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Examining the challenges of mobile robots to perform collaborative transports considering industry experts insights and hardware experiments

Untersuchung der Herausforderungen mobiler Roboter bei der Durchführung kollaborativer Transporte unter Berücksichtigung der Erkenntnisse von Industrieexperten und Hardware-Experimenten

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Collaborative transportation using a group of mobile robots enables companies to increase the utilization of their fleets and to transport larger loads without additional investments. The expert interviews conducted with industry representatives suggest that there is a need for research in this direction. However, challenges remain, especially in the necessary communication and control. The investigations of the driving characteristics of mobile robots with the help of a high-precision tracking system also reveal that significant deviations from the predefined trajectories can be observed due to the hardware of the vehicles. These results demonstrate the future need for research with regard to the control strategies of the networks and the motor control.

[Keywords: automated guided vehicle, autonomous mobile robot, real-world experiments, marker-based tracking, cooperative transport]

Der kollaborative Transport durch einen Verbund mobiler Roboter eröffnet Unternehmen die Möglichkeit, die Auslastung ihrer Flotten zu erhöhen und größere Lasten ohne zusätzliche Investitionen zu befördern. Die durchgeführten Experteninterviews mit Industrievertretern legen den Schluss nahe, dass ein Bedarf für Forschung in dieser Richtung besteht. Allerdings zeigen sich weiterhin Herausforderungen, insbesondere in der dafür notwendigen Kommunikation und Ansteuerung. Die Untersuchungen der Fahreigenschaften von mobilen Robotern unter Zuhilfenahme eines hochpräzisen Trackingsystems offenbaren zudem, dass durch die Hardware der Fahrzeuge signifikante Abweichungen von vorgegebenen Trajektorien zu verzeichnen sind. Diese Resultate demonstrieren den künftigen Forschungsbedarf hinsichtlich der Steuerungsstrategien der Verbunde sowie der Motoransteuerung.

[Schlüsselwörter: fahrerloses Transportfahrzeug, mobiler Roboter, reale Versuche, Marker-basiertes Tracking, kooperativer Transport]

1 INTRODUCTION

This paper aims to explore the challenges and opportunities associated with collaborative transport solutions in the industry. In particular, the focus is on how mobile robots can be leveraged to enhance the flexibility and efficiency of logistics processes in small and medium-sized enterprises.

1.1 MOTIVATION

Challenges such as the shortage of skilled workers and the pressure of international competition require progressive automation, even in small and medium-sized companies (SMEs) [1]. Mobile robots play a central role in the automation of production and logistics processes. Existing standards such as VDA5050 support the efficient integration of different robots into existing systems. However, the high investment costs involved are usually a major obstacle. In addition, most mobile robots are designed for a specific transport task (small load carriers, pallets, trolleys, etc.) and therefore offer limited flexibility in their use. However, SMEs in particular often require such versatility, and purchasing different robots for each application is usually not feasible.

Enabling mobile robots to perform collaborative transports offers companies the opportunity to use existing fleets of mobile robots to transport large, heavy and irregularly shaped loads. By temporarily combining multiple mobile robots into transport groups the robots implicitly gain more capabilities and thus increase the flexibility of the fleet without any further investment.

1.2 PREVIOUS WORK

Preceding publications [2] and [3] have presented a novel approach to uniformly control the robots within a transport group regardless of their wheel configuration and the arrangement of the robots. Effectively the transport group is considered a single vehicle with many wheels in their respective relative positions. The Omni-Curvature-Parameters are used to determine the possible driving maneuvers and can therefore be applied to determine the possible movement of the group. Further in [3] a multi-layer communication model (see Figure 1) considers the necessary steps to perform a collaborative transport and extends the existing communication in mobile robot fleets by the level of cooperative communication. Here, the necessary information for the joint movement is exchanged, requiring low latency, frequent updates, and a stable connection.

1.3 OVERVIEW OF THE CHAPTERS

This paper is structured into three main parts. First the results of eight interviews with industry experts and a survey with further 25 representatives of the mobile robot industry are presented claiming the need for industry ready solutions for collaborative transports and highlighting the major challenges foreseen by the experts in the development and implementations. After a description of the real-world mobile robotics lab and the used hardware the driving behavior of industry standard hardware is analyzed to get insights which challenges need to be addressed when trying to perform robust and reproduceable collaborative transports under industry conditions. The fifth chapter shows the results of experiments regarding the communication for mobile robots using Wi-fi and discusses the possible issues arising from communication latency or losses. Finally, the findings are discussed and an outlook on future developments with regards to the challenges identified is given.

2 EXPERT INTERVIEWS

An expert interview provides the opportunity to obtain information that is not publicly accessible. In the context of this work, a semi-structured interview was employed in accordance with the classification system proposed by Helfferich (2011). This method was selected due to its flexibility. To ensure comparability of the interviews, a guideline was developed to maintain a consistent structure of topics and similar questions for the various experts. During the interview, the primary focus was on the research context of cooperative transportation, with the flexibility to make adjustments in the personal interaction to obtain more in-depth data in the relevant expertise.

Table 1 gives an overview of the interviewed industry experts and their respective area of expertise. Each statement that has either been stated or supported by one or more experts is indicated with the Expert number in brackets behind. The survey was conducted with 25 industry representatives, each either being users or developers of mobile robots.

The results of the interviews were classified into four categories: the necessity for flexible cooperative transportation, the requirements for communication, possible control strategies and the open challenges for realizing cooperative transportation.

2.1 NECESSITY FOR COOPERATIVE TRANSPORTS

Collaborative transportation is increasingly being recognized as an interesting innovation in the growing market for mobile robotics. Rather than relying on a few large vehicles, companies can own numerous smaller vehicles that work in groups, providing the flexibility needed to transport large loads efficiently (I04, I07). This approach is particularly advantageous for companies requiring customized and adaptable transport solutions, as cooperative transportation allows for significant operational flexibility (I02). Despite its potential, the industry remains in its infancy, with relatively few companies currently utilizing mobile robot systems on a large scale with more than 10 vehicles (I06, I02). In the future, medium-sized companies in particular will benefit from mobile robot solutions, whereby the development of practical, scalable solutions is essential for broader acceptance (I01). The application of cooperative transportation is especially promising in sectors like aerospace and large-scale construction, where the maneuverability of intelligent, cooperative systems offers superior performance compared to traditional heavy-duty vehicles (I03). However, while the demand for such systems is evident, there remains a significant gap in the availability of practical concepts ready for implementation, underscoring the need for further research and development (I02).

2.2 CONTROL STRATEGIES

In the field of mobile robot control, a distinction is made between centralized and decentralized control methodologies. However, this is typically referred to as route planning, traffic control, and order allocation. The results of the online survey indicate that 44% of respondents do not believe that a decentralized control system will be a viable solution in the future. Additionally, 80% of those surveyed assume that there will always be a centralized component to the control system. It is important to distinguish between decentralized control, in which vehicles make their own decisions, and decentralized communication, in which communication does not take place via central nodes but directly peer-to-peer. The following section will focus exclusively on the topic of control.

As experts in the field have observed, a centralized approach offers the advantage of consolidating all information in a single, centralized location, taking into account global information. This can be particularly useful for the approximate planning of the route (I05). Decentralized communication between vehicles is seen as particularly relevant for local coordination between participants (I01). Centralized control systems reach their limits, especially with a large number of participants. One concern with decentralized control is that the computers on the vehicles may reach their limits if too much evaluation is necessary, but experts consider the currently available computing power to be sufficient (I06). Communication that does not go through the control center is generally seen as positive and necessary. However, decentralized approaches can also cause problems with the synchronization of time between vehicles if there is no central clock. (I02) The subsequent section will examine the various communication technologies that have a significant impact on vehicle control.

2.3 COMMUNICATION REQUIREMENTS FOR COOPERATIVE TRANSPORTATION GROUPS

In the context of mobile robotics, Wi-Fi represents the most utilized technology for communication. This conclusion is supported by both the expert interviews and the results of the online survey. Wi-Fi is a technology that has reached a high level of maturity and is currently in widespread use in other domains as well. Most companies have already established the necessary infrastructure and expertise (all experts). The bandwidth is adequate for most use cases in the domain of mobile robotics (I02, I05). However, it can potentially be a limiting factor if not utilized with caution (I06). The security of communication has also been sufficiently researched, and industrial companies have demonstrated a high level of trust in this technology (I01, I04). The potential for remote access via the Internet also presents the opportunity for companies to reduce the time spent on lengthy travel for straightforward issue resolution (I02). Furthermore, communication with the peripherals of vehicles is already accomplished via Wi-Fi, including fire protection gates and transfer stations (I02).

But there are also disadvantages to the use and operation of mobile robots using Wi-Fi. Most prominently, the network coverage represents a significant challenge. In factory settings and warehouses, numerous sources of interference impede the efficacy of wireless connections, leading to sometimes multiple minutes without a connection (I01, I02, I06-I08). Upgrading the technology is frequently infeasible or requires considerable effort. This necessitates the development of solutions by manufacturers of automated guided vehicles that can accommodate transient loss of connection (I02). Latency in a Wi-Fi system with many participants can also be a challenge (I06).

Table 1.: Overview of the Experts

Reference	Expert Profiles for the interviews
I01	Head of department at logistics research institute, expert in mobile robotics.
I02	CEO of a start-up, specializing in mobile robot software development.
I03	CEO of a start-up focused on remote-controlled mobile robots and distribution.
I04	Senior manager in safety technology for mobile robotics solutions.
I05	CTO of a start-up, expert for fleet manager and multi-vendor robot integration
I06	CEO of a start-up offering plug-and-play mobile robot integration solutions.
I07	Technology expert in intelligent logistics and cost-effective mobile robots.
I08	Head of logistics development specializing in mobile robot control strategies.

The experts view 5G as a significant addition to the existing communication technology landscape, alongside established standards such as Wi-Fi. In particular, the high data rate and the large number of potential participants in a network are identified as significant advantages (I07, I05, I06). A notable drawback is the industry's limited experience, the limited number of providers of the technology and higher cost as well as and the lack of existing infrastructure (I01, I02, I05, I06). Hybrid solutions combining Wi-Fi and 5G are also possible here.

Other noteworthy technologies include Bluetooth and ZigBee, which have a relatively limited range but are highly reliable. (I01, I03) ZigBee also employs a decentralized communication approach that could be highly relevant, particularly in cooperative driving scenarios (I03). Bluetooth is seen as a potential source of conflict with Wi-Fi frequencies, and some companies are therefore critical of its use (I02, I08). Light communication is also utilized in certain instances. However, the data rate is relatively low, and it is typically only used in static scenarios, such as communication with a charging station. (I02). The issue with employing these alternatives in the context of cooperative transportation is that there is a necessity to work with the existing hardware that is installed on the vehicles. Given the competitive nature of the market, it is not feasible to alter or expand the communication hardware due to financial constraints (I06, I08). In addition, companies that build vehicles lack the expertise and experience that has already been built up for Wi-Fi, for example (I03).

2.4 MAIN CHALLENGES IDENTIFIED BY THE EXPERTS

In the present context and in the foreseeable future, experts consider Wi-Fi to be the most promising technology for cooperative transportation. But the main challenges are a loss of connection and the latency in the system (all experts). By separating the communication levels, however, the communication model presented in Brenner et al. [3] also allows a switch to one of the promising communication technologies of the future (in this case, the relevant cooperative level). Use cases with large fleet sizes show that the available bandwidth is already reaching its limits, which needs to be considered when implementing new concepts requiring further communication effort (I05). Interferences due to steel, other machines or humans often create additional problems (I08). Industry experience shows that having methods in place that deal with temporary connection loss is inevitable to provide robust and therefore industry-accepted functionalities. (I06, I02)

Another critical point identified is the aspect of safety. The vehicles within the transport group need to dynamically adapt their safety fields maintaining a steady safety perimeter allowing for obstacles to be detected without disturbing each other's view (all experts). Additionally possible overhanging load needs to be accounted for (I03).

Some of the experts consider the synchronization of the vehicles to form the transportation group as a core issue in trying to develop a robust and repeatable functionality (I01, I06, I08). With the desynchronization posing a major threat as inconsistent Wi-fi coverage might lead to loss of connection (I04, I06).

More hardware-focused problems might arise from possible drifting of the vehicles from their planned trajectory caused by factors such as slip, mechanical play or irregularities in the floor (I01, I02, I03, I08). Therefore, a control strategy to monitor and adjust the relative positions is crucial for a trouble-free operation during a transport. Currently commonly installed sensors available might not be sufficient to create and maintain the formation necessary.

Next to all these technical aspects stands the before mentioned high investment cost to acquire and deploy mobile robots within one's system. Increasing the flexibility and capabilities of mobile robots can therefore greatly increase the ROI, albeit closely considering and integrating the identifies challenges to ensure a robust method which is simple in its use and integration in current and future systems.

Additionally, to the issues determined by the experts, experiments were conducted further investigating the difficulties to be addressed when carrying out cooperative transports within typical industry conditions. First the impact of the hardware is analyzed to gain insights on which issues need to be considered when implementing a control strategy for mobile robot transport groups. Followed by experiments examining the impact communication issues might have on the feasibility of robust cooperative transportations.

3 REAL WORLD MOBILE ROBOT LAB

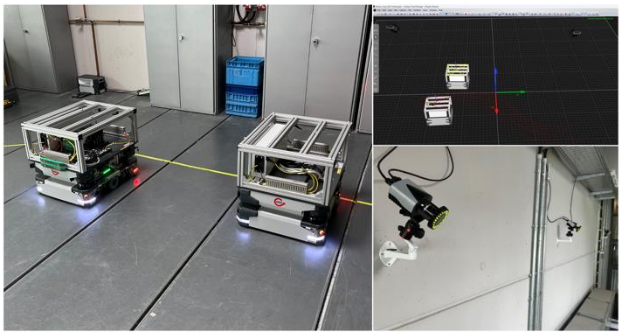

Figure 1. Real world mobile robot lab components

The distributed future laboratory for mobile robotics with the two locations at the IFL of the KIT in Karlsruhe and the IFT of the University of Stuttgart is used as a real test environment. Two modified Karis Pro vehicles from GEBHARDT Fördertechnik GmbH are available here for research purposes. The vehicles have a differential drive and are controlled using the ROS environment. The vehicles communicate with each other and central control systems using Wi-Fi. A marker-based tracking system from Qualisys is used for high-precision measurement of the position and movement of the vehicles. The measurement setup consists of 10 infrared cameras of type Miqus M3 with a resolution of 2 megapixels, which are distributed in such a way that all areas of the room can be seen simultaneously by at least two cameras. The systems are calibrated before the measurements so that they have a measurement accuracy (average error) of less than 1 mm in the relevant test area.

4 HARDWARE IMPACT

Letting AGVs follow a trajectory without control results in deviations between the target and the actual trajectory. To demonstrate this, tests were carried out with two Karis Pro AGVs. Four different test scenarios are presented below – driving straight, turning on the spot, driving in a circle and following a U-shaped trajectory.

In the first test, the vehicles are aligned at a distance of approximately one meter from each other. A program is started simultaneously on both vehicles, which causes the vehicles to drive four meters forwards and then four meters backwards in a loop. Figure 2 shows the course of the geometric center of the vehicles. If the trajectory was followed perfectly, only one horizontal line would be seen for each vehicle. However, the lines show shifts, as the vehicles are drifting away from and towards each other. After 31 repetitions, the vehicles had already come so close to each other that an emergency stop was triggered. AGV 1 shows an angular offset of approx. 27° compared to the initial orientation and an offset in position of over 800 mm. AGV 2 has a corresponding angle offset of approx. 10° and a position offset of over 500 mm. The vehicles therefore behave differently despite their identical design.

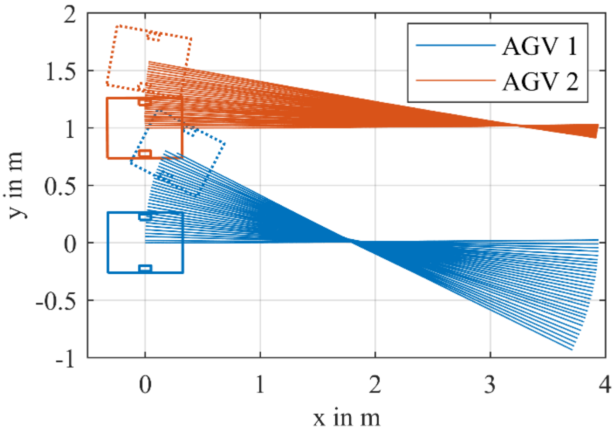

Figure 2. The recorded trajectories of two AGVs going back and forth.

This is also illustrated in Figure 3, where the 31 repetitions of the two AGVs are shown individually. It should be noted that the x-axis is given in meters and the y-axis in millimeters. The journeys always start at the coordinate origin with the vehicles aligned parallel to the x-axis. The vehicles have a systematic error that causes them to make a slight left turn. On the other hand, the vehicles behave slightly differently on each journey and there is therefore also a random error. The mean deviation between the start and end position is approx. 29 mm for AGV 1 (standard deviation approx. 2.2 mm) and approx. 19 mm for AGV 2 (standard deviation approx. 2.9 mm).

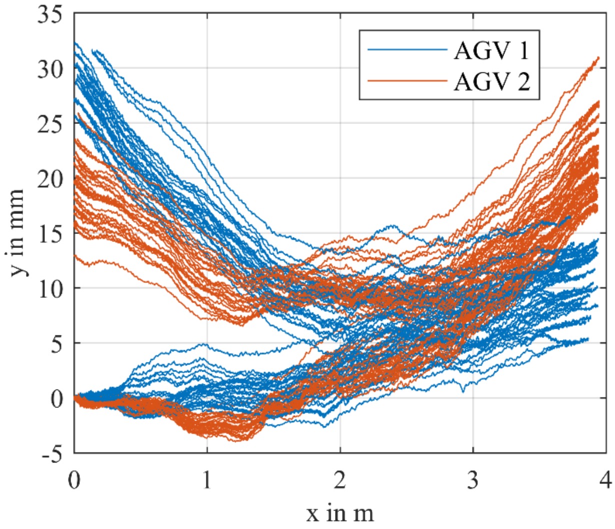

Figure 3. The recorded trajectories of two AGVs going back and forth. Each journey is plotted separately.

In the second test, the vehicles rotate around their center for 106 revolutions. Figure 4 shows the trajectory of the center point of both vehicles. The end position of the vehicles is shown with dashed lines and is aligned at the same angle as the start position for a better visual comparison of the positional drift. The centers of the vehicles do not remain in one place but move in one direction. The center point of AGV 1 moves approximately 106 mm and of AGV 2 180 mm.

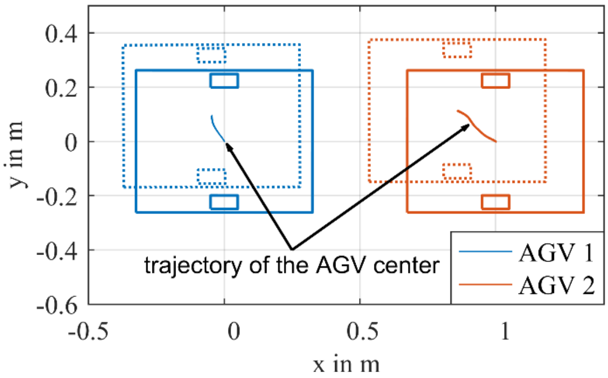

Figure 4. The recorded trajectories of the centers of two AGVs turning on the spot.

In the third test, the vehicles are to drive a circle with a diameter of 4 meters. Figure 5 shows 52 laps driven by each vehicle. Here, too, it can be seen that the vehicles behave differently. AGV 2 shows more deviations between its laps than AGV 1. It is noticeable that the recorded trajectory of AGV 2 shows two areas where there is comparatively much variation between the individual laps and two areas where there is little variation. This again suggests the presence of a systematic error.

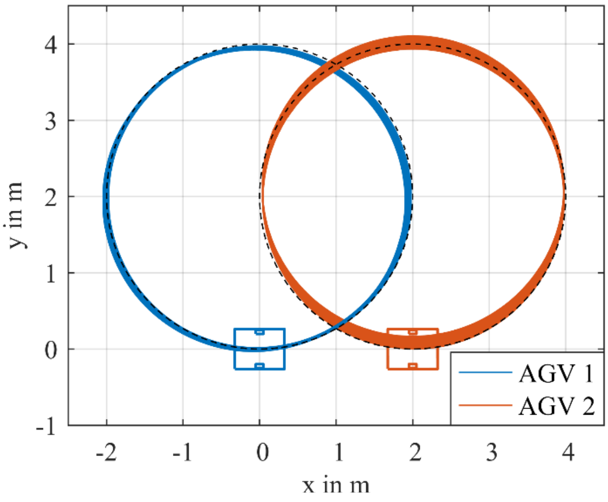

Figure 5. The recorded trajectories of two AGVs driving circles.

Finally, the vehicles are programmed to follow a U-shaped trajectory. Figure 6 shows three journeys forwards and backwards for each vehicle. The vehicles are aligned at a distance of one meter from each other. As AGV 1 drives on the outer curve and AGV 1 on the inner curve, AGV 1 covers more distance and drives larger radii than AGV 2. AGV 1 shows greater deviations of the given trajectory than AGV 2. The distance between the final position and the initial position is also greater for AGV 1 (approx. 620 mm) than for AGV 2 (approx. 190 mm).

The tests show that the distance and alignment of the two vehicles traveling as a group does not remain constant. The vehicles run the risk to lose a jointly transported load.

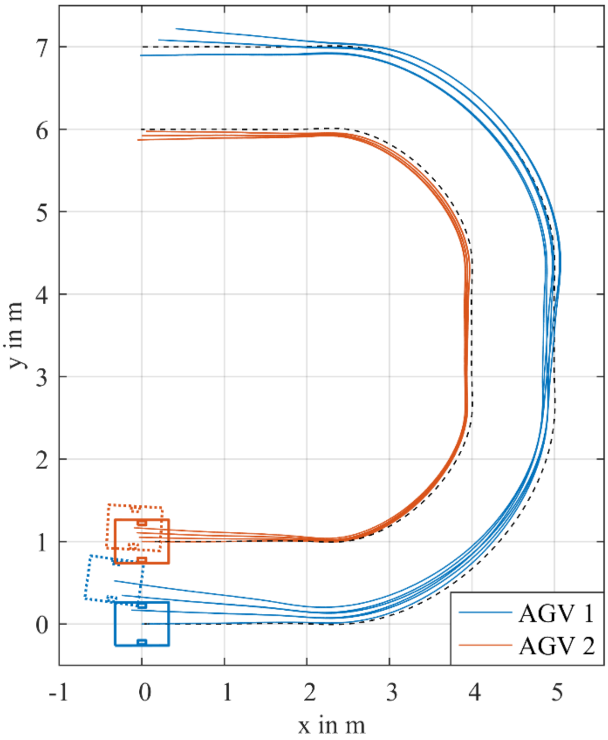

Figure 6. The recorded trajectories of two AGVs following a U-shaped path.

Reasons for this can be found in communication, the electronics and mechanics. In this section, some possible hardware-based causes of errors will be looked at. The AGVs examined here have two fixed driven wheels for moving. If the wheels rotate at different speeds, the AGV moves in a curve, otherwise it moves in a straight line. Figure 7 illustrates the steps for the vehicle to follow a trajectory. The required velocities of the two drive motors can be calculated from the specified trajectory. The velocities are then sent to the motor controllers, which regulate the motors to the desired velocity. The drive torque of the motors is transmitted via a gearbox to the wheels, which set the AGV in motion through friction.

In all these steps, errors can occur. The calculation and setting of velocities are time-discrete instead of continuous. This leads to a discretization error. Next, the velocities are sent to the controllers via a bus system. Due to different latencies of the bus system, the controllers receive their target velocities with a time delay. If one wheel is controlled to a specified velocity faster than the other, the AGV moves in a slightly different curvature than specified. The controllers are also inert and cannot arbitrarily quickly compensate velocity deviations. Additionally, gearboxes have mechanical play. This leads to positioning errors, especially when accelerations and decelerations alternate. Slip occurs between the wheel and the ground. If this is more prominent on one wheel, the AGV takes a different curve than intended. Furthermore, slippage on both sides leads to lower velocity and less distance traveled. Reasons for (one-sided) slippage can be an uneven floor, contamination and an uneven mass distribution of the AGV.

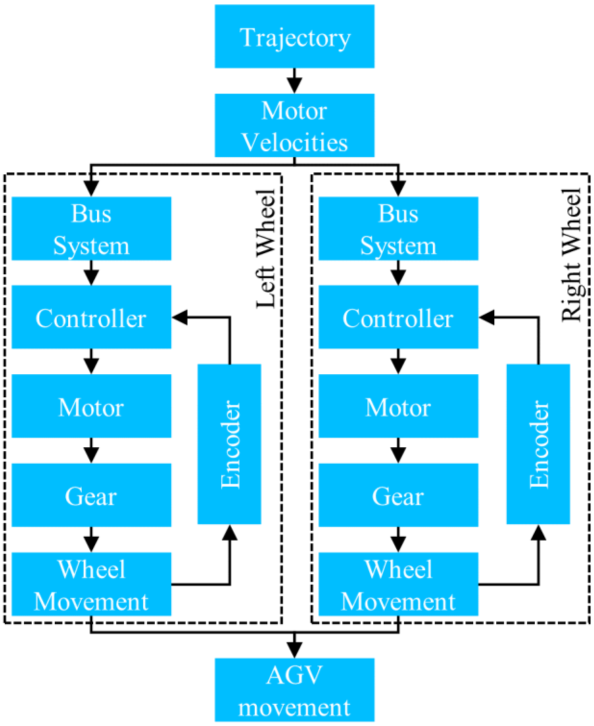

Figure 7. Schematic overview of the steps for the vehicle to follow a trajectory

The wheels themselves contain several sources of error. They have a certain width on which the actual contact point with the ground is located. The distance between these two contact points is the effective track width and is relevant for the actual curve radius travelled. It can vary due to wear, manufacturing and assembly tolerances, uneven ground and different loads. Furthermore, misalignment of the wheels and different wheel diameters can lead to a deviation in the curvature travelled. The reasons for this can lie in manufacturing tolerances or wear. Lastly, the camera tracking system also has a measurement error. However, this is less than 1 mm and therefore very small.

5 COMMUNICATION IMPACT

As the experts claim Wi-fi is the current and at least near future communication technology in the mobile robot industry. The experiments aim to gain insights into the basic behavior of message transmission via Wi-fi and the resulting effects on the driving behavior. The experiments were therefore conducted using Wi-fi with a TCP/IP connection.

5.1 EXPERIMENTAL SETUP

For the communication tests two of the described mobile robots were used. To minimize the effect of the hardware components on the driving behavior 30 runs were performed, restarting and repositioning the robots to their starting pose after each run. Figure 8 shows the experimental setup with Robot 1 on the bottom and Robot 2 on top. During the runs the robots were sent identical driving commands through the TCP/IP connection.

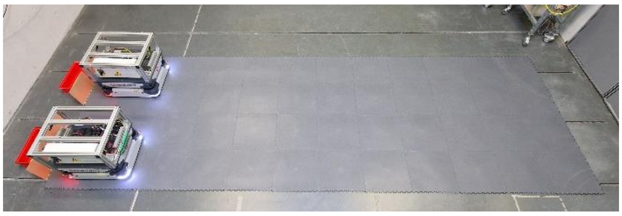

Figure 8. Experminetal setup for the communication tests

Threading was used to achieve a near synchronous sending of the commands to both mobile robots. Each message was sent with an ID and the timestamp taken right before the sending of the message using the current world time. Upon receival the message was again directly timestamped and then further processed and pushed into the vehicles ROS control to perform the given drive command. Both robots were to perform 3 seconds of 1 m/s drive followed by 3 seconds of 0.5 m/s drive. Then a 3 second stop time was sent to the vehicles, continuously recording each received message. Then the robots were sent 6 seconds of -0.5 m/s followed by 5 seconds of -0.25 m/s. The brakes were unlocked at the start and at any point of the movement.

The messages were sent with a 100 Hz frequency which is 10x the required frequency for the motor controllers to keep up the given drive command before assuming connection loss. In addition, a queue was set up which holds the last value if no new one is received to match the 100 Hz publish frequency of the ROS node which triggers the execution of the drive commands. All of the code for the test runs was written in python.

In addition to the recording of the messages the movement of the robots was recorded using the tracking system. This was done to analyze the possible latencies between the sent and therefore expected trajectory and the actual trajectory driven by the robots. The general Wi-fi load in the network was not considered. To minimize the possible effects the experiments were conducted after usual business hours.

5.2 RESULTS

After the 30 test runs were completed all message logs were evaluated. To verify if any messages were lost the IDs of the received messages were checked for completeness. The time difference between the sending of the message and the receival was calculated resulting in the transmission times of the messages. Figure 9 and Figure 10 visualize the average transmission times over the 30 test runs for each of the two robots. To enhance the understanding of the variability and central tendency within each bin, boxplots are overlaid on the histogram. The mean transmission time over all runs is indicated with the orange dotted line. All messages that had a transmission time over 200 ms were pooled into one bin for better visibility.

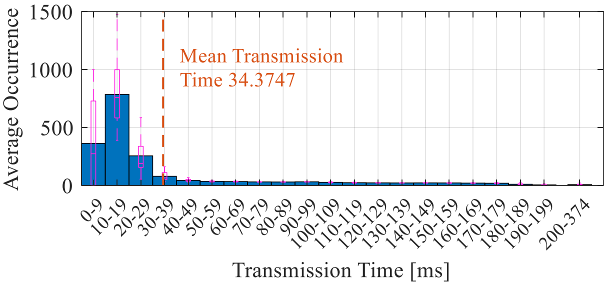

Figure 9. Average occurrence of transmission times for Robot 1 over all test runs

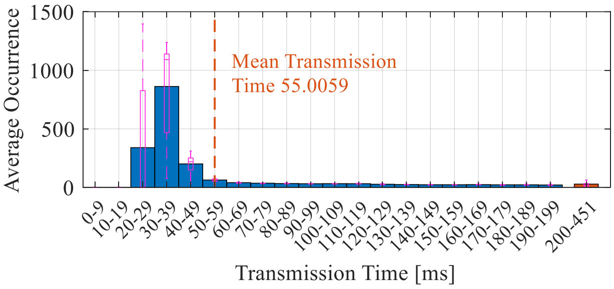

Figure 10. Average occurrence of transmission times for Robot 2 over all test runs

The mean transmission for both robots shows that in principle the minimum required time difference between messages for the motor controls is achieved. However, since the variance is visibly greater than the send- and control frequency of 100 Hz (10 ms) the queue is steadily increasing, creating a slight offset between the expected and actual movement. Possible explanations for the shift to the right between the two diagrams can be found in the slight offset created by the threading or general network handling as the messages are sent very close to each other. Despite this the effects of the communication latency itself seems to be manageable, even for high frequency requiring control strategies. However, a high Wi-fi availability is required. Figure 11 and Figure 12 show close-ups of the average transmission times. The higher transmission times are much less frequent for all runs, once again suggesting a manageable impact of the transmission latency.

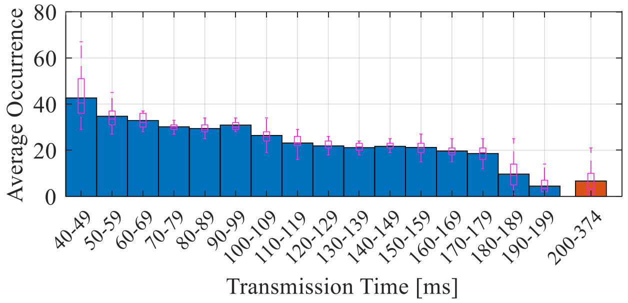

Figure 11. Close-up of the average transmissions of Robot 1

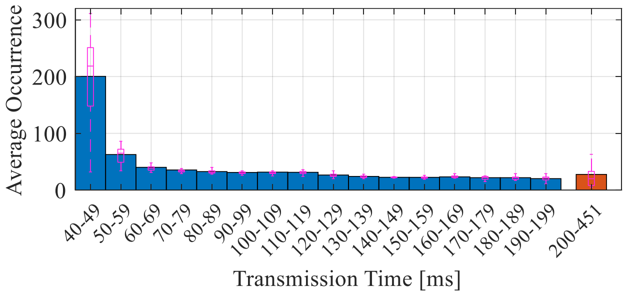

Figure 12. Close-up of the average transmissions of Robot 2

Figure 13 shows the tracked velocities of both robots for one arbitrary test run. The slight delay between the given and therefore expected velocity and the actual velocity can be observed. Most of the fluctuations were disturbances not visible to the naked eye. When looking at the average over all 30 runs as can be seen in Figure 14 the offset and fluctuations are slightly less observable as especially the larger deviations disappear. This indicates that the fluctuations stem come from standard control effects and minor floor irregularities which mostly average out after multiple test runs.

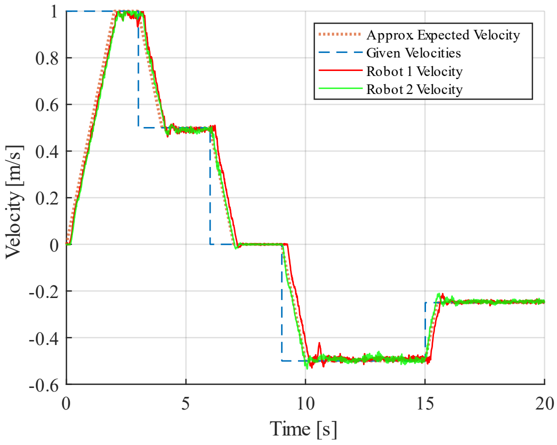

Figure 13. Exemplary velocities for Robot 1 and 2 for an arbitrary test run

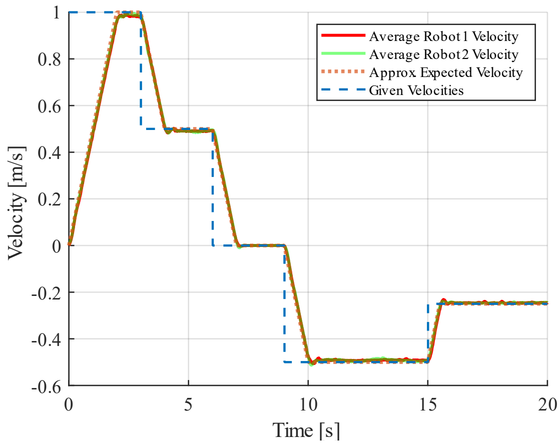

Figure 14. Average velocities over 30 runs of Robot 1 and 2 compared to the given and expected velocities

The observations made provide valuable insight into the communication limitations over Wi-fi connection. The latency remained in a manageable range although the variance suggests that a simple queueing setup on the robot side isn't sufficient. A higher frequency of processing the received messages is therefore advisable in addition to a mechanism to bridge phases of high latency due to network overload or perhaps even connection losses. Also a mechanism to guarantee a highly synchronous control of all robots within a transport group is to be considered for future work.

6 CONCLUSION AND OUTLOOK

In this work, the major challenges for collaborative transportation from the industry were determined based on eight expert interviews and a supplementary online survey with 25 participants. Based on the results, initial investigations were carried out on real mobile robots in the distributed future laboratory for mobile robotics at the Karlsruhe Institute of Technology and the University of Stuttgart with regards to hardware and communication. It was concluded that the experts' statements are not just theoretical difficulties, but also exist in reality.

According to the surveys, there is a need for cooperative transportation, especially among SMEs, but also is a lack of well-founded approaches to implementation. Safety technology in particular is seen as a major hurdle. Synchronization and recognition of the initial placement of the mobile robots' configuration could also pose challenges for implementation. Although there are various communication technologies in the industry, experts see Wi-Fi as the only communication that can realistically be used in the near future. It is possible that 5G could offer a valid alternative here in the future. Another constraint is that in the highly competitive mobile robot market, a new feature such as collaborative transportation must not result in significant cost increases, for example due to additional communication hardware. This must be taken into account for solutions that are used in industry.

The experiments with simple hardware control have shown that intelligent control is necessary. A simple reproduction of predefined trajectories is not sufficient here, since strong deviations occur during repetitions. There are many different influencing factors here, such as manufacturing tolerances or degrees of wear and tear, so that different deviations from the specified trajectory occur even in vehicles of the same design as those used for the experiments.

For the communication of control data via Wi-Fi, no significant influences on the driving behavior could be determined due to the latency of the transmission in an exemplary set-up. Connection failures and a lack of coverage of the working areas still pose a problem. Especially, since these are a frequent problem in industrial environments, as confirmed by the experts. Appropriate strategies must be developed in future to bridge such communication failures and, if necessary, to switch to a safe state.

The presented hardware and communication tests are not to be seen as test for possible control strategies for cooperative transport group or mobile robots in general. The goal was to identify and qualitatively classify the impacts and possible challenges that must be faced when implementing such control strategies, especially in the context of trying to perform collaborative transports with industry-standard mobile robots and communication technologies.

Future work aims to consider the insight from the experts and survey as well as the results of the experiments conducted. In the next steps, the disruptive influences must be independently determined and analyzed in order to quantify their impact. Based on this, strategies for control, trajectory planning and synchronization must be developed to enable cooperative transport. In addition, further vehicle types are available for future investigations in the distributed future laboratory for mobile robots.

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LITERATURE

[1] ABB Robotics Deutschland – Branchenumfrage Mittelstand und Logistik, im Auftrag von ABB, durchgeführt von Civey im Oktober 2021, https://new.abb.com/news/de/detail/88111/robotik-im-mittelstand-und-in-der-logistik-civey-umfrage-im-auftrag-von-abb-zeigt-geteiltes-bild (aufgerufen 23.08.2024)

[2] C. Brenner, A. Colomb (2022), „Anwendung der Omni-Kurven-Parameter zur Bestimmung der Aktor-Stellgrößen und universellen Bewertung der Bewegungsmöglichkeiten unterschiedlicher Fahrwerke “, in Logistics Journal: Proceedings, Vol. 2022.

[3] Brenner C, Enke C, Schumacher P, Schröppel M, Schulz R, Furmans K (2023). Decentralized Collaborative Transport in Heterogeneous Robot Fleets Through Four Levels of Communication based on Omni-Curve-Parameters. Logistics Journal : Proceedings, Vol. 2023.

[4] C. Helfferich, *Die Qualität qualitativer Daten: Manual für die Durchführung qualitativer Interviews*, 4. Auflage. in Lehrbuch. Wiesbaden: VS, Verl. für Sozialwiss, 2011.

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