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EXTENDING TELEOPERATED DRIVING USING A SHARED X-IN-THE-LOOP ENVIRONMENT

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ABSTRACT

The strong progress in modern vehicle system technology requires new methodological approaches for the development and validation of new vehicle systems. In particular, due to increasing automation, classical development methods and testing scenarios need to be evolved. Consequently, the publication focuses on an extension of teleoperated driving by the X-in-the-loop (XIL) approach. Within this framework, the classical concept based on VPN-LTE networking is analyzed and discussed at first. With this implementation, the remote control of a real vehicle is presented based on the use of a dynamic driving simulator. Especially for the development and validation of such concepts, an extension with the XIL methodology can improve this process. For this reason, the architecture of teleoperated driving is subsequently extended by networking with additional system components. The feasibility, the functionalities as well as the challenges that arise with such an extension based on the XIL methodology are shown. Within the scope of this study, the achieved transmission times for the control variables and for the video data stream are demonstrated. Based on different driving maneuvers, the achievable repeatability is discussed.

Index Terms - Driving Simulator, X-in-the-Loop, Teleoperated Driving

1. INTRODUCTION

The increasing degree of automation and the development of numerous new driving functions is increasing the level of complexity significantly. Furthermore, there are also ever growing demands on automated vehicle systems and their driving functions, so functional safety and general fail-safety are becoming a high priority. However, numerous development steps are still necessary before full-scale automation of traffic can be achieved. Networking and also teleoperation of vehicles can significantly support the integration of an automated traffic operation. In the area of networking, the X-in-the-loop methodology has emerged as a promising approach for vehicle development. Here, different development domains are networked and combined as required depending on the application. Numerous studies are currently dealing with possible use cases and the general use of this methodology, cf. [1] and [2]. According to this principle, teleoperations as well as modified forms of them can be easily implemented. In the classical sense, teleoperation means that a human driver can intervene in the driving operation of automated vehicles in certain situations. As an example, the case of an error or a situation unknown to the automated vehicle can be mentioned here. The human driver can control the vehicle remotely via a wireless connection and bring the vehicle back into safe operation. The following work can be cited as examples for this: [3], [4] and [5]. However, since according to the XIL approach the networking of other domains of any kind is also feasible, teleoperation can also be implemented in a wider sense as a result of a remote-control center or a higher-level control unit. If local control processes are not able to bring the automated vehicle into a safe state, e.g., because specific control units have failed, central (e.g., cloud-based) control units could take over further vehicle operation for a short time. This paper addresses such an extension of classical teleoperated driving with the XIL approach. A real test vehicle is networked with a real-time computing platform. A real-time capable vehicle simulation environment can be implemented on the platform. As a result, by integrating the real vehicle dynamics and the motion profile into this central simulation environment, an interaction between the real vehicle and the simulation environment can be achieved via a wireless network. On the one hand, this allows remote control of the real test vehicle analogous to teleoperated driving, but also offers the advantage of integrating virtual traffic objects into a driving scenario. From a development point of view, this offers many advantages for testing and validating new teleoperated driving functions, as well as for developing new remote control algorithms.

2. STATE OF THE ART

2.1 Teleoperated Driving Concept

In general, teleoperation means the remote control of systems by a geographically separated operating unit. In the automotive context, this is mostly used to enable external interventions in the case of a failure of automated driving functions. Using a wireless network, a remote driver can then control the vehicle and bring it into safe operation. An overview of the concept of teleoperated driving is presented e.g. in [6]. The interaction between the remote driver and the vehicle are usually proceeds by a human-machine interface (HMI). The design and requirements of such an HMI are addressed in [3].

Over a wireless network, the image data from a camera installed in the vehicle is transmitted to the remote driver's workplace. The remote driver can react to the traffic situation based on the received images. The remote driver's inputs are also transmitted to the vehicle. A suitable actuator must be installed in the vehicle so that the incoming commands can be executed. [6]

In [7], a two-way median latency of 100 ms was already demonstrated for video data transmission via LTE and the UDP-protocol. The fact that the LTE network is generally suited for the application of teleoperated driving is also shown in the results of [4]. The authors of [4] specify that the latencies caused by LTE on the routes they measured in Germany are predominantly below 250ms, making the general approach of teleoperated driving possible.

Especially in public transport, teleoperation of automated vehicles offers a great advantage since an entire fleet of vehicles can be controlled from a central location by a few remote drivers. This reduces the planning and workload for the operation of such automated transport vehicles. [3]

2.2 X-in-the-Loop Methodology

Using the X-in-the-loop approach (XIL), the various in-the-loop methods can be combined based on a suitable network topology. Essential concepts on this topic have been presented in [1], [8] and [9], among others. In particular, [10] attempted to further generalize the XIL approach. The XIL concept to be applied in this context is based on the explanations in [2] and is shown in Figure 1.

The top layer "Application" represents the integrated component (e.g. a simulation process, a test bench, a subcomponent, etc.). The following layer Functional Mock-Up Interface (FMI) represents an optional function. An FMI may be necessary to provide the exchanged signals suitable for different applications. The "Protocol" level provides the communication protocol for the data exchange. The last layer "Gateway" provides the data communication and routing between all network nodes. [2] The individual systems can be networked either by wire or by wireless connection.

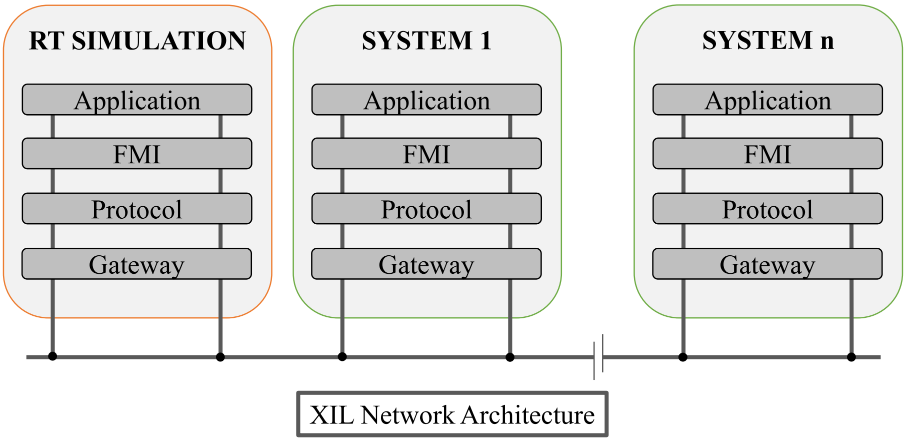

Figure 1: General XIL architecture based on [2]

3. INTEGRATION OF DISTRIBUTED TEST SETUPS

In this paper, two concepts for teleoperated driving are considered and discussed. First, the classical approach, analogous to the explanations in section 2.1, is implemented and analyzed. In this context, the teleoperative remote control of a real test vehicle by a remote driver is considered on the basis of a dynamic driving simulator. In the further process, this classical approach is extended and modified by the integration of the presented XIL methodology (section 2.2). The remote control of the test vehicle will then take place, involving a shared distributed simulation environment, no longer by a human driver, but by a controller on a central real-time platform. In both cases, the actuation commands will be transmitted via a wireless VPN-LTE connection.

In this regard, the second use case creates an extended development environment for testing and optimizing possible functionalities of teleoperated driving. Based on appropriate research, both concepts are analyzed and explained with respect to possible use cases. In the process, possible advantages and any limitations or challenges that need to be solved through further research or improved technological approaches will also be discussed.

In the following, the existing systems are first described individually. Subsequently, the proposed concepts or architectures of both use cases are presented and explained, including the experimental procedure. The networking topology is also discussed.

3.1 Laboratory Environment

The laboratory environment mainly consists of a real-time computer with an implemented vehicle simulation environment. Within the framework of the XIL methodology, this acts as a master in such a way that all measured variables and external signals merge here. A hexapod driving simulator (see Figure 2) based at Thuringian Innovation Center for Mobility (ThIMo) at Technical University of Ilmenau was integrated into the XIL network. The simulator has active operating elements, such as accelerator pedal, brake pedal and a steering wheel for the input of target values by an operator. The visualization is provided by a 98 inch 4K monitor, so that the operator can have a good overview of the driving action. Using an inertial measurement unit (IMU) implemented near the headrest, perceived driving accelerations can be measured.

Figure 2: Dynamic driving simulator of the laboratory environment

The integration into the described XIL network is realized within the scope of this study by using a VPN router. Local systems such as the directly connected driving simulator are integrated directly via a LAN network. External and especially mobile systems such as a test vehicle are integrated into the network via a secure VPN tunnel. In this way, data can be exchanged between the simulation environment and the other system components. Table 1 summarizes the technical data and the associated functions.

Table 1: Configuration of the laboratory environment

Equipment		Functionality
Real-time computer + operator PC		• real-time vehicle simulation • integration of motion data of the remote test vehicle • local display of shared real/virtual simulation environment • stationary data logger • generation of control demand values for autonomous teleoperated driving tasks
VPN router		• wireless remote XIL connection • exchange of the shared real/virtual simulation data
Driving simulator		• generation of control demand values for human teleoperative interventions
	4K 98 inch TV	• integration remote video stream from remote test vehicle
	Active pedals	• feedback real brake pedal feel
	Active steering wheel	• feedback real steering feel
	IMU	• measurement of perceived driving accelerations

3.2 Remote Test Vehicle

A classic SUV equipped with the appropriate measurement systems was used as the remote test vehicle, see Figure 3.

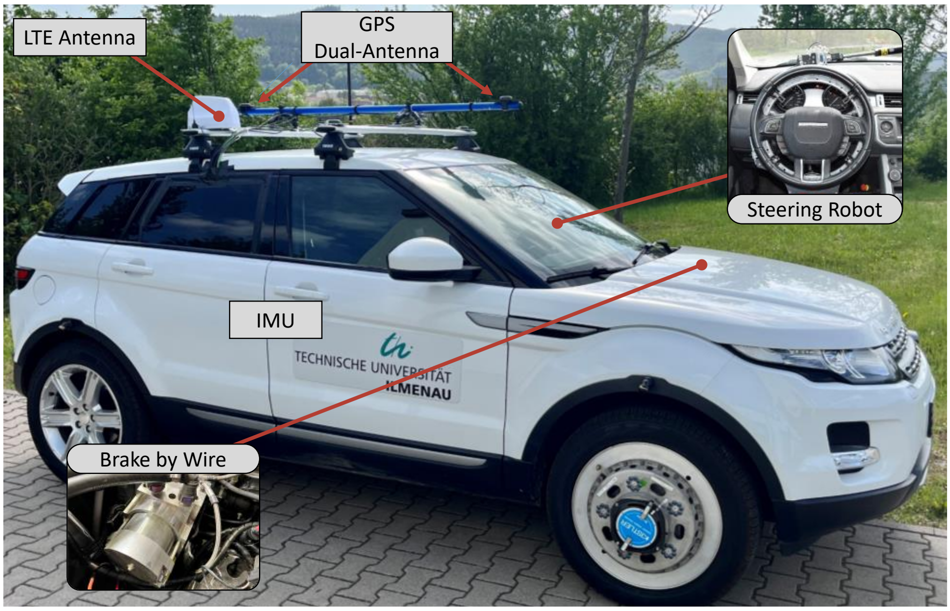

Figure 3: Remote test vehicle

To ensure the integration into an external vehicle simulation environment, the remote test vehicle positions and the movement behavior must be determined precisely in any case. For this purpose, a GNSS system with an NTRIP receiver is used, so that a very precise position determination is possible via differential GNSS signals. Dual antenna options can also be used to determine the vehicle angles and the sideslip angle.

Table 2: Equipment of the remote test vehicle

Equipment	Functionality
GNSS	• localization vehicle positions
DGNSS-Addon (NTRIP)	• localization optimization
Dual-Antenna (GNSS)	• vehicle angles / side slip angle
IMU	• vehicle accelerations / rotation rates
Real-time computer + operator laptop	• transformation of vehicle coordinates to virtual map coordinates • local display of shared real/virtual simulation environment • mobile data logger
LTE/VPN Router	• wireless remote XIL-Connection • exchange of the shared real/virtual simulation data
Steering robot	• integration of external steering commands
Camera system (Webcam)	• live video capturing
Single board computer	• live video stream as local web server
Brake-by-Wire System	• integration of external brake commands

In addition, an IMU can be used to determine vehicle accelerations and vehicle rotation rates. All measured variables are transferred into a mobile real-time computer. The remote test vehicle is integrated into the XIL network of the laboratory environment via an LTE mobile network using a secure VPN tunnel. To demonstrate teleoperated driving functions, the test vehicle was equipped with a steering robot that can implement external steering commands dynamically and reproducibly. Using a webcam stream, the vehicle's field of view is transmitted to the driving simulator. A classic single-board computer is used for this purpose, which opens a local web server. In addition, the test vehicle has a brake-by-wire system that can be used to inject external brake signals. Table 2 summarizes all the technical data on the test vehicle.

3.3 Architecture Use Case 1: Teleoperated Driving

The first use case deals with classic teleoperated driving in order to represent a benchmark scenario for the following XIL extensions. Here, a remote driver controls the external remote test vehicle using the dynamic driving simulator in the laboratory environment, see Figure 4.

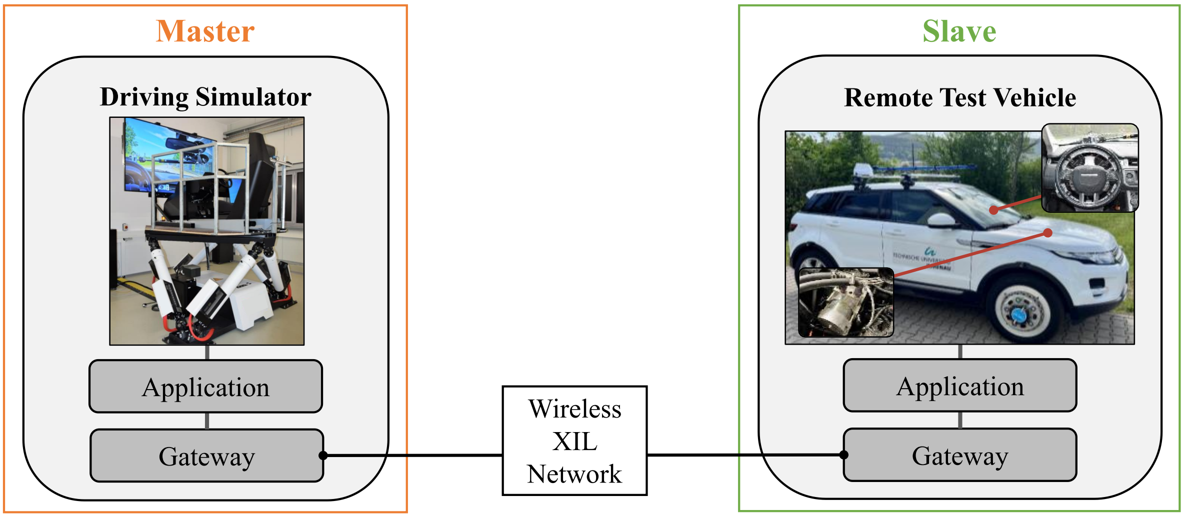

Figure 4: Architecture Use Case 1 - Teleoperated Driving

The active controls of the driving simulator (pedals and steering wheel) allow freely configurable pedal and steering wheel characteristics, so that similar operating feedback can be provided in the driving simulator as in the remote test vehicle. Based on the dynamic motion system, the remote driver can better perceive the driving speed and dynamics of the test vehicle compared to a static driving simulator.

The data transmission is performed using the XIL network. Specifically, the data from the remote test vehicle are integrated into the network of the laboratory environment using a wireless LTE-VPN connection. The LTE-VPN tunnel enables bidirectional data exchange between all local XIL systems and the remote test vehicle.

In the context of this paper, the remote test vehicle is only used as a demonstrator for the implementation of possible teleoperated driving functions. The authors are aware that the configuration of the test vehicle does not allow the implementation of full independent teleoperated driving, since no external input of throttle pedal is possible. Accordingly, this use case focuses on lateral vehicle guidance based on the control of the steering robot by a remote driver on a dynamic driving simulator. The control of the vehicle speed is implemented by the safety driver of the real remote test vehicle.

The specific driving maneuver is shown in Figure 5. The remote driver located in the driving simulator controls the steering robot of the real vehicle via the wireless connection. As a driving maneuver, the avoidance of a real obstacle is analyzed. The remote driver acts independently, so that significant deviations in the trajectories driven between the various tests can be expected.

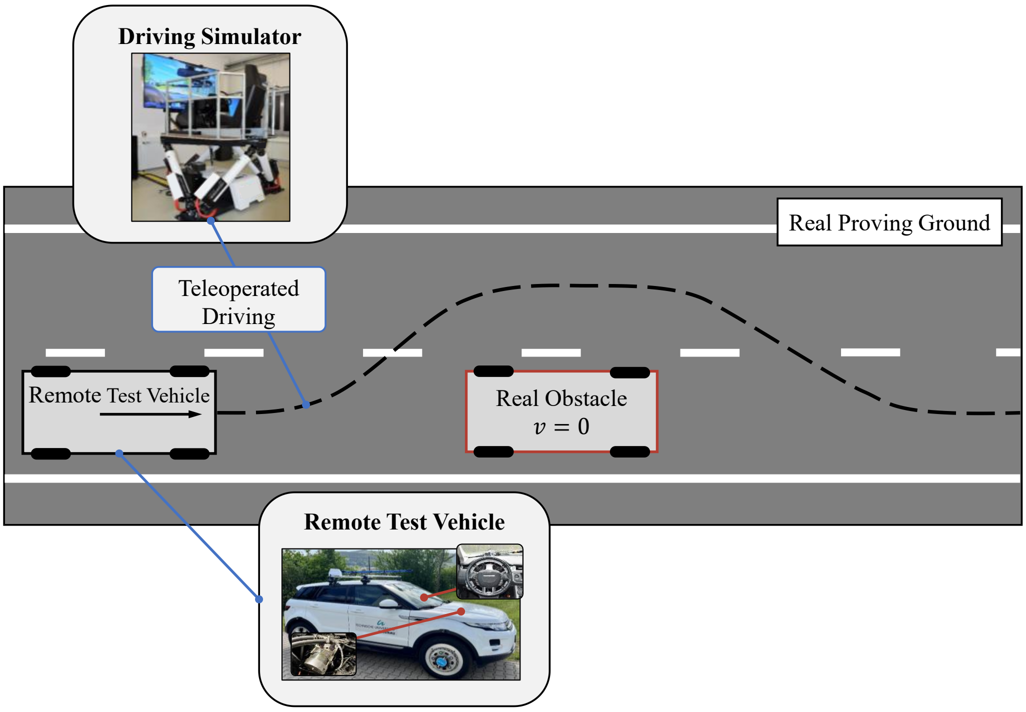

Figure 5: Test Setup Use Case 1 - Teleoperated Driving

The use case can be analyzed and used to test key functionalities. In addition, the data transfer times can be used to check the operability of the general concept.

3.4 Architecture Use Case 2: XIL Extended Teleoperated Driving

The second use case shows the extension of teleoperated driving by the XIL methodology. The real remote test vehicle is networked with the real-time vehicle simulation of the laboratory environment, as illustrated in Figure 6.

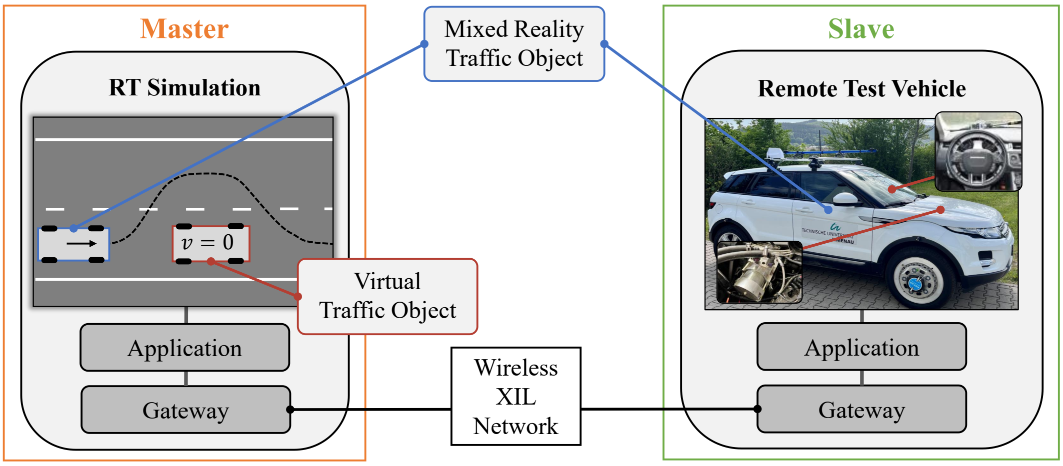

Figure 6: Architecture Use Case 2: XIL Extended Teleoperated Driving

This architecture can also be described as an extension by an external shared virtual simulation environment. The data transmission also takes place here via LTE-VPN. Analogous to the general XIL description, the real-time computer of the laboratory environment with the integrated vehicle simulation acts as the master. It provides the real-time vehicle simulation with a virtual environment. A virtual map of the real test track is used for the driving maneuvers, see Figure 7.

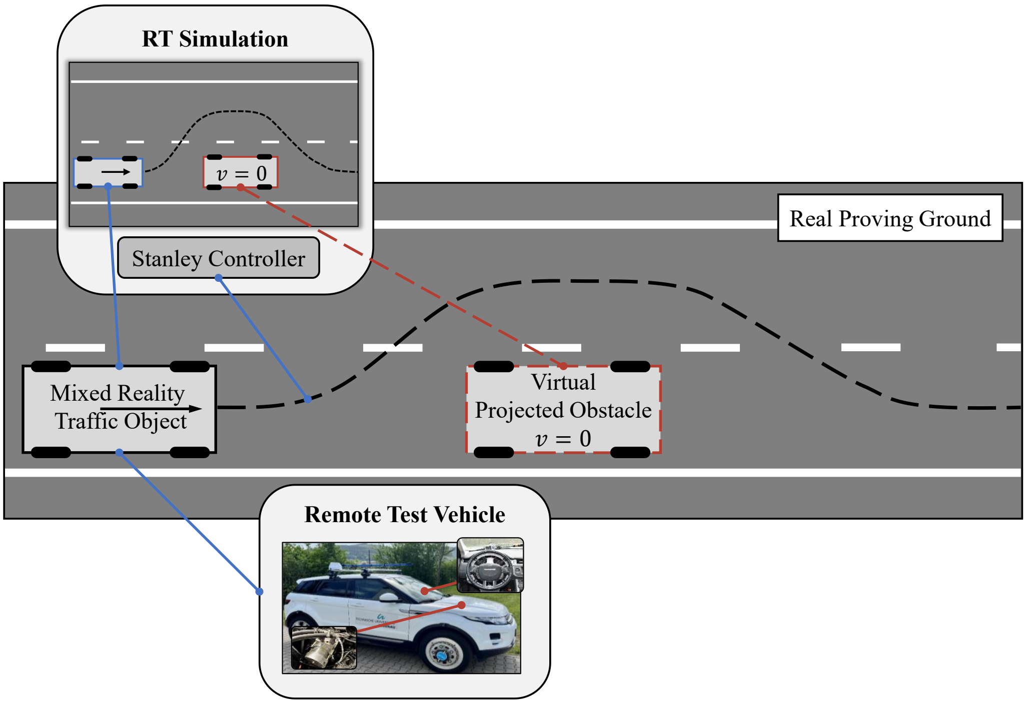

Figure 7: Test Setup Use Case 2: XIL Extended Teleoperated Driving

The mixed reality traffic object used in the simulation represents the interface to the real remote test vehicle. In this architecture, the mixed reality traffic object is replaced by the real vehicle movement and the real driving dynamics of the real remote test vehicle with respect to its virtual position data and its simulated driving dynamics. Specifically, this is done by converting the GNSS position of the Real Vehicle into local map coordinates of the simulation environment. The position data obtained in this way are transmitted to the simulation environment together with the vehicle dynamics (vehicle speeds, accelerations, angles, etc.). The mixed reality traffic object is updated within the simulation using this data. By integrating the real remote test vehicle into the virtual real-time simulation environment, interactions between the real remote test vehicle and other virtual simulation objects can be investigated safely.

This approach can be used to test and validate new teleoperated driving functions at an early stage of development. In this context, the real-time platform can be seen as a central control unit that sends teleoperated driving commands to the remotely tested vehicle. In this use case, no capacities of a real driver are needed for the tests. The dynamic driving simulator is not used in this case. Furthermore, this approach can be used to develop and test decentralized autonomous teleoperative driving functions.

To analyze the functionality of the proposed concept, a simple Stanley controller according to [11] is used as an example. The controller is implemented on the real-time master simulation environment within the laboratory environment. The integration of the vehicle simulation using the XIL extension allows the real vehicle to react to virtual obstacles. Specifically, the Stanley controller is used to compute the necessary steering commands for the remote test vehicle to avoid a virtual obstacle. The steering commands are transmitted to the real test vehicle via the

LTE-VPN connection. Consequently, the master simulation environment remotely controls the real remote test vehicle.

The corresponding explanations about the Stanley controller are shown in Figure 8. To generate steering commands to follow a target trajectory, the lateral distance $e_{lat}(t)$ between the vehicle and the target trajectory as well as the angular deviation $e_{\psi}(t)$ between the vehicle orientation and the angle of the nearest trajectory segment are used [11].

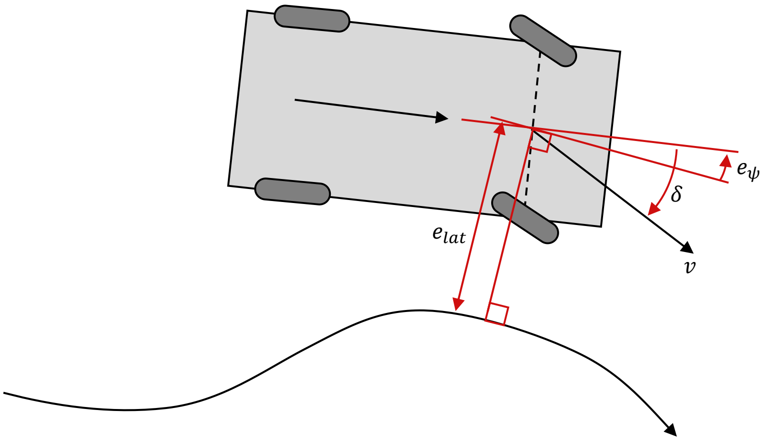

Figure 8: Contexts of the Stanley controller based on [11]

Based on [11], this results in the following formula for calculating the desired steering angle of the wheels $\delta(t)$:

$$\delta(t) = e_{\psi}(t) + arctan\frac{k_1 \cdot e_{lat}(t)}{v(t)}, \qquad (1)$$

with the constant k_1 as gain factor based on the lateral deviation and the variable $v(t)$ as vehicle speed.

For the specific implementation, another gain coefficient k_2 was added to amplify the angular deviation, as well as another constant to realize a velocity offset k_3 to prevent dividing by zero. As a result, the modified equation for this publication for the lateral controller is given by:

$$\delta(t) = k_2 \cdot e_{\psi}(t) + arctan\frac{k_1 \cdot e_{lat}(t)}{k_3 + v(t)}. \qquad (2)$$

By including the steering ratio, it is possible to generate a demand steering wheel angle for the installed steering robot.

Based on the vehicle interaction between the virtual and the mixed reality traffic object, a trajectory is generated for the remote test vehicle to avoid a critical vehicle interaction. The required steering angle is determined by the master simulation environment using the implemented Stanley controller. The steering wheel angle is transmitted to the remote test vehicle via the XIL wireless network connection. The steering robot converts the desired values into real vehicle movements. To complete the loop, the measured vehicle positions, movements and driving dynamics are transmitted back to the RT simulation so that the mixed reality traffic object can be updated within the virtual environment.

With the virtually generated target trajectory and the regulation as a result of the Stanley controller, a significantly higher reproducibility can be achieved compared to use case 1.

In addition to the data transmission times, the desired trajectory and the actual trajectory are also considered as parameters for analysis.

4. RESULTS

In this section, the performed experiments will be analyzed and evaluated. The leading scenario was the avoidance of an obstacle, which required a double lane change. Since teleoperated driving is only to be expected in the context of low vehicle speeds, all tests were carried out at a target speed of 20 km/h.

For a better understanding of the results of the two use cases, the driving scenario was also performed manually by a conventional driver. The associated results are referred to as "Manual Driving". No teleoperated functions were involved in this reference scenario.

First of all, the communication delay between remote test vehicle and laboratory environment can be determined in general. The communication delay may affect the real-time capability of the experiment. The distribution of the time delays for data transmission to control the remote test vehicle over the described LTE VPN connection can be seen in Figure 9.

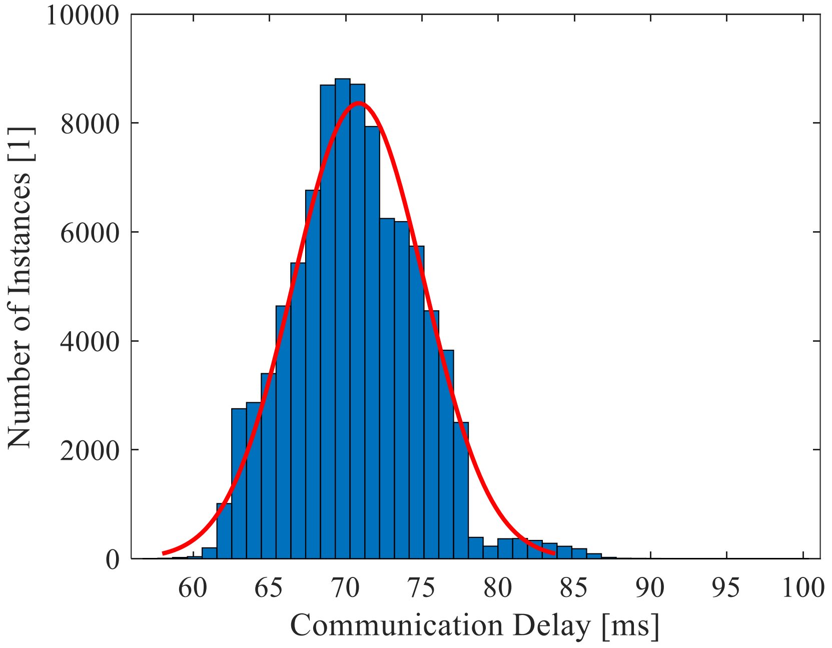

Figure 9: Distribution of the communication delay for remote test vehicle control

It can be clearly seen that delays in data transmission are normally distributed. The specific values are also given in detail in Table 3. On average, the round trip time delay for the control loop of the data transfer from the laboratory environment to the remote test vehicle and back is 70.85 ms. Based on the low standard deviation of 4.29 ms, it can be seen that there is a stable communication setup.

Table 3 also lists the delay times for the supply and transmission of the webcam stream (visual delay). It should be noted that this aspect only occurs in Use Case 1, the teleoperated driving.

The visual delay is composed of the delay of the camera image delivery and the delay of the communication over the LTE-VPN network. At 109.16 ms, the visual delay is on average 38.31 ms higher than the delay of the vehicle control.

Table 3: Communication delay of visual and control data transfer

Category:	Min:	Avg:	Max:	SD:
Control Delay	56.99 ms	70.85 ms	99.99 ms	4.29 ms
Visual Delay	93.98 ms	109.16 ms	134.69 ms	7.81 ms

The delay times may have a significant influence on the maneuverability of the vehicle. Before the vehicle can react to new conditions, the data transfer must first be completed. Depending on the current vehicle speed, this can result in a significant driving distance without a direct vehicle control. The impact of this principle on the use cases will be analyzed in the following sections.

4.1 Results Use Case 1: Teleoperated Driving

The results of the first use case (see chapter 3.3), the pure teleoperated driving compared to a manual driving, are shown in Figure 10. It shows the driven vehicle trajectories and a virtual reference trajectory in order to be able to assess the deviations of the various tests. It is shown that the repeatability of teleoperated driving is worse than with conventional manual driving. This is mainly due to the limited sensing of the driving situation. In addition, the delays of the control and the visualization lead to an increased reaction time and a deviation of the trajectory to the reference line. It was also noticed that the lateral distance to the obstacle was less during the teleoperated drives than during the comparison drives with manual driving. The teleoperated control of the vehicle is affected by several limitations: limited visual environment perception, limitation of the field of view depending on the visualization components, poor distance estimation, delay effects in visualization and control. Most critically, the environment perception due to the reduced field of view was evaluated as missing important data for the operator to plan and execute a suitable trajectory.

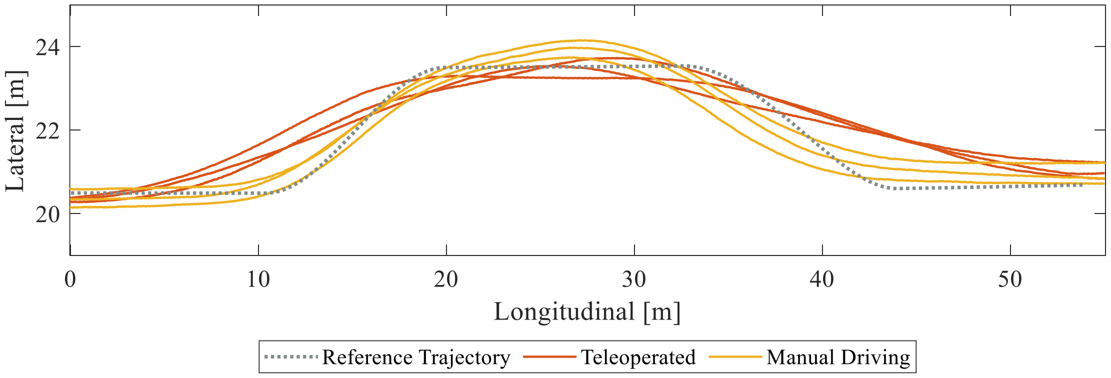

Figure 10: Comparison of the trajectories of teleoperated and manual driving

It is particularly obvious that the first lane change to avoid the obstacle was performed significantly earlier by the remote driver during the teleoperated driving tests. It is also noticeable that the driver turned back into the lane at a much later point in time. This shows well the worse distance estimation through the remote workplace, the driving simulator.
Despite these relevant challanges, the tests demonstrated the functionality of the concept for teleoperated driving. In all cases, the obstacle could be avoided without any problems and without the need for the safety driver to intervene. The safety distance to the obstacle was given in all cases. In particular, it is possible to optimize distance perception and reaction time through better visualization and further reduction of data transmission delays.

4.2 Results Use Case 2: XIL Extended Teleoperated Driving

The last series of tests were run with the help of the XIL environment and by using a Stanley controller based on chapter 3.4. Based on the reference trajectory and the vehicle coordinates of the remote test vehicle, the desired steering wheel angle is calculated in the XIL simulation environment on the real-time computer of the laboratory environment and transmitted over LTE-VPN to the remote test vehicle. The real remote test vehicle performed the same maneuver as the simulated vehicle. Figure 11 shows the obtained results. The first thing that becomes apparent here is the specified desired trajectory. The three characteristic curves (Stn 1, Stn 2 and Stn 3) show the results of the XIL tests carried out with the Stanley controller. In each case, the vehicle was placed at the same starting point and then performed the steering movements itself.

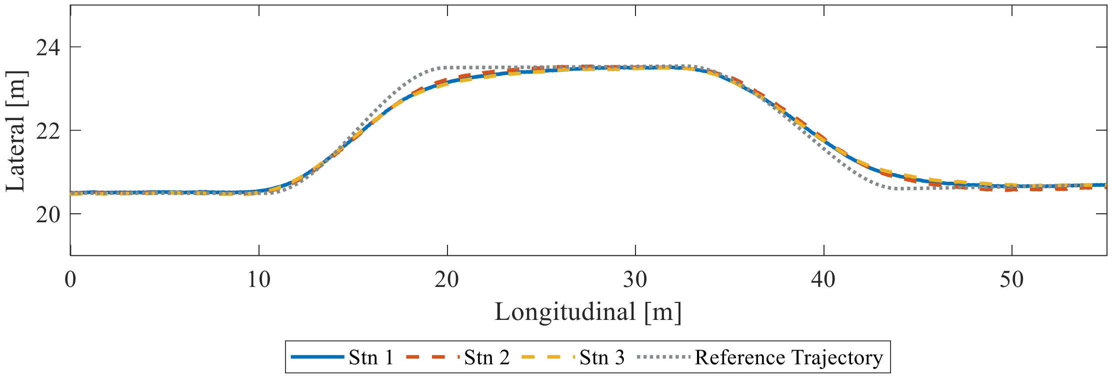

Figure 11: Comparison of trajectories with XIL extended teleoperated driving in combination with the Stanley controller

The results show particularly good repeatability with low mean deviations. The error values are plotted in Table 4. In the three tests performed, mean deviations from the desired reference trajectory ranged from 0.104m to 0.144m. The tests have shown that the exclusion of the human component from the functional chain results in a significant improvement of the repeatability.

Table 4: Evaluation of XIL extended teleoperated driving

Trajectory:	Mean Deviation	Standard Deviation	RMSE
Stn 1	0.144 m	0.197 m	0.192
Stn 2	0.104 m	0.110 m	0.147
Stn 3	0.125 m	0.167 m	0.171

In addition, the XIL networking results in further advantages in the execution of tests. By integrating a shared simulation environment, any real and virtual components can be exchanged against each other. In this case, the real obstacle of the test track was replaced by a virtual obstacle in the shared simulation environment. This allows risk-free testing of new functionalities and new controllers, such as in this case the implementation of a lateral controller for teleoperated remote controls.

In addition, the delay of the image transmission and the reaction time of the human are eliminated in this case. Only the delay of the LTE-VPN transmission for controlling the vehicle remains. Finally, Figure 12 shows the comparison of the three different concepts (teleoperated driving, manual driving, XIL networking with Stanley controller) with the best individual test in each case. The XIL tests with the Stanley controller show the best results compared to the reference trajectory.

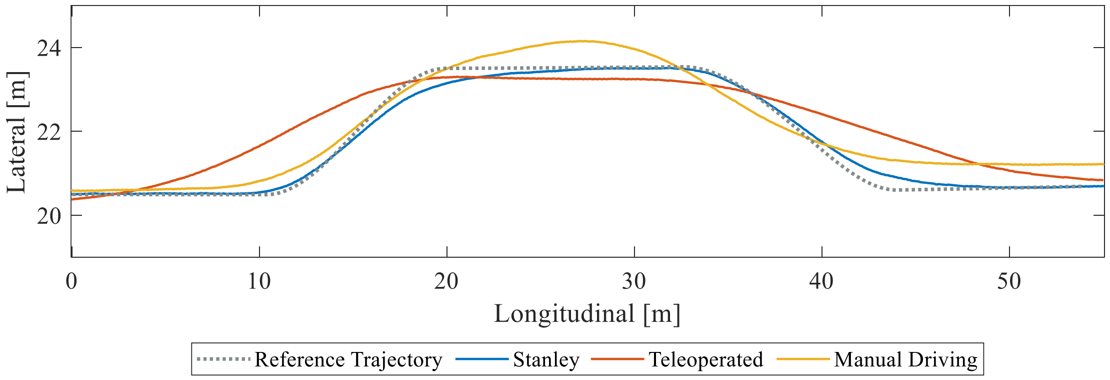

Figure 12: Final comparison of the implemented use cases

5. CONCLUSION AND OUTLOOK

The teleoperated approach to control automated vehicles presents problems in terms of situational perception and control of the vehicle, and last but not least, time delay also plays a critical role in terms of safe control of the vehicle in emergency situations. In this study, the general functionality of teleoperated driving was first demonstrated. Problems and current challenges were remarked.

Furthermore, an approach to extend teleoperated driving based on the XIL methodology was presented. The networking of different system components with a shared simulation environment showed clear advantages. In this case, a real obstacle could be replaced by a virtual obstacle. The control of the test vehicle was performed by an external computing unit with implemented simulation environment. New teleoperated or autonomous driving functions can thus be tested with low risk. Further components can be easily integrated into the process due to the modular networking structure.

In conclusion, the XIL approach is a promising alternative or supplement to teleoperated driving. Also, an XIL environment enables the development and testing of teleoperational concepts and systems, as different scenarios can be developed in the simulation environment, which can then be used to validate the teleoperational concepts. In this way, other teleoperated driving assistance systems could also be developed and validated in the future. Further planned research activities are aimed at reducing the data transmission delay.

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