2023 IEEE International Conference on Robotics and Automation (ICRA 2023)
May 29 - June 2, 2023. London, UK

A Digital Twin for Teleoperation of Vehicles in Urban Environments

Philipp Kremer*, Navid Nourani-Vatani†, Sangyoung Park*
*Smart Mobility Systems, *Technical University of Berlin*, † Imperium Drive Ltd., UK
{philipp.kremer, sangyoung.park}@tu-berlin.de, navid@imperiumdrive.com

Abstract— **Teleoperated driving (ToD) is increasingly considered as a fallback solution for autonomous driving. Up to now, ToD requires a highly reliable mobile network capable of transmitting multiple video streams with low latency. Recently, significant advancements have been made in vehicular sensors and perception algorithms, which have huge implications for the challenges faced in ToD. We envisage that a real-time digital twin that tracks the remote vehicle's environment will play a crucial role in reducing the required communication bandwidth and providing a more convenient teleoperator interface, ultimately enhancing safety of ToD in crowded environments. Furthermore, it would allow various degrees of cooperation between automated driving functionalities and human teleoperators. In this paper, the concept of digital twin for ToD is outlined and a proof of concept is implemented using a real-world vehicle simulator and a teleoperator hardware setup. A significant reduction in required bandwidth is reported by transmitting less video data and reconstructing the scene from the digital twin.**

I. INTRODUCTION

The trend towards fully autonomous vehicles is manifesting in the increasing number of car manufacturers, startup companies and researchers who spend tremendous efforts to develop market-ready products with the promise of increased traffic safety, reduced emissions and relief from undesired driving tasks. While assistive driving functions such as lane keeping and cruise control (level 1-3 according to SAE [1]) are already on the market, the step towards automated driving beyond level 3 without a continuously attentive safety driver is still a long path to go. Challenges include a myriad of scenarios that a car can face in complex urban environments, the difficulties in verifying the safety of AI-based algorithms and unsolved ethical concerns [2], [3].

One promising solution is teleoperated driving (ToD), where a human remains in the control loop from a remote site over a communication link and is ultimately responsible for decision making. ToD has been demonstrated in various forms including direct teleoperation, where a remote teleoperator gives steering, acceleration and braking commands, and remote assistance, where the teleoperator intervenes only when autonomous driving fails to resolve a traffic situation.

It is claimed that by using teleoperation, the operational design domain (ODD) of semi-autonomous vehicles could be expanded, thereby relieving passengers from the driving task. Additionally, in cost-sensitive commercial transportation, one teleoperator could be responsible for multiple trucks or one truck could be operated by multiple drivers, minimizing down time and transforming the truck driver's profession into an office job [4].

However, ToD over a mobile communication link introduces new technical challenges. Teleoperation typically requires streaming of multiple high definition videos facing the front and sides, which should reach the teleoperator within a fraction of a second, i.e. $<300\,\mathrm{ms}$ [4], [5]. Additionally, the latency of the steering and acceleration commands back to the vehicle is also critical [6]–[8]. Hence, most proposed ToD systems so far have restricted application domains or limited maximum speeds to 30 km/h [9].

Here, we take a cue from the fact that a significant share of the data sent over the network might be irrelevant for the teleoperator. ToD simply assigns the perception task entirely to the human teleoperator, thereby ignoring that onboard perception algorithms already offer significant autonomous perception and decision making capabilities. We envision that a combination of remote human perception with local sensing will be the key enabler for ToD in complex urban scenarios at higher velocities under constrained network environments. For example, by transmitting appropriate forms of interpreted data, e.g. modified videos or object lists, the requirements on the network could be alleviated.

In order to achieve such hybrid forms of ToD, it is essential to maintain real-time data of the vehicle and the surroundings and present it to the teleoperator in appropriate forms. Furthermore, the increasing availability of high precision static information including speed limits, traffic signs and lane information as so-called high definition maps facilitates this approach.

In this work, we shed light on methodologies based on accurate models of the static environment and real-time models of the dynamic parts of a traffic scenario, i.e. a digital twin, to enable safe ToD in urban environments.

Our contributions are summarized as follows:

- We introduce the concept of a digital twin for ToD system and outline the high-level system architecture.
- A proof of concept of ToD utilizing a digital twin is implemented using a real-world vehicle simulator and teleoperation hardware setup.
- We demonstrate the reduction in the required bandwidth by implementing digital twin-based scene reconstruction schemes.

This work was partly funded by Einstein Center Digital Future.

979-8-3503-2365-8/23/$31.00 ©2023 IEEE

II. RELATED WORKS

In this section, we give an overview of the existing literature in the field of teleoperated control as well as the concept of digital twins.

The time delay and limited situational awareness of the teleoperator have been the bottlenecks of ToD. Therefore, numerous prior works focused on improving the situation awareness using various interfaces and video qualities [10], [11]. The works report that a virtual reality-based head-mounted display improves the perceived immersion, but not necessarily enhances safety. Further, it was found that video quality has a significant impact on the ability to remotely steer the vehicle. Another work suggested that systematic development of an immersive, adaptable real-time interface, which also integrates LIDAR point clouds, maximizes the operator's situational awareness despite limited field of view [12].

Technological feasibility of ToD in today's mobile networks has been demonstrated already [13], but still network bandwidth requirements of the multiple real-time video streams for teleoperation is an issue. It is often considered that ToD requires at least 3 Mbps bandwidth and a maximum glass-to-glass latency of 300 ms. One way to resolve this issue is to create a whitelist of geographic areas where the network is strong enough for teleoperation [5]. Another approach to reduce the amount of data being transmitted while minimizing the teleoperator performance degradation is realized by blurring parts of the video outside the field of view using bilateral filters and hence increase the compression ratio [14]. An adaptive bitrate allocation algorithm based on a quality of service prediction can also improve the situational awareness and visual quality of ToD [6].

However, most of the works so far addressing the limited network bandwidth focused on data from onboard cameras. Considering the recent advances in perception algorithms and availability of data from other sources such as HD maps, merging of such data into a digital representation, i.e. a digital twin, offers numerous possibilities for ToD.

The digital twin concept first conceived in the field of product life cycle management describes the ensemble of a physical entity, its virtual representation and a bi-directional data link in between [15]. The concept has already been introduced in other domains including the mobility sector. For example, a unity-based digital twin of an ego vehicle in a virtual scene was used to design a customized cruise control system with the help of cloud computing [16]. The digital twin has also been used for connected and autonomous vehicles comprising roads, vehicles and traffic infrastructure with the purpose of testing vehicular communication functions [17]. In another work, a digital twin was adopted to design a cooperative driving system for unsignalized intersections [18]. Using a virtual reality human-machine-interface, a safe slot is suggested to the driver based on the motion estimation of other connected vehicles. While digital twins are increasingly recognized by the automotive domain, to the best of our knowledge, this work is the first to consider it for ToD for the purpose of reducing the required network bandwidth and improve the operator's telepresence.

III. A DIGITAL TWIN ARCHITECTURE FOR ToD

Fig. 1 presents the proposed architecture of ToD in urban scenarios utilizing a digital twin. The upper part of the figure describes digital twins and the lower part describes the physical world. The physical world comprises three main components, i.e., the teleoperated vehicle, communication and roadside infrastructure, and the teleoperator workstation. The digital twin comprises the HD map, list of tracked objects and infrastructural information around the teleoperated vehicle.

A. Physical World

Teleoperated vehicle: The teleoperated vehicle is equipped with actuators, perception sensors and a communication interface capable of streaming the real-time sensor data to the remote operator workstation. It is also able to execute commands received from the operator. We expect various sensors to be present onboard and some data, such as video, can be streamed directly over the network while other data, e.g. from RADARs and LIDARs, would be processed onboard and then streamed. Typically, a teleoperated vehicle is equipped with multiple cameras facing the front, the sides and the rear to provide sufficient information to the teleoperator.

Communication and roadside infrastructure: Communication and roadside infrastructure enables real-time streaming of sensor data to the teleoperator and delivers teleoperation commands back to the vehicle. Bandwidth and latency of the communication network are the key technical challenges for teleoperation. Network status has to be closely monitored to provide reliable information to the teleoperator.

There could be other sources of information such as roadside cameras/sensors and road side units (RSU) transmitting the status of traffic signals or other traffic participants. Such information can be used together with data from the teleoperated vehicle to improve the telepresence of the teleoperator, while avoiding to provide the same information as part of a video stream.

Operator workstation: The operator workstation comprises the immersive interface that allows the teleoperator to interact with the vehicle. Typical setting involves multiple displays to show streams of real-time video facing different directions, a steering wheel and an acceleration pedal and a brake pedal. The teleoperator will interpret the information to make driving decisions, i.e. requesting steering and acceleration commands, which are communicated back to the vehicle.

B. Digital Twin for Teleoperation

Digital twin for teleoperation is analogous to the digital twin in other applications such that a real-time digital copy of the physical object, the teleoperated vehicle and its environment is maintained. It makes use of massive amount of raw and processed data generated from onboard sensors,

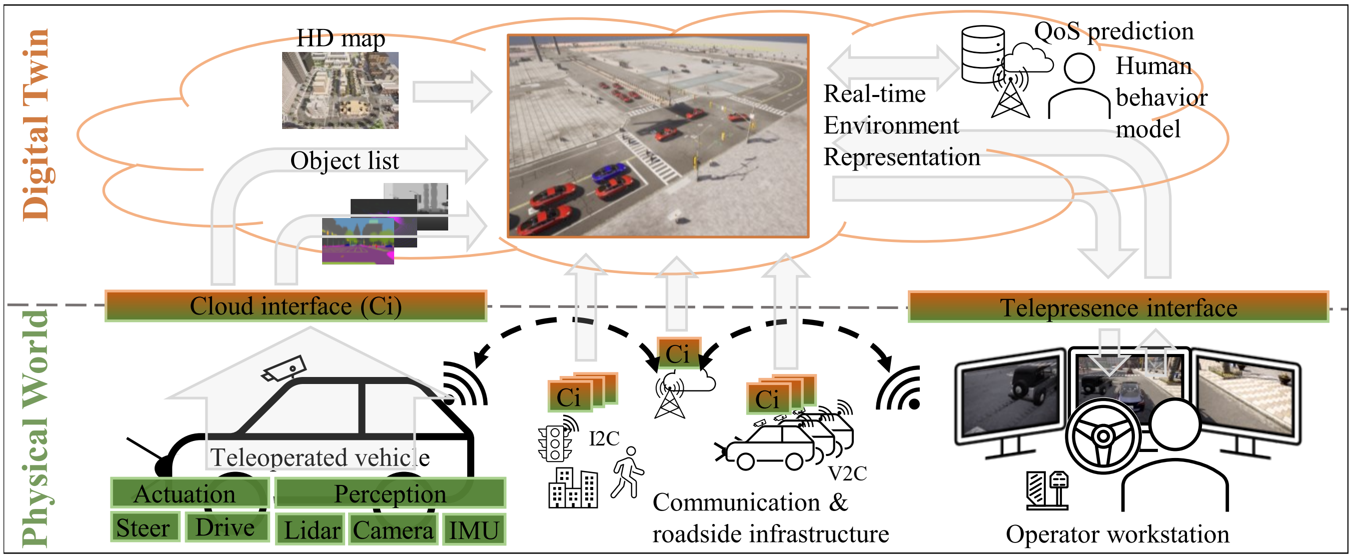

Fig. 1. Our proposed digital twin architecture for a teleoperated vehicle including infrastructure-to-cloud (I2C) and vehicle-to-cloud (V2C) communication. The Cloud interface (Ci) comprises the components to abstract the physical world ("twinning") according to the entity it is deployed on (vehicle, infrastructure, etc.), while the Telepresence interface creates the user interface with the available date.

perception algorithms and from other road users and roadside infrastructure.

In Fig. 1, we assume that the computing nodes from both the vehicle and the operator workstation are utilized to realize the digital twin. On the vehicle side, object tracking algorithms keep a record of objects, i.e., position, speed, size and type, in the surrounding environment apart from the raw video data streamed to the teleoperator. At the operator workstation (or the cloud) side, communicated data from the vehicle is merged with data available from other sources such as HD maps and roadside infrastructure to provide a comprehensive and complete telepresence environment to the teleoperator.

Fig. 1 does not assume specific implementations of a digital twin, but essentially, digital copies of the vehicle's surrounding environment on the vehicle side and the teleoperator side synchronized to the physical world. As there is restricted bandwidth and latency in the communication link between the vehicle and operator workstation, minimizing the time distortion and maximizing the accuracy are the key challenges in the digital twin implementation.

C. Cloud- and Telepresence Interfaces

What information to transmit from the vehicles and how to display it to the teloperator are the key issues affecting the teleoperation quality. Therefore, we define two interfaces: *cloud interface* and *telepresence interface* handling the two aspects respectively.

Cloud Interface: Cloud interface is essentially about determining which data should be sent and how often it should be sent. Here, the network bandwidth constraints and the quality of telepresence should be considered. If too little information is transmitted, e.g., low quality/frame rate video, teleoperator will not be able to perceive the situation correctly. If more information is transmitted than the available bandwidth, a bottleneck will occur resulting in too much delay and timely decisions cannot be made.

TABLE I

OPTIONS FOR DATA TRANSMISSION DEFINED IN THE CLOUD INTERFACE.

Transmitted data	Parameters	Exp. bandwidth
HD videos	20 FPS/720p or 480p	3-4 Mbps
Masked videos of objects & low qual. background	20 FPS/720p or 480p	$<$ 1 Mbps
Masked videos of objects & ego veh. coord.	20 FPS/720p or 480p	$<$ 0.5 Mbps
Object lists incl. ego veh.	20 FPS	$\approx$ 200 kbps

A range of options that the cloud interface can provide are listed in Table I. The first option in the table is the conventional teleoperation where multiple real-time video streams, facing all sides, are compressed and transmitted over the network. The second option pre-processes video data and transmits important objects in high quality and the background in low quality to save bandwidth, and hence reduce the teleoperation latency. The third option does not transmit the background video, but transmits the coordinates of the teleoperated vehicle. The last option, the most progressive approach, transmits only the object lists containing the pose, speed, size and type of the road users detected by the onboard sensors of the teleoperated vehicle and the status of other dynamic objects such as traffic signals.

Telepresence Interface: Telepresence interface determines how the information gathered from various sources and the digital twin is displayed to the teleoperator. Telepresence interface is not only about providing as high quality video as possible to the teleoperator, but also enhancing the experience beyond, for example, by overlaying additional information such as objects outside the line of sight. In addition, the quality of ToD at night or in poor weather condition could be improved significantly beyond direct teleoperation using only video streams by integrating additional sensor data.

Table II shows options for the telepresence interface. The

TABLE II

OPTIONS FOR TELEPRESENCE INTERFACE.

Data sources	Conditions	Risks
HD videos streams	Excellent network (>3 Mbps)	Delay in case of sudden network disruption
Obj. images overlayed on low qual. backgr.	Modest network (> 1 Mbps)	Undetected objects
Obj. images overlayed on HD map	Modest network (> 0.5 Mbps)	Localization error
Scene reconstr. from obj. list and HD map	Bad network (< 0.5 Mbps)	Undetected objects and localization error

first option, telepresence interface displaying multiple HD video streams is the conventional setup. In case of limited network bandwidth, such a scheme suffers from large latency or poor video quality rendering teleoperation difficult.

The second option transmitting only the important objects in high quality and the background in low quality can reduce the bandwidth requirement, and hence provide better telepresence than the first option.

The third option merges the communicated object images together with the scene generated from the HD map. As the background video is not transmitted, further reduction in bandwidth requirement can be made.

The last option recreates the scene from HD maps and spawning objects on the reported positions. This is the digital twin at the top-center in Fig. 1, which is elaborated in Section IV. This can drastically reduce the required bandwidth as no video is being streamed, hence achieves much lower latency.

There are risks involved in each option. The options relying on onboard object detection and tracking algorithms are subject to the limitations in their accuracy. Therefore, there is a risk some objects might be undetected and not presented to the teleoperator. The options utilizing HD maps require accurate localization. While these risks are present today, we note that significant technological advances are being made in both fields and as such we foresee that these will be less of an issue in the near future. In the next section, we show an implementation of teleoperation setup based on the digital twin architecture.

IV. DIGITAL TWIN FOR TOD IMPLEMENTATION

This section presents our implementation of digital twin for ToD on a simulator-based environment. The processing pipelines of the four methods we compare are presented in Fig. 2. A full implementation of the digital twin described in Section III is a huge undertaking and therefore, we focus on demonstrating the key aspects of the digital twin for ToD, i.e. the two interfaces and merging of data. This setup gives us accurate localization of the ego vehicle and the other traffic participants, perfect image segmentation, fusion and tracking and allows us to test and verify the validity of our hypothesis, which are about understanding how much up-link data can be reduced when applying different options and the feasibility of operating a vehicle in an urban settings through a digital twin representation.

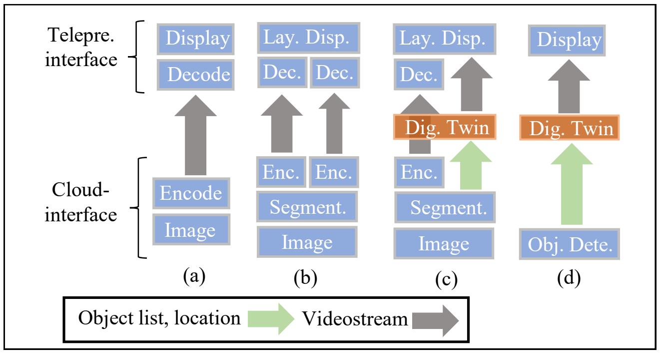

Fig. 2. Processing pipelines of the telepresence- and cloud interface for the different methods: (a) Conventional video stream, (b) Layered display with two video streams of differing quality, (c) Object video stream and background from digital twin, (d) Full digital twin-based scene based on object list

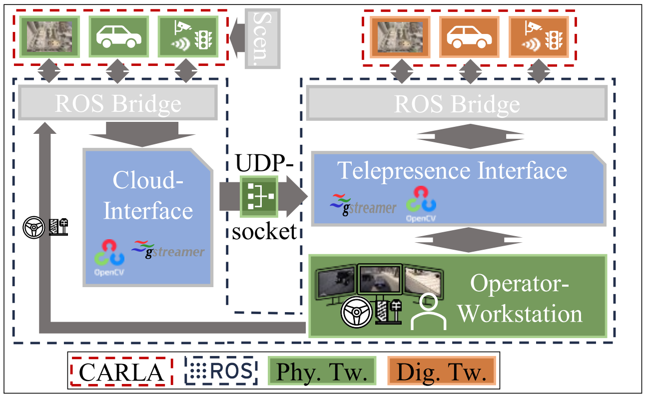

Fig. 3. Simulation setup of the teleoperation framework with digital twin.

A. Overall Setup

Fig. 3 depicts our overall setup. It comprises components corresponding to the physical world depicted in green and the digital twin in orange as well as software implementation details. Regarding the teleoperated vehicle side, we utilize an open-source autonomous driving simulator *CARLA*[1]. CARLA supports customized sensors including cameras on the vehicle, which will generate data for realistic urban driving scenarios. As CARLA is widely used for developing autonomous driving, we believe that it can later be replaced with a real vehicle without losing generality.

Regarding communication network, video generated from the vehicle's camera is processed and compressed by *GStreamer*[2] pipeline to be transmitted over UDP socket connection to the operator workstation. Other information, such as vehicle location and other sensor data as well as the teleoperation commands are transmitted to via ROS messages. Here, we do not assume particular network protocols, e.g. cellular or WiFi-based, but generic network parameters such as the required bandwidth and latency are monitored. Detailed implementations of the specific network behaviors, such as geographical coverage, interference, etc., are left as a future work.

---

[1] https://carla.org/

[2] https://gstreamer.freedesktop.org/

On the operator workstation side, a steering wheel, acceleration and brake pedals are used. The operator watches the streamed video to provide steering and acceleration commands, back to the CARLA simulator.

As a middleware, the open-source robot operating system (ROS[3]) was selected as it can be conveniently integrated with CARLA by using the provided *ROS Bridge* package. ROS also allows us to have a modular and portable design.

The cloud- and telepresence interface are implemented on separate ROS nodes. The cloud interface receives the sensor/video data from ROS topics provided by ROS bridge and processes it to generate the data for the options described in Table I and Fig. 2. For image processing, *OpenCV*[4] is used while video encoding and streaming is handled by a customized GStreamer pipeline.

B. Cloud- and Telepresence Interface

In this subsection, we provide implementation details of the two interfaces and how digital twin can benefit the ToD.
Cloud interface: We implemented the four options described in Table I and Fig. 2 in our setup. For direct streaming of videos, the raw video generated from CARLA is compressed using the x264 encoder.

Implementation of masked videos of objects starts with recognized objects in the video. In our setup, we have used the segmentation camera, which provides the ground truth for object recognition in the CARLA simulator. We draw a rectangular box around each object to distinguish it from the background. Then, two video streams are prepared where the first one is compressed in high quality with a black background and the second one is the background compressed in low quality as shown in Fig. 4. The quality is controlled by setting the quantization value for each video stream in our setup. For the third option in Table I, the world coordinate of the teleoperated vehicle is transmitted instead of the background video.

The fourth option, sending only the object lists to the operator workstation instead of any video stream is implemented by obtaining the coordinates of the objects within a designated perimeter from the ego vehicle. Current implementation of the telepresence interface relies on the ground truth provided by CARLA, but can be replaced by real algorithms without major modifications to the interface.
Digital twin and telepresence interface: Four telepresence interfaces shown in Table II are also implemented in our setup. The first option does not require involvement of the digital twin as it can simply decode the HD video streams and display them to the teleoperator. The second option is implemented by decoding the two video streams, i.e. one containing the objects and the other containing the background, and overlaying them on each other. The bandwidth savings compared to the first option and quality of the resulting video stream is presented in the next section and also the supplementary video.

For implementing the third option, the usage of a digital twin and an HD map is required. From the reported coordinates of the teleoperated vehicle, the background image is generated from the HD map on the operator workstation. The image is then merged together with the video stream containing only the objects. Here a digital twin tracking the position of the teleoperated vehicle on the HD map is maintained on the operator workstation. Note that there are a number of companies recently offering such an HD map [19]. In our implementation, a second instance of CARLA, separate from the one modeling the physical world, running on the operator workstation is used as an HD map.

The fourth option again uses the HD map like the third option, but the objects are tracked in the digital twin based on the reported information about the objects. In our implementation, we utilize again the second instance of CARLA and place generic vehicles on the map to generate video streams to be shown to the teleoperator. At the operator workstation, the positions of all the objects including the teleoperated vehicle are maintained on a HD map, i.e. as a digital twin as shown in Fig. 6. Currently, we do not apply sophisticated motion/network models, e.g. using Kalman filters, to minimize the distortion from time delay, but such models could be applied to enhance the telepresence in the future.

In the following section, we present how much bandwidth reduction can be achieved from using the digital twin and the interfaces, which improves the telepresence.

V. EVALUATION

A. Comparison of Bandwidth Utilization

In order to compare the bandwidth utilization of different segmented parts of the scene and thus give an estimate of the benefits a digital twin could bring in terms of network load, we select a representative, urban traffic scenario and save the required sensor data into a ROS-bag file. The processed data is then fed into the described streaming pipeline, but instead of transmitting the stream over the network, it is saved into a Matroska file, which is a flexible, open-source container format to store the compressed videos. Additionally, the generated object list is stored in a separate ROS-bag file to give an estimate of the required data rate for a purely object list-based approach.

Fig. 5 illustrates the resulting data rate for the different methods of telepresence discussed above. As a baseline, the video stream of the front-facing camera with the default quantization value of $Q = 20$ is selected.

The layered display approach in comparison leads to almost a halving in required bit rate, while maintaining the visual quality of dynamic objects (also see video demonstration). Further reduction is achieved if only the relevant, object-related segments of the video are transmitted as a high quality ($Q = 10$) stream. The third column of Fig. 4 illustrates such stream, which requires the combination with a HD map at the teleoperator workstation to bring the objects back into the situational context.

---

[3] https://www.ros.org/

[4] https://opencv.org/

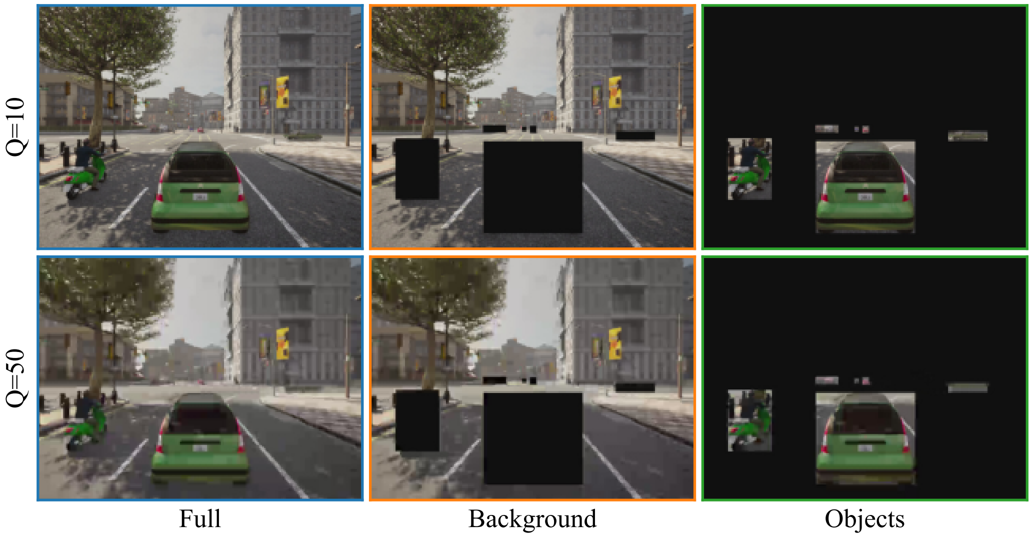

Fig. 4. Screenshots of video streams in our urban scenario for two different qualities (High quality $Q = 10$ and low $Q = 50$). The semantic segmentation-based splitting of the scene into two streams (background and objects) is exemplified. For a better impression on the quality differences the reader is referred to the attached video[6]. Frame colors correspond to Fig. 5.

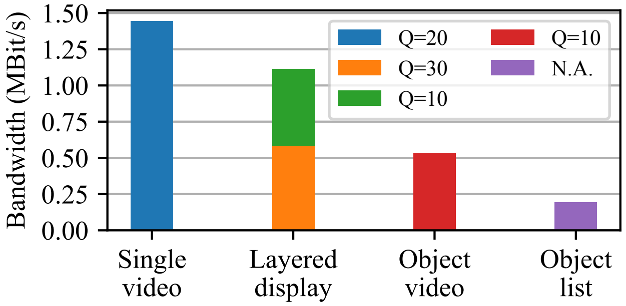

Fig. 5. Resulting data rate for the different setups: Full video stream in medium quality, layered display composed of two streams with low ($Q = 30$, background) and medium ($Q = 20$, objects) quality, purely object videos in high quality and object list.


(a) (b)

Fig. 6. (a) Traffic scene at busy intersection in Carla, ego vehicle blue on the left; (b) The same scene in the Digital Twin recreated using the object list data. Note that vehicle types are not distinguished at this stage.

As a last step of abstraction, we only transmit an object list using a customized ROS-message which identifies unique actors in the scene and localizes them in a 2D plane. This results in another, significant reduction in bandwidth. As shown in Fig. 6, transmitted data is still sufficient to recreate a recognizable scene in the Digital Twin. However, in reality, this highly depends on the accuracy of object detection. Taking this into consideration is left to future work.

To give a visual impression, some resulting stand-still, decoded images are presented in Fig. 4. They demonstrate the output of the Cloud Interface for the layered display setup at different quantization values, where $Q = 50$ is close to maximum compression and $Q = 10$ is almost lossless. Compression leads to a loss in details, e.g. in the leafs of the tree. However, from a teleoperator's point of view, such losses are not expected to significantly reduce driving performance and thus constitute a reasonable trade-off with bandwidth utilization. In a future work, this will be further investigated with a respective user study. For a better impression of the resulting quality differences, the interested reader is referred to the corresponding videos, as they allow a better judgement of the subjective driveabilty of the scenes.[6]

VI. CONCLUSION AND FUTURE RESEARCH

In this work, we propose the usage of a digital twin in order to facilitate teleoperation of highly automated vehicles in urban environments under constrained network conditions. By utilizing the available sensor data and intelligence on the vehicle, the bandwidth that is required to maintain a virtual representation of the vehicle environment is significantly reduced.

Our experiments reveal that the operator's telepresence, which is an important factor for decision making and driving safety, can be recreated from the digital twin. Benefits include a significant reduction in network load, the ability to avoid driver distraction by irrelevant parts of the scene, changing view and appearance according to the teleoperator's needs and incorporation of additional data from infrastructure and other vehicles.

As the presented work constitutes an architectural framework for functions that can be realized using a Digital Twin, our future research points towards realizing such functions and incorporate fleet- and infrastructure data. Additionally, to examine the applicability, a user study will investigate the effects on the human operator and identify possible improvements.

---

[6] https://youtu.be/RmJnGOAU26w

REFERENCES

[1] *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*, Society of Automotive Engineers (SAE) Std., 2021.

[2] E. Yurtsever, J. Lambert, A. Carballo, and K. Takeda, "A survey of autonomous driving: Common practices and emerging technologies," *IEEE Access*, vol. 8, pp. 58 443–58 469, 2020.

[3] Mercedes-Benz. [Online]. Available: https://www.mercedes-benz.de/passengercars/technology-innovation/mercedes-benz-drive-pilot/stage.module.html

[4] G. A. Association, "Tele-operated driving (tod): System requirements analysis and archi- tecture," 2021.

[5] S. Neumeier, E. A. Walelgne, V. Bajpai, J. Ott, and C. Facchi, "Measuring the feasibility of teleoperated driving in mobile networks," in *2019 Network Traffic Measurement and Analysis Conference (TMA)*, 2019, pp. 113–120.

[6] A. Schimpe, S. Hoffmann, and F. Diermeyer, "Adaptive video configuration and bitrate allocation for teleoperated vehicles," in *2021 IEEE Intelligent Vehicles Symposium Workshops (IV Workshops)*, 2021, pp. 148–153.

[7] I. Johansson, S. Dadhich, U. Bodin, and T. Jönsson, "Adaptive video with srceam over lte for remote-operated working machines," *Wireless Communications and Mobile Computing*, 2018.

[8] J.-M. Georg, J. Feiler, S. Hoffmann, and F. Diermeyer, "Sensor and actuator latency during teleoperation of automated vehicles," in *2020 IEEE Intelligent Vehicles Symposium (IV)*, 2020, pp. 760–766.

[9] T-Systems. [Online]. Available: https://www.t-systems.com/de/en/industries/automotive/connected-mobility/teleoperated-driving

[10] J.-M. Georg, J. Feiler, F. Diermeyer, and M. Lienkamp, "Teleoperated driving, a key technology for automated driving? comparison of actual test drives with a head mounted display and conventional monitors," in *21st International Conference on Intelligent Transportation Systems (ITSC)*, 2018, pp. 3403–3408.

[11] J.-M. Georg, E. Putz, and F. Diermeyer, "Longtime effects of videoquality, videocanvases and displays on situation awareness during teleoperation of automated vehicles," in *IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, 2020, pp. 248–255.

[12] J.-M. Georg and F. Diermeyer, "An adaptable and immersive real time interface for resolving system limitations of automated vehicles with teleoperation," in *IEEE International Conference on Systems, Man and Cybernetics (SMC)*, 2019, pp. 2659–2664.

[13] AutonomouStuff. [Online]. Available: https://autonomoustuff.com/news/autonomoustuff-offers-teleoperation-solutions-from-designated-driver

[14] S. Neumeier, V. Bajpai, M. Neumeier, C. Facchi, and J. Ott, "Data rate reduction for video streams in teleoperated driving," *IEEE Transactions on Intelligent Transportation Systems*, pp. 1–16, 2022.

[15] D. Jones, C. Snider, A. Nassehi, J. Yon, and B. Hicks, "Characterising the digital twin: A systematic literature review," *CIRP Journal of Manufacturing Science and Technology*, vol. 29, pp. 36–52, 2020.

[16] Z. Wang, K. Han, and P. Tiwari, "Digital twin simulation of connected and automated vehicles with the unity game engine," in *IEEE 1st International Conference on Digital Twins and Parallel Intelligence (DTPI)*, 2021, pp. 1–4.

[17] C. Yang, J. Dong, Q. Xu, M. Cai, H. Qin, J. Wang, and K. Li, "Multi-vehicle experiment platform: A digital twin realization method," in *IEEE/SICE International Symposium on System Integration (SII)*, 2022, pp. 705–711.

[18] Z. Wang, K. Han, and P. Tiwari, "Digital twin-assisted cooperative driving at non-signalized intersections," *IEEE Transactions on Intelligent Vehicles*, 2021.

[19] TomTom. [Online]. Available: https://www.tomtom.com/products/hd-map/