of automatization would enable the vehicle operation without the need of a driving license holder, which would be substituted by a vehicle operation supervisor. A higher level of automatization or even full automatization and therefore autonomous vehicles even allow for the complete replacement and retrenchment of a driver or supervisor.

Another solution is the more economic and personnel efficient usage of existing passenger and freight transport service capacities for example by combining both transport worlds. An example for that approach is Ride-Parcel-Pooling [2], where the same vehicle is used for a combined transport of passengers as well as city logistics parcels.

The present paper tries to provide a potential answer towards both of the above-mentioned solutions. An automated vehicle which can be used for the combined transport of passengers and parcels in an urban environment. For this purpose, an automated and connected cycle rickshaw is introduced to provide passenger trips as well as to contribute towards city logistics. The rickshaw was developed as part of the research project TEMPUS (Test Field Munich - Pilot Test for Urban Automated Road Traffic) [3] financed by the German Federal Ministry of Digital and Transport.

The automated and connected rickshaw represents a sustainable and efficient solution for developed and for developing countries. Due to its full electrification it contributes to reduced emissions in urban areas and due to the light weight, it additionally benefits from a low energy consumption per kilometer travelled. The reduced width of the rickshaw additionally contributes to a smaller space consumption in moving and standstill travel as well as to an increased accessibility on narrow streets especially in dense urban areas.

The following chapters give and overview of the current state of research in this field and describe the technical setup of the automated rickshaw as well as its potential use cases and application areas.

2. LITERATURE REVIEW

Besides offering a financial advantage over classical vehicle concepts due to reduced labor costs, vehicle automatization promises a more efficient use of space, less energy consumption and improved delivery times in urban areas. Furthermore, automated and ultimately autonomous vehicles can lead to less local noise and air pollution in urban areas since this technology typically relies on electrification to supply the energy needs of incorporated sensor systems and vehicle actuators. Since most urban delivery services nowadays still rely on classical internal combustion engine delivery vehicles, the aforementioned advantages are also expected to apply to urban delivery services. In recent years, a lot of research has been concentrated on the development of such automated and autonomous vehicle concepts for urban delivery services that differ significantly in the use of infrastructure, vehicle speeds and the vehicle size, or respectively carrying capacity. A topology has been proposed to classify these vehicle concepts, which has been slightly adjusted for the sake of this study:

- Automated **road** vehicles:
  - *Low-speed* road vehicles
  - *High-speed* road vehicles
- (Semi-)Automated **sidewalk** vehicles:
  - *Low-speed* sidewalk vehicles
  - *Low-speed* follower sidewalk vehicles

The proposed topology first classifies the vehicle types by the use of infrastructure. While road vehicles use the vehicular carriageway, sidewalk vehicles share pedestrian or bicycle infrastructure with other road users. Due to safety reasons, sidewalk vehicles are usually limited to pedestrian walking speeds of around 5-6 km/h, whereas automated road vehicles are differentiated by their speed levels. Usually, automated road vehicles tend to operate on lower speed levels when complex interactions with other road users have to be expected, in particular with cyclists and pedestrians. Less complex urban driving situations, like on city highways or main arterials, usually allow for operation on higher speed levels. Furthermore, the vehicle concepts differ in size which highly relates to their carrying capacity. Automated sidewalk vehicles are usually designed to carry one or few parcels to deliver to one customer at a time. Automated follower sidewalk vehicles are designed to support human labor by autonomously carrying loads. Automated road vehicles are in general designed for higher carrying capacities comparable to or even exceeding those of classical delivery vans. Especially the difference in vehicles sizes results in various different scenarios for urban deliveries that either deploy single vehicles or a combination of vehicles from a departure point (e.g., post offices, stores, warehouses) to the customer destination. A combination of vehicles is for example a larger road vehicle that carries several automated sidewalk vehicles to a specific point and deploys them to deliver customers located in the same neighborhood, which allows the larger road vehicle to act as a mobile distribution center. [4]

Several projects have investigated the potential of automated larger road vehicles, mainly bus-like shuttles, for urban deliveries within living labs, demonstrations and trials in European cities. For example, the project *ALEES – Autonomous Logistics Electric Entities for City Distribution* established a field test of possible urban delivery applications in Mechelen, Belgium back in 2018, showcasing that automated road vehicles are suitable for urban delivery services in a densely populated area [5]. With the recently started project *LivingLAPT – Living Lab for Autonomous Public Transport and Logistics Services*, autonomous shuttle logistics services will be established in the City of Ricany in the Czech Republic, Hasselt in Belgium, Konsberg in Norway and Helmond in The Netherlands while developing a robust transnational safety framework [6]. A combination of automated urban delivery and passenger transport services was investigated within the project *TaBuLa-LOG – Combined Passenger and Freight Transport in Automated Shuttles* in Lauenburg/Elbe in Germany [7]. Companies launching first urban delivery services with automated road vehicles, both in Europe, e.g. [8] and the USA, e.g. [9] further illustrate the market maturity of this technology for certain urban situations.

Besides the specific use for urban delivery services, European cities massively investigated the use of automated road vehicles, mainly bus-like shuttles, in public transport with successful implementations in real traffic conditions in the recent years, e.g. for Germany [10-17].

An example for a project that investigated the use of automated sidewalk vehicles for delivery services is an automated delivery system operated by the university start-up *HUGO* that was offered on campus Johanneberg of Chalmers University of Technology back in 2020 [18]. One of the first trials in the urban context of European cities was performed with the project *LogiSmile – Last-Mile Logistics for Autonomous Goods Delivery* that piloted a fully autonomous delivery system in Esplugues de Llobregat in Spain, Hamburg in Germany and Debrecen in Hungary in 2022 [19]. With the recently started project *TaBuLa-LOGplus – Smart Control Center for Automated Transport Robots and Buses*, Lauenburg/Elbe in Germany will further investigate the integration of automated sidewalk vehicles into the combined passenger and freight transport system [20].

Automated vehicle costs still remain high and for urban deliveries, the costs for automated delivery vehicles can only be balanced out by the saved costs for labor [4]. Particularly for developing countries with significantly lower labor costs compared to industrialized countries, a cheap, affordable and easy to maintain automated delivery vehicle is necessary to ensure scalability of the technology and urban delivery concepts.

The presented rickshaw is consisting mostly of affordable and widely available components and presents a practicable alternative to high-cost automated vehicles especially for developing countries. In Table 1, a summary of various exemplar autonomous driving platforms is provided, demonstrating the diversity in hardware and software choices.

Table 1 – Exemplar autonomous driving platforms.

Reference	Hardware						Software Stack
	Computer	Camera	LiDAR	RADAR	IMU	V2X	
Boreas [21]	-	FLIR Blackfly S	Velodyne Alpha-Prime (128-beam)	Navtech CIR304-H	Applanix POS LV	-	Custom Dataset Collection
fortuna [22]	dSpace Micro Autobox II, IBM Power PC, Intel i7, Nvidia Drive PX 2	Sekonix 120◦ FOV	Velodyne VLP-32C, VLP-16	smartmicro UMRR-146	iMAR iNAT FSSG - 1	Prototype 5G Interface	Apollo
EDI dbW [23]	Nvidia Drive PX 2, Aurix TC297	Sekonix SF3323	Velodyne HDL-32	Continental ARS-408	GPS RTK + IMU #	EDI V2X	CARLA HiL
OpenPodCar [24]	-	-	Velodyne VLP-16	-	-	-	Custom ROS
Tongji's [25]	Intel i7 PC	IDS UI-5240CP	Velodyne HDL-32E, ibeo LUX 4L	Delphi ESR, RSD	GPS + Inertial	-	Custom ROS
Tsinghua [26]	Industrial PC	AVT 1394	IBEO LUX 16L, SICK 291-S05	Delphi ESR mmWave	NovAtel SPAN-CPT	-	Custom Stack
Apollo Auto [27]	Neousys 6108GC with GTX1080	Argus FPD-Link	Velodyne VLS-128	Continental ARS408-21	NovAtel GPS	-	Apollo

For instance, the DARPA Grand Challenge has played a crucial role in the early stages of the development of autonomous driving platforms and has been supported by other influential programs including the Urban Challenge and the Intelligent Vehicle Initiative. The authors have conducted a detailed analysis of these platforms in previous studies [28, 29], including an overview of the architecture utilized in automated racing systems [30, 31].

3. TECHNICAL SETUP OF THE RICKSHAW

The following chapter summarizes the technical setup of the proposed vehicle concept, consisting of the vehicle's hardware architecture, its software architecture as well as an evaluation concept to determine the functionality and integration of the used hardware and software components.

3.1. Hardware Architecture

The design and engineering of the automated rickshaw components, specifically the compute stack, require careful consideration of the data traffic patterns at various nodes, as shown in Table 2.

Table 2 – Network requirements for cooperative connected & automated vehicles [32, 33].

System Nodes / Data Traffic Sources	Typical Quantity	Data Traffic Rate (Mbps)	Arrival Pattern	Delay Deadline (ms)
LiDAR	1 – 10	2 – 100	Periodic	10
RADAR	4 – 8	0.1 – 15	Periodic	10
Ultrasonic	8 – 16	0.01 – 0.23	Periodic	20
Camera (30 fps compressed) - ADAS	2 - 16	~52	Periodic	33
Camera (60 fps compressed) - ADAS	2 - 16	~103	Periodic	10
Camera (30 fps uncompressed) - Automated Driving	2 - 16	~7000	Periodic	33
ADAS Sensors		~34	Event-Driven	10
Normal Control		0.5 – 1	Periodic	5 - 50
Critical Control		0.5 - 1	Event-Driven	0.1

To accommodate the diversity of incoming data traffic and to meet crucial deadlines, the backbone network must be designed to operate efficiently. The current architecture employs multiple computing elements to distribute the workload, ensuring adequate workload isolation and facilitating seamless integration through the use of standardized interfaces. The rickshaw can be controlled using either radio remote control (long-range) or autonomous driving modes, ensuring reliable performance. The components can be adjusted to provide a range of desired autonomy and data resolution levels. The heterogeneous nature of the generated data underscores the significance of sensor fusion in this system. In terms of sustainability, the rickshaw cockpit is constructed entirely of recyclable polyethylene and the engine design incorporates materials that are free of rare earths.

Table 3 shows an overview of hardware components and the software stack used for the development of the proposed vehicle concept, which is further specified in Figure 1.

Table 3 – Overview of used hardware components and software stack.

Hardware						Software Stack
Computer	Camera	LiDAR	RADAR	IMU	V2X	
Intel Core i7, Nvidia AGX Orin, Raspberry Pi 4	Stereo Labs ZED2i, ecosystems See3CAM	Ouster OS1-32, Livox Mid-40, Livox Mid-100	smartmicro UMRR-11	xsens MTI-680G	Unex OBU-301E, Cohda MK5	Autoware ROS

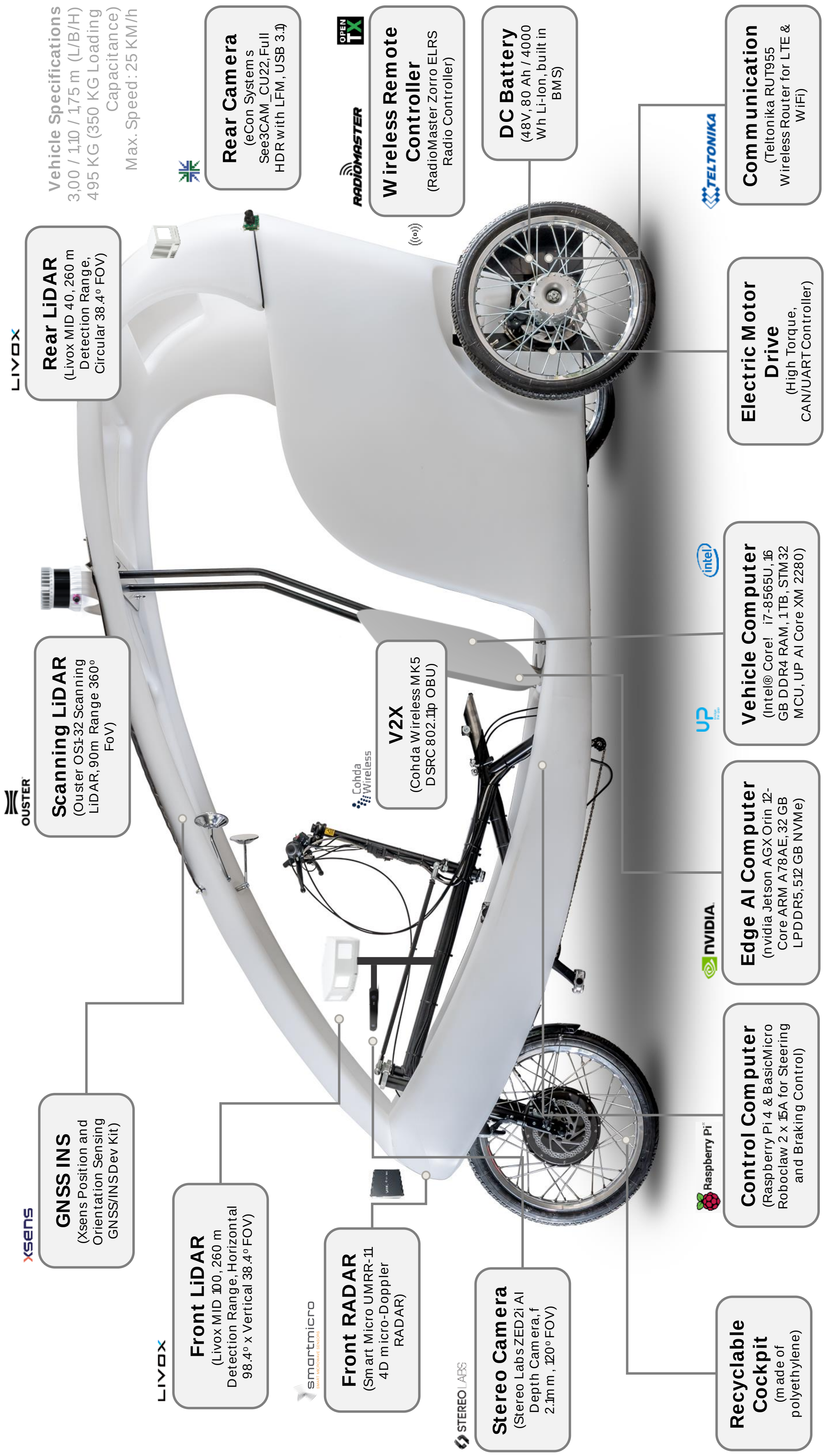

Figure 1 – Overview of hardware components (with indicative placement).

The rickshaw's hardware architecture is designed using a standard 12V system, making it easy to install automotive-grade components. The main control computer is a Raspberry Pi 4, housed in an IP67-rated enclosure and paired with a 2-channel BasicMicro Roboclaw regenerative motor controller. The motor controller's Battery Eliminator Circuit (BEC) can provide up to 5V 3A, which is used to power the Raspberry Pi 4. The Raspberry Pi 4 receives radio signals from the RadioMaster Zorro controller via a ELRS CRSF micro receiver connected over UART and uses the channel information to control throttle and steering with the aid of an angle sensor for positional feedback.

The Up Extreme Edge Computing Kit serves as the primary vehicle computer and is connected to the CAN bus. Other components include DSRC-based Vehicle-to-Everything (V2X) Onboard Units (OBUs) and an xsens MTI-680G rugged GNSS/INS module capable of Real Time Kinetics (RTK). The Nvidia AGX Orin Developer Kit handles data processing from various sensors, including LiDAR and RADAR point clouds received over a high throughput ethernet bridge and camera data received over high-speed USB.

The three computing elements are connected by a high-speed ethernet backbone network to facilitate information exchange. The vehicle computer is equipped with an Intel I210 NIC, which also supports Time Sensitive Networking. Future plans include testing deterministic communication across multiple devices by adding a RealTimeHAT Automotive [34] on the Raspberry Pi 4.

Figure 2 illustrates the hardware architecture of the proposed vehicle concept and how the individual hardware components are integrated into a comprehensive system.

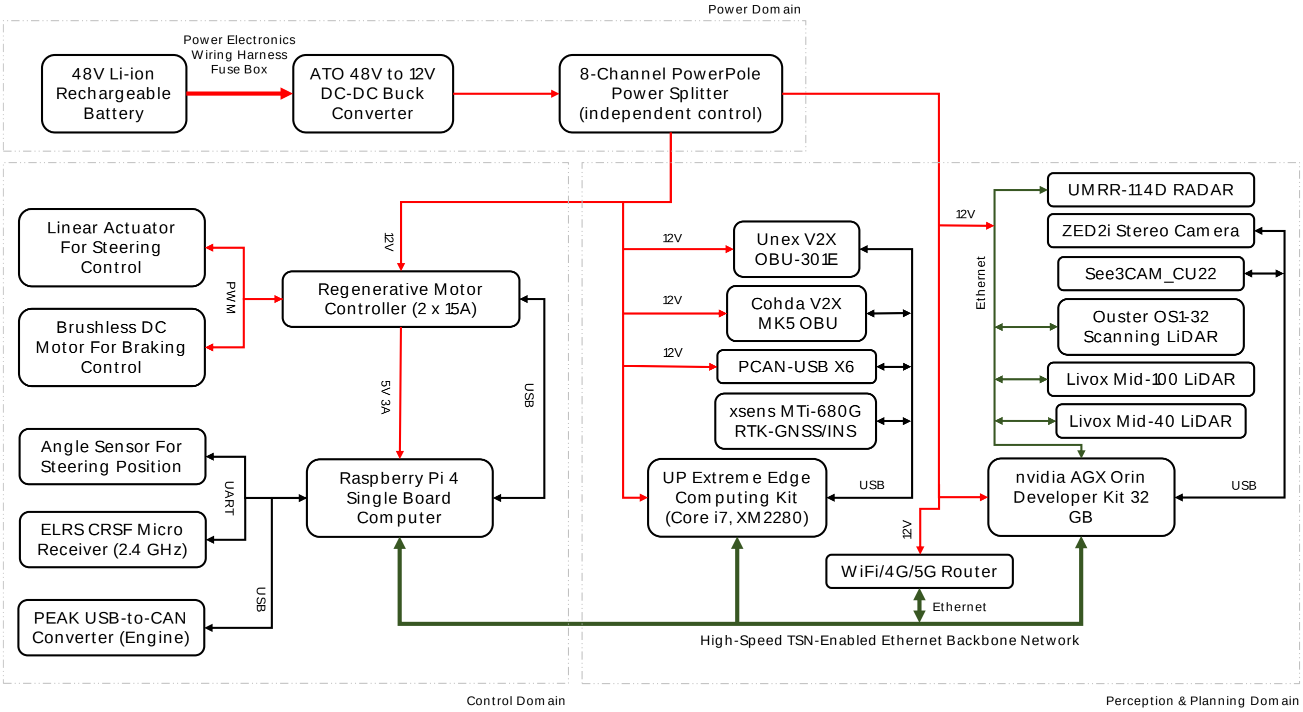

Figure 2 – Hardware architecture.

3.2. Software Architecture

The following Figure 3 shows the high-level software architecture of Autoware, that is being utilized for the development of the proposed vehicle concept.

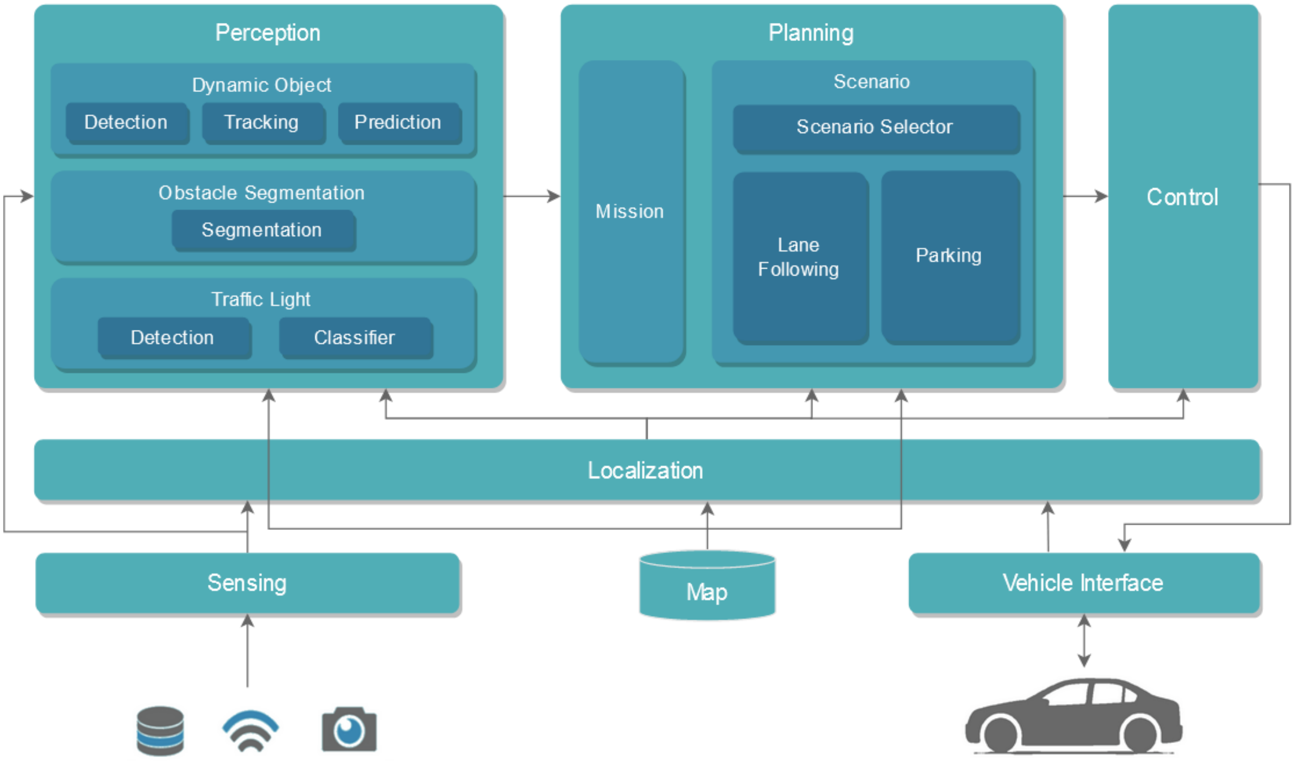

Figure 3 – High-level software architecture, based on [35].

The Autoware Stack serves as the foundation of the software architecture due to its modular design and ease of replacing existing modules. The architecture includes the following components:

- Sensing Design.
- Map Design.
- Localization Design.
- Perception Design.
- Planning Design.
- Control Design.
- Vehicle Interface Design.

The architecture provides micro autonomy, which results in a trade-off between computational performance and functional modularity due to data path overhead. The Vehicle Interface Design is adapted (using Python) to the needs of the automated rickshaw, with a Raspberry Pi 4 serving as the custom control unit and running Raspbian OS. The Up Extreme Edge Computing Kit runs Ubuntu 20.04 with the ROS Noetic Ninjemys, while the Nvidia AGX Orin Dev Kit runs Jetson Linux 35.1 (based on Ubuntu 20.04). The sensing nodes are primarily located on the AGX Orin, while the localization, planning, and control nodes are primarily situated on the vehicle computer with some local modifications. The software architecture is also planned to transition to ROS2.

3.3. Evaluation Concept

To evaluate the overall concept and determine the functionality and integration of the used hardware and software components the rickshaw will be tested at the Bavarian testbed for connected and automated mobility in the south of Munich [36]. Here, different urban street layouts can be set up to examine the feasibility of the vehicle in various pre-defined and controllable environments and scenarios. In addition to that, the rickshaw will be evaluated in different use-cases focusing on the interaction with other traffic participants like pedestrians, cyclists, and other vehicles.

4. POTENTIAL USE CASES AND APPLICATIONS

The described concept of a medium-sized automated vehicle is designed as alternative for high-cost automated road vehicles for lower financial budgets. Compared to the topology for classification of vehicle types, described in chapter 2, the described vehicle concept differs in terms of size and potential use of infrastructure. The considerably lower land use compared to automated bus-like shuttles might enable new dimensions in urban delivery as infrastructure not accessible by large-sized vehicles could suddenly be used, like bicycle paths or parks. Furthermore, passenger and / or freight transport in low velocity dedicated areas like university or business campuses are potential application areas of the described vehicle concept. The limited spatial extent of such areas makes an application of on-demand services for automated passenger transport less complex compared to large-scale urban applications. The vehicle concept furthermore holds the potential for the development of customized transport solutions for mobility-impaired people [37].

A special focus in the use cases lies in the potential application areas for developing countries, since the vehicles hardware as well as the sensor and automation hard- and software are representing a cheap and affordable solution also for lower financial budgets. The presented rickshaw is consisting mostly of affordable and widely available components stemming for example from the growing market for electrified bicycles. Therefore, an easy and long-term access to the components as well as their maintenance and spare parts availability is guaranteed. Additionally, the hardware components can easily be retro-fitted to any kind of light vehicle, not only to three-wheeled rickshaws. The modular vehicle architecture approach also enables an easy replacing of individual components. The used software stack is open source and can therefore easily be used as well as adapted to individual needs and applications. In summary, the presented rickshaw presents and easy and cheap automated vehicle solution especially for developing countries to cover both passenger transport and city logistics.

5. CONCLUSIONS, DISCUSSION & OUTLOOK

This paper presents a promising and affordable zero-emission rickshaw for connected and automated driving. The vehicle benefits from a low space consumption which allows for various potential application areas in urban passenger and freight delivery. As a backup solution to the automated driving stack, the rickshaw will also be equipped with a remote radio controller to be able to overtake control or completely drive the vehicle manually.

The next steps in the vehicle development on the hardware side include a further increase in the communication capabilities especially by enhancing the current V2X communication based on ITS G5 80211.p with CV2X via 4G and 5G cellular networks. Additionally on the roadmap is equipping the rickshaw with a screen for the passengers to visualize the vehicle’s surroundings based on the detector fusion. This will allow for an easier on-spot validation of the object detection algorithms as well as contribute to an increased perceived safety of passengers.

Further potential lies in the building of a second rickshaw to elaborate further the interaction between several automated vehicles especially in the field of platooning.

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