Transport Robots in Automated Shuttles

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Until now, passenger and freight transport have mostly been considered separately. In terms of sustainable mobility, which aims to reduce the volume of traffic and increase the utilization of transport capacities, the combined transport of people and goods is being investigated in the TaBuLa-LOG project. One aspect of this is the integration of a transport robot developed by researchers at the Hamburg University of Technology.

Outside metropolitan areas, local public transport services by bus are often unsatisfactory, regularly underutilized, and require high levels of public subsidy [1]. In the District Duchy of Lauenburg, research is therefore being conducted into how the local public transport service can be supplemented and made more attractive in the future by autonomous driving [2]. One aspect of this is the transport of goods with the help of transport robots, which could cover sections of the route in automated shuttles together with passengers and thus increase capacity utilization and cost-effectiveness. TaBuLa is the abbreviation for „Test Center for Autonomous Buses in Duchy of Lauenburg County". This describes the fact that tests for the use of automated or autonomous buses are carried out in a test environment in the Duchy of Lauenburg County. The addition "LOG" stands for the integration of a logistics component in the form of a transport robot with the designation Laura for "Lauenburg's automated robot delivery". At the Hamburg University of Technology (TUHH), the transport robots are being developed at the Institute for Technical Logistics. The Institute for Transport Planning and Logistics is investigating possible applications and acceptance of combined passenger and goods transport.

REAL-LIFE LABORATORY IN LAUENBURG/ELBE

In the project, the transport of internal mail of the city administration was selected as an exemplary use case. Three logistics scenarios were tested in daily traffic between different

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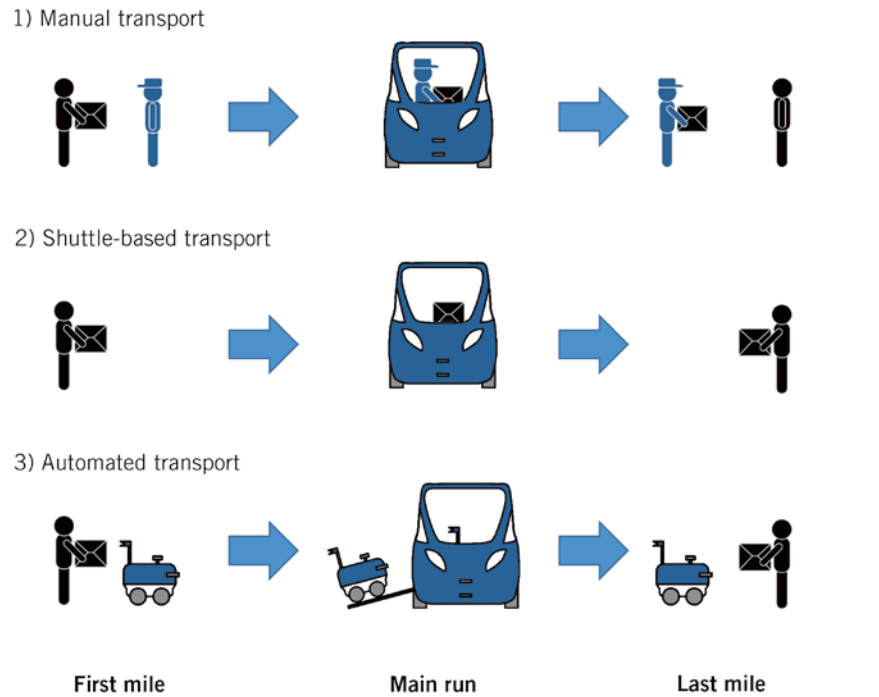

FIGURE 1 Test scenarios for the transport of in-house mail (© TUHH)

locations of the administration in Lauenburg/Elbe, **FIGURE 1**:

Scenario 1: Transport of mail by one person in an automated shuttle and handover at the destination address,

Scenario 2: Transport in an automated shuttle with direct handover of the mail to a receiving person at the corresponding stop, and

Scenario 3: Complete transport of the mail with the transport robot including its travel in the automated shuttle.

In the morning, mail was collected from the postal distribution center using a shuttle and delivered to the City Hall. After the mail was sorted, it was distributed

- between the administrative buildings in the immediate vicinity and
- using a shuttle to the Elbe navigation museum further away and back.

The challenges for the shuttle and the transport robot in the historic city were manifold: federal highway with traffic lights, traffic-calmed area with a high volume of tourists, various road surfaces with parts of large stone pavers, narrow and steep old town alleys and wooded areas as well as overpasses and underpasses. [3]

USE IN THE SHUTTLE

The shuttles were used to extend the operating radius of the transport robots and at the same time to increase the utilization of the bus line through the integrated transport of goods. Two Arma DL4 4WD minibuses from the manufacturer Navya were used as shuttles, which were approved as people movers for public transport [4]. The automation level according to SAE International can be assigned to conditional automation (SAE Level 3). Around 7463 km were covered in mixed traffic at speeds of up to 18 km/h from 2019 to 2021, and 4664 passengers were transported without accidents.

Adjustments were necessary for the expansion of the regular bus service to include the transport of goods: Traffic authority orders and an amendment to the permit under the Passenger Transportation Act as well as an adjustment to the timetable were made for the additional installation of stops. At two stops, it was possible to implement a barrier-free exit via the construction of stop platforms. Modules were installed at the shuttles, traffic signals and stops that enable actions to be triggered via Bluetooth, such as requesting a green phase at a traffic signal.

LAST MILE BY TRANSPORT ROBOT

Transport robots for the use on roads or sidewalks have not been available for sale individually until now. Therefore, suitable transport robot prototypes had to be newly developed and built by the TUHH, shown in **FIGURE 2**.

APPROVAL

According to the German Road Traffic Act (StVG) and the Vehicle Registration

FIGURE 2 Prototype of Laura entering the shuttle (© Dominik Pietzko)

Ordinance (FZV), compact transport robots are considered motor vehicles, since they are machine-operated and do not move permanently on tracks (§ 1 StVG and § 2 FZV). However, provided that a maximum design speed of 6 km/h is not exceeded, such vehicles remain exempt from registration and operating permits (§§ 1 and 4 FZV).

Two exemption permits had to be obtained for the operation of the transport robots: Firstly, for deviations from the construction and operating regulations of the Road Traffic Licensing Regulations (StVZO), and secondly, for the use of sidewalks in deviation from the Road Traffic Regulations (StVO). The application for the exemption permits was made in close coordination with the responsible authorities at municipal and state level. The applications for exemptions were based on expert opinions from TÜV Nord Mobilität. As part of the assessment, the compliance of the robots with the requirements of the StVZO - where applicable - was ensured. In addition, appropriate application of motor vehicle-specific industry standards and specifications had to be demonstrated, particularly for the approval of automated driving functions. These included both the areas of functional safety (ISO 22626) and safety of the intended functionality (ISO/PAS 21448). Part of the safety concept drawn up in this context is continuous on-site monitoring by trained personnel.

HARDWARE

The structural basis of the transport robots is a Jackal robot base from the manufacturer Clearpath Robotics equipped with fail-safe brakes. Built upon that is an aluminum frame with side panels made of acrylic glass plates. In the further design, the specifications of the StVZO were considered accordingly, for example in the design of the braking behavior, by rounding off protruding edges, attaching lights and reflectors or electromagnetic shielding of components and cables. The small vehicle is 51 cm long, 43 wide and 62 high and travels at a maximum of 6 km/h, which is about walking speed. The load compartment is designed for transporting an exchangeable Euronorm container that holds 20 l of goods with a maximum total mass of 3 kg.

The transport robots are equipped with a variety of sensors. An essential component is a multi-layer laser scanner, which is used both for localization and for detecting obstacles in the travel path. Obstacle detection is supplemented by four active stereo cameras, which are tilted downwards to each side and monitor the vicinity of the robots. This is particularly necessary when navigating in the shuttle in close proximity to other passengers. Four ultrasonic sensors serve as a separate system for detecting obstacles.

Remote control of the robots and intervention in the automated ride is possible at any time via a Bluetooth controller. A redundant radio emergency stop system is also installed.

SOFTWARE

The software of the transport robots was developed based on the Robot Operating System (ROS). For individual functions, such as localization, existing ROS libraries were used. Other sub-functions had to be newly implemented.

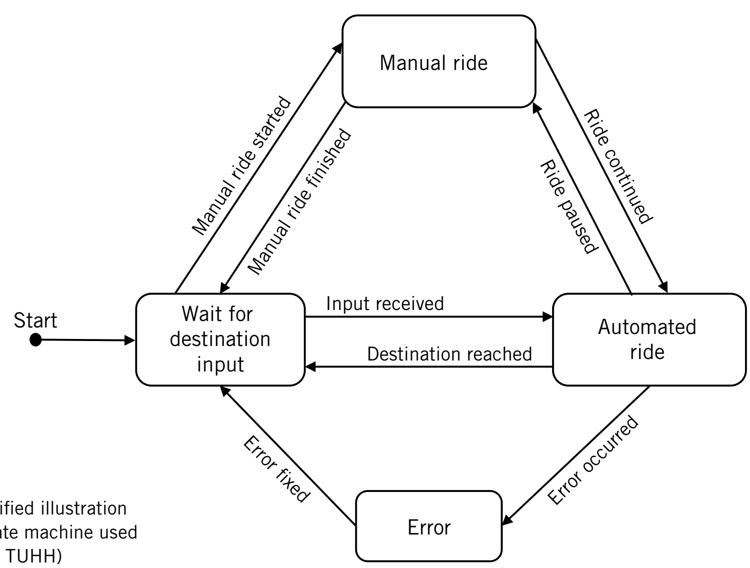

FIGURE 3 Simplified illustration of the finite state machine used in the robot (© TUHH)

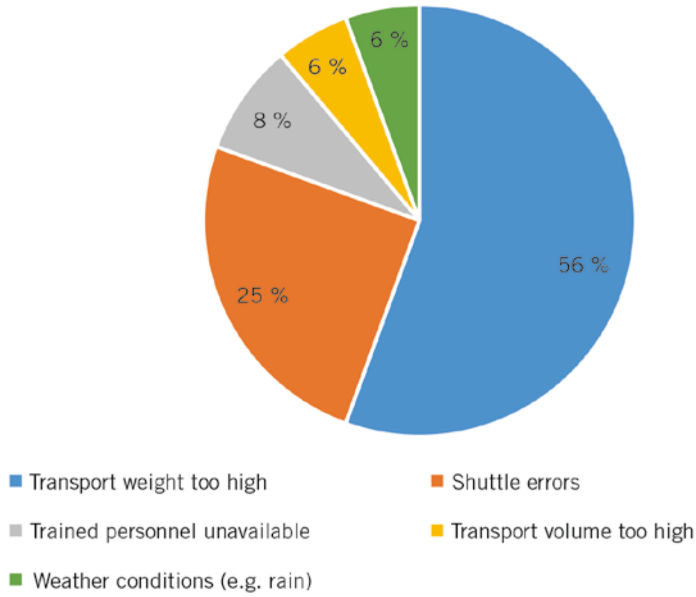

FIGURE 4 Identified reasons of disruptions of transports (© TUHH)

These sub-functions are linked using a new, strongly concurrent, event-based implementation of a finite state machine. This is a software architecture that allows a complex process to be broken down into smaller individual tasks in an illustrative way, **FIGURE 3**. The highly concurrent approach of this implementation allows all individual sub-functions to be run in parallel and activated or deactivated as needed. The event-based architecture allows each sub-step of the transport process to be interrupted at any time in order to react to malfunctions and interrupt the automated ride if necessary. This was done to meet the requirements of the safety concept.

The next travel destination is selected via an integrated touchscreen. The robots can move freely within a predefined area, but adhere to the right-hand drive requirement.

ACCOMPANYING RESEARCH ON ROBOT OPERATION

The testing of the scenarios for combined passenger and goods transport ran from April to November 2021. A total of 72 test runs were carried out, 21 of which are assigned to scenario 3 and were documented with the aid of survey forms from accompanying and administrative personnel. In the process data on weather, temperature, number and weight of transported shipments as well as process times and disruptive factors was collected.

In general, it was found that Scenario 1 (manual transport) is the most efficient in terms of time and extremely resistant to disruptions. Scenario 3 (automated transport) was particularly interesting as a use case, but offered various disruptive factors: excessive transport weight or transport volume, shuttle disruptions or unavailability of trained accompanying personnel. Weather conditions were a comparatively minor disruptive factor during this period, **FIGURE 4**.

The surveys of passengers and the public after they had become acquainted with the vehicles on their acceptance show a generally positive attitude toward the technology and the new use case. There is also trust towards the technology, but at the same time it remains important that the vehicles are accompanied by personnel, **FIGURE 5**. The findings confirm surveys conducted in 2020 that had investigated the acceptance of automated shuttles [5].

CONCLUSION

In summary, the results of the TaBuLa-LOG project show that it is legally and technically feasible to implement combined automated operation of transport robots and shuttles. At this point in time, the identification and implementation of relevant requirements in particular is

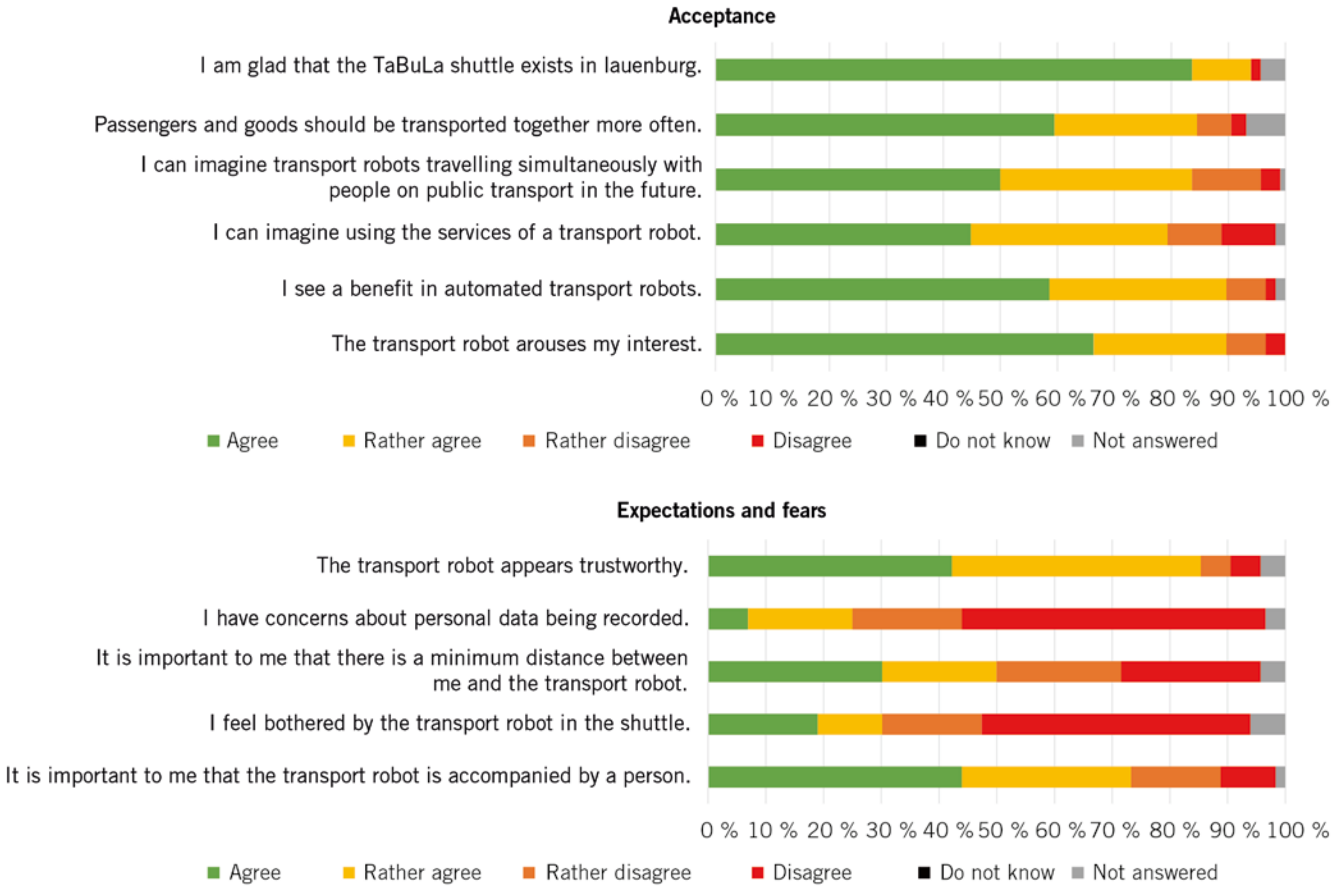

FIGURE 5 Results from passenger and public opinion survey (sample n=116) (© TUHH)

time-consuming. A clear legal framework for mobile robots in public spaces is lacking. Early involvement of a motor vehicle expert as well as key stakeholders is advisable.

On the robot side, there is a particular lack of compact components and sensors designed for use in road traffic. The interconnection of infrastructure, shuttles and digital applications has produced good solutions, but has proven challenging when disruptions occur due to a multitude of components and people involved.

For combined logistics processes, useful use cases are emerging with high levels of public acceptance; more extensive studies on costs and transferability are yet to be conducted. Future work should pursue an expansion of automation, such as moving toward remotely monitored operation from a control center without an attendant on site. Testing of beneficial and sustainable logistical use cases will play an important role.

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