DOI: 10.2195/lj_proc_thiel_en_202310_01
URN: urn:nbn:de:0009-14-58243

From Concept to Reality: Developing Sidewalk Robots for Real-World Research and Operation in Public Space

Vom Konzept zur Realität: Entwicklung von Gehwegrobotern für die praxisnahe Forschung und den Betrieb im öffentlichen Raum

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Mobile robots operating on sidewalks promise to automate various tasks of public life. At present, however, such robots are still a relatively new and rarely encountered technology. In Germany, these robots are operated in the context of isolated pilot tests. There are only a few commercial operators and just as few publicly accessible documented robot developments and test operations by research institutions. Yet it is research in a real-world setting that is essential for the development and validation of systems and algorithms. In this contribution, we present a research robot platform for use on sidewalks in public space: Using delivery robots as a practical example, a mobile robot was developed, equipped for real-world research, and approved for manual and automated deployment on streets and sidewalks in the German city of Lauenburg/Elbe. This paper presents the development process adapted from common automotive technical standards, describes the identified requirements for the robot, the derived robot concept, and finally its implementation in an approved prototype delivery robot. In particular, we discuss remaining limitations and present extensive lessons learned. In this way, we not only comprehensively present the current requirements for such robots and how to implemented them, but also support further research in this relevant field.

[Keywords: autonomous mobile robots, sidewalk operation, public space, robot requirements, real-world research]

Mobile Roboter, die sich auf Gehwegen fortbewegen, versprechen die Automatisierung verschiedener Aufgaben des öffentlichen Lebens. Derzeit sind solche Roboter jedoch noch eine relativ neue und selten anzutreffende Technologie, in Deutschland beispielsweise nur im Rahmen einzelner Pilotversuche. Es existieren nur wenige kommerzielle Betreiber und ebenso wenige öffentlich zugänglich dokumentierte Roboterentwicklungen und Testbetriebe durch Forschungseinrichtungen. Dabei ist gerade die Forschung in einem realen Anwendungsfeld für die Entwicklung und Validierung von Systemen und Algorithmen unverzichtbar. In diesem Beitrag stellen wir eine von uns entwickelte Forschungsroboterplattform für den Einsatz auf Gehwegen im öffentlichen Raum vor: Es wurde ein mobiler Roboter am konkreten Beispiel von Lieferrobotern entwickelt, für praktische Forschung in einem realen Einsatzumfeld ausgerüstet und eine Genehmigung für den manuellen und automatisierten Betrieb auf Straßen und Gehwegen in der deutschen Stadt Lauenburg/Elbe erhalten. Dieser Beitrag stellt den Entwicklungsprozess in Anlehnung an gängige technische Standards aus dem Automobilbereich dar, beschreibt die identifizierten Anforderungen an die Roboter, das abgeleitetes Roboterkonzept und schließlich dessen Umsetzung in Form eines genehmigten prototypischen Lieferroboters. Insbesondere diskutieren wir verbleibende Einschränkungen und stellen umfangreich gewonnene Erkenntnisse dar. Damit stellen wir nicht nur umfassend dar, welche Anforderungen aktuell an solche Roboter gestellt werden und wie diese umgesetzt lassen, sondern unterstützen auch die weitere Forschung auf diesem relevanten Gebiet.

[Schlüsselwörter: autonome mobile Roboter, Betrieb auf Gehwegen, öffentlicher Raum, Anforderungen an Roboter, praxisnahe Forschung]

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1. INTRODUCTION

Mobile robots offer a promising solution for automating a wide range of tasks beyond industrial environments, such as public space cleaning, food delivery, and last-mile transportation [1–3]. Autonomous last-mile deliveries are expected to grow by a factor of 4 by 2027 [4], the market volume for delivery robots is expected to grow by a factor of 5 by 2026 [5], highlighting the need for research in this area.

Operation on sidewalks in close proximity to pedestrians and other road users introduces various challenges arising from the specific task at hand, service in outdoor environments, and legal regulations [6]. There is a scarcity of published concepts and empirical studies addressing these challenges for both commercial operators and research institutions. Moreover, no currently commercially available robots are simultaneously explicitly designed for outdoor transportation, authorized for road traffic use, and adaptable for research in real-world applications.

This paper aims to fill this gap - using the practical example of a prototype research sidewalk autonomous delivery robot (SADR) - by (1) presenting the requirements for such vehicles, (2) showcasing a design approach and (3) discussing the results and lessons learned. By doing so, this contribution supports real-world research on public space automation and related technical systems. The presented results can also act as necessary, though not sufficient, guidance for the deployment of commercial robots outside of research contexts.

The methodology is based on a applied, exploratory research approach, utilizing the research projects *TaBuLa-LOG* [7] and *TaBuLa-LOGplus* [8] as a foundation. As part of these projects, an automated prototype delivery robot was built and approved for operation on public sidewalks in the city of Lauenburg/Elbe, Germany (see Figure 1). This paper builds on the results of the TaBuLa projects published so far (see [7]). It extends the previous descriptions of the robot by a detailed presentation of the relationships between requirements, concept and implementation. This is complemented by the experience gained from continuing to operate the robots in the ongoing research project. Furthermore, this work serves to make the results obtained available to an international audience.


Figure 1: Robot prototype "Laura" boarding an automated shuttle (image: Marko Thiel).

Regarding the robot's automation, the following context should be noted: The vehicles are referred to as SADRs, although they are classified as automated vehicles according to SAE Level 2 and require constant monitoring by a dedicated operator. This is based on the German regulatory framework in place at the time the robot was developed, which did not include a higher level of autonomy. Nevertheless, the automated driving capabilities of the robots are not limited by this.

The contribution is structured as follows: Section 2 gives an overview of the existing literature regarding requirements for SADRs and also introduces projects that developed SADRs or similar robots. Section 3 describes the methods used to define the requirements and translate them into real prototypes. Additionally, the approach used for validation is presented. Section 4 includes the derived requirements for robots in public space and subsequently, in Section 5 their implementation into robot concepts and prototype vehicles. Section 6 contains a brief description of the validation results. Finally, in Section 7 we discuss in detail the results of the robot development.

2. REQUIREMENTS AND DESIGN OF DELIVERY ROBOTS IN LITERATURE

The overall goal of this paper is to showcase the development of a sidewalk autonomous delivery robot (SADR) for operation in public space from concept to reality. SADRs are a broad field of research and the relevant literature can be clustered into four main topics that will be covered in this section. First, there will be an overlook of commercial SADR projects. Second follows an overview of research projects developing or using SADRs. The third topic focuses on research projects on robots in partly public spaces or intralogistics environments without being constrained to operation on sidewalks. Lastly, other generally relevant SADR topics are summarized.

To start with there are several commercial SADR providers for automated robot deliveries in public spaces. Most of them like *Starship Technologies* [9], *Serve Robotics* [10], *Ottonomy* [11], *TERAKI* [2], and *Yandex* [12] offer deliveries by robots operating on sidewalks as a business-to-business service. *Kiwibot* is providing deliveries solely on university campus premises and therefore in privately-owned facilities [13]. All of the above-mentioned companies provide a brief overview of their robot design on their web pages and include useful information such as maximum velocity, battery capacity, size of cargo compartments, or sensor setup used for navigation. However, they do not provide detailed descriptions of the structural design of the robot apart from a blog post that gives further technical insights on the development process for one of the

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Yandex robots [14]. Still, this excludes information on the software used or on the extent to which the robots are able to match legal requirements posed by the operational environments. To address the regulatory framework of SADRs, Hoffmann and Prause issued a case study on the *Starship Technologies* robot [15]. Their work provides insights into basic legal challenges and points out that liability and acceptance topics are the main issues while implementing SADRs. Nevertheless, information on the technical implementation of Starship's robots to address these requirements is not provided. Brandt et al. also identified a need of regulation for delivery robots while issuing a case study on Starship delivery robots in CEP-delivery in the city of Hamburg [3]. They identified legal framework conditions, but further information on technical implementation is missing.

Coming from the commercial to the scientific context, several projects develop or use delivery robots for research purposes. The project *UrbANT* developed and produced three sidewalk-based autonomous delivery robots. The focus of their research was human-machine interaction, the development of the driving unit and different cargo compartments as well as the automation of the robot. Information on the implementation of legal requirements to drive on sidewalks or in public spaces in general is missing [16]. The *efeuCampus Bruchsal* project developed a SADR for parcel deliveries in the context of researching smart city concepts. A brief description of the design and functionality of the robot is provided, however, the implementation of the legal requirements for driving on sidewalks is not further examined [17]. The project *Ready for Smart City Robots* implemented a SADR prototype with the *Clearpath Husky* robot as base. A short description of the sensor setup used and the design of the robot platform is available on the project page, but there is no information given on requirements for driving in public spaces [18].

In addition, several research projects developed transport robots that are not intended to operate on sidewalks. Instead, they operate on partly public spaces like company or university premises. In the project *5G Kaiserslautern* autonomous robots for use on the university campus are developed and the implementation of 5G network technology to connect the robot to a control center is explored. The main focus of the project's publications lays on the network connectivity, therefore no detailed technical description of the robot or legal requirements is available [19]. For intralogistics applications the *Fraunhofer IML* developed a palette transport robot named *Odyn*, which was constructed for indoor- and outdoor operation on company premises [20]. Another active field of research is the development of transport robots for hospital logistics, as shown in the project *5G RemRob*. 5G network technology is used to achieve autonomy through cloud based computing and presents another use case in a challenging environment [21]. In the *Bacchus* project agriculture and inspection robot prototypes were developed to illustrate the beneficial effects of robots in agricultural applications [22]. Both projects do not provide insights on the requirements and design process to fit in public spaces.

Besides publications treating practical implementations, there are several papers addressing requirements to the development of SADRs, without actually implementing these. Jaller et al. present a general literature review to provide an overview of robot technologies including SADRs and Drones and to derive brief policies, regulations and theoretical requirements for implementing these [23]. Gathering information on autonomous delivery robots (ADRs), Srinivas et al. review different papers on factors affecting ADR deliveries from an operations management point of view [24]. Sorooshian et al. gather challenges for last-mile delivery technologies, but only on basic level without directly deriving requirements for the implementation of a transport robot [25].

Mason Marks presents different projects on SADRs and further collects several features of US state laws as part of a working paper [26]. The features generally outlined are weight, speed and paths to drive. Additionally, some subjects that are not covered by the inspected laws are gathered such as the width of the robot, communication between robots and pedestrians, data collection and collision avoidance. However, there is no information on a specific project or robot that can fulfill the mentioned features. In another work considering regulatory aspects, Hoffmann and Prause discuss which legal framework should apply to autonomous deliveries and point out the legal challenges for the implementation [15].

The *ZEN-MRI* project evaluates the requirements for human-robot interaction of service robots in city centers. The main focus lies on developing interaction and communication strategies between humans and robots [27]. Mintrom et al. also focus on the human-robot interaction and develop policies to cope with new technology in general. A policy checklist for future robots containing safety, privacy and ethics, productivity, esthetics, co-creation, equitable access and systemic innovation issues is provided [28]. Focusing especially on the technology acceptance aspect of autonomous robots Abrams et al. propose a new aspect of existence acceptance for modelling the acceptance of delivery robots [29].

A method to assess the readiness of a traffic environment for robots is proposed by Arntz et al. without directly addressing a specific implementation of the presented guidelines [30]. Researching in a similar direction, Plank et al. describe a prototypical implementation for assessing the operational surrounding of robots in public spaces by using data aggregation and evaluation based on OpenStreetMap data [31]. Also in the context of robot operation in public, Salvini et al. present a supplement to the *EN ISO 13482:2014* on safety of service robots in public spaces to include the hazards for pedestrians and bystanders [32].

Studies in the field of autonomous driving concerning sensor concepts can also be interesting for SADRs. There are several studies assessing requirements to sensor concepts. For example Zhang et al. investigate the influence of different weather conditions on typical sensors used for autonomous driving. [33]

None of the above-mentioned publications provides a detailed overview of the requirements for SADRs operating in public space. In addition, a detailed description of the design of a robot implementing these requirements is neither available for commercial SADRs in public space, nor for research purposes.

3. METHODS

As stated before, the results presented in this paper are based on the development of a transport robot prototype and the insights obtained in the context of the research projects TaBuLa-LOG [7] and TaBuLa-LOGplus [8]. Within these projects, a delivery robot was developed and validated for use on public sidewalks in Germany. These different phases, which were progressed sequentially, are described in detail in the remainder of this section. It is important to note that the development was highly iterative with multiple intermediate steps and system prototypes. The following descriptions only reflect the high-level, sequential structure of the process.

The development and validation were supported by experts from two *TÜV NORD Group* companies, *TÜV NORD Mobilität GmbH & Co. KG* and *TÜV NORD CERT GmbH* (both subsequently referred to as TÜV Nord).

3.1 ROBOT DEVELOPMENT

Due to the operation of the robot prototype in public traffic areas, TÜV Nord advised to develop the robot in alignment with safety standards for conventional passenger cars: *ISO 26262 Road vehicles - Functional safety* [34] and *ISO/PAS 21448 Road vehicles - Safety of the intended functionality (SOTIF) [35]*. The overall development was therefore based on the core processes and work products described in these standards. The following methods were employed:

- Description of the robot and its electrical and electronic systems in an item definition
- Hazard Analysis and Risk Assessment (HARA)
- Derivation of safety goals
- Development of safety mechanisms
- Analysis of the proposed safety mechanisms
- System and software validation

The robot's development followed three main phases: (1) identification of requirements, (2) derivation of a robot concept that takes these requirements into account, and (3) implementation of the concept in hardware and software.

During the first development phase, efforts were focused on identifying domains that give rise to requirements for mobile robots, their development and operation (building on [6]). Detailed requirements were then collected for each domain. Deriving these requirements and their sources is particularly important because compact sidewalk robots are a new category of vehicle for which this information is not yet publicly available.

Several methods were employed to identify requirements: Workshops with robotics and logistics experts, interviews with TÜV Nord automotive experts, consultations with traffic authorities in the German federal State of Schleswig-Holstein as well as literature and regulatory text searches. The regulatory framework is an important source of requirements for the design and equipment of robots in public traffic, as sidewalk robots are classified as motor vehicles in Germany (see [36]). From a traffic law perspective, three German regulations in particular were examined for requirements: (1) *Vehicle Registration Regulations* (FZV [Fahrzeug-Zulassungsverordnung]), (2) *Road Traffic Licensing Regulations* (StVZO [Straßenverkehrs-Zulassungs-Ordnung]), and (3) *Road Traffic Regulations* (StVO [Straßenverkehrs-Ordnung]).

In the second development phase, a first robot concept was derived based on the identified requirements. This concept defines, for example, the number and technology of sensors needed without specifying a particular design or choosing a particular product. Several concept options were discussed, considering the typical strengths and weaknesses of different sensor systems. In addition, consultations were held with TÜV Nord's automotive experts on how to equip the robot to comply with traffic regulations.

Finally, derived from this robot concept, an implementation design was created in the third phase followed by the assembly of the robot prototype. This implementation concept includes the selection of components to be procured, the selection of components to be manufactured in-house, and the selection of explicit electrical parts and subassemblies, such as specific sensor devices.

3.2 ROBOT VALIDATION

The validation of the robot prototype has two objectives: to ensure system functionality and to demonstrate qualification for public spaces. In the following, we assume the required functionality of the systems. Its verification is an integral part of the iterative, standards-based development process. Validation therefore focuses on demonstrating the suitability of the robot for use on public sidewalks. Successful validation is based on three criteria:

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URN: urn:nbn:de:0009-14-58243

1. A technical testing organization confirms that the robot is roadworthy and successfully implements the requirements of road traffic regulations.

2. A technical testing organization verifies that both the development process as well as the documentation produced follow the core processes and work products described in the established technical standards.

3. The robot receives an exemption permit for use in road traffic and on sidewalks.

For validation, TÜV Nord has been commissioned with the testing of the prototype vehicle and its documentation. The proof of roadworthiness is based on inspecting the implementation of the Road Traffic Licensing Regulations. This has been done through a series of driving and laboratory tests. These tests are based on the specific requirements described in the following Section 4. A summary of the specific tests and their results is given in Chapter 6. Based on test reports from TÜV Nord, applications for special permits were then submitted to the traffic authorities in Schleswig-Holstein. Exemptions are required for operation on sidewalks and for any distinctive technical features of the robot.

4. ROBOT REQUIREMENT ANALYSIS

The requirements for capabilities and equipment needs of the prototype robot arise from several areas. These requirements serve as the basis for subsequent conceptual design and robot development. For organization, related identified requirements are grouped into five categories:

1. Main functional requirements

2. Use case related requirements

3. Operational context related requirements

4. Operational design domain related requirements

5. Implementation specific requirements

In the following subsections, the individual five areas are presented separately. Each area is composed of a brief overview and a table detailing requirements, clustered by domain. All stated requirements, that are not part of the regulatory framework, result from workshops with logistics, robotics and automotive experts.

4.1 MAIN FUNCTIONAL REQUIREMENTS

In the case of mobile robots, the basic requirements are largely independent of the specific use-case and operating environment of the robot, see Table 1. They relate to the general function of automated driving and the subsystems required: Locomotion, perception, planning and control. Furthermore, generic features such as computing power, energy supply and data connectivity are included. Options for manual control and intervention are also listed, which we assume to be still necessary in the future.

Table 1: Robot requirements addressing main functions for mobile robots.

Domain	Short Title	ID	Description [*Source/Comment*]
Locomotion	Drive	01	The robot shall be able to propel itself.
	Steering	02	The robot shall be able to change the direction of travel.
	Braking	03	The robot shall be able to brake.
Perception	Obstacle Detection	04	The robot shall not collide with static or dynamic obstacles.
	Localization	05	The robot shall be able to determine its position and orientation.
Control	Deliberation	06	The robot's control system shall be able to coordinate the overall process.
	Planning	07	The robot shall be able to determine a path from its current position to its target position.
	Motor Control	08	The robot's control system shall command the motor(s) and steering system in such that the robot moves along a specified path.
Compute	Data Processing	09	The robot's computer system shall have sufficient computing capacity to control the robot and process the sensor data.
Energy	Power Supply	10	The robot's power supply shall have sufficient power and capacity to supply the drive train as well as to all computer and sensor modules.
Data Connections	Intercomponent Communication	11	The robot's subsystems and components shall be connected to the robot's control system via cable-based data links.
	External Communication	12	The robot shall have wireless external communication interfaces.
Remote Control	Manual Remote Control	13	The robot shall provide a means for precise, manual control via a remote, wireless control device.

4.2 USE CASE-RELATED REQUIREMENTS

While the main functional requirements address core functions of automated vehicles, the equipment of robots also significantly depends on the intended use, e.g., last-mile delivery or sidewalk cleaning. In the presented case, a robot is to be developed for use in research projects regarding last-mile deliveries. This results in various additional requirements concerning the storage of the goods to be transported. It also requires a flexible and extensive equipment for research activities (see Table 2).

4.3 OPERATIONAL CONTEXT RELATED REQUIREMENTS

Using a vehicle in public traffic imposes a number of requirements. In addition to the vehicles' suitability for outdoor use, there are also requirements arising from German road traffic law. Mobile robots are classified as motor vehicles, even if they are only operated on sidewalks. As a result, robots are subject to the same construction and operating regulations as conventional passenger cars – although not all requirements are applicable (e.g., regulations on seats and seat belts). Table 3 lists the requirements identified as relevant (see also [7, 36]).

The envisioned application environment for the robots developed here also includes transit rides on public transportation, which will be investigated using the example of automated shuttles and conventional busses. This results in further requirements, such as the ability to navigate on a ramp. Two non-technical requirements arise from the use in public spaces, not listed in the table: An exemption permit is required for deviations from the construction and operating regulations. In addition, an exemption is required for use on sidewalks, as the use of motor vehicles on sidewalks is not permitted by law.

4.4 OPERATIONAL DESIGN DOMAIN RELATED REQUIREMENTS

The requirements specification is strictly separated into the general operating context (outdoor, road traffic) and the operational design domain. The ODD includes, for example, the detailed description of the operational environment, the ambient conditions, and the traffic environment in which the robot is to be operated.

The ODD is crucial for vehicle validation, since the vehicle's functionality, and in particular the safety systems, must be proven under all operating conditions defined in the ODD. In the use case presented here, we restrict the ODD of the robot with respect to the ambient conditions. This serves to reduce the extend of the required validation evidence to a level that is realistic in the context of a research project. Robot requirements addressing the ODD are illustrated in Table 4.

Table 2: Robot requirements addressing use case specific adaptations.

Domain	Short Title	ID	Description [*Source/Comment*]
Cargo Transport	Cargo Compartment	14	The robot shall have a cargo compartment.
	Transport Container	15	The cargo compartment shall be able to hold a standard Euro container.
	Secure Container Storage	16	The transport container shall be protected from unintended release even when traveling on uneven surfaces.
	Outdoor Transport	17	The transport compartment shall be protected from weather conditions.
	Operating Time	18	The operating time of the robot shall cover the transport tasks of one operating day without recharging.
User Interaction	User Interface	19	The robot shall have an interface for user communication and interaction.
Research	Research Data	20	The robot shall facilitate the recording and retrieval of research data. [R*ecording of multiple sensor data streams*]
	Diverse Sensor System	21	The robot's sensor system shall provide a range of different sensor modalities for research purposes. [E.g., LiDAR, (stereo) camera or infrared camera]
	Compute Overhead	22	The robot's computer equipment shall provide adequate additional capacity for the execution of research-related features. [E.g., non-optimized research code or state of the art object detection algorithms]
	Established Open-source Software	23	The robot's control system shall be developed on the basis of established open-source software.
	Rapid Prototyping	24	The robot control system shall be easily expandable with new functions or process components.

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Table 3: Robot requirements addressing the operational context. For requirements resulting from traffic law see [36].

Domain	Short Title	ID	Description [*Source/Comment*]
Outdoor Deployment	Weather Conditions	25	The robot and its systems shall be protected from splash water.
Traffic Integration	Maximum Speed	26	The robot's maximum design speed shall be not more than 6 km/h for operation without registration. [*§ 1 FZV*]
	Fixed Maximum Speed	27	The robot's maximum design speed shall not be easy to change by the user and changes must be clearly visible. [*§ 30a StVZO*]
	Safe and Easy Steering	28	The robot's operating device shall enable easy and safe steering. [*§ 38 StVZO*]
	Lighting Equipment	29	The robot shall be equipped with front white lights and reflectors, rear red lights and reflectors and side yellow reflectors. [*§ 53 StVZO*]
	Protruding Edges	30	Protruding outer edges shall have a radius of at least 5 mm. [*§ 30c StVZO*]
	EMC Shielding	31	The robot shall be equipped with electromagnetic compatibility (EMC) shielding. [*§ 55a*]
	Mechanical Brakes	32	The robot shall be equipped with a mechanical braking system. [*§ 41 StVZO*]
	Minimum Deceleration	33	The robot's minimum deceleration shall be 3.5 m/s^2. [*§ 41 StVZO*]
	Sound Signals	34	The robot shall have a device for sound signals. [*§ 55 StVZO*]
	Vehicle Identification	35	The robot shall be tagged with a vehicle identification number. [*§ 59 StVZO*]
	Owner Identification	36	The owner’s (contact) data shall be affixed to the robot. [*§644 StVZO*]
	Data Recording	37	The robot shall store diagnostic data on travelled distances, manual takeovers or handovers into automated mode. [*Consultation with TÜV Nord*]
	Right-hand Driving	38	The robot shall obey the right-hand driving rule. [*§2 StVO*]
	Sidewalk Deployment	39	The robot shall not obstruct other road users. [*§ 30 StVZO*]
Public Transport Integration	Passenger Detection	40	The robot shall detect passengers and their objects in its immediate vicinity.
	Ramp Usage	41	The robot shall be able to enter a bus via its wheelchair ramp.
	Navigation in Confined Spaces	42	The robot shall be able to navigate safely and precisely in confined interior spaces.

Table 4: Robot requirements addressing the operational design domain (ODD).

Domain	Short Title	ID	Description [*Source/Comment*]
Operational Environment	Ground Clearance	43	The robot shall have sufficient ground clearance for passing door thresholds and lowered curbs as well as uneven ground surfaces.
	Road Surfaces	44	The robot shall be able to travel across different road surfaces (tar, cobblestones, gravel and sand paths).
	Steering Radius	45	The robot shall be able to turn on narrow sidewalks less than 1.5 m wide.
	Operating Area Size	46	The robot shall be capable of localizing itself in a large operating region.
Ambient Constraints	Weather Constraints	47	The robot shall be able to operate in light precipitation (rain, snow) that still provides sufficient visibility. [*Restricted ODD for reduced validation effort]*
	Lighting Constraints	48	The robot shall be able to operate during daytime in good visibility conditions. [*Restricted ODD for reduced validation effort]*
Other Road Users	Mixed Traffic Areas	49	The robot shall operate safely on mixed traffic areas with other motor vehicles (cars, trucks, buses) and vulnerable road users (pedestrians bicyclists).
	Vulnerable Road Users	50	The robot shall operate safely among vulnerable road users (pedestrians, bicyclists, and motorcyclists).

4.5 IMPLEMENTATION SPECIFIC REQUIREMENTS

This section focuses on the requirements that result from the specific implementation of the robot. First, these are requirements derived from the vehicle safety concept addressing hazards and risks arising from both the robot function and the operating environment. Safety measures target functional safety aspects as covered by ISO 26262. These can be random and systematic system failures, but also consider behavior outside the limits of the original specification as well as reasonably foreseeable misuse as described in SOTIF. For this application, the safety mechanisms primarily aim to ensure that the accompanying operators can take control of the vehicle at any time and interrupt the automated functions. Second, requirements often arise not only from safety-related functions, but also from decisions made during the design of the robot. Therefore, requirements that result from later iterations of the vehicle concept are summarized, when implementation details have already been defined. For example, the ventilation concept results not only from the distribution and placement of components, but also from their thermal emissions and operating conditions.

As a result, the requirements formulated here are specific to the developed robot and its operating environment - and might not translate to other vehicles. Nevertheless, the requirements are presented at a level of abstraction that may be useful for other projects. Table 5 lists the implementation specific requirements.

Since the robot is being developed as part of a research project, certain requirements can be omitted, e.g., topics from the area of product safety law.

Table 5: Robot requirements addressing specific implementation decisions.

Domain	**Short Title**	**ID**	**Description [*Source/Comment*]**
Safety Mechanisms	Emergency Stop	51	The robot shall be equipped with an emergency stop button.
	Remote Emergency Stop	52	The robot shall be equipped with a remote-controlled emergency stop switch.
	Fail-Safe Brakes	53	The robot shall be equipped with fail-safe brakes.
	Overridability	54	The robot's control shall always be manually overridable.
	Error Indications	55	The robot shall clearly indicate errors to the operator.
	Reactiveness	56	The robot's control system shall react to hardware and system faults with corresponding error modes.
	Battery Monitoring	57	A low battery level shall trigger an error.
	Visibility	58	The robot shall be clearly visible to other road users.
	Obstacle Detection Modalities	59	The robot shall use multiple sensing modalities for obstacle detection.
	Gentle Stop	60	In the event of significant system failures, the robot shall be safely brought to a standstill.
	On-site Supervision	61	The robot shall be constantly supervised on site by an operator (system validated as SAE Level 2).
Specific Design Decisions	Cooling	62	The interior of the robot shall be actively ventilated.
	Cargo Door	63	The cover of the cargo compartment shall be detachable.
	Data Privacy	64	The robot shall be equipped with a camera icon indicating video recording.

5. ROBOT CONCEPT AND IMPLEMENTATION

The following section outlines the robot concept derived from the requirements formulated in the previous section. Furthermore, the final robot prototypes constructed on this basis are presented. The description is divided into four subsections for clarity and easier mapping to the requirements. First, the basic structure of the robot is presented. Next, the perception system is described. Then the control system is explained. Finally, the specific equipment features are introduced. Different views of the robot and the arrangement of the main components are shown in Figure 2 and 3 at the end of this section.

5.1 BASIC STRUCTURE OF THE ROBOT

The basic structure comprises the chassis of the robot, which houses all components as well as the transported goods. At its core, the robot consists of a modified third-party skid-steer base platform with a custom-built housing mounted on top. The robot base includes an aluminum body with four wheels driven by two motors. This allows the robot to turn on the spot and navigate in narrow environments. Both motors were exchanged for two identical units with additionally integrated fail-safe brakes. Due to the increased installation space needed, it was necessary to choose units with attached right-angle gears.

The custom transport housing features a large cargo space that can hold a standardized Euro container. It is accessible through a magnetically closing side door. Electronic components are housed in compartments at the front and rear of the unit. Further components, especially the battery, are located under the cargo area inside the base.

Cooling the robot's interior plays a key role in the design, as the combination of electromagnetic compatibility (EMC) shielding and weatherproofing of the housing complicates the task of keeping temperature of the technology compartment low. To allow a controlled intake and circulation of cooling air, six small-sized high-performance computer fans are embedded in the housing behind holes with a diameter less than 20 mm to avoid breaching the EMC shielding.

The housing itself is made of basic construction elements. Rounded aluminum profiles are used for the frame. Acrylic panels are attached as side panels to to protect the interior of the robot from external influences. All electrical connections between the transport structure and the robot base are designed as plug connectors to ensure good accessibility. Table 6 and Table 7 summarize the concept and implementation of the robot's basic structure in greater detail

Table 6: Concept and implementation of the robot's basic structure (1/2).

Addressed Requirements		**Concept**	**Implementation**	
Short Title	**ID**	**Hardware & Software**	**Hardware & Software**	**Comment**
Drive	01	- Differential drive - Commercial platform	- Four-wheeled skid-steer base platform: *Clearpath Jackal* - One motor per side - Pneumatic tires - No separate springs/shock absorbers	- Robot can turn on the spot - Stable driving is still limited (track width is borderline)
Steering	02			
Steering Radius	45			
Navigation in Confined Spaces	42			
Ground Clearance	43			
Road Surfaces	44	- Pneumatic tires		
Braking	03	- Electronic motor brakes		
Sidewalk Deployment	39	- Compact robot footprint		
Mechanical Brakes	32	- Mechanical brakes - Fail-safe activation	- Replacement gear motors with attached mechanical fail-safe brakes: *Midwest Motion* gear motor with attached fail-safe brakes and encoders	- Same manufacturer as Jackal motors - Includes electronic braking
Fail-Safe Brakes	53			
Minimum Deceleration	33	- 3.5 m/s^2 as full deceleration for electronic brakes - 3.5 m/s^2 equivalent delay for mechanical brakes	- 3.5 m/s2 set as deceleration when releasing the controller's dead man's switch • 3.5 m/s2 equivalent brake acceleration for the mechanical fail-safe brakes through delayed activation	- A lower acceleration is used during normal driving

Table 7: Concept and implementation of the robot's basic structure (2/2).

Addressed Requirements		**Concept**	**Implementation**	
Short Title	**ID**	**Hardware & Software**	**Hardware & Software**	**Comment**
Cargo Compartment	14	- Housing mounted on top of the base platform	- Square aluminum frame attached to the *Clearpath Jackal* - Side and top panels made from acrylic glass	
Outdoor Transport	17			
Weather Conditions	25			
Protruding Edges	30			
Transport Container	15	- Standard Euro container	- Euro container with size 40 cm x 30 cm and 22 cm height (ca. 20 l)	
Cargo Door	62	- Detachable side hatch to access the cargo compartment	- Removable side door - Acrylic panel, secured on the bottom by pins, secured on the top by magnets	
Secure Container Storage	16	- Mechanical slip out protection	- Additional metal brackets to prevent the Euro container from slipping out	- Secured against loss, not against unauthorized access
Cooling	62	- Cooling fans to circulate air	- Six small-sized high-performance computer fans embedded in the housing	
Power Supply	10	- Replacement of the installed battery with a battery of higher capacity and sufficient power delivery	- Custom made battery to fit the available space in the robot base - 480 Wh and 40 A battery management system	
Operating Time	18			
Visibility	58	- Attachment of a flag	- Orange flag on fiberglass pole (bike accessory)	

5.2 PERCEPTION SYSTEM

As stated in chapter 4, capable perception systems are essential for the operation of mobile robots. The main task of a perception system is to sense the robot's environment, for example to detect obstacles in the surroundings or to determine the robot's position relative to a reference (e.g., a map).

The operational environment of the robot places additional demands on the perception systems. First, the sensors are exposed to different environmental and weather conditions, such as rain or snow, darkness or blinding sunlight. Here, the ODD was limited as described in Section 4.4. On the other hand, a large measurement range is required to be able to use contours at a distance of tens of meters for localization, but also to reliably detect persons directly in front of the robot.

The following sensor configuration was chosen, which also meets the requirements of the research domain with multiple sensing modalities, while also contributing to increased safety (see Table 8): A 3D LiDAR is centrally mounted on the robot and is used both for localization and obstacle detection. Localization is further supported by data from two inertial measurement units (IMU) as well as motor encoders. In order to detect obstacles in the immediate vicinity - primarily in areas outside of the LiDAR's field of view - a downward facing active stereo camera is installed on each of the robot's four sides. Two passive stereo cameras are mounted on the front and rear of the robot to provide additional obstacle detection and research data acquisition capabilities. GNSS is integrated to enable geofencing applications and to switch between different maps within the robots' extensive operating area.

Table 7: Concept and implementation of the robot's perception system.

Addressed Requirements		**Concept**	**Implementation**	
Short Title	**ID**	**Hardware | Software**	**Hardware | Software**	**Comment**
Localization	05	- Satellite based absolute localization - Geofencing for map switching	- GNSS receiver in robot base with one external antenna: *Clearpath Jackal (built in)*	- Currently only manual map switching - Currently being updated to RTK GNSS
Diverse Sensor Setup	21			
Operating Area Size	46			
Localization	05	- 2D LiDAR - Localization on 2D map	- 3D LiDAR sensor: *Velodyne VLP 16* - Particle filter localization on single (middle) scan layer: *AMCL* - Obstacle detection by object height thresholding on full point cloud	- Single scan layer mimics 2D LiDAR
Obstacle Detection	04	- 3D LiDAR		
Obstacle Detection Modalities	59			
Diverse Sensor Setup	21			

Localization	05	- Support 2D localization with odometry data:
		  - IMU
		  - Wheel encoder
			- Motor encoder in robot base: *Clearpath Jackal (built in)*
			- IMU from two cameras: *Stereolabs ZED2 (IMU built in)*
			- Fusing of IMU and wheel encoder data: *ROS robot_localization package (Kalman filter)*
			- Further input for particle filter localization (see below)
				- ZED2-IMU more accurate than Jackal integrated IMU

Obstacle Detection	04	- Downward oriented depth sensors around the vehicle	- 4x active stereo: *Intel RealSense d435* - Obstacle detection by distance thresholding on point cloud data - Sensing of edges around the robot (e. g. ramp)	- Detection only for protruding obstacles
Obstacle Detection Modalities	59			
Passenger Detection	40			
Ramp Usage	41			
Diverse Sensor Setup	21	- RGB stereo cameras, forward and oriented backward oriented	- 2x passive stereo: *Stereolabs ZED2*	- Currently not used for obstacle detection
Research Data	20	- Interface for direct recording on external storage	- Accessible data interface: *USB 3.0*	

5.3 Control System and User Interface

The main components of the robot's user interface include a touch display for monitoring the robot and its system state, as well as for entering driving goals. A modified PlayStation 4 Bluetooth controller is used for manual operation of the robot.

Computing power is provided by a combination of three networked machines: A computer for motor control already integrated in the Jackal base platform, an additional industrial PC for the overall process control and sensor data processing (LiDAR and active stereo cameras), and a GPU-centric unit for computer vision applications. The computing units run on a Ubuntu Linux operating system and ROS robotics middleware to provide the underlying software platform.

A custom-designed, safety-oriented robot control architecture based on a hierarchical finite state machine (HFSM) is used to control the robot's process (see [37]). Processes can be interrupted at any time to transition to specific error modes. The architecture also allows for easy configuration of the robot by separating functional features from the state machine definition. A detailed overview is provided in Table 9.

Table 9: Concept and implementation of the robot's control system.

Addressed Requirements		**Concept**	**Implementation**	
Short Title	**ID**	**Hardware | Software**	**Hardware | Software**	**Comment**
User Interface	19	- Touch screen interface	- Touch screen monitor mounted on the robot's top with custom build user interface - Red highlighting for errors	
Error Indications	55	- Clear error indications on the user interface		
Manual Remote Control	13	- Wireless controller	- Bluetooth controller: *PlayStation 4* - Separate control of longitudinal and angular velocity by two joysticks - Left shoulder button as dead man's switch - Right shoulder buttons for speed level selection (3 distinct speed levels)	
Safe and Easy Steering	28	- Dead man's switch - Multiple speed levels - Custom button for horn activation		
Data Processing	09	- x86 computer	3x computer configuration: - x86 On-Bot computer: *Clearpath Jackal integrated PC* - x86 industry PC: *Pokini I v3* - GPU edge device: *Nvidia Jetson Xavier AGX*	- GPU device used to process data from *ZED2* cameras
Compute Overhead	22	- Separate computer for GPU processing		
External Communication	12	- Mobile communication Hardware	LTE module for x86 industry PC: *Sierra M.2 LTE module*	
Established Open-source Software	23	- Linux operating system: Ubuntu - Robot middleware: ROS 1	- *Ubuntu 18.04 LTS* - *ROS Melodic*	- Currently being updated to *Ubuntu 20.04, ROS Noetic*
Deliberation	06	- Easily configurable state machine for robot control	- HFSM implementation with separation of functional features and state definitions - Interruptible at any time with transition to error modes	- See [37]
Rapid Prototyping	24			
Reactiveness	56	- Reaction to errors at any time		
Gentle Stop	60	- Fall-back in case of failure of all systems broadcasting drive commands	- Monitoring of drive signals and initiation of a smooth braking maneuver	
Planning	07	- Standard global planning algorithm	- Dijkstra's algorithm provided by ROS for global path planning: *ROS global_planner package*	
Planning	07	- Standard local planning algorithm - Standard motor controller	- Dynamic window approach (DWA) provided by ROS for local path planning: *ROS dwa_local_planner package* - Motor controller in robot base: *Clearpath Jackal (built in)*	- This local planner is not the standard *base_local_planner*
Motor Control	08			
Intercomponent Communication	11	- Ethernet	- 5-port 100 Mbps ethernet switch	
Right-hand Driving	38	- Driving corridor per direction	- Map layers with right-side driving corridors for each direction of travel	
Maximum Speed	26	- Limited maximum velocity	- Configuration file with maximum speed parameter set to 6 km/h	
Fixed Maximum Speed	27	- Hash of configuration file	- Hashing of the configuration file with the specified maximum speed - Hash is accessible in UI for verification	

5.4 Specific Equipment Features

In addition to the components of the concept and its implementation described so far, there are a number of elements that go beyond the actual core functions of mobile robots. On the one hand, these are equipment details required by road traffic legislation, such as lighting equipment and EMC shielding. On the other hand, these are safety mechanisms specifically tailored to the robot designed to provide safety above what is already built into the general structure and control system, see Table 10.

Our safety concept for robot operation relies on robot supervision by an operator, limiting the official classification of the robot prototypes to SAE level 2. A major purpose of safety functions is therefore to allow for manual take-over of the robot control at any time and to stop the robot in case of failure of the wireless controller (this addresses the requirement ID 61 On-site Supervision but also the requirements ID 49 Mixed Traffic Areas and ID 50 Vulnerable Road Users). Limiting the ODD is also part of the safety concept. In this way, the requirements Weather Constraints (ID 47) and Lighting Constraints (ID 48) are addressed.

Table 10: Concept and implementation of specific equipment features.

Addressed Requirements		**Concept**	**Implementation**	
Short Title	**ID**	**Hardware | Software**	**Hardware | Software**	**Comment**

Lighting Equipment	29	- Attachment of approved automotive lighting components	- Car trailer accessories:
			  - White light with integrated reflector
			  - Red light with integrated reflector
			  - Orange reflective tape	

EMC Shielding	31	- Shielding of all cables and technical compartments - Installation spaces with antennas outside of shielding	- Copper foil applied to acrylic side panels - Shielding of cables with metal mesh - Aluminum frame with ground straps	- Extra snap ferrite on the LiDAR connection wire
Sound Signal	34	- Software generation of a typical horn sound - Playback via loudspeaker	- Horn sound generated in real time - Playback via concealed USB speakers - Clearly indicated 3D-printed button for horn activation on the wireless controller	- Overlay of multiple sine frequencies
Vehicle Identification Number	35	- Engraved vehicle identification number	- Engraving on the right front chassis with a unique vehicle identification number	

Owner Identification	36	- Attachment of contact information to the vehicle	- Foil decal with additional information:
			  - Contact information (left side)
			  - Camera icon (front and rear)	

Data Privacy	64	- Attachment of a video camera icon		

Data Recording	37	- Logging of important vehicle data	- Log files with the following data
			  - High-level control state changes
			  - Location and time of manual takeovers
			  - Location and time of handovers to automated mode	

Emergency Stop	51	- Fixed emergency stop button on the vehicle	- Two parallel mechanisms to cut of the motor's power supply and engage the mechanical fail-safe-brakes:
			  - Fixed button on the robot's top
			  - Remote button: *Tyro Indus*
				- No available remote stop systems certified to ISO 26262

Remote Emergency Stop	52	- Remote emergency stop button worn by the accompanying person		
Overridability	54	- Manual control of the robot always has priority	- Instant transition to manual mode when dead man's switch is pressed	
Battery Monitoring	57	- UI battery level display	- Permanent UI battery level display - Highlighting of low battery levels	

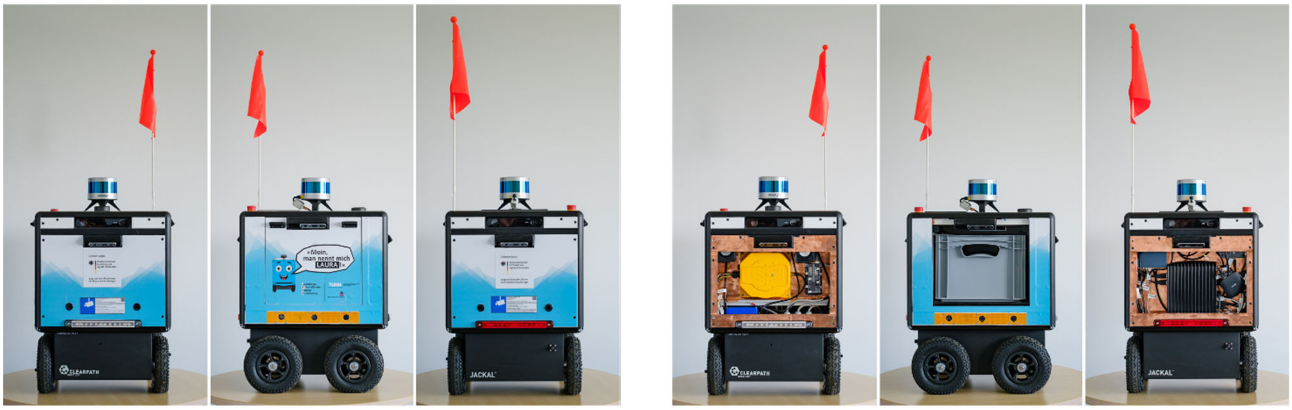

Figure 2: Prototype robot "Laura" - front, side and rear view (with and without side panels).

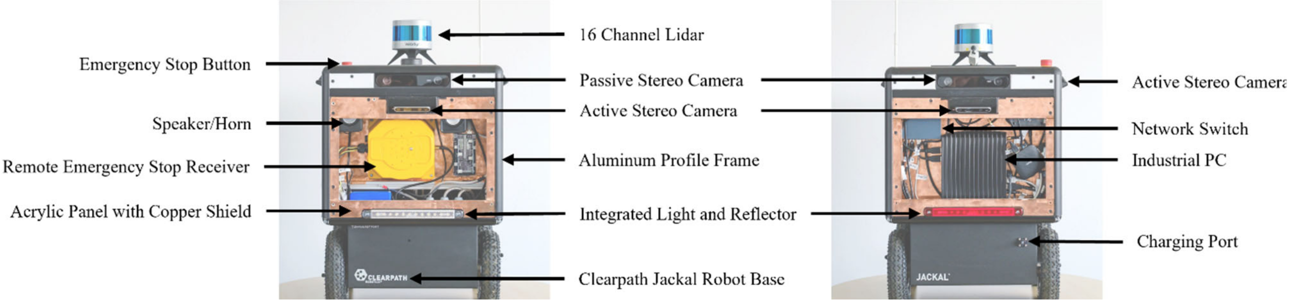

Figure 3: Main equipment of the "Laura" prototype robot – front and rear view.

5.5 ROBOT VALIDATION

The following section presents the results of the robot validation as described in Section 3. Successful validation was defined by three criteria: (1) Verification of roadworthiness by TÜV Nord, (2) Verification of the application and documentation of the core processes of automotive safety standards by TÜV Nord and (3) obtaining exemption permits for use in road traffic and on sidewalks.

The technical roadworthiness vehicle testing consisted of a test of electromagnetic compatibility (EMC) in a certified laboratory and of driving tests and vehicle measurements in our institute's testing hall. EMC tests according to *EU/ECE R10* are intended to verify that the robot's EMC emissions do not exceed the permitted limits and that the robot continues to function as intended when exposed to a defined intensity of electromagnetic radiation.

The EMC emission measurements were successful and confirmed the effective shielding of the robot. Immunity tests were performed with reduced field strength to account for the prototype nature of the robot and to protect the built-in sensors, which are not specifically designed for automotive applications. After consultation, this was considered uncritical from both a technical and safety point of view.

Driving tests and measurements in the testing hall verified the successful implementation of the remaining requirements of the Road Traffic Licensing Regulations. Testing included visual inspection, weight determination, and braking tests on straight and inclined surfaces. Beyond laboratory tests, the robot's remote controlled and automated driving functions were demonstrated in the operating area in the city of Lauenburg/Elbe.

In addition to testing the vehicle itself, TÜV Nord assessed the documentation of the vehicle development process and the performed system verification measures. It was verified that the approach as described in Section 3 is correctly aligned with the key methods of ISO 26262 and ISO/PAS 21448.

Based on the successful external assessment by TÜV Nord, exemption permits were successfully applied for:

- Operation of the robot on sidewalks,
- exemptions for remaining technical deviations from legal requirements (e.g., no driver's seat) and manual operation of the robot in Germany,
- automated operation of the robot in a defined operating area in Lauenburg/Elbe.

DOI: 10.2195/lj_proc_thiel_en_202310_01
URN: urn:nbn:de:0009-14-58243

The exemption permits were subject to a number of conditions, e.g., constant supervision by trained operating personnel, who must also be in possession of a valid European class "M" driver's license (see [36]).

6. DISCUSSION

With this study, a practical example is given to illustrate the process of designing a mobile transport robot prototype for research purposes that is assessed suitable for operation in public spaces by the responsible authorities. Given the fact that the official exemption permit mentioned before was successfully obtained, the overall validity of the presented approach for the existing use case can be assumed. To achieve this exemption permit, multiple different technical inspections were carried out by the TÜV Nord regarding electromagnetic compatibility as well as conformity with the German Road Traffic Licensing Regulations. Additionally, potentially occurring risks and hazards were identified, evaluated and necessary countermeasures derived. The technical inspections as well as risk assessments were provided to the responsible traffic authority when requesting the official exemption permit.

The general development process was iterative in accordance with ISO 26262 and minimal viable products were used for testing subsystems under real conditions before implementation to prevent later, costly adjustments. It has been further shown that modularity can bring advantages in terms of development, testing and accessibility, but it also creates challenges for highly integrated systems and compact robots regarding system complexity and limited installation space. In particular, a modular separation of drive base and housing is sensible regarding a different need for customizability. While the robot structure may change frequently with changing use cases or sensor concepts, the drive base tends to remain unchanged and can be purchased separately, as done in the example presented here. However, the acquisition of a base leads to additional dependencies or inflexibilities and integration challenges. This relates on the one hand to the available installation space and on the other hand to the design of the drive system with regard to the maximum vehicle weight including payload.

Further, the use of well-established open-source solutions such as Ubuntu and ROS as the software base for a research robot prototype can be recommended. It provides access to a diverse set of tools and packages that provide implementations of various robot functions such as localization, mapping or navigation. However, there are some regulatory concerns regarding the proof of safety for open-source solutions. For commercial robot manufacturers or operators, independently developed software could prove to be more appropriate regarding the increased effort necessary for validating software.

This already illustrates that certain limitations arise with the prototypical nature of the robot regarding the general applicability of the presented approach. The focus on research-related tasks rather than the mass production and commercial deployment of robots is one of the main factors for this. Further, as the focus on the robot operation was limited to the German city of Lauenburg/Elbe, the technical inspections as well as the exemption permit for the operation were worked out in cooperation with local traffic authorities and TÜV Nord. An official and standardized regulation on technical requirements for mobile robots operating sidewalks in German public spaces is yet to be developed. Thus, it cannot be guaranteed that the technical requirements for the robot construction will be the same in cooperation with authorities or institutions responsible in other regions of Germany. In addition, some of the implemented safety systems explicitly address our vehicles. Other robots and their design would have to be tested analogously, which could lead to a different result.

The limitation of the robot's use case to research-related applications allowed for omitting some regulations that would be required in the case of serial production and commercial deployments such as the Product Safety Act or the Radio Equipment Directive. Although this work does not cover all of the requirements for commercial robots, the requirements that are presented here are still applicable to these robots. Therefore, this paper still provides a valuable contribution to commercial applications that can be seen as basic requirements to be fulfilled.

During the development and design process, a number of topics emerged that offer particular areas for discussion. To discuss those topics in an orderly manner, the following subsections are divided into five domains considering general robot design, modification of the purchased robot base, the selected components, software and regulations.

6.1 GENERAL ROBOT DESIGN

The general material selection was adequate for the given application and the prototypical nature of the constructed robot. The use of aluminum profiles allows quick assembly and disassembly, is stable, cheap and easy to process. Further, the availability of profile designs with rounded outer edges allows fulfilling the requirement of outer edges with less than 5 mm radius. Acrylic glass cutouts allow a weatherproof design of the housing, but are in contrast to the aluminum profiles less flexible and difficult to process. The combination of aluminum profiles and acrylic glass needs an additional layer of copper or aluminum foil to fulfill the requirements regarding EMC-shielding. Further, the selected materials lead to a relatively high overall high weight and thus a reduced maximum payload.

A conflict while developing the robot was providing accessibility versus security. On one hand, easy accessibility of technology components is important for maintenance

DOI: 10.2195/lj_proc_thiel_en_202310_01
URN: urn:nbn:de:0009-14-58243

and iterative development of the robot. On the other hand, the security of the technical compartments against unauthorized access, weather conditions and incoming or outgoing electromagnetic radiation was another essential development goal. In this case, the security was prioritized, which lead to a decrease in accessibility. Potential improvement can be found in separating the inner support structure holding technology components from the protective outer shell. An ideally seamless outer shell made out of a single material (e. g. fiberglass) with an integrated EMC-coating could seal the robot against water, electromagnetic radiation and unauthorized access, while ideally providing good accessibility through a quick assembly and disassembly.

6.2 MODIFICATION OF THE PURCHASED ROBOT BASE

This section provides an overview of the experience gained in modifying the robot base that was initially purchased. Recharging the robot without simultaneous operation being possible leads to delays in the development phase and could possibly decrease the availability of the robot. Here, the implementation of mains operation would facilitate software development and testing while recharging the battery. For this aspect and also for the availability of the robot, when no socket is available, the introduction of a modular battery pack, that can be changed while the robot is running represents an improvement.

Due to a relatively high center of gravity in combination with a short wheel-base and track width, the driving behavior of the robot prototype can be quite instable on uneven surfaces. This and the vibration caused by the movements tend to be problematic for the perception systems. In addition, this limits the ability to drive over curbs, edges or ramps. Cobblestones, other uneven ground surfaces and emergency braking maneuvers on slopes or with high velocity increase the instability. A possible solution would be an extension of the wheelbase and track-width in combination with a suspension system. Currently, only the pneumatic tires provide a damping effect. Alternatively, the center of gravity could be reduced. This can be achieved by using wheel hub motors, which would be more space efficient and therefore offer the chance transfer the entire technology components to the bottom of the robot. Nevertheless, wheel hub motors with built-in mechanical brakes are difficult to source externally.

6.3 SELECTED SENSOR SETUP

The setup was designed to match the requirements of a research platform. Therefore, a diverse sensor setup was selected. This allows to test different sensor combinations on one platform and compare them to each other.

For a commercial or more focussed deployment, a reduced sensor setup would be sufficient, as the basic driving functions of an autonomous delivery robot can be realized with a fraction of the implemented perception setup. This would lead to potential cost, weight and space savings and underlines once again limitations regarding the general applicability of the presented approach.

6.4 SOFTWARE

So far, the software of the robot was only briefly discussed, primarily where it is directly related to the hardware used. But even in this reduced context, some insights can be derived. When driving on uneven ground, the robot tends to pitch, causing the ground to enter the field of view of the middle LiDAR channel used for localization. Therefore, it is necessary to ensure that these ground reflections are not detected as environment features, or that the detections can be suppressed accordingly. Additionally, the maximum safe speed of the robot is highly dependent on the surface conditions as well. Uneven floors or edges/ridges require a significant reduction in speed to ensure safe operation. So far, a low, conservative speed is used. It would be desirable to have a dynamic speed specification that either directly senses the evenness of the ground or adjusts the speed based on predefined zones.

Further, ground reflections must not be recognized as obstacles. Again, countermeasures are recommended. The current approach to obstacle detection is based on height thresholding. Thus, declining edges (e.g., curbs) cannot be detected from above. It is desirable to have an additional safety mechanism to prevent the vehicle from falling off edges/cliffs if the localization is disturbed.

Besides, a poor localization can further lead to unpredictable driving behavior. It is therefore necessary to detect degraded localization performance, which is not explicitly supported by many standard implementations of 2D localization algorithms. Therefore, we developed a feature that exposes the internally hit ratio between the current measurement and the reference map used by AMCL, which is currently being tested.

While the previous points address specific challenges, there is one issue that affects the entire software development process: The time required for architecture and code reviews, as well as for achieving a high level of test coverage, is immense and should not be underestimated, particularly in the context of research projects.

6.5 REGULATIONS

Mobile robots operating in public traffic on roads and sidewalks are to be classified as motor vehicles under German law. This gives rise to a number of important points that need to be considered, but also a number of issues that still require clarification (see [36]):

First of all, there is no appropriate EC vehicle class for mobile robots in public spaces, and accordingly, there are no specific regulations for such vehicles. The requirements that currently have to be considered, result exclusively from the national German legal framework, which, however, in many instances already contains references to international regulations. In any case, these requirements must be considered in the development of robots as soon as those robots are to be operated on more than just closed private sites.

In contrast to mobile robots that are intended to be used in intralogistics contexts and for which comprehensive standards exist, different standards are likely to apply to robots in public spaces. In the research projects, we followed the safety standards for (autonomous) motor vehicles in coordination with TÜV Nord. Still, these standards are not developed specifically for mobile robots in public spaces, particularly operating on sidewalks, which leaves room for interpretation.

Finally, an explicit legal framework for autonomous motor vehicles is available in Germany since [34. The extent to which this legal framework is directly transferable to robots does not appear to be conclusively clarified at present as already mentioned in the previous point (see [36]). In any case, high efforts and costs are to be assumed. In case of a research project, it proved advantageous to classify the robot only as a partially automated vehicle according to SAE Level 2 and therefore outside the new legal framework. Although this requires constant monitoring by a responsible person, it allows the technical systems to be tested in a real environment with less effort and cost than a classification in higher autonomy levels.

7. CONCLUSION AND OUTLOOK

The intent of this paper is to support research in the area of public space automation by presenting a prototypical research delivery robot - from initial requirements to two approved, realized vehicles.

Requirements were identified that address the specific domain of mobile robots in public road environments, particularly for operation on sidewalks. It was further demonstrated how these requirements can be translated into a robot concept and finally into a concrete SAE Level 2 prototype vehicle. As part of the validation process, assessments of a technical testing organization ensured that the development of the robot was adequately aligned with relevant industry standards. They also confirmed that the robot complies with road traffic regulations as far as technically applicable. Any remaining deviations from regulations were addressed by obtaining exemption permits.

In conclusion, mobile robots for real-world research can be successfully built and approved in the context of research projects. However, operational restrictions are foreseeably necessary, e.g., continuous monitoring as well as a limitation of the ODD regarding unfavorable weather conditions. Even considering these restrictions, the time and cost involved should not be underestimated. It was also shown that the robot requirements, the robot concepts and their implementation can only be generalized to a limited extent. This can be attributed to a significant number of robot-specific design characteristics, e.g., different implementations of safety mechanisms, but also to a lack of a uniform set of rules. While there are now regulations for self-driving cars in Germany, they do not explicitly cover sidewalk robots. There are also no safety standards that specifically address this area.

The prototypical nature of the developed robot implies a number of limitations, such as the reduced payload, missing protection against unauthorized access to the cargo compartment or the restricted ODD. These should be addressed in future adaptations and developments. Furthermore, raising the SAE Level to enable strictly remote monitoring of the robot (e. g. in a control center) should be considered to no longer be dependent on permanent on-site monitoring (see [8]).

An even higher degree of automation - ultimately without supervision - places far-reaching demands on the technical systems and their verification besides the necessary legal framework for autonomous robots. For example, both the robot's control system and its perception system must prove reliability and safety in any situation (e.g., construction sites, densely occupied sidewalks) and under any conditions (e.g., snowfall, soiled sensors).

Finally, results from other research groups are still sparse, so further published work on this topic is desirable. This also extends to the area of requirements and their legal and normative basis, where further research is needed.

FUNDING INFORMATION

This work is based on research conducted within the projects “TaBuLa-LOG - Combined Passenger and Goods Transport in Automated Shuttles” [7] and “Smart Control Center for Automated Transport Robots and Buses in the City of Lauenburg/Elbe - TaBuLa-LOGplus” [8], both funded by the German Federal Ministry for Digital and Transport.

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DOI: 10.2195/lj_proc_thiel_en_202310_01
URN: urn:nbn:de:0009-14-58243

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