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5G BLUEPRINT

Next generation connectivity for enhanced, safe & efficient transport & logistics

D4.2: Tele-operated docking system use case

Final report

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Abstract

This report delves into use-case 4.2 of the 5G-Blueprint project, encompassing two sub-use cases, 4.2a and 4.2b. Use-case 4.2a focuses on teleoperation and autonomous docking of a truck-trailer combination, involving hardware and software development. Key software components include a high-fidelity model, path planner, and two path-following controllers: pure pursuit and model predictive. Hardware elements encompass a teleoperation centre, communication hardware, localization tools, and a real truck. Rigorous testing across phases showed the system effectively met KPIs, with the model predictive controller outperforming the pure pursuit controller. In addition, a small pilot study examined teleoperating a truck, revealing the need for better camera placement, realistic setup, sound integration, ergonomic design, and calibration. Recommendations for short initial routes and more research into gaming experience's impact were suggested. Use-case 4.2b involved teleoperating a skid-steer, indicating that while the operator was faster with a regular skid-steer, further improvements and training could enhance teleoperation efficiency, particularly in challenging environments.

Keywords: Autodocking, Teleoperation, 5G, Network, Skid-steer, HMI

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CI	Classified, information as referred to in Commission Decision 2001/844/EC	
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R: Document, report (excluding the periodic and final reports)

* DEM: Demonstrator, pilot, prototype, plan designs

DEC: Websites, patents filing, press & media actions, videos, etc.

OTHER: Software, technical diagram, etc

EXECUTIVE SUMMARY

This report focuses on use case 4.2 of the 5G-Blueprint project, which is further divided into two sub-use cases, 4.2a and 4.2b.

Use-case 4.2a involves teleoperation and autonomous docking of a truck and trailer combination. To achieve this, the project developed both hardware and software components.

On the software side, essential components include a high-fidelity model, a path planner, and a path-following controller. Two different versions of the path-following controller were tested: a Pure Pursuit Controller (PPC) and a Model Predictive Controller (MPC).

The hardware elements encompass a teleoperation centre, communication hardware, localization hardware, and a real vehicle (the truck). The project unfolded in three phases: the modelling phase, the Minimum Viable Platform (MVP) phase, which introduced a 1:3 scaled truck for initial testing, and finally, the full-scale phase, where all components were implemented and tested on a real truck and trailer combination operating in logistic centre environments.

To assess the developed autonomous docking functionality, Key Performance Indicators (KPIs) were established and rigorously tested at various test sites. In conclusion, the autonomous docking system functions effectively within the specified KPI limits. The MPC controller demonstrated superior performance compared to the PPC, excelling in docking the truck in tighter spaces with smoother curves, less oscillatory behaviour and exhibiting greater resilience to variations in network quality. Network quality has emerged as a noteworthy concern, as the autodocking functionality relies heavily on a remote connection over 5G, making it sensitive to network latency, which can impact its overall performance.

In addition to the development, a small pilot study was performed which aimed to study the effects of teleoperating a truck with professional truck drivers. Seven participants gained practical experience with teleoperated driving, offering valuable insights. Key findings include the need for improved camera placement, realistic setup resembling a truck cabin, sound incorporation, ergonomic arrangements, and better calibration. The study suggests starting with short routes, visualizing haptic experiences, and exploring the influence of gaming experience on teleoperation. These recommendations aim to enhance the Human-Machine Interface (HMI) for teleoperated trucks and inform future research in the field.

Use-case 4.2b involves teleoperating a skid-steer. For this use-case a skid steer was modified to make it suitable for teleoperation from a teleoperation centre. After the development phase, rigorous testing was done in order to examine the overall performance and investigate its potential. The tests provided insights into its potential use. While the operator was consistently faster using a regular Skid-Steer, several factors like pile size and training influenced the results. The operator found the teleoperated Skid-Steer usable and drivable, but efficiency was hindered by challenges in perceiving the bucket's depth and height. With improvements and proper training, teleoperation can be more efficient. It offers advantages in health-risk or complex environments but requires further research and system enhancements to match the efficiency of regular operation.

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ABBREVIATIONS

ADAS	Advanced Driver Assistance System(s)
CAN	Controller Area Network
CRG	Curved Regular Grid
ECU	Electronic Control Unit
EF	Enabling Function
EPO	Emergency Power Off
ETA	Established Time of Arrival
EU	European Union
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAN	Hogeschool Arnhem en Nijmegen
HMI	Human Machine Interface
IPKW	Industriepark Kleefse Waard
KPI(s)	Key Performance Indicator
LTE	Long-Term Evolution
MIMO	Multiple Input Multiple Output
MPC	Model Predictive Controller
MQTT	MQ Telemetry Transport
MVP	Minimum Viable Platform
NSA	non-Standalone
NTRIP	Networked Transport of RTCM via Internet Protocol
OXTS	Oxford Technical Solutions
POV	Point of View
PPC	Pure Pursuit Controller
RTD	Round Trip Delay
RTK	Real Time Kinematics
RTLS	Real Time Localisation System
SA	Standalone
TCP	Transmission Control Protocol
TNO	Nederlanse Organistatie voor Toegepast-Natuurwetenschappelijk Onderzoek
TOC	Teleoperation centre
UDP	User Datagram Protocol

1 INTRODUCTION

1.1 Use-case introduction

In the dynamic environment of modern transportation and logistics, innovation is the driving force behind evolving industries. The integration of 5G cloud based autonomy, particularly in the logistics sector, has emerged to enhance efficiency, safety, and sustainability. The 5G-Blueprint project is an EU funded Horizon2020 proejct, poised study and showcase the potential of 5G technology for teleoperation and autonomy within the logistics sector. To do this, four use-cases were developed. **Use-case 4.2** (Figure 1), the focal point of this project report, explores two critical facets of the 5G-Blueprint project.

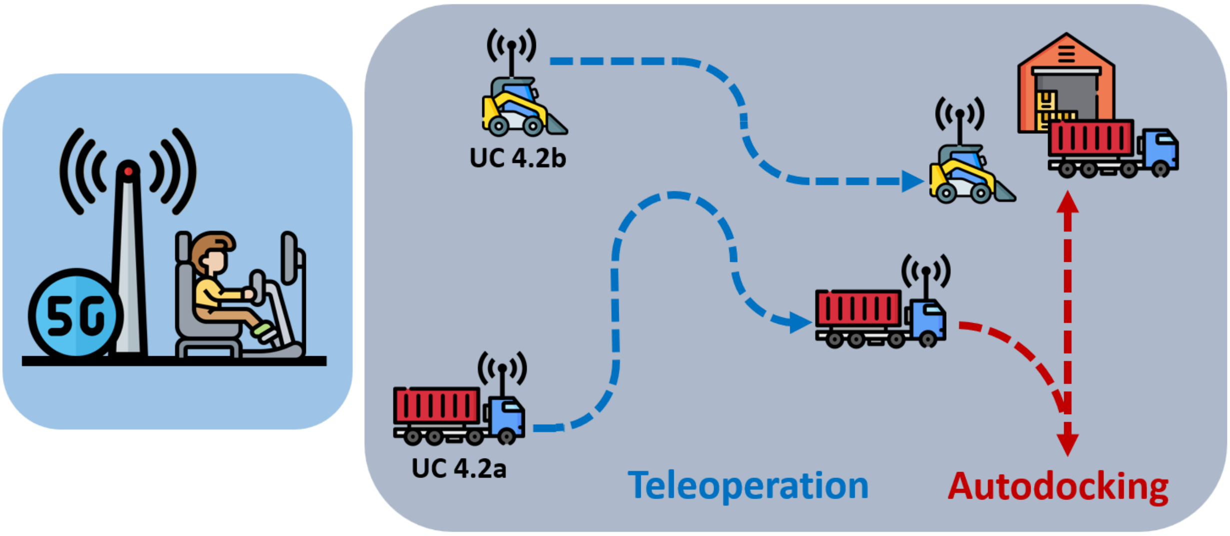

Figure 1: Use-case 4.2 visualisation.

Use-case 4.2a: **Teleoperation and Autonomous docking of a truck-trailer combination**, from now on referred to as "Autodocking," represents an innovative solution that addresses the challenges of docking processes in the logistics domain. This use case delves into the development, implementation and testing of an autodocking functionality that can autonomously dock a truck and trailer combination, an operation traditionally reliant on human expertise. Autodocking can have numerous benefits which will be shorty higlighted below:

- Enhanced Efficiency
  - Autodocking could streamline the often complex and time-consuming docking process and therefore reduce dwell times and improve overall efficiency.
- Precise Maneuvering
  - The autodocking functionality is capable of highly precise maneuvers. Therefore, autodocking could ensure that trucks and trailers are positioned very exact, thus reducing the margin of error in docking procedures.
- Safety improvement
  - By minimizing human error, autodocking could reduce the risks of collisions, jacknife situations or misalignment thus enhancing overall safety.
- Labor Savings
  - By automating the docking process, companies can reduce their reliance on skilled truck drivers for complex maneuvers, thereby potentially saving on labor costs. This is particularly important looking at the overall driver shortage, the logistics sector is facing.
- Space Optimization
  - Autodocking can make better use of limited space in busy loading and unloading

areas, helping maximize the capacity distribution centers.

- Reduced Driver Stress
  - Drivers often experience stress during the docking process, especially in challenging conditions. Reversing over a right curve is considered very challenging for drivers and therefore drivers prefer to reverse over a left corner. This way they can look out of the window and have beter perception. Autodocking has no preference and could therefore reduce stress and result in beter drive well-being.
- 24/7 Operations
  - Autonomous systems can operate around the clock without fatigue, breaks, or limitations due to working hours, significantly improving the overall efficiency.

Usecase 4.2b: **Teleoperation of a Skid-Steer**. Teleoperation empowers the remote control and management of machines, therefore allowing control in applications where physical presence may be limited or dangerous. This use case investigates the intricacies of teleoperation technology and its potential across industries relying on skid-steer equipment. Next to skid-steer equipment this use-case can easily be translated to other machines that are used for cargo handling like cranes and wheel loaders. Teleoperation of skid-steers can have numerous benefits. Some of them are listed below:

- Enhanced Safety
  - Operators can remotely control skid-steer equipment in hazardous environments, reducing the risk of injury or exposure to harmful conditions.
- Versatility
  - Teleoperation technology allows for more versatile use of skid-steer machines, enabling them to perform tasks in a broader range of applications.
- Remote Accessibility
  - Skid-steer equipment can be operated from a distance, making it suitable for applications in remote or inaccessible areas.
- Reduced Operator Fatigue
  - Operators can work from a comfortable and safe environment, reducing fatigue associated with prolonged on-site operations.
- Operational Continuity
  - Teleoperation ensures that work can continue even in adverse weather conditions or other situations that might hinder on-site work.

The use of 5G in both use cases is crucial because of its low latency, high bandwith, reliability and stability.

In conclusion, both Autodocking and Teleoperation technologies offer a multitude of advantages, from enhanced efficiency and safety to cost savings and increased operational flexibility. This project report aims to provide an overview of these the usecase with its two sub-usecases, delving into the development, implementation and testing of both technologies thus showing the overall potential these technologies have.

Next to the development of the use-cases, some Enabeling Functions (for short EF's) were developed. This was done to be able to better intergrate the overall use-case with for example supply chain management. The EF's that were integrated in UC4.2a are:

- EF1, Enhanced Awereness Dashboard
- EF7, Established Time of Arrival (ETA) Sharing

Althought the actual development of the EF's lies out of the scope of this report since it was done by other project partners, it's worth mentioning that they are integrated within the autodocking functionality. For a more extensive description fo the EF development please see 5G-Blueprint deliverables D6.1, D6.2 and D6.3 regarding the enbaling functions.

1.2 Methodology and report structure

This paragraph will give a brief description of the methodology that is used during the project which will also represents the structure of the report. This is visualised in Figure 2.

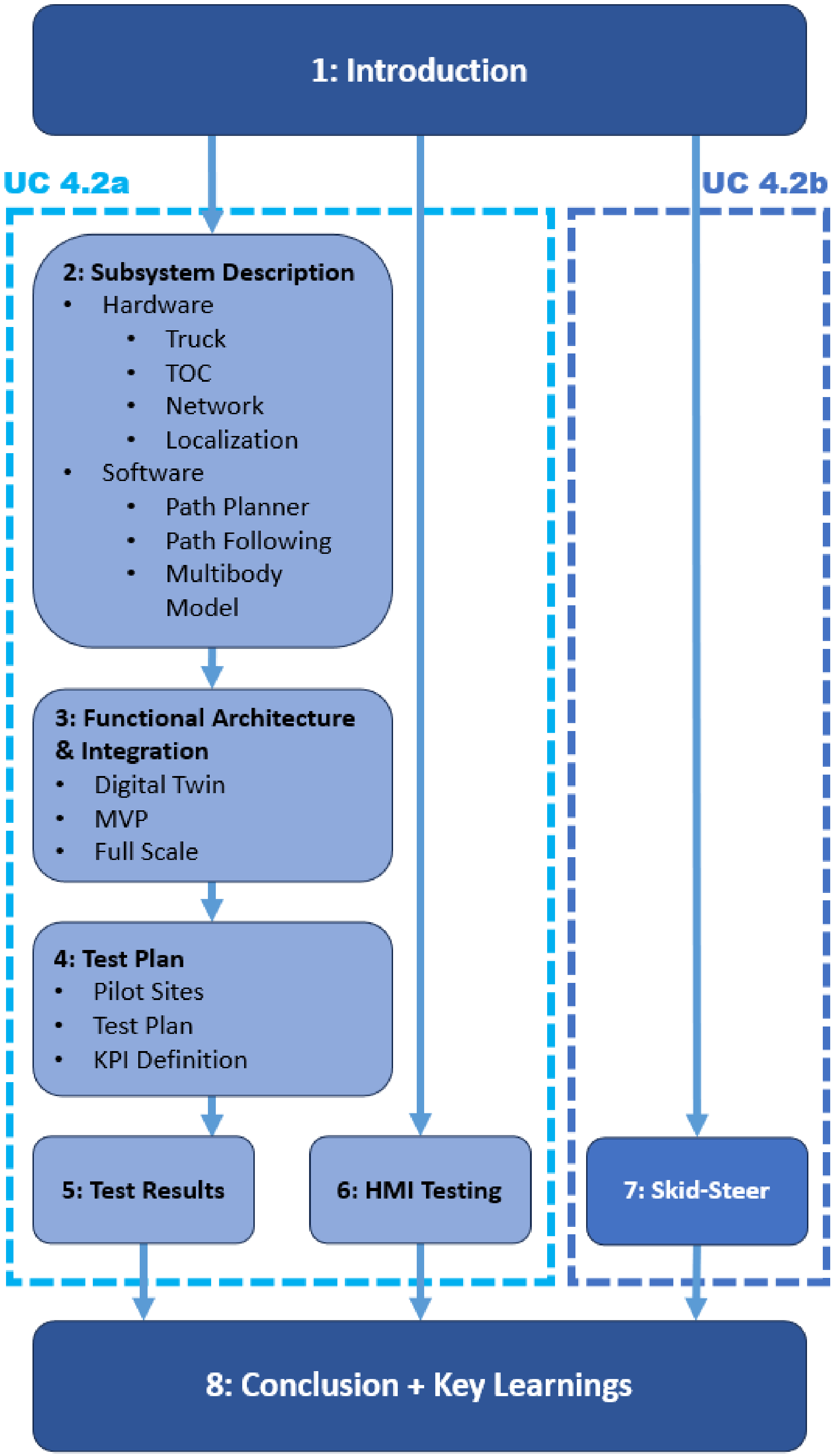

Figure 2: Report structure.

Chapters 2, 3, 4, and 5 describe the development, implementation and testing of the autodocking functionality (UC 4.2a). More specifically:

Chapter 2 describes the subsystems needed for teleoperation and autodocking in terms of hardware and software. For hardware these are:

- The Teleoperation Centre (TOC) from where the teleoperater will control the truck remotely.
- Communication hardware to establish the 5G connection between the teleoperation centre and the truck.
- Localization hardware to locate the truck which is needed for the autodockign functionality.
- The vehicle (truck)

For software these are:

- A path planner which will plan the desired docking path from arbitrary starting position to point the destination point represented by the dock.
- A path following controller controlling the steering angle and the speed ensuring that vehicle combination follows the planned path precisly to end up at the dock within the defined limits
- A high fidelity model, which is used for simulation of truck dynamics and controller development.

Chapter 3 describes the functional architecture and integration of the autodocking autodocking functionality. This was done in three phases.

- The modelling phase, where the high fidelity model is used for early developments.
- The Minimum Viable Platform (MVP) phase, where a 1:3 scaled truck was used for initial real life testing of the autodocking functionality
- Full-scale development which includes the final working version of the autodocking functionality on a full-scale truck and trailer combination.

Chapter 4 describes the test conditions, test sites and Key Performance Indicators (KPIs) for the autodocking functionality.

Chapter 5 describes and discusses the results of the testing that were done througout the project.

Chapter 6 is a standalone chapter that describes additional research on Human Machine Interface (HMI) testing that was done to invesigate how real truck drivers experience teleoperating a truck.

Chapter 7 is standalone chapter that describes the development, implementation and testing of teleoperating the skid-steer (UC 4.2b). If you as a reader are only interested in the skid-steer results, you can directly go to Chapter 7.

Chapter 8 combines all the findings given throughout the report and summerizes that into a clear and understandable conclusions and recommendations.

2 SUBSYSTEM DESCRIPTION

2.1 Hardware

As mentioned in the introduction, the autodocking functionality contains four hardware components. These are:

- Teleoperation centre and teleoperation hardware
- Communication platform
- Localization sensorics
- Vehicles

which are described hereafter, in terms of basic functionality, inputs and outputs.

2.1.1 Teleoperation

The architecture of teleoperation is shown in Figure 3, consisting of a teleoperation centre, the vehicle and a Gateway, which is the heart of the system. All vehicles and remote stations connect to the Gateway where the vehicle or the remote station is authenticated. Once they are authenticated, they report their status to the gateway, and a connection can be established. Once connected, the driver is able to see the image streamed from the vehicle, as well as its speed and other data. The driver may then choose to take over the vehicle and drive it remotely to a desired location.

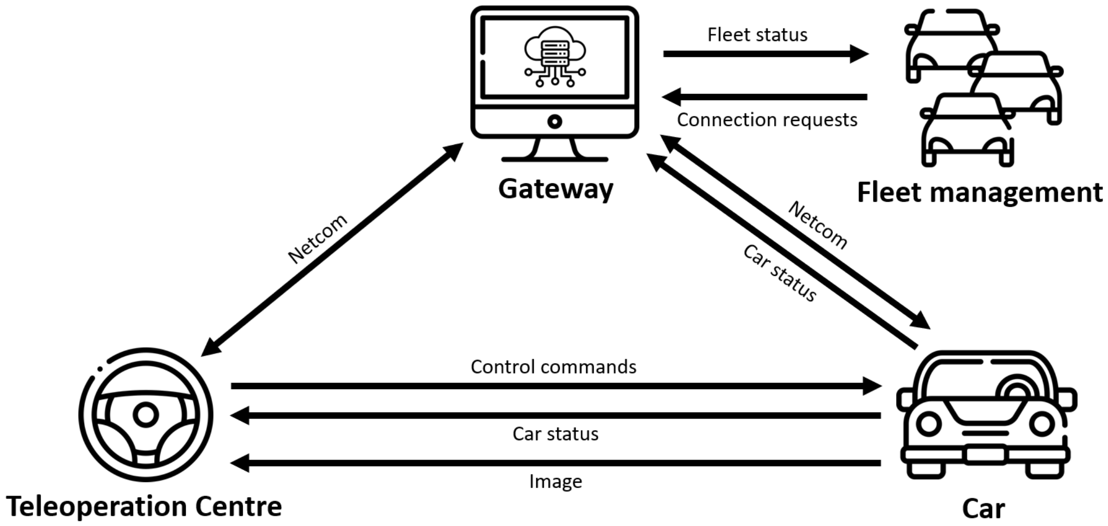

Figure 3: System architecture of teleoperation.

2.1.1.1 Teleoperation centre

The teleoperation centre is the environment in which the operator can control the vehicle remotely. The teleoperation centre, the displays, and HMI that is presented to the driver is shown in Figure 4. The teleoperation centre set-up was used both for the scaled vehicle as for the full-scale vehicle and didn’t change. For UC4.2a, the centre composed of:

- Seat for the operator.
- Monitors to display different Points of View (POV) of the cameras installed on the truck.
- Main controls, i.e., steering, braking, throttle and gear as a regular truck.
- A desktop to process the controls & algorithms, including a mouse & keyboard.
- HMI integrated in the front view camera stream, including information icons and signals.
- 5G Router for connection with the remotely operated vehicle.

- The gateway shown in Figure 3 is cloud based and is not physically present in the teleoperation centre.

Figure 4: Teleoperation centre.

2.1.1.2 Teleoperation hardware

The vehicle side consists of hardware component as well, to be able to drive teleoperated and to enable activation of the autodocking functionality remotely. This is done in collaboration with V-tron and RoboAuto since the DAF truck is also used for the Remote Take Over, use case (UC4.4).

In the DAF an Electronic Control Unit (ECU) is placed with all the necessary teleoperation hardware. It holds two switches (connected to each other), the RoboAuto drive-by-wire system, two Sierra wireless XR90 5G routers and electrical components like DC/DC converters (Figure 15). Furthermore, 6 cameras are installed in the truck, which are used for visual feedback to the operator. They are connected to the switch via ethernet cables, which also provides the power to the cameras. To control the streaming nodes of the cameras three modified Jetsons (with Power over Ethernet) are connected to the switch as well via ethernet cables. Next to this the RoboAuto drive-by-wire system is connected to the switch, which translates the operator's inputs to dedicated CAN (Controller Area Network) signals for steering, braking & throttle. Furthermore, it can also hold extra CAN outputs for certain operations, like activating the autodocking functionality. And it can send vehicle information, like vehicle speed or gear, back to the operator.

2.1.2 Communication Platform

To facilitate teleoperation and remote activation of the autodocking functionality, a communication link between the operator side and the vehicle side is required. This is accomplished by using two Sierra wireless XR90 5G routers as described in the previous paragraph, one at the teleoperation centre side and one at the truck side, both with KPN 5G Sim cards. Via this 5G communication link, control signals are sent, and video streams are received.

Since the scope of this use-case is to evaluate and demonstrate the capabilities of teleoperation and the autodocking functionality, no further details will be given on the 5G communication side in this document. For more information about the 5G communication, please see 5G-Bluerpint deliverable D5.4, "*Final Report on the 5G Network evaluation*".

2.1.3 Localization sensorics

A Real Time Localization System (RTLS) will be used for the automated docking functionality that continuously provides positional information about the Tractor Semitrailer combination, i.e., position (X, Y) and orientation (ϴ) with respect to a fixed earth-based coordinate system. The provided information should be highly accurate because the available space and tolerances are limited as stated in the KPIs in D7.2.

For the Use Case a Real Time Kinematic (RTK) positioning system will be used, which is capable of centimetre-level positional accuracy, as well as providing accurate orientation (order of 0.1º) using dual antennas. RTK is a technique used to enhance the precision of position data derived from satellite-based positioning systems, e.g., it increases the accuracy of GPS (Global Positioning System) signals. A reference station, also referred to as a base station, measures the signal, and send out real-time differential correction to a receiver that utilises the corrections. Figure 5 visualizes this principle.

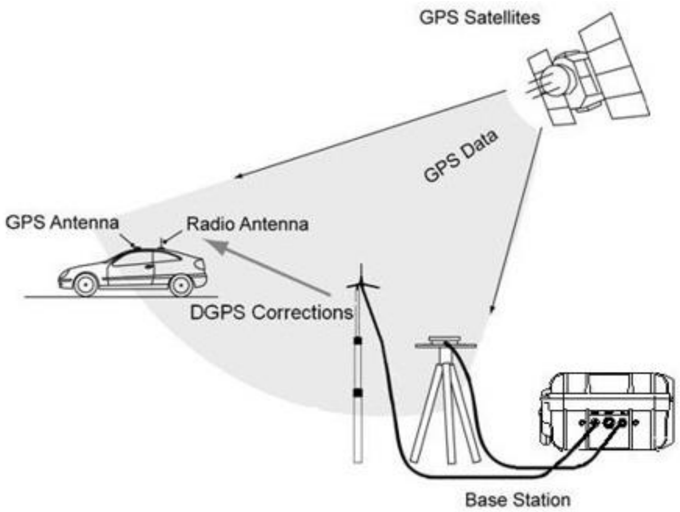

Figure 5: Real Time Kinematic (RTK) positioning system.

It might be nice to notice that some versions of 5G networks already incorporate these RTK GPS differential corrections to be send over the air. However this was not yet incorporated in this project since the reliability was not yet sufficient for this use-case. The RTK system used for UC 4.2a is from Oxford Technology Solutions Ltd (OXTS, 2023), a company with over two decades of experience in high precision GNSS (Global Navigation Satellite System) receivers and navigation. The total system used consists of:

- 2 RT-XLANs
- RT1003 unit, including 2 antennas.
- RT3000v3 unit, including 2 antennas.
- RT Base Station, including radio antennas.

The set-up of this localization system was very similar throughout the project. The RT1003 unit was placed in the truck and the RT3000v3 unit was located in/on the trailer. The RT3000v3 was located in/on the trailer since this unit has a better positional accuracy (see Table 1). And since, for docking, the main interest is the position of the trailer. Both units had two antennas and they were placed as far as possible from each other, to receive the highest orientation accuracy. The Base Station was located as close as possible to the vehicle with a clear connection to the sky. Via the radio antennas the RT3000v3 could receive the differential corrections and transmitted them to the RT1003 via the XLANs. Figure 6 shows the main components of the complete system and Table 1 shows some performance and data sheet values of the units.

RT1003 Unit

RT3000v3 Unit

RT Base Station

RT-XLAN

Figure 6: Main components of the OXTS RTK localisation system used for UC4.2a.

Indicator	Unit	RT1003	RT3000v3
Position accuracy (RTK)	[m]	0.02	0.01
Heading accuracy	[º]	0.10	0.10
Velocity accuracy	[km/h]	0.10	0.05
Mass	[kg]	0.45	1.40
Dimensions	[mm]	142 x 77 x 41	184 x 120 x 71
Input voltage (dc)	[V]	10 – 31	10 – 50
Power consumption	[W]	9	15

Table 1: Data sheet values of the RT1003 and RT3000v3 units.

2.1.4 Vehicles

2.1.4.1 1:3 Scaled Truck and Trailer combination

Two vehicles were used for UC 4.2a. First up is a 1:3 scaled truck and trailer combination shown in Figure 7. The scaled truck was used for the first real life testing of the autodocking functionality. With its close representation of a real truck and trailer combination, this platform was used to test the initial controller performance, test the accuracies of the localization hardware and test how the autodocking functionality would react to real life noise i.e., vibrations, signal distortion, sensor noise, etc. A scaled platform was chosen in order to have easier access and make overall testing more convenient (less space needed, less risk of accidents, no need of qualified driver etc.). This scaled truck served as the minimum viable platform (MVP) during the MVP tests and demos in July 2022 at the Verbrugge Scaldia terminals.

Figure 7: 1:3 Scaled truck and trailer combination used for first developments and MVP testing.

In order to make the original acquired vehicle (Scaled-Rigs, 2018) eligible for testing of UC4.2a several modifications were needed. The vehicle was modified into a ‘drive-by-wire’ vehicle. For this, a DC motor with an encoder was installed on the steerable axle in order to enable the truck steer-by-wire functionality. Furthermore, the motor controller for the longitudinal control was tuned so that it was configurable with the actuation signals of both the teleoperation system and the autodocking functionality. This all was combined with an OLIMEX E407 microcontroller that could receive actuation signals from either the teleoperation centre or the autodocking functionality via CAN and actuate the corresponding actuators accordingly i.e., DC steering motor and DC drive motor. A 12V Battery was installed to power the RTK GPS system for localization. Figure 8 shows the process of modifying the scaled truck.

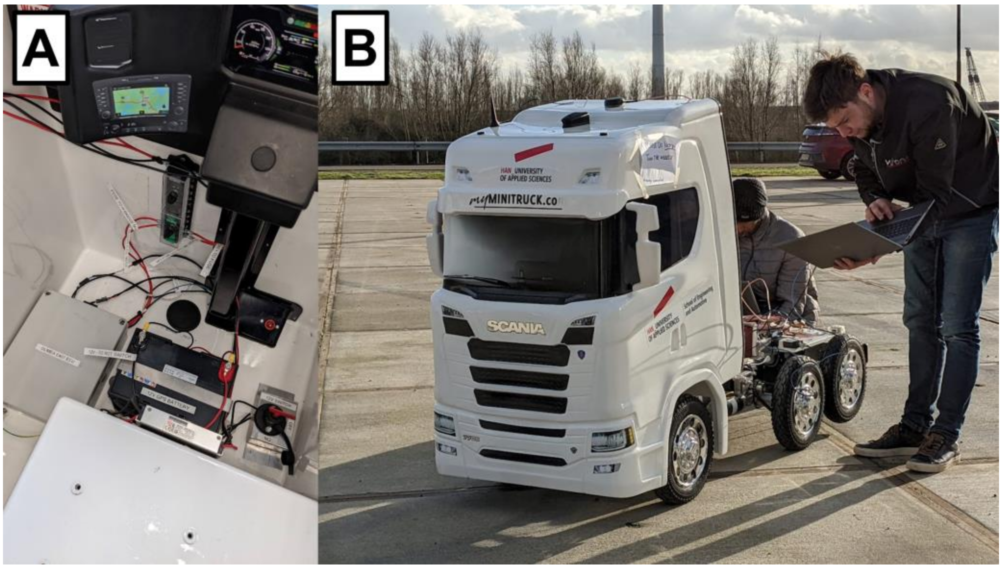

Figure 8: A) Wiring and hardware inside truck cabin. B) First 'hardware in loop' testing.

Next to making the scaled truck drive-by-wire, the RTK GPS hardware was installed together with the teleoperation hardware. As mentioned, the teleoperation hardware consists of six cameras, a router and a drive-by-wire controller that outputs the teleoperation steering signals in CAN to the microcontroller of the scaled truck.

Figure 9 shows the scaled truck and trailer after all the modifications in working state as used for the MVP testing[1] described in deliverable D7.2.

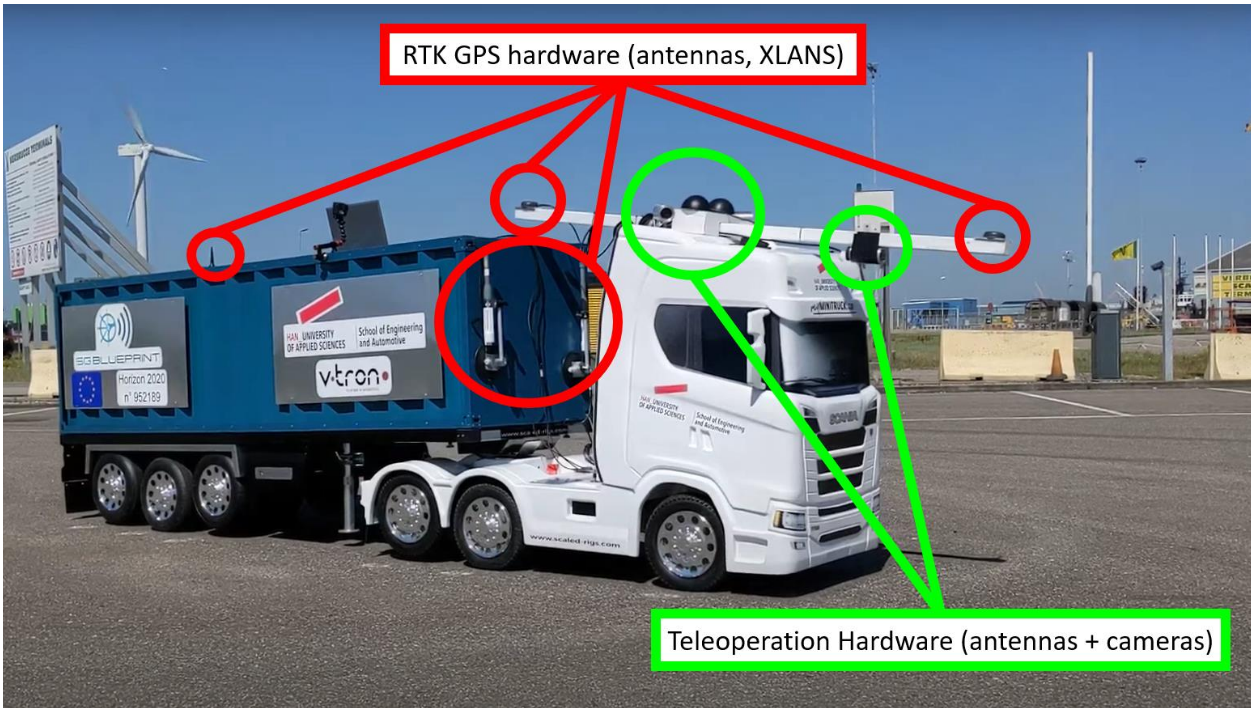

Figure 9: Scaled Truck and Trailer as used during the MVP testing.

[1] Note that the RTK GPS antennas on the tractor are placed on a beam. This is done since the antennas need to be a certain distance apart for optimal operating conditions.

2.1.4.2 Full-scale truck and trailer combination

The second vehicle is a full-scale DAF XF truck with a container chassis trailer as shown in Figure 10. Once the MVP testing phase of UC 4.2a was completed, this truck was used for the full-scale development phase of the use-case.

Figure 10: DAF XF with container chassis trailer.

The DAF XF had to be modified to be suitable for both teleoperation and autodocking. The main modifications that needed to be made were done to convert the DAF XF into a drive-by-wire vehicle which was not the case in its original state. To make the DAF fully drive-by-wire, the following modifications had to be made.

- Replace original steering wheel for a steering wheel with an electrical motor as shown in Figure 11.

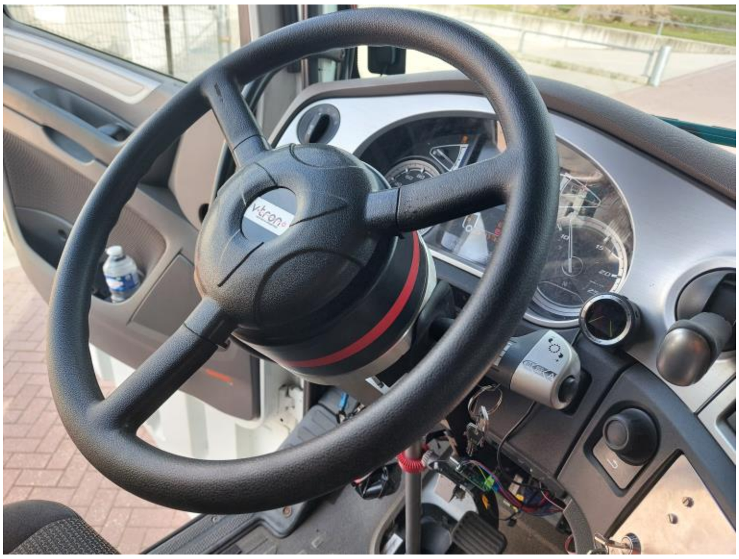

Figure 11: Electrical motor under steering wheel for electric steering control.

- Add electrical motor with cam on the brake pedal for electrical braking as shown in Figure 12.

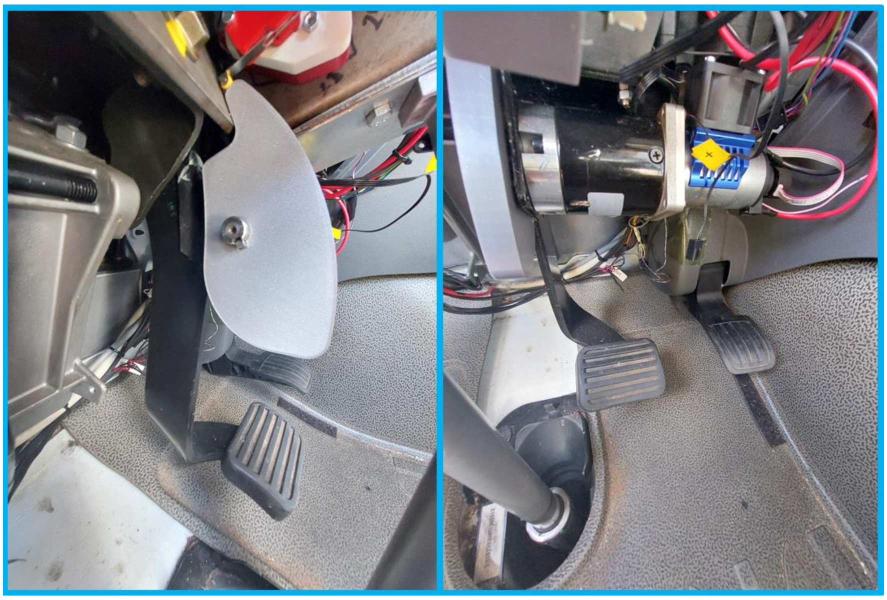

Figure 12: Electric motor with cam on existing brake pedal.

- Use original CAN throttle signal for electrical throttle response.
- Add servomotor on the gear shifter for electrical gear shifts as shown in Figure 13.

Figure 13: Servomotor with 3D printed mount on original gear shifter.

All modifications to the DAF were done in such a way that normal operating of the vehicle is still possible. A manual override is therefore always possible and realised by pressing the emergency buttons as shown in Figure 14. As can be seen, two emergency buttons are present. A ‘hard’ and a ‘soft’ shut-off. The soft shut-off only shuts of the electrical driving components i.e., the steering wheel motor, braking motor and throttle overwrite. Pressing the EPO (Emergency Power Off) soft button enables manual driving. The EPO hard button shuts off all electrical components plus the ECU’s attached to it. This button can be pressed in case of emergencies or to reset the drive-by-wire system.

Figure 14: Emergency buttons (‘hard’ and ‘soft’ shut-off).

Next to making the truck drive-by-wire, the teleoperation hardware developed, implemented and tested in the MVP was installed in the DAF XF. The box that contains both the routers and the additional hardware needed (micro-controllers, ethernet splitters, CAN output, etc.) is shown in Figure 15.

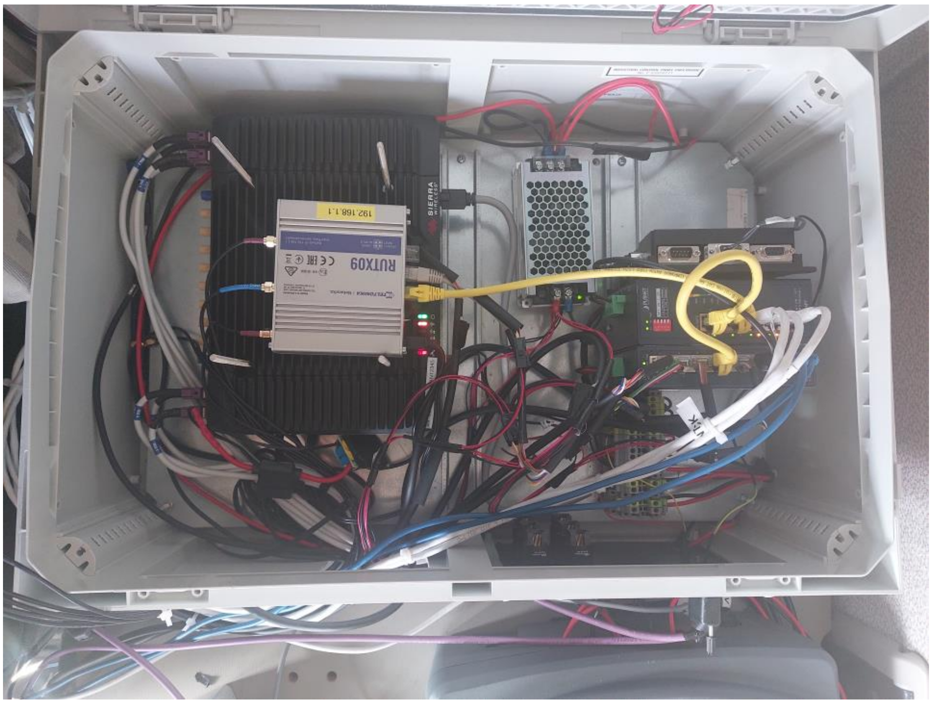

Figure 15: Teleoperation hardware inside truck cabin.

Furthermore, the six cameras were mounted on the truck. Determining the right position took some time and still can be modified. This is something that will be extensively discussed in Chapter 6, *“Human Machine Interface testing”*. The mounting positions of the cameras is shown in Figure 16.

Figure 16: Camera mounting positions.

2.2 Software

Next to developing the hardware, the software algorithms for the autodocking functionality were also developed. The software architecture consists of three parts. A high-fidelity vehicle model, the path planner and the path tracking controller discussed hereafter.

2.2.1 High-Fidelity Vehicle Model representation

The first step in testing the autodocking functionality is to model and simulate the vehicle in the target environment. This involves modelling the vehicle-infrastructure interaction since distribution centres often contain sloped docks, and hence, the feasibility to perform autonomous manoeuvres in such environments has to be evaluated. The model also offers the possibility to test and simulate controller performance. Independent models for the tractor-semitrailer and the road surface are required that can interact together via tyre models. The following sub-sections describe the multi-body model of the tractor-semitrailer and the virtual environment and road surface that together make up the high-fidelity model representation.

2.2.1.1 Multi-body vehicle model

When low speed manoeuvrability is considered, typically simplified kinematic models are used. A kinematic model is a simplified representation of the motion of a vehicle. It focuses solely on describing the movement, position, and velocity of the vehicle combination, using mathematical equations and geometric relationships. Tyre slip phenomenon can also be modelled into kinematic equations of motion; however, they involve added complexity, lack of modularity, fail to capture the suspension dynamics, and crucially, do not interact with infrastructure models.

Figure 17: Multi-body tractor-semitrailer model in the virtual test site.

To overcome the limitations of kinematic models, multi-body modelling methodologies are used. The multi-body formalism of the vehicle dynamics of a tractor-semitrailer using a tool such as MATLAB's Simscape (Mathworks, Simscape Multibody, Model and simulate multibody mechanical systems, 2023), automatically generates equations of motion for vehicle components which significantly influence the vehicle dynamic behaviour. A library of heavy vehicle components called the Commercial Vehicle Library is used, consisting of pre-modelled and fully parametric vehicle assemblies (e.g., truck, trailers, semitrailers, etc.) and additional vehicle components (brake system, driveline, etc.). This library of models in Simscape is validated using actual test data (Kural, 2019). Figure 17 shows the tractor-semitrailer modelled in Simscape's virtual environment.

2.2.1.2 Infrastructure model

Figure 17 also shows the modelled test site. The infrastructure model includes the actual surface profile of the distribution centre. To achieve this, the Curved Regular Grid (CRG) road model standard is used to model road sections to perform any manoeuvre of interest. CRG offers the ability to model road sections with parameters such as roughness, width, curvature, banking, and also custom surface profiles, the latter of which is used in this project. The TNO Delft-Tyre modelling package for MATLAB provides the resulting vertical, lateral and longitudinal forces of the tyres, by employing the Magic Formula tyre model (Besselink, 2006). These tyre models have the ability to interact with the CRG road surface. Figure 18 shows the modelled road surface of the pilot test site.

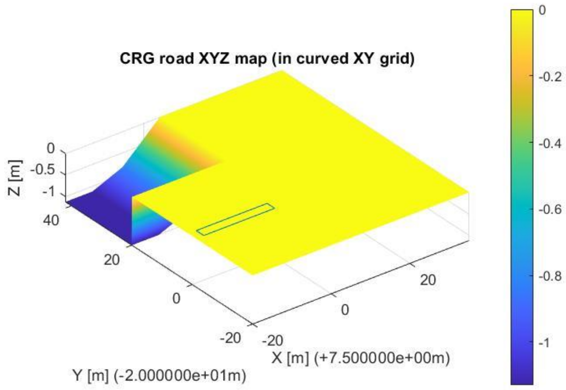

Figure 18: CRG road surface model of the test site.

2.2.2 Path Planner

The path planner's primary role is to create a viable path from the initial autodocking position to the desired dock, facilitating vehicle manoeuvring. It must consider non-holonomic constraints, the environment's layout, and the start and final dock locations, which can in principle be arbitrary positions in 2D space.

The environment is represented as polygons, defining free spaces and static obstacles. Knowledge of final dock position is essential and is considered as input provided by warehouse management system connected to ETA (Established Time of Arrival). In Figure 19, blue polygons depict free manoeuvring areas, while red ones indicate static obstacles. The RTK GPS system establishes the map using a local coordinate frame and arbitrary heading, aligning features accordingly. Figure 19 illustrates one of the test sites.

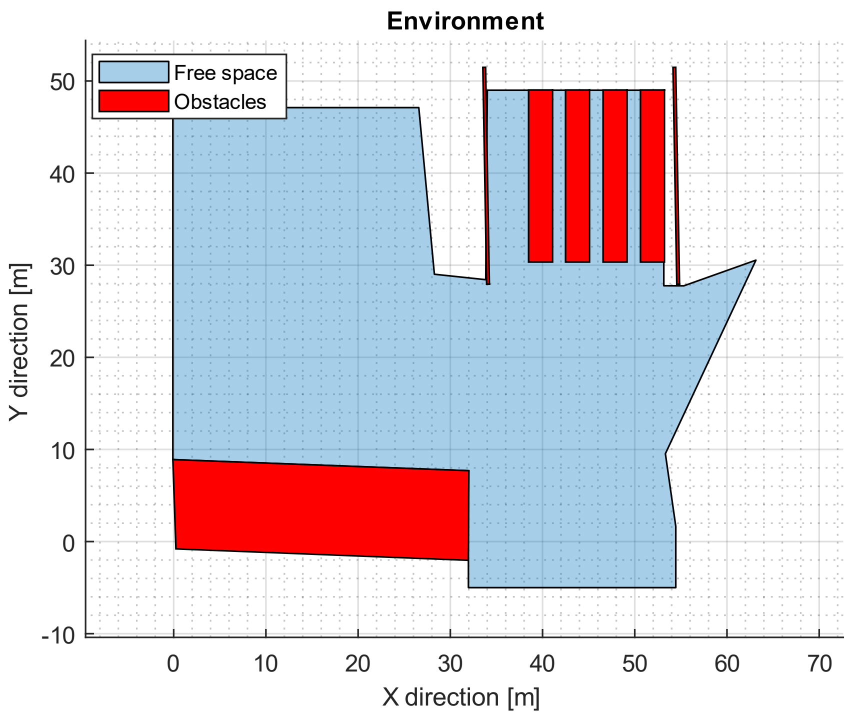

Figure 19: Environment description of Distribution centre in path-planner.

A lattice-based path planner was initially developed, where the environment is divided into set of discrete states. These states encompass the vehicle's centre position in the x and y directions, yaw angle, and articulation angle (Devasia, 2019). The primary goal is to find a path that connects two discretized states: the initial state when autodocking is initiated and the final state at the docking location within this discretized environment. The scaled truck's initial state comes from onboard GPS units, while the final position is received via the EF7 message, including Established Time of Arrival (ETA) and dock ID.

To navigate between these discrete states in the environment, the planner computes path segments known as motion primitives. These are essential because a tractor-semitrailer cannot move freely in all directions and must adhere to specific paths between discrete states. These motion primitives are derived by solving an optimal control problem, taking into account the articulated vehicle's kinematic equations and physical constraints on its parameters. This approach ensures that the generated paths are kinematically feasible for the vehicle yet optimised for specific cost function. Detailed information on formulating the optimal control problem, defining a cost function for parameter optimization, and handling kinematic constraints is available in (Devasia, 2019) and (Kannan, 2021). Solving this optimal control problem yields optimal motion primitives connecting any two discretized states. Figure 20 illustrates the motion primitives generated for a single articulated tractor-semitrailer combination at initial yaw angles of 0° and 45°.

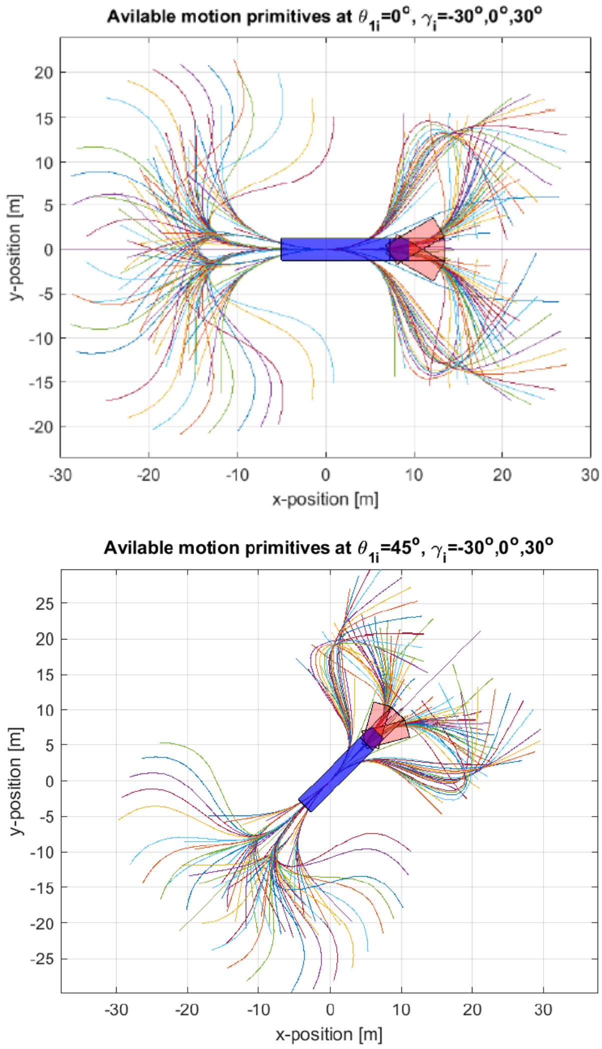

Figure 20: Motion Primitives for the initial angles $\theta_{\{1i\}} = 0°$ (above) and $45°$ (below), red and blue rectangles represent the truck and semitrailer, respectively.

After the generation of the motion primitives and defining the environment, an algorithm is required to find a combination of these motion primitives to traverse from one point in the environment to the other. For this purpose, the graph search algorithm A* algorithm is used. The A* algorithm is explained in detail in (Devasia, 2019). The A* algorithm works with a collision detection module (Devasia, 2019) which checks for collisions while planning the paths so that the paths that are generated avoid all the polygonal obstacles.

2.2.2.1 Path Planner improvements

The original path planner was rigorously tested with on the scaled truck and trailer combination (MVP), revealing certain drawbacks. In the densely crowded docking environment where obstacles closely approach the vehicle combination, fine grid discretization becomes essential. However, the sheer volume of possible grid combinations posed challenges for convergence, despite efforts to optimize processing time. Consequently, an alternative solution was needed. The prior path planner, although offering flexibility and optimal bidirectional paths, suffered from issues of completeness, discretization errors, and very demanding computational time.

The new path planner that is developed is a versatile combination of a Bezier curve generator and a kinematic tractor semitrailer model with a path following controller. Initially, the system acquires the semitrailer's initial axle position via onboard GPS (RTK GPS) and the required dock information from EF7. These inputs are pivotal for generating the path for the specific vehicle combination. Based on how the driver prepares for the docking manoeuvre, either the bidirectional or the unidirectional reverse path planning algorithm is executed. It is determined by the relative position of the dock with respect to the position and orientation at which the autodocking operation is triggered. When the bidirectional algorithm is triggered, an intermediate point is established for bidirectional docking. This can be tuned for different environments where the path planner is deployed. It is defined with respect to the dock position (laterally and longitudinally) and the angle of the semitrailer in this intermediate position is also tuned with respect the environment. Figure 21 showcases an intermediate point for the 4th dock in this particular environment.

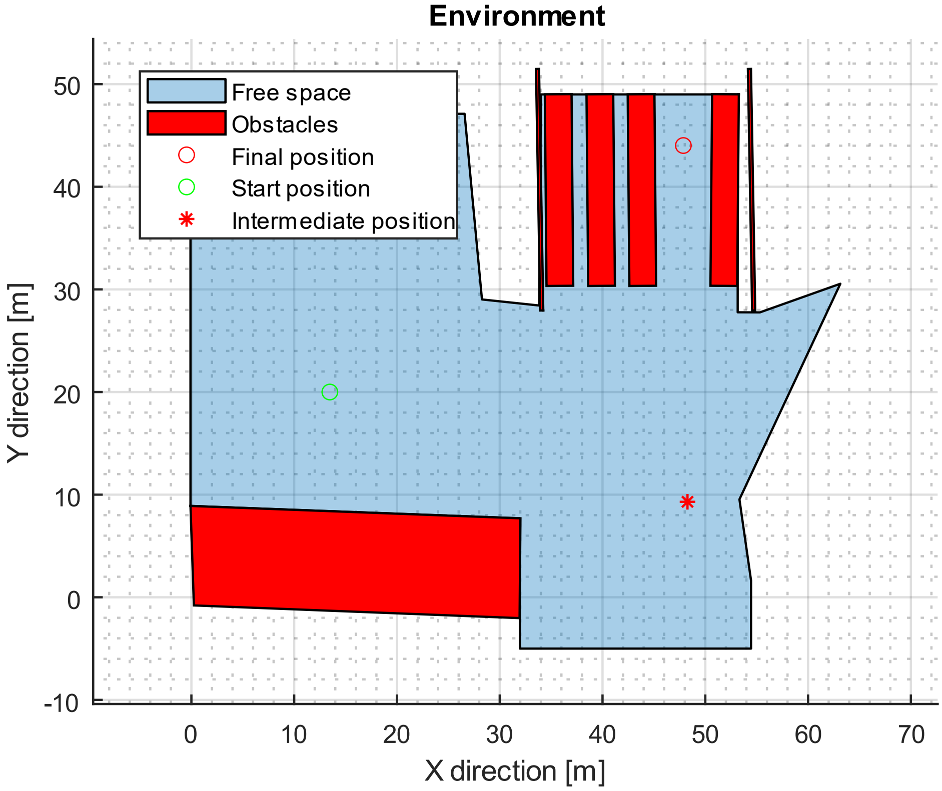

Figure 21: Establishing the intermediate point.

The problem now simplifies to creating kinematic paths: from start to the intermediate point in the forward direction and from the intermediate to final positions in reverse. This is where Bezier curves and the kinematic path-following vehicle model come into play. Various Bezier curves, each with distinct curvatures and guide points shown in Figure 22, connect these respective points. The direction t_i represents the initial orientation of the vehicle and t_f denotes the final. The curve with the lowest maximum curvature is chosen as input for the path tracking controller, which operates on a kinematic vehicle model.

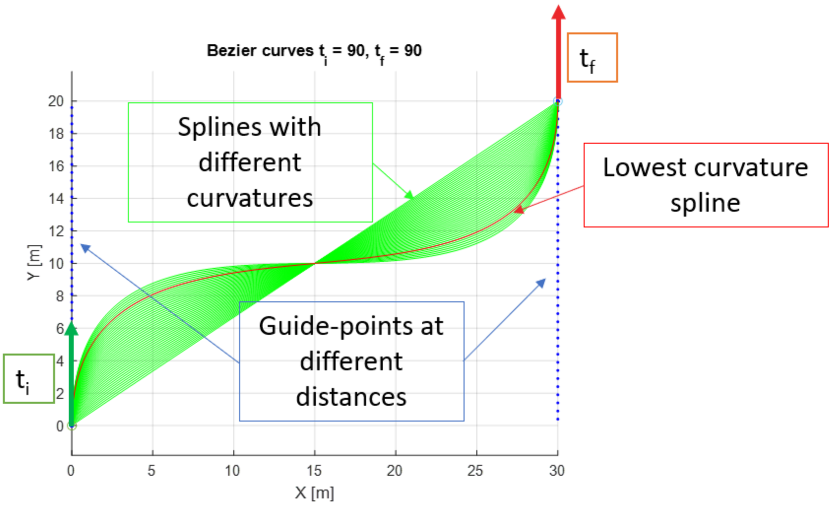

Figure 22: Bezier curve creation.

These curves are then used by the path following controller as a reference trajectory. The kinematic model is then simulated over the reference Bezier curves to obtain the trajectory which is taken by the tractor semitrailer model. The trajectory undergoes collision checks with static obstacles. If collision-free, it proceeds to the path-following controller for the actual truck to follow. The complete path is visualized in Figure 23. In conclusion, this path planner framework is highly adaptable and customizable for diverse docking environments. While setup time is a consideration, it ensures the generation of smooth, low-curvature paths using Bezier curves and a kinematic model. Path planning is deterministic and comprehensive, with predictable computational time, approximately 1.5 seconds on a laptop with Intel(R) Core(TM) i7-8750H CPU @ 2.20GHz processor and 16 GB of RAM.

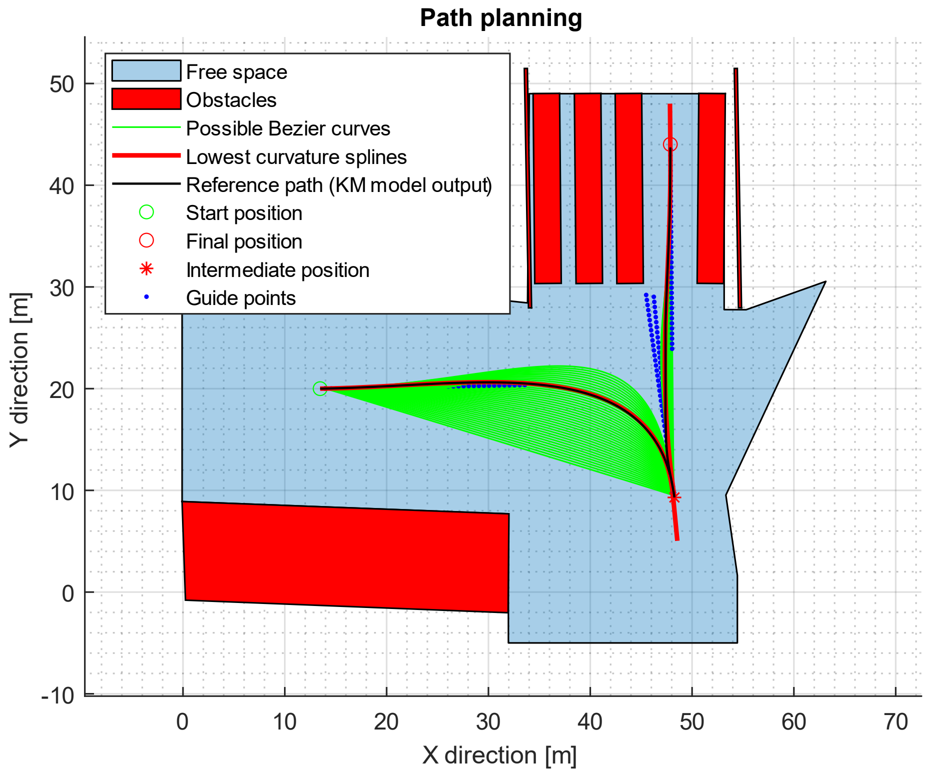

Figure 23: Bidirectional planned path.

2.2.3 Path Following Controller

Two types of Path Following controllers are used for this use-case.

2.2.3.1 Pure Pursuit Control (PPC)

The Pure Pursuit Control (PPC) algorithm in combination with kinematic inversion described in (Kural, 2019) was implemented as the path tracking controller for the MVP and the first tests on full-scale. This algorithm computes the angular velocity required to move the tractor-semitrailer from its current position to reach waypoints along the calculated reference path. The linear velocity is not controlled by this algorithm since the autodocking functionality works with constant speed set points.

To steer a vehicle along a path, the PPC needs some inputs: the vehicle position $[x, y, orientation]$ and the reference path (planned path of path planner). The reference path contains 1000 set of desired $[x, y]$ points, which are the waypoints. Based on the real-time vehicle pose and the waypoints, the algorithm looks ahead from the vehicle and steers accordingly as shown in Figure 24.

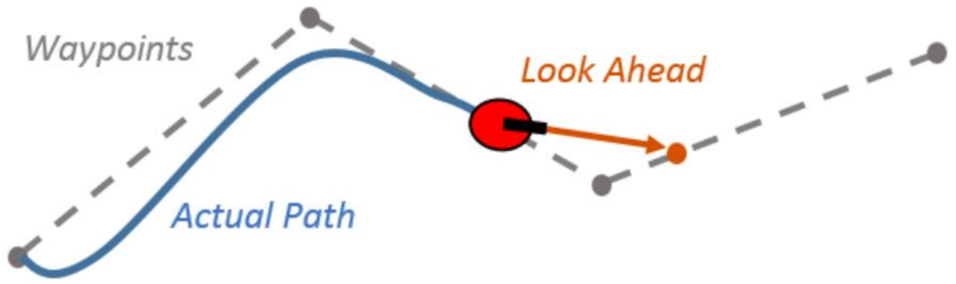

Figure 24: Pure Pursuit Controller following waypoints.

However, to control a tractor-semitrailer which is an articulated vehicle where the semitrailer axle needs to follow the reference path instead of the steering axle, an additional step is required. Inverse kinematics equations of motion is the additional step that converts the PPC output (angle that semitrailer needs to turn) to the steering wheel angle on the tractor.

Equations of motion are derived based on the Figure 25, where the steering angle δ can be computed based on the known semitrailer pose $[(x_1, y_1), \theta_1]$ and articulation angle γ_1 (from the RTK GPS system).

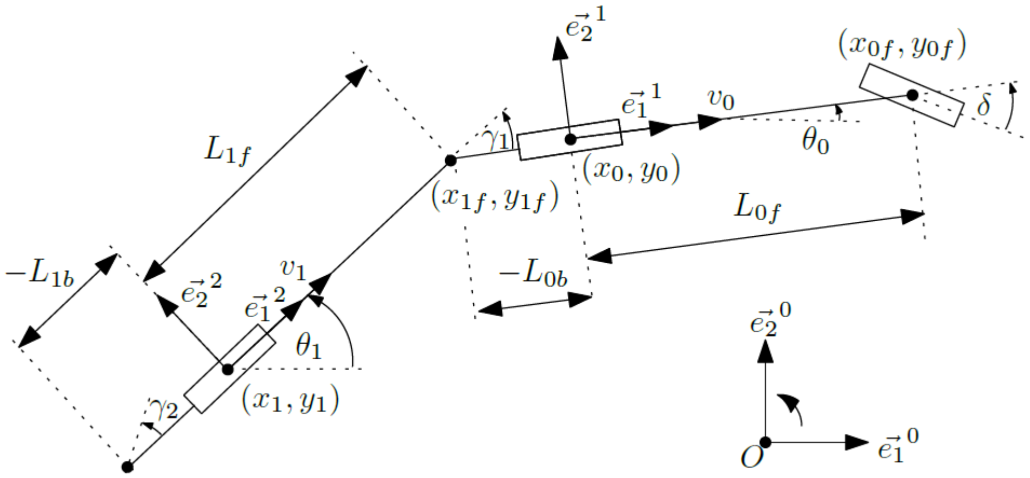

Figure 25: Kinematic representation of the tractor-semitrailer (Kural, 2019).

The PPC allows for tuning the lookahead distance, which is the distance shown in red in Figure 24. This parameter is tuned to achieve a smooth driving behaviour while also following the reference path accurately.

2.2.3.2 Model Predictive Control (MPC)

Based on learnings from MVP phase and in order to improve the robustness of the path tracking controller (dealing with steering offsets, slow steering response of the full-scale truck, tyre slip, varying trailer lengths, network latency jitter, localization inaccuracies, etc.), an advanced control technique known as Model Predictive Control (MPC) was developed and subsequently implemented on the full-scale truck.

The MPC described extensively in (Dekker, 2022) is capable of effectively controlling non-linear Multiple-Input and Multiple-Output (MIMO) systems. The MPC algorithm optimizes the navigation objectives and vehicle behaviour over a finite time window, using online numerical optimization tools. This allows the controller to compensate for deviations from the reference path caused by a range of factors, including dynamical limitations, measurement noise arising from GNSS localization, and process noise from the steering actuator. Figure 26 shows this concept in the timeline graph, where the MPC predicts the vehicle behaviour given certain inputs over a prediction horizon. Thus, by utilizing MPC we are able to achieve accurate and reliable steering control for our vehicle combination.

A discrete-time nonlinear model is used to predict the state evolution of the vehicle over the prediction horizon. At each time step, when new localization measurement is provided by the RTK-GPS, an optimization problem is solved to compute the optimal sequence of control inputs. In this implementation, the MPC is made to minimize a cost function. This cost consists of three terms which aim at minimizing the tracking error, while following a desired reference velocity and suppressing large adjustments of control inputs (this term allows the controller to provide smoother steering instructions to the driver). Furthermore, the controller considers the dynamics and vehicle limitations, such as the maximum steering rate and articulation angles, as constraints. This implementation improves upon the PPC due to the added optimization and the ability to deal with non-ideal situations.

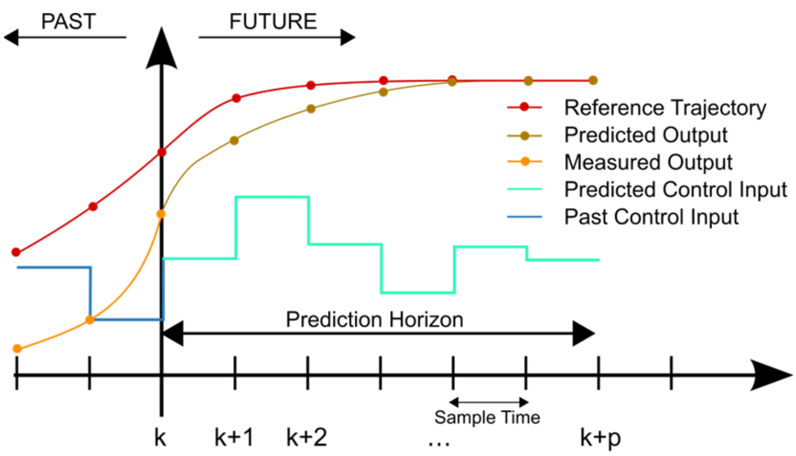

Figure 26: Model Predictive Control working over a prediction horizon (Wikipedia, 2023).

To ensure that the MPC runs on the teleoperation centre PC, the FORCES PRO solver for MPC is used (Mathworks, FORCES Pro, 2022). This solver generates an efficient code of the MPC such that the controller can run in real-time. The implementation of this is shown in Figure 27. The MPC in MATLAB's Simulink is optimized by the FORCES PRO, while the rest of the structure (reference path generation, RTK GPS, etc.) remains the same.

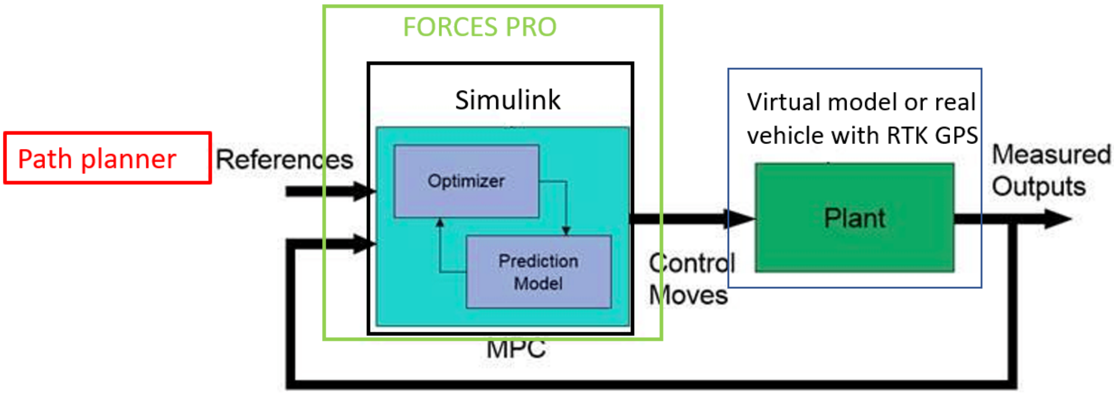

Figure 27: Use of FORCES PRO solver with MATLAB.

3 FUNCTIONAL ARCHITECTURE & INTEGRATION

3.1 Functional Architecture

The Autodocking with the driver in the loop Use Case deployed on the full-scale prototype is a combination of teleoperation and fully automated functionalities and shares the necessary data for the relevant EFs. Figure 28 shows the schematic of this architecture and can be divided into two main parts, the first / upper part being the architecture of the system in the teleoperation centre and the second / lower part being the one in the teleoperated vehicle. Table 2 shows the different signals send over the 5G communication network. The connection type, used in Figure 28 can also be found in the table for cross-references describing name of signals, units, type of protocol, and sampling frequency.

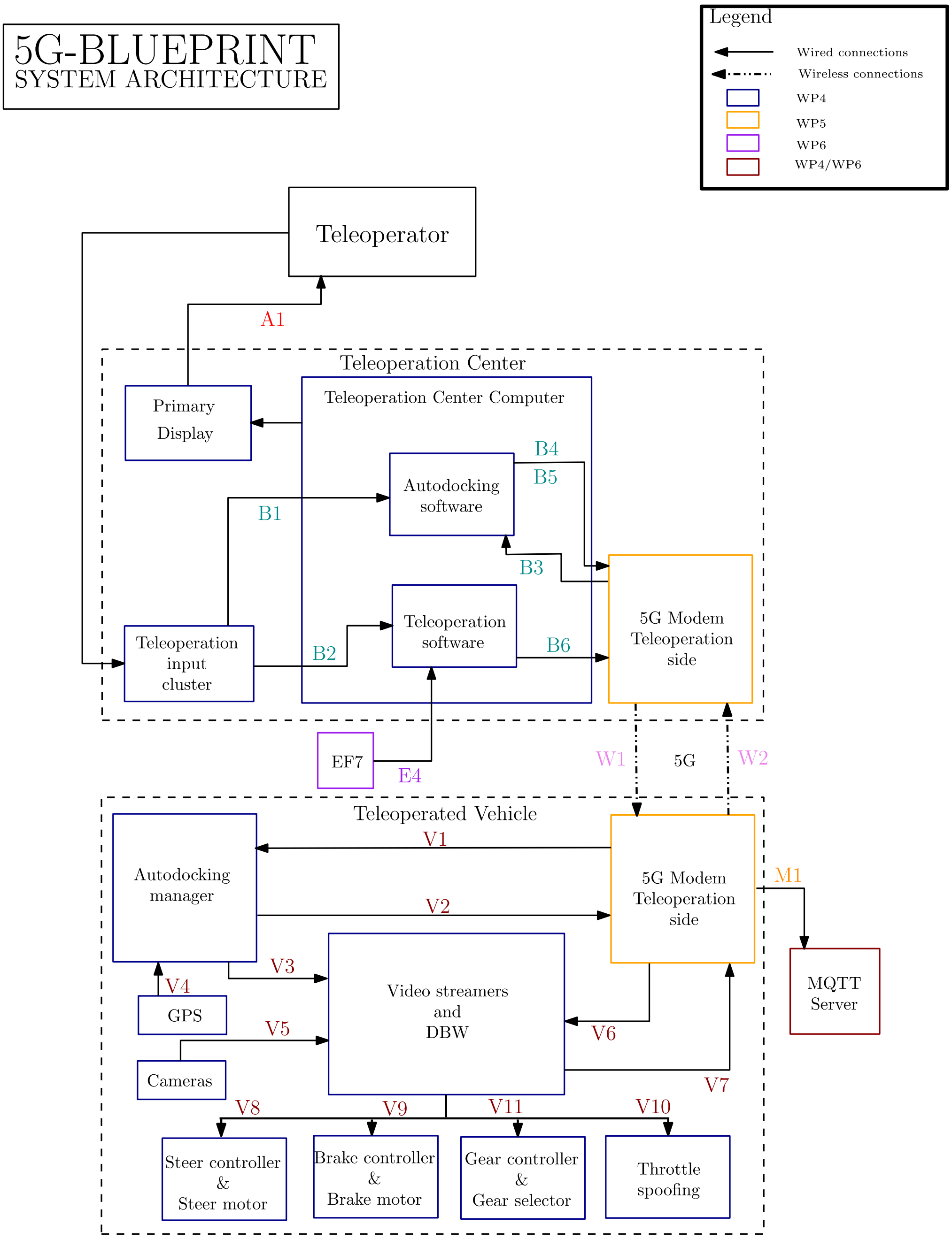

Figure 28: System software architecture.

Table 2: The different signals send over the 5G communication network.

Connection	Signals	Units/Values	Protocol	Frequency (Hz)
A1	Video stream	-	-	30fps
	Speed	km/hr		
	Driving mode	[teleoperation/autodocking]		
	Gear selected	[RT,R,N,D,DT]		
B1	Autodocking activation	[1/0]	-	On demand
B2	TO Steering	[-]	-	50
	TO Brake	[-]		
	TO Throttle	[-]		
	TO Gear	[-]		
	Teleoperation activation	1/0		
	Autodocking activation	1/0		
B3	Position	[m]	TCP/IP	20
	Yaw angles	[deg]		
B4	AD Steering	[-1.0,1.0]	TCP/IP	20
	AD Throttle	[0,1.0]		
	AD Brake	[0,1.0]		
	AD Gear	[254,255,3,4,5,6] = [RT,R,N,D,DT]		
B5	Planned path	m	TCP/IP	-
B6	Steering	[-1.0,1.0]	UDP	50
	Throttle	[0,1.0]		
	Brake	[0,1.0]		
	Gear	[254,255,3,4,5,6] = [RT,R,N,D,DT]		On demand
E1	Speed advice	[-]	-	-
	Warning	[-]		
	Routing messages	[-]		
E2	Collison Warning	[-]	-	-
E3	Shared world model with detected objects' pose	[-]	-	-
E4	ETA	hr or mins	HTTP	On demand

	Dock number		[-]	Server	
W1	Vehicle + System control messages		[-]	TCP/IP or UDP	Various freq. from source
W2	Video streams		[-]	UDP	30 frames
	GPS signals		Inherited	TCP/IP	20
	Vehicle telemetry		Inherited	UDP	50
V1	AD Steer angle		[-1.0,1.0]	TCP/IP	20
	AD Throttle		[0,1.0]		
	AD Brake		[0,1.0]		
	AD Gear		[254,255,3,4,5,6] = [RT,R,N,D,DT]	TCP/IP	On demand
V2	GPS Position		m	TCP/IP	20
	GPS Yaw angles		deg		
	GPS Speed		m/s		
	Tracking error		m		
V3	AD Steer angle		[-1.0,1.0]	CAN	20
	AD Throttle		[0,1.0]		
	AD Brake		[0,1.0]		
	AD Gear		[254,255,3,4,5,6] = [RT,R,N,D,DT]		On demand
V4	GPS Positions		m	CAN	50
	GPS Yaw angles		deg		
V5	Video Streams		[-]	UDP	30
V6	TO Steer angle		[-1.0,1.0]	UDP	50
	TO Throttle		[0,1.0]		
	TO Brake		[0,1.0]		
	TO Gear		[254,255,3,4,5,6] = [RT,R,N,D,DT]		On demand
	TO and AD activation		[1/0]		On demand
V7	Vehicle telemetry	Speed	m/s	UDP	50
		Steering radius	rad		

	Driving mode TO and AD activation	[1/0]		On demand
V8	Steer signal	[-1.0,1.0]	CAN	100
V9	Brake signal	[0,1.0]	CAN	100
V10	Throttle signal	[0,1.0]	CAN	100
V11	Gear Selector	[254,255,3,4,5,6] = [RT,R,N,D,DT]	CAN	100
M1	GPS Position	m	TCP/IP	20
	GPS Yaw angles	deg		
	GPS Speed	m/s		
	Tracking error	m		
	Planned path	m		On Demand

(TO = Teleoperation, AD = Autodocking)

3.2 Remote Autodocking Functionality

In order to run the autodocking functionality remotely from the teleoperation centre, the system needs to be able to communicate with number of the systems in the truck. As previously mentioned, the teleoperation hardware on the truck enables remote connection from the truck side. A similar strategy is used on the teleoperation centre side consisting of a 5G router to enable the teleoperation centre to communicate with the truck. Figure 29 shows how the teleoperation PC is made to be available for autodocking.

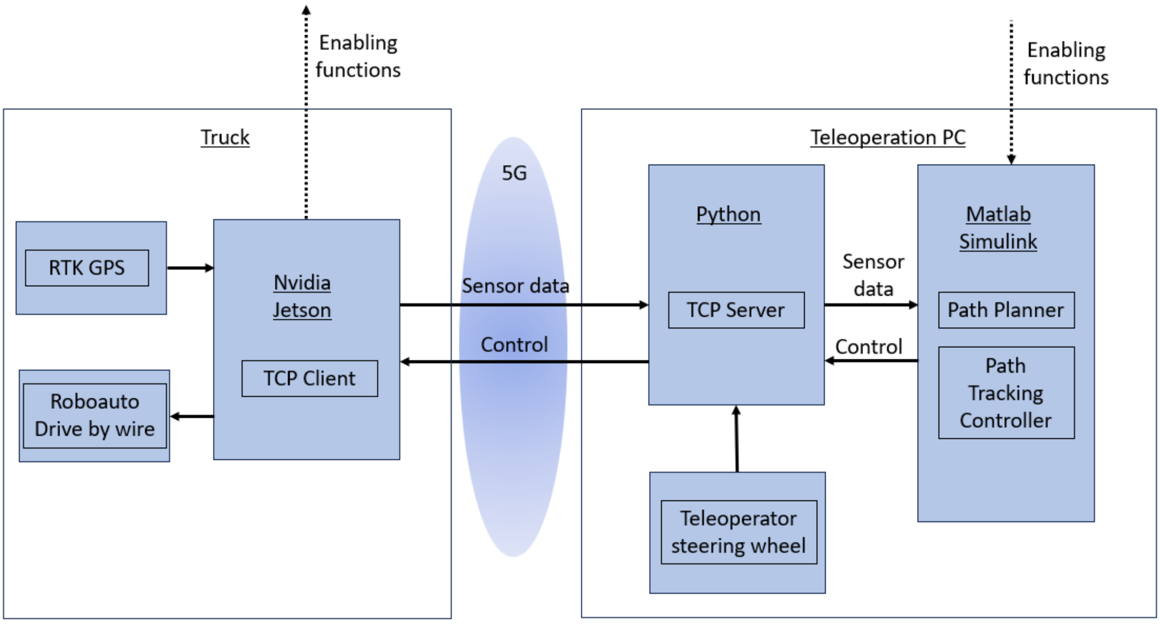

Figure 29: Remote autodocking functionality implementation.

3.2.1 Setup on the truck

An Nvidia Jetson TX2 computing board is installed in the truck that performs multiple tasks:

- Gathers the RTK GPS data through Controller Area Network (CAN) communication.
- Sends the sensor data to the teleoperation PC via 5G.

- Receives the control inputs from the teleoperation PC via 5G.
- Sends autodocking control inputs to the Roboauto drive-by-wire system.

The communication via 5G is done through the use of a TCP (Transmission Control Protocol) client-server system. The truck side is a TCP Client that is constantly connected to a TCP server in the teleoperation PC.

3.2.2 Setup on the teleoperation PC

In the teleoperation PC, two sets of software are running. One is the TCP server running in Python and another is the actual path planner and path tracking controller running in MATLAB/Simulink. The TCP server is always running regardless of whether or not the teleoperator wants to perform autodocking. When the teleoperator decides to use the autodocking function, the following sequence of actions takes place:

- The TCP server receives the button press of autodocking function from the steering wheel, which triggers the following steps.
- The initial pose of the vehicle is taken from the sensor data, this is passed on to the MATLAB/Simulink environment.
- The path planner uses this initial pose and the target dock information from the enabling functions, to generate a reference path.
- The path tracking controller then takes control of the vehicle via the TCP server – TCP client – Roboauto drive-by-wire.
- The teleoperator can continuously view the reference path, the real-time video of the vehicle, and can choose to use the brake or take back control anytime.

3.3 Network integration

Exact details of the process of sending control signals and receiving camera streams, vehicle telemetry and GPS data via the 5G network is outside of the scope of this use case, therefore no further details will be given on the 5G network integration. For more details about the network integration and performance, please see 5G-Blueprint deliverable D5.4, "*Final report on the 5G network evaluation*". However a few words are given on the necessity of the 5G network for this use-case.

- First of all, a lot of data has to be sent and received via the wireless network, e.g., control signals, commands, 6x video streams, GPS data, etc. The amount of data can result in challenges when it comes to wireless networks, for example with 4G. 5G has more capacity and bandwidth, therefore being able to handle the vast amount of data for use cases as teleoperation and automated-driver-in-the-loop-docking.
- Another important parameter is speed / latency. Higher latencies can have negative effects, especially for teleoperation, but also for autodocking purposes. Due to the limited space at the distribution centres precise and accurate control is necessary. Having delays will increase complexity. To a certain extent this can be taken care of by the path following controller. However, when the delay is too high (>100 ms) it might not be possible to perform the autodocking functionality anymore within the limits. Low latency i.e., less than 100 ms is therefore key for an automated docking functionality.
- When looking into the business-case of autodocking it makes more sense to autonomously dock multiple tractor-trailer combinations at once at distribution centres. For this, not only a powerful computer and controller is necessary but also a network that can deal with vast amounts of data, at very high speed / with low latency. When operating certain functionalities all at the same time it can be questioned whether networks like 4G can handle this.
- Another business-case aspect is the localization of the tractor-trailer unit. As of now, this

is done with the OXTS RTK system, a high-end system. The main expense of this system is the base station, which is used to get differential corrections to the onboard GPS units. However, a 5G network can also provide cloud based differential corrections, provided by the base stations inside the cell-towers via a NTRIP connection. Having these corrections available at all times can increase the usage of functionalities like autodocking, something that 4G[2] does not offer.

3.4 EF integration

When the truck arrives at the distribution centre, the autodocking sequence requires the final dock number for initiation. This information is sourced from EF 7, which shares the ETA and destination details for the truck's docking. The HTTP server set up by Be-Mobile provides the necessary dock number by querying the distribution centre's location in a specified web address, responding with the truck ID, ETA, and dock number in string format.

The enabling functions require data sharing from this use case. The EFs require real-time information about the truck-trailer's position as well as the reference path of autodocking sequence. Hence, Table 3 shows the data that is shared with other EFs.

Table 3: Data shared with Enabling Functions.

Category	Message structure	Data
Tractor position	cell array	Longitude (earth fixed coordinate system) or X (local coordinate based on an origin at test site) Latitude (earth fixed coordinate system) or Y (local coordinate based on an origin at test site) Heading angle Longitudinal speed Yaw rate
Tractor inputs	cell array	Reference set point for steer angle Reference set point for speed
Semitrailer position	cell array	Longitude (earth fixed coordinate system) or X (local coordinate based on an origin at test site) Latitude (earth fixed coordinate system) or Y (local coordinate based on an origin at test site) Heading angle Longitudinal speed Yaw rate

[2] KPN has done some tests with these NTRIP differential corrections via the 5G network. And even though the tests were very limited, and not tested with this use-case, the results looked very promising.

		Tracking error
Path information	cell array	Reference path in earth fixed coordinate system or local coordinates.
		Final pose available from reference path

This data is uploaded in real-time at 100 Hz to an MQTT[3] server. This is done via the Roboauto's drive-by-wire system. All the data listed here is available in the Nvidia Jetson device in the truck. The Jetson continuously shares the above table data to the drive-by-wire system, which in-turn uploads the data to the server.

[3] MQ Telemetry Transport.

4 TEST PLAN

4.1 Pilot Sites

4.1.1 Scaled prototype pilot sites

As mentioned earlier, the autodocking functionality was first developed on a 1:3 scaled truck-trailer combination (the Minimum Viable Platform).

The different development tests performed with the scaled combination were performed on the parking deck of HAN University of Applied Sciences. It contains a flat concrete surface, resulting in good grip, minimum slip and no inclinations. Furthermore, it offers sufficient space and flexibility to perform the different tests. Figure 30 shows the parking deck pilot site, including the 1:3 scaled truck trailer combination.

Figure 30: Parking Deck test site at HAN University of Applied Sciences.

Furthermore, the autodocking functionality was also tested and performed at the premises of Verbrugge Scaldia Terminals located in Vlissingen (Netherlands) during the 2022 June formal review meeting. The pilot site was also a concrete parking lot with some minor inclination, as can be seen in Figure 31.

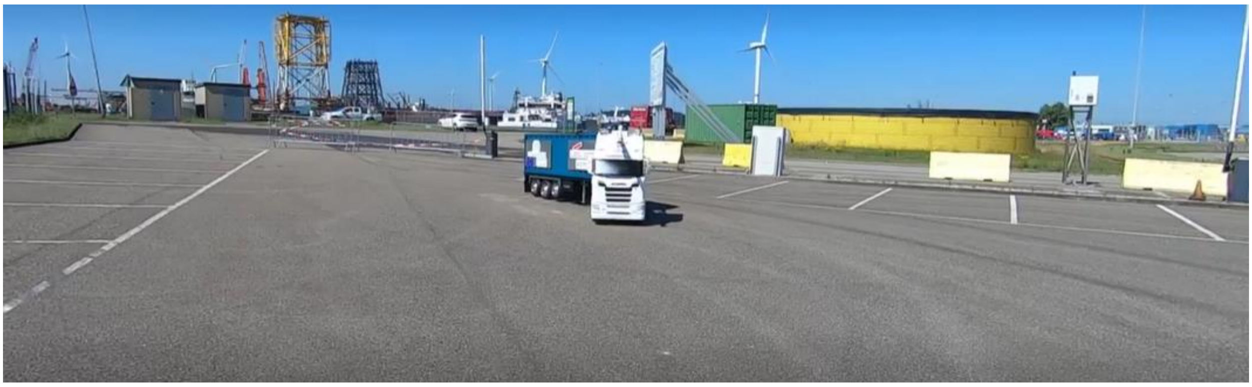

Figure 31: Pilot site at Verbrugge Scaldia Terminals at the 2022 June review meeting.

4.1.2 Full Scale MSP Onions pilot site

At the last instance, the autodocking functionality was tested on a full-scale combination at the site of MSP Onions, shown in Figure 32, offering sufficient space and flexibility to deploy Use Case 4.2a. The test site can be categorized into docking area consisting of five docking stations (light grey tarmac in Figure 33) and a parking lot where trucks and cars can park and where shunting manoeuvres can be made (Dark grey tarmac in Figure 33).

Figure 32: MSP Onions test site frontal view.

Figure 33: MSP Onions test site top view satellite photo.

Exact measurements of the overall terrain were done at the site and technical drawings were made to provide more insight.

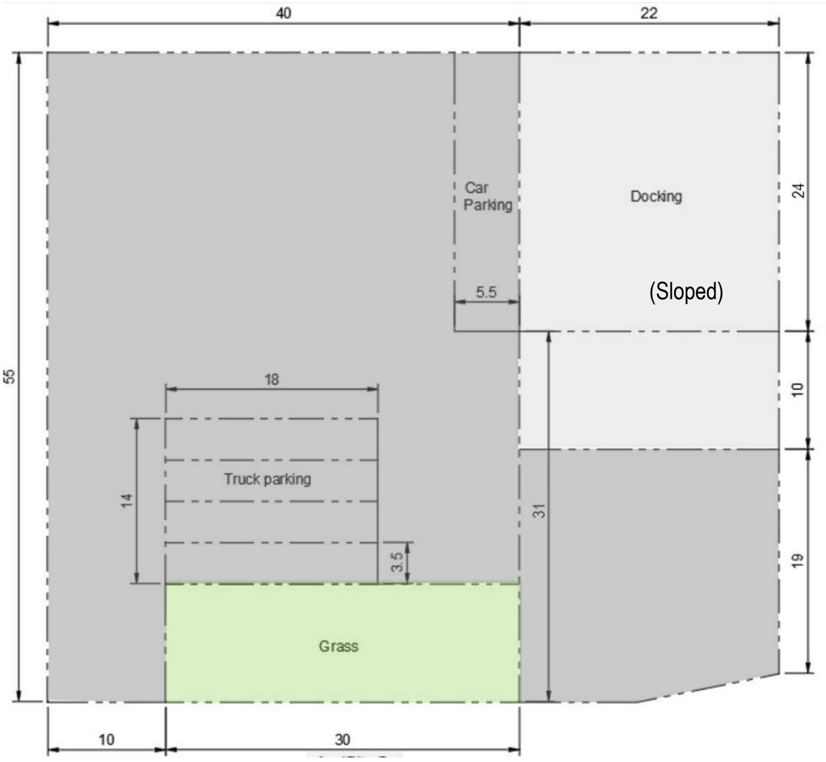

Figure 34: Top-view dimensions MSP Onions site (dimensions in meters).

The light grey area in Figure 34 is the area where the five docking stations are located, as shown in Figure 35.

Figure 35: Docking gates at MSP Onions.

As visible in Figure 35, in front of each docking gate there is a set of yellow lines which helps the driver to gain environmental awareness and guide the vehicle combination to the docking gate. The yellow lines then continue with the solid metal beams which ends 2.3m away from the docking gate and which ensure that semitrailer is positioned such it will not hit the docking gate. The specific dimensions of the docking platform are shown in Figure 36.

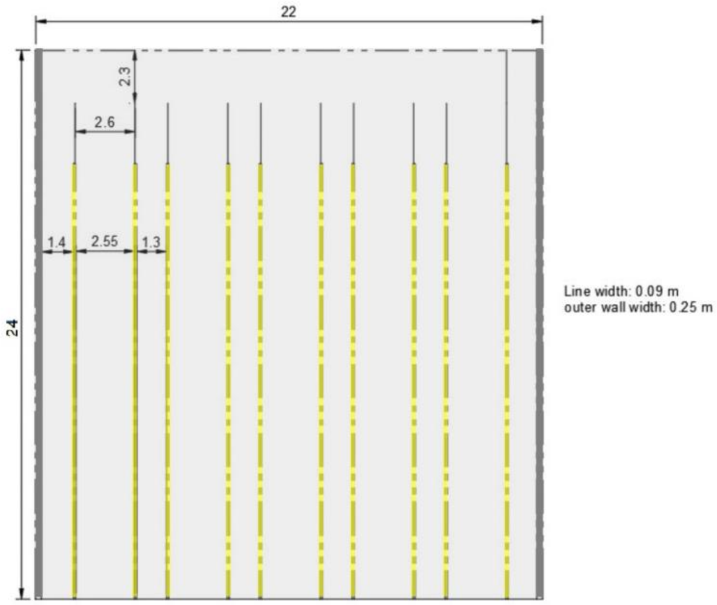

Figure 36: MSP Onions docking area dimensions (dimensions in meters).

In Figure 35. it is also visible that the docking area has a slope down to make sure that the trailer floor is levelled with the door of the building. The slope dimensions are provided in Figure 37.

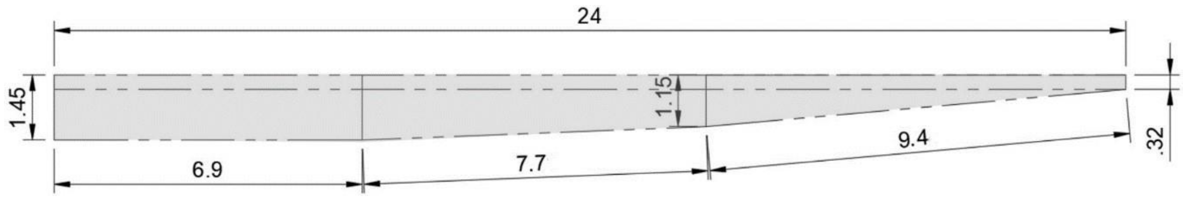

Figure 37: Slope dimensions at docking area (dimensions in meters).

As seen in previous figures the docking area contains five of loading/unloading gates. The dimensions of each of the gates are given in Figure 38.

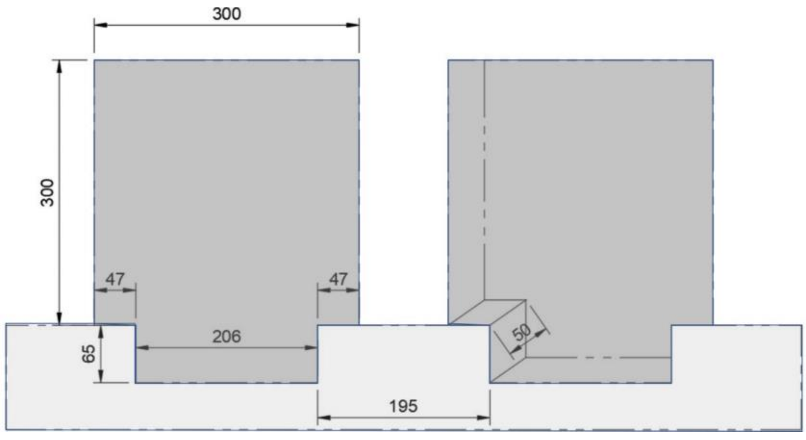

Figure 38: Dimensions of the doors at MSP Onions (dimensions in centimetres).

The operational tolerances are ruled by the pitch between the solid metal rails (see Figure 35), where the semitrailer axles need to fit. Hence the clearances between the rails and the parked trailer tyres were measured on both sided to quantify the tolerance. The clearances are shown in Figure 39 and Figure 40 and results in the tolerance of ±10cm of lateral absolute lateral error with respect to the centre of the loading gate. The absolute orientational error of the trailer when docked is calculated to be less than 1 degree with respect to the gated frontal wall. This small tolerance again emphasizes the need for very precise localization.

Figure 39: Clearance left side (±8.5 cm).

Figure 40: Clearance right side (±13.5 cm).

4.1.3 Industiepark Kleefse Waard (IPKW)

After the considerable amount testing and validation of the autodocking functionality at MSP Onions, some improvements have been implemented to the entire system, like the path planner improvements and the Model Predictive Controller. To validate that the functionality was still working properly, i.e., within its KPIs, some more tests have been done at IPKW (Industriepark Kleefse Waard), an industrial area in Arnhem, close to HAN University of Applied Sciences.

Figure 41 shows a top view satellite image of the pilot site, containing a road and a docking area (blue marked area). Furthermore, on the left side of the docking area a larger space was available, where shunting manoeuvres could be made at the time of the tests there were no cars parked on the road or on the area next to the docking area.

Figure 41: IPKW test site top view satellite photo with blue colour designating the test area.

The docking area used for the tests is quite similar to the docks at MSP Onions. At the beginning it has some inclination and near the end it becomes a flat surface. These docks, as shown in

Figure 42, don't have solid beams or lines on the floor to indicate the dock. But the docks are of the same size as the ones at MSP Onions.

Figure 42: Docks at IPKW.

4.2 Test Plan

This paragraph briefly describes the performed tests at the different test sides. Information is provided on high level, since low level description can be found in the appropriate documents (i.e., D7.2 and D.7.4 (STD & STP)).

The tests performed with the teleoperated Skid-Steer (UC 4.2b) are described in the dedicated Chapter 7, *"Skid steer testing"*.

Before the multiple test plans are discussed, firstly Table 4 shows all the tests performed throughout the project at the various test sites and various test objectives. The various test plans are also described more extensively below.

Table 4: Project test overview.

Time period	Test objective:	Test site
Jan 2022 – June 2022	MVP Development	Parking deck @HAN
July 2022	MVP testing + formal review meeting	Verbrugge Scaldia Terminals @Vlissingen
Feb 2023	PPC performance testing + gathering statistical relevance data	MSP Onions @Nieuwdorp
September 2023	MPC performance testing + gathering statistical relevance data	Industriepark Kleefse Waard @Arnhem

4.2.1 PPC Testing @HAN (on MVP)

The scaled truck-trailer combination (MVP) was developed in order to have easier access and to make overall testing easier and safer. Furthermore, successful completion of the KPIs on the scaled level provides a solid basis for implementation on the full-scale level.

The different tests performed with the MVP can be classified in two types:

1. Preliminary / Validatory tests: to test and validate all the involved subsystems of the autodocking manoeuvres with the help of simple manoeuvres:
    a. Teleoperation. The system follows the operator's input.
    b. Path-Tracking-Controller. A predefined reference path will be followed.
    c. Pure Pursuit Controller (PPC) & Path planner combination. Generating paths which will be tracked by the PPC.
2. Automated docking tests: which include all the stages of the actual docking procedure.

Preliminary and validatory tests

For teleoperation no specific tests have been created, and it was only validated whether the vehicle behaved as expected by the teleoperator's input, e.g., go left when steering left. All kinds of "normal" operation was tested, like driving forward and reverse, steering left and right and being able to make proper manoeuvres like a 90^o turn or parking.

The PPC was tested by providing it with predefined paths which should be followed / tracked within the KPIs. This was tested with the following (simple) manoeuvres:

- Tracking a straight line of ±10-15meters, both forward and reverse.
- Tracking a 360^o Circle with tangential entry and exit trajectories, both forward and reverse.

To ensure that the path planner can generate kinematically viable paths and the PPC can track these reference paths in a safe and accurate manner, the following tests were performed:

- Generate and track a straight line of ±10-15meters, both forward and reverse.
- Generate and track a 90^o degree turn, both forward and reverse and left and right.
- Generate and track a parallel parking manoeuvre, including forward & reverse motions.

Automated docking manoeuvres

The autodocking tests consisted of different tests where the combination starting from a randomly chosen starting point and had to define a path to a certain end position. The controller should track the path within the defined KPIs. The overall manoeuvre consists of a forward path (curve to the right) and a rearward path (semi-straight line to dock). The starting point and end point have been varied over time, but in such a way that the path was viable within the vehicle's kinematic capabilities.

Throughout all the tests, the vehicle was driving with a constant speed of 1.5 [m/s]. Parameters like radius have been varied over time to be sure the system could handle all kinds of situations. The measurements have been taken with the RTK GPS system (location, heading, tracking error, etc.) and the laptop/computer holding the path planner and path tracking controller.

4.2.2 PPC Testing @ MSP Onions

The test results of the PPC on the full-scale truck-trailer combination were gathered during the tests at MSP Onions in Vlissingen. The testing consisted over full automated teleoperator in-the-loop docking manoeuvres executed multiple times to collect statistical data. Figure 43 shows a top view of how one autodocking test looked like.

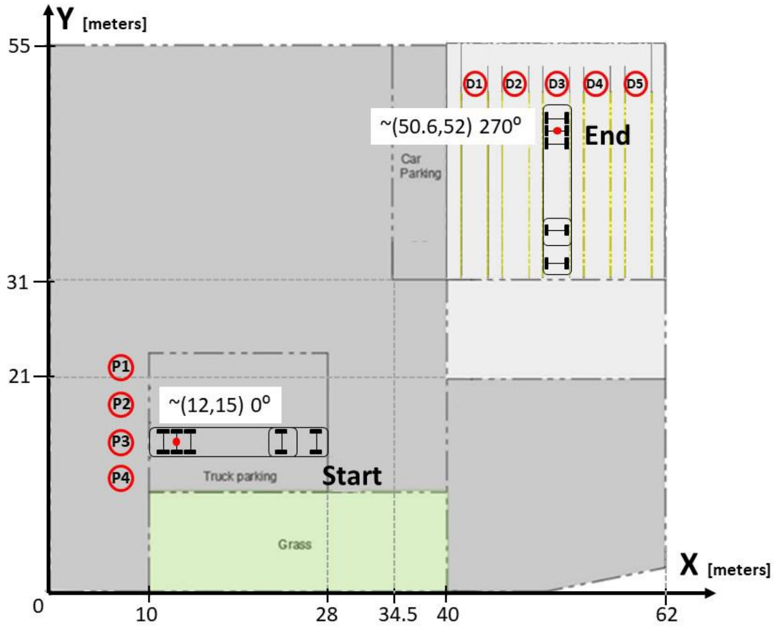

Figure 43: Top view of autodocking test at MSP Onions test site.

The vehicle combination was driven remotely on the premises of MSP to a starting position for the autodocking manoeuvre. Remote driving was done from the Teleoperation Centre located at the MSP Onions office. The docking manoeuvre was started at one of the Start points (either P1, P2, P3 or P4) and ended at the end point which is a dock (either D1, D2, D3, D4 or D5). The autodocking functionality as described above was initiated from the teleoperation centre and the truck started the docking manoeuvre. The overall manoeuvre consists of a forward path (curve to the right) and a rearward path (semi-straight line to the dock).

Throughout all the tests, the vehicle was driving with a constant speed input of 30% throttle. And a safety operator was always in the vehicle to abort a test when required. The KPIs were measured with the use of the RTK GPS system, the teleoperation PC and measurements by hand (i.e., tape measurements).

During these tests, EF1 and EF7 were also tested, as well as the network performance of the 5G infrastructure. The results are not mentioned in this report since it only contains the autodocking results.

4.2.3 MPC Testing @ Industriepark Kleefse Waard (IPKW)

The test results of the MPC on the full-scale truck-trailer combination were gathered during the tests at IPKW in Arnhem. The testing consisted over full automated teleoperator in-the-loop docking manoeuvres executed multiple times to collect statistical data. And are therefore very similar to the tests performed at MSP. The main difference is the MPC controller instead of the PPC controller.

4.3 KPI definition

Before the KPIs can be presented, it is important to discuss what the KPIs are and how they are measured. The KPIs for the autodocking functionality are listed in Table 5.

Table 5: Autodocking functionality KPIs definition.

#	KPI	Definition	Target values
1	Path Planning Time	The time it takes the path planner to plan the desired path for docking	< 60 [sec]
2	Tracking Error Real Time	The lateral (Y) deviation of the actual position of the axle of the trailing unit with respect to the generated path during manoeuvring.	< 0.5 [m]
3	Final Docking State Error	The difference between the actual docking position and the planned docking position after the docking manoeuvre is performed. The Final Docking state error is divided into three parts: A) Lateral (Y) B) Longitudinal (X) C) Orientation angle (θ)	A = < 10 [cm] B = < 10 [cm] C = < 2 [deg]
4	Elapsed Time	The time between the initial movement and the final stop of movement at the end position.	< 150 [sec]
5	GPS Position Accuracy	The accuracy of the GPS positioning system in cm.	< 10 [cm]
6	GPS Heading Accuracy	The accuracy of the GPS Orientation in degrees.	< 1 [deg]

All these KPIs were measured during the testing. How these KPIs were measured is explained in Table 6.

Table 6: KPI measurement methodology.

#	KPI	Measurement Methodology
1	Path Planning Time	The path planning time was measured withing the path planning software (MATLAB) by the use of a timer. The timer would start when the path planner started and would end when the path was planned. The measured time was logged in the datafile of that specific test.
2	Tracking Error Real Time	The tracking error was calculated withing the path tracking controller software (MATLAB). The lateral tracking error was calculated by comparing the actual position of the truck-trailer combination (GPS) to the position where the truck-trailer combination should be according to the planned path.
3	Final Docking State error	The Final Docking State Error was measured by hand when the truck was finally stopped. The planned docking position was marked, and the difference was measured with a measuring tape. The final docking state error was also checked by comparing the final docking coordinates of the GPS with the end dock coordinates (pre-defined end point of path planner). This was done for both the lateral and the

		longitudinal errors. The Final Orientational Docking State error was calculated by comparing the orientation at the end point (logged from GPS) with the pre-defined path planner end orientation.
4	Elapsed Time	The total elapsed time was measured withing the path planning and path tracking software (MATLAB) by the use of a timer. The timer would start when the path planner started and would end when the truck reached the end point and stopped moving. The measured time was logged in the datafile of that specific test.
5	GPS Position Accuracy	The GPS position accuracy was read out from the GPS system and logged in MATLAB. The accuracy was measured over the full test and averaged for a final value. The min. and max. values were also examined, but there were no outliers since the GPS position accuracy is very constant over time.
6	GPS Heading Accuracy	The GPS orientation accuracy was read out from the GPS system and logged in MATLAB. The accuracy was measured over the full and averaged for a final value. The min. and max. values were also examined, but there were no outliers since the GPS orientation accuracy is very constant over time.

5 RESULTS & DISCUSSION

5.1 High fidelity model results

The simulation model of the tractor-semitrailer is used to prepare for the MSP Onions test site by running through the autodocking scenario, where the path planner and path tracking controller are tested. The Figure 44 shows the reference path generated for an example docking situation at the test site along with the trailer's path during the forward and reverse manoeuvre. Simulations like these were performed for various dock locations and starting points to ensure that the autodocking workflow is works well before testing with the physical vehicles.

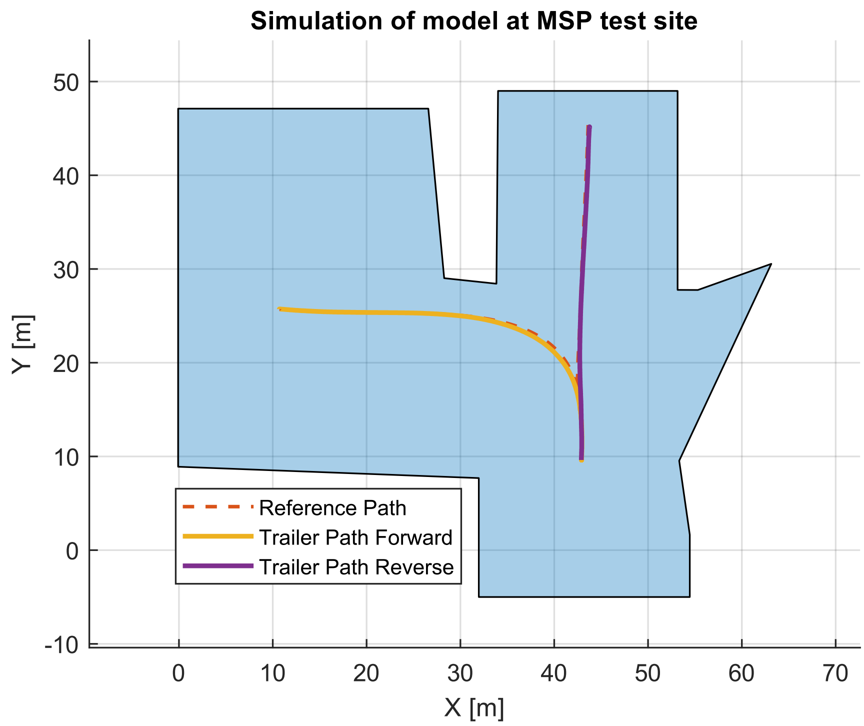

Figure 44: Simulation of an autodocking manoeuvre at MSP Onions test site

5.2 Scaled Prototype Results (MVP)

Table 7 shows the average KPI results of the testing done on the MVP (scaled prototype). Since this prototype is developed as a MVP to proof the technology (i.e., Proof of Concept), not enough tests were performed to also be able to say something about statistical relevance. Due to this reason the results of the MVP testing are presented in a different way compared to the full-scale development results.

Table 7: MVP KPI results.

#	KPI	Definition	Target values	Measurement PPC @HAN
1	Path Planning Time	The time it takes the path planner to plan the desired path for docking	< 60 [sec]	32 [sec]

2	Tracking Error Real Time	The lateral (Y) deviation of the actual position of the axle of the trailing unit with respect to the generated path during manoeuvring.	< 0.5 [m]	0.27 [m]
3	Final Docking State Error	The difference between the actual docking position and the planned docking position after the docking manoeuvre is performed. The Final Docking state error is divided into three parts: A) Lateral (Y) B) Longitudinal (X) C) Orientation angle (θ)	A = < 10 [cm] B = < 10 [cm] C = < 2 [deg]	A = 5.7 [cm] B = 10.2 [cm] C = 0.46 [deg]
4	Elapsed Time	The time between the initial movement and the final stop of movement at the end position.	< 150 [sec]	153.4 [sec]
5	GPS Position Accuracy	The accuracy of the GPS positioning system in cm.	< 10 [cm]	3.8 [cm]
6	GPS Heading Accuracy	The accuracy of the GPS Orientation in degrees.	< 1 [deg]	0.23 [deg]

When looking at Table 7, it can be concluded that the elapsed time and longitudinal final docking state error KPI target values are not met. The elapsed time KPI isn't being achieved due to slower processors in the system (compared to the full-scale development), hampering the efficiency of the process. Additionally, the overall time it takes to complete the process is influenced by the speed of the truck and the length of the autodocking manoeuvre (longer distance take longer to cover). The longitudinal KPI was not met because the MVP lacked speed control and brakes, making it challenging to achieve the desired performance. In the absence of these features, controlling the truck's speed and stopping it was solely reliant on the natural rolling distance after disengaging the throttle. This approach is highly dependent on factors like truck speed, rolling resistance, and surface slope, which affected the ability to consistently meet the KPI. Since the cause of the KPI issue was well-understood, and it was determined that the full-scale application had brakes, no further development efforts were directed at addressing this specific KPI shortfall.

5.3 PPC & MPC Full Scale Results

Table 8 shows the average results of the KPIs together with the target values of both the Pure Pursuit Controller (PPC) testing at MSP Onions and the Model Predictive Controller (MPC) testing at IPKW. These are average values done over 48 successful autodocking tests and 46 successful autodocking tests, respectively.

The 48 PPC tests were executed during three testing days at the end of February 2023. The weather was cloudy with no rain during the three days. No noticeable variations in weather were noted. The autodocking functionality was tested with the use of the 5G NSA network since the 5G SA network was not available at the test site. As described in the previous sections, the autodocking tests were performed using a forward movement (curve to right) and a rearward movement (semi-straight line). The manoeuvre type was not changed during the 48 tests. however, the dock number was changed, and the starting position differed per time.

The 46 MPC tests were executed during three testing days at the beginning of September 2023. The weather was sunny with some clouds. No noticeable variations in weather were noted. The autodocking functionality was tested with the use of the 5G NSA network since the 5G SA network was not available at the test site. The autodocking tests were performed using a forward movement (curve to left) and a rearward movement (curve to right). The manoeuvre type was not changed during the 46 tests, yet the starting position was always kept random.

Table 8: PPC and MPC KPI results.

#	KPI	Definition	Target values	Measurement PPC @MSP	Measurement MPC @IPKW
1	Path Planning Time	The time it takes the path planner to plan the desired path for docking	< 60 [sec]	15.0 [sec]	11.0 [sec]
2	Tracking Error Real Time	The lateral (Y) deviation of the actual position of the axle of the trailing unit with respect to the generated path during manoeuvring.	< 0.5 [m]	0.16 [m]	0.09 [m]
3	Final Docking State Error	The difference between the actual docking position and the planned docking position after the docking manoeuvre is performed. The Final Docking state error is divided into three parts: A) Lateral (Y) B) Longitudinal (X) C) Orientation angle (θ)	A = < 10 [cm] B = < 10 [cm] C = < 2 [deg]	A = 3.6 [cm] B = 8.4 [cm] C = 0.4 [deg]	A = 5.17 [cm] B = 8.33 [cm] C = 0.63 [deg]

4	Elapsed Time	The time between the initial movement and the final stop of movement at the end position.	< 150 [sec]	117.3 [sec]	153.59 [sec]
5	GPS Position Accuracy	The accuracy of the GPS positioning system in cm.	< 10 [cm]	3.7 [cm]	4.0 [cm]
6	GPS Heading Accuracy	The accuracy of the GPS Orientation in degrees.	< 1 [deg]	0.25 [deg]	0.07 [deg]

Table 9 shows the statistical relevance information for the tests performed per KPI for the PPC controller.

Table 9: KPI Statistical values (PPC controller).

KPI	Std. Deviation	95th Percentile	Unit
Path Planning Time	5.88	25.71	Seconds
Tracking Error Real Time	0.03	0.21	Meters
Final Lateral Docking State error	3.3	9.1	Centimetres
Final Longitudinal Docking State error	8.03	20.4	Centimetres
Final Orientational Docking State error	0.34	1.01	Degrees
Elapsed Time	13.07	135.88	Seconds
GPS Position Accuracy	0.17	4.00	Centimetres
GPS Heading Accuracy	0.29	1.00	Degrees

Table 10 shows the statistical relevance information for the tests performed per KPI for the MPC controller.

Table 10: KPI Statistical values (MPC controller).

KPI	Std. Deviation	95th Percentile	Unit
Path Planning Time	0.49	11.71	Seconds
Tracking Error Real Time	0.03	0.12	Meters
Final Lateral Docking State error	2.83	9.15	Centimetres
Final Longitudinal Docking State error	6.04	20.75	Centimetres
Final Orientational Docking State error	1.11	3.66	Degrees
Elapsed Time	4.91	160.40	Seconds
GPS Position Accuracy	0.01	0.07	Centimetres
GPS Heading Accuracy	0.02	0.08	Degrees

5.4 Discussion

It can be concluded that all KPIs are within the desired target values. Still, it is important to discuss the certain KPIs in a bit more detail. Table 11 gives an overview of all the KPIs of each individual version of the autodocking functionality that can be used to make the overall discussion more understandable. All the values shown in Table 11 are the absolute averages of all the tests performed.

Table 11: All KPIs for each version of the autodocking functionality.

KPI	MVP	Full scale Truck (PPC)	Full scale Truck (MPC)
Path Planning Time	32 [sec]	15 [sec]	11 [sec]
Tracking Error Real Time	0.27 [m]	0.16 [m]	0.09 [m]
Final Lateral Docking State error	5.7 [cm]	3.6 [cm]	5.17 [cm]
Final Longitudinal Docking State error	10.2 [cm]	8.4 [cm]	8.33 [cm]
Final Orientational Docking State error	0.46 [deg]	0.4 [deg]	1.63 [deg]
Elapsed Time	153.4 [sec]	117.3 [sec]	153.59 [sec]
GPS Position Accuracy	3.8 [cm]	3.7 [cm]	4.0 [cm]
GPS Heading Accuracy	0.23 [deg]	0.25 [deg]	0.07 [deg]

5.4.1 Reliability on good network quality

Since the performance of the autodocking functionality is highly reliant on network quality, firstly the reliability on good network is discussed. The results described in Paragraph 5.3 at IPKW were performed with 5G NSA network with much poorer network quality than used at MSP Onions site. Figure 45 shows a screenshot of the network performance, where the download and upload latencies are in the 100s of milliseconds (186 and 214 milliseconds respectively).

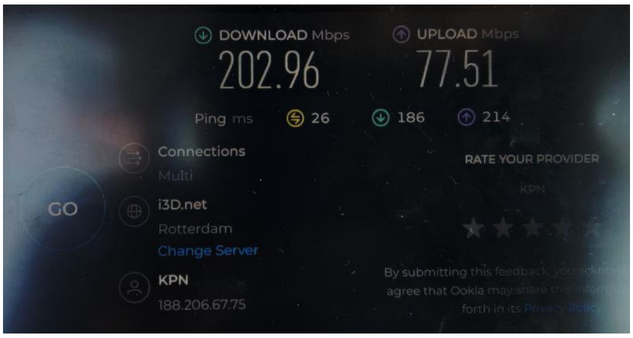

Figure 45: Network quality at IPKW.

This has an effect on controller performance and overall KPIs, since GPS data sampling, control loop speed and actuator control loop speed are all faster than the network speeds present at IPKW. This causes undesired behaviour of the vehicle. Bad network quality also influences the video stream quality, although the video stream quality is not relevant to the KPIs referred to in this document, it shows the impact on the system overall. A snapshot of the video streams is shown in Figure 46, where the side view screens have extreme flickering.

Figure 46: Flickering video streams.

Throughout the tests at IPKW, the Round Trip Delay (RTD) of the GPS related messages were logged. An analysis of the RTD was conducted to quantify the impact of network related delay on the MPC performance. Big spikes were noticed in the delay as shown in Figure 47. Although the average RTD (left graph) is around 70 [ms], it is not consistent. The spikes in the delay regularly are above 100 [ms], which is slower than the control loop. Furthermore, the variation in the delay is also very high. Variation causes undesirable behaviour in systems, especially when it is greater than control loop speed.

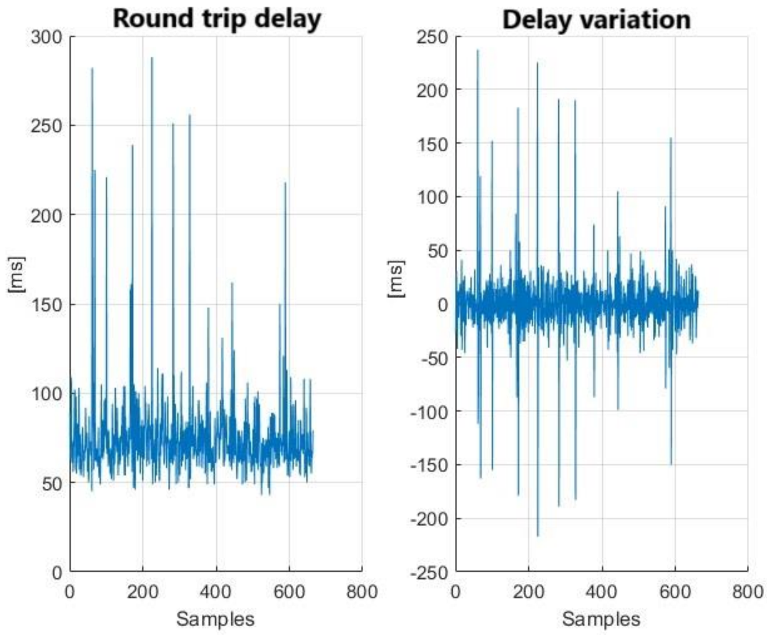

Figure 47: Round Trip Delay and Delay variation.

When the network speed fluctuates, it implies that the messages in the TCP stream will also fluctuate in arrival timing at the destination. The Figure 48 shows an example of this using logged data from tests conducted at different times of the year. In March of 2023, tests were performed at IPKW to prepare for tests at MSP site. Comparing this with the tests conducted in September of 2023, the input data consistency is worse in September. The graph shows the X position of the semitrailer for a similar mostly straight-line manoeuvre. The variation in samples received over time is clearly greater in September, than in March. This results in a higher standard deviation of delay variation.

Figure 48: Variation in consistency of data samples received.

The delay variation not only applies to input data to the controller, but also to the control outputs being sent to the truck. When steering command signals are sent from the autodocking controller PC to the truck in a varying frequency, the truck will not behave as expected and will start to be oscillatory. Oscillatory control outputs (in this case steering commands) are known to be caused by delays in communication. An example of this is shown in Figure 49, where the blue lines in the top right graph show the oscillatory behaviour.

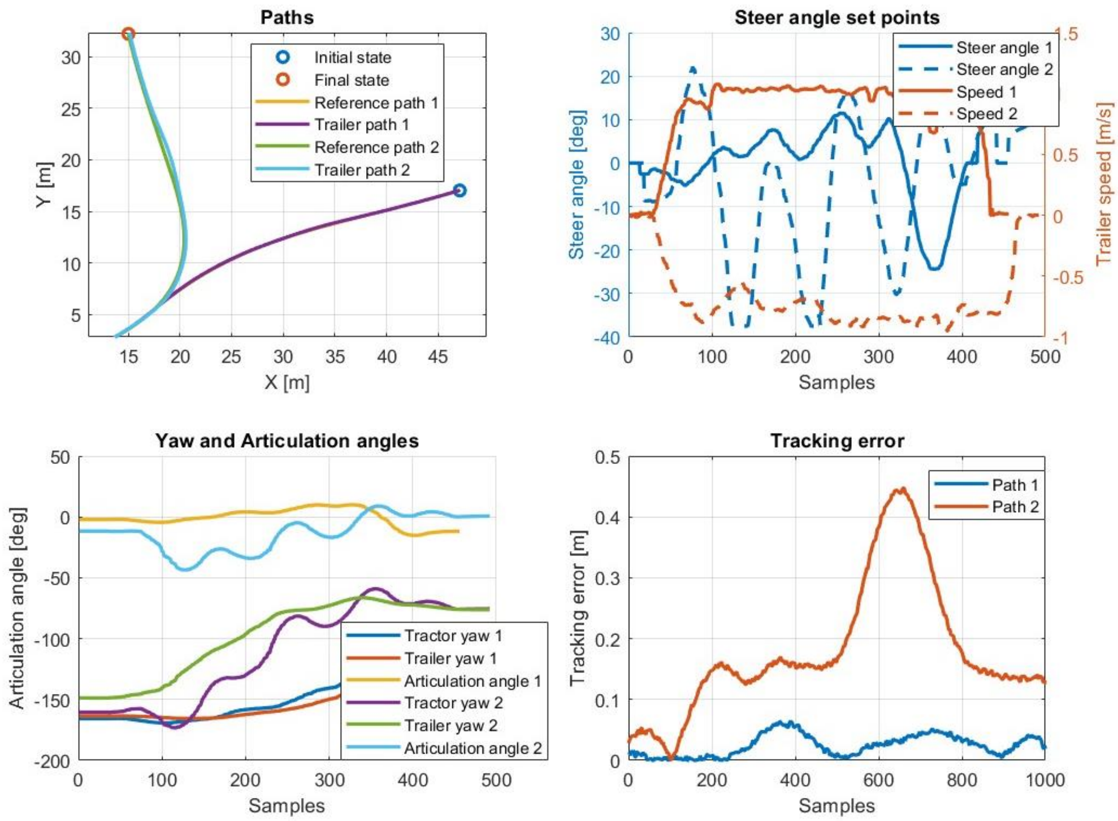

Figure 49: Effect of network quality on autodocking performance.

Statistically, looking at the standard deviation of the RTD gives more insights. Figure 50 shows a histogram comparison between 2 tests, one which was successful and another where the KPIs were not satisfied. The standard deviation histogram on the left was for a successful test, whereas the one on the right resulted in the unsuccessful test. The variation deviates much wider, with fewer counts close to 0 compared to a successful test.

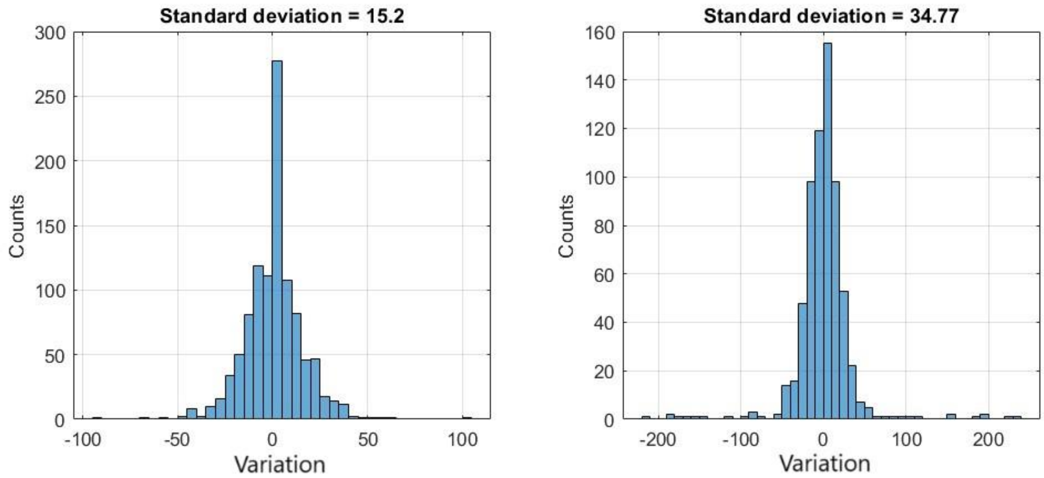

Figure 50: Histograms of the delay variation in [ms]. Left: successful test, Right: unsuccessful test.

Large variation also causes the drive-by-wire system in the truck to apply brakes and bring steering wheel back to neutral position for safety. Although this lasts for only around 1 [s] for each big spike in delay, this of course interferes with the controller performance. In order to mitigate the oscillatory behaviour of the steering commands with the ideal control settings, the network performance has to be consistent (variation has to be minimal). This will allow the Model Predictive Controller (MPC) described in 2.2.3.2 to effectively predict the future states of the system.

However, since we cannot change the network performance at the test site, The controller was tuned throughout the test days at IPKW in order to mask the network issues. As described in Paragraph 2.2.3.2, the MPC can suppress large adjustments of control inputs in the cost function (this term allows the controller to provide smoother steering instructions to the driver). By increasing the weightage given to steering suppression in the cost function compared to the path tracking and velocity tracking weight, a smoother, slower steering response is achieved. In other words, this slows down the behaviour of the controller such that the delay variation will not cause rapid changes in control output. This is only possible because of the advanced control strategy of the MPC.

In Figure 51, two test results are shown, the top row shows an unsuccessful test because of oscillatory steering and the bottom row shows a successful test due to increased weightage to steering suppression. In both tests, the standard deviation of the delay variation was above 30. It is important to note that this tuning method only works due to the slow speed nature of the autodocking situation. If faster dynamics were to be controlled, such as a lane change manoeuvre at high speed, the network delays will definitely need to be consistent.

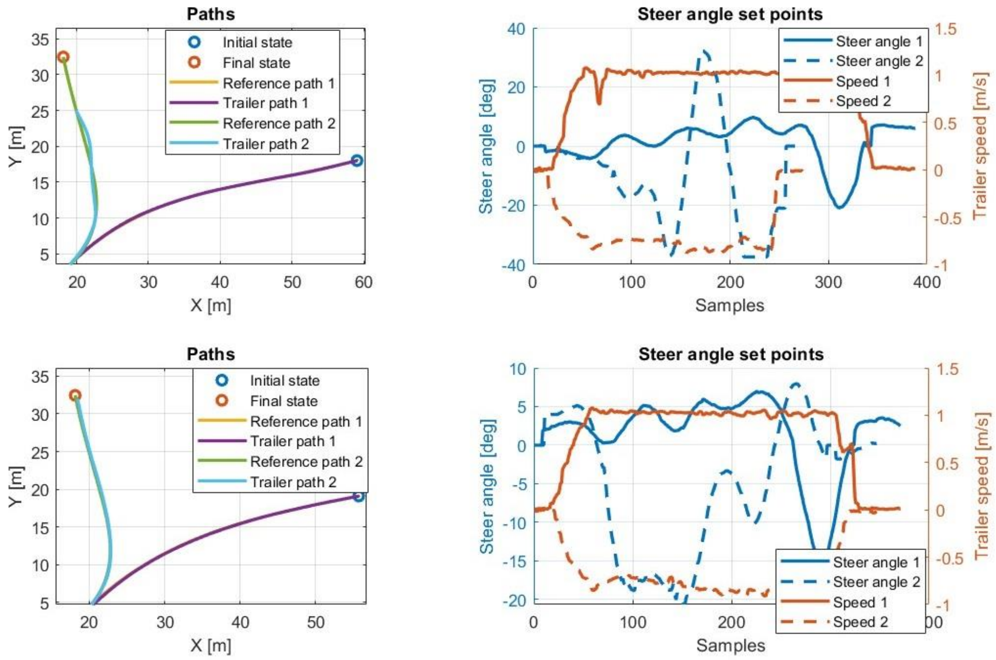

Figure 51: MPC performance tuning to fix network related effects. Top: unsuccessful test, Bottom: successful test.

5.4.2 Path Planning Time

The Path Planning KPI is well within the target value of under 60 seconds for each version of the autodocking functionality. The speed of the path planner is mainly determined by the strength of the computer it runs on. The better the processer of the computer, the faster the path planner. Additionally, looking at Table 11, there is also a big improvement noticeable between the MVP and the full-scale truck. The computer that runs the path planner didn't change between MVP and full-scale truck, but the code generation for the path planner was improved which more than halved the path planning time. Since the path planning takes place locally on the remote PC, it is not affected by network quality.

5.4.3 Tracking Error Real Time

The tracking error real time is the tracking error of the truck-trailer combination during the docking manoeuvre and indicates how well the truck-trailer combination can follow the planned path. This KPI is highly sensitive to the right path following controller parameters. The tracking error of both the PPC and MPC is very constant with a standard deviation of just 3 centimetres (Table 9 and Table 10). The tracking error is highly dependent on network quality. Since the GPS coordinates are sent via 5G to the remote PC which in return sends the corresponding steering, throttle and brake commands. When the network quality is bad, a noticeable difference can be seen. When latency is high or fluctuates, the truck deviates more from the planned path since the information for the path following controller (GPS coordinates) arrive later which in return delays the control commands that will also arrive later at the truck (as shown in Figure 48). So it is important to notice that network quality can be a bottleneck for autodocking, especially when the network quality is bad as explained in paragraph 5.4.1, "Reliability on good network quality".

5.4.4 Final lateral, longitudinal and orientational docking state error

The final docking state errors are very important KPIs when it comes to autodocking since these correspond to the end position of the trailer. Big errors mean that the truck trailer combination is not parked rightly at the dock. And with only 10cm play at most docks laterally, these KPIs come very narrow. The errors are also highly dependent on network quality for similar reasons as described in the previous subsection. High latencies result in big offsets at the end position. This was especially noticed in narrow surroundings when the network quality was bad. When surroundings are or places to dock are narrow, the paths that are planned are tight. If big offsets occur due to high latency, the truck is for example unable to dock straight at a dock because of its dynamics resulting in a high orientational docking error (Figure 48). With a good network quality, this is not the case. The autodocking functionality will still work properly. But it can be concluded that network quality is a highly dependent factor of these KPIs. Especially if test ground dimensions are tight. This was not the case during the testing at MSP onions since there was enough space and the network quality was good, but it was the case when testing the MPC controller at IPKW. Unfortunately, the network quality was very poor compared to the tests at MSP Onions. This resulted in worse KPI values as described in paragraph 5.4.1: “Reliability on good network quality”.

Looking at Table 11, it can be noticed that the longitudinal docking error is higher compared to the lateral docking error for both the PPC and MPC controller. This can be explained by the fact that speed control is not yet implemented in the autodocking functionality, making stopping at exactly the right spot longitudinally quite challenging. As of now, the truck will stop with applying throttle some distance before the desired end point and apply the brakes at the end point. Tuning and timing this to be exact is challenging. If the truck is for example on a slope, or approaching with a bit higher speed, the longitudinal error changes. When implementing speed control (maintaining a fixed speed), determining the brake point is easier. During the testing, this was not yet implemented hence the higher error value for the longitudinal error. Additionally, network quality also plays an important role in the longitudinal error. If for example the latency is 0.1 seconds at a docking speed of 5 km/h. A delayed braking signal of 0.1 seconds already results in a 14 centimetre overshoot longitudinally. This will eventually result in a higher standard deviation which is a result of different docking slope, minor variations in approaching speed, GPS accuracy and Network quality which all effect the moment the truck will brake near the end point.

5.4.5 Elapsed time

The elapsed time KPI is not necessarily dependent on network quality, but there are other factors that affect it. For example, the path planning time is included in the total elapsed time so the factors that affect the path planning time also affect the elapsed time. Furthermore, the overall docking manoeuvre and especially the length of the paths affect it as well. Longer paths take longer to drive since the overall speed of the truck is ±5 km/h. Speed is therefore also an important factor. There is an improvement of 36.1 seconds to be seen when the MVP is compared to the full-scale truck (Table 11). This is mainly due to the reduction of path planning time as explained in the previous paragraph. The elapsed time of the MPC testing is way higher compared to the PPC testing. The reason for this is the length of the planned path which was larger at IPKW. It can be acknowledged that this KPI is therefore not as meaningful. It is suggested that in future research, it may be more meaningful to use a KPI that is based on a prescribed minimal velocity. This change is proposed to create more objective metrics, as the current KPI is heavily influenced by the length of the manoeuvre in both directions, which was not consistently defined.

5.4.6 GPS position and orientation accuracy

The GPS accuracies are very important KPIs since they highly affect the overall errors and therefore the functionality of the autodocking system. These are listed as KPIs since the lateral margin at a dock is on average 10 centimetres which calls for a highly precise GPS system. As can be seen in Table 9 and Table 10, the KPIs are well within the target values and are also very constant. The position accuracy KPI has a standard deviation of just 0.17 and 0.01 centimetres and the orientation KPI has standard deviation of 0.29 degrees. Also, when looking at the 95th percentile, 95 percent of all the measured position and orientation accuracies are within the target values of 10 centimetres and 1 degree respectively.

5.4.7 PPC vs MPC

Now that the KPIs are discussed and their reliance on network quality is addressed. It is important to discuss which form of controlling the autodocking functionality is preferred. Unfortunately, due to poor network quality at the IPKW test site, as explained in the previous Paragraph, the KPI values of the MPC controller are not as “set in stone” that they immediately prove that the MPC is preferred over the PPC controller. However, the lack of visible improvement in terms of KPI values is mainly a result of poor network quality as explained in the previous paragraph. The reasons why the MPC controller is still preferred over the PPC controller are listed below.

- **Less fluctuations in controller behaviour:**
  MPC takes into account a dynamic model of the system and predicts future states over a specified prediction time horizon. It optimizes control inputs over this horizon to minimize a cost function. This predictive nature of MPC allows it to proactively account for potential disturbances and uncertainties. In contrast, PPC typically relies on fixed classical control laws and may react less effectively to changing conditions or disturbances. This can result in more fluctuations in the system's behaviour. This can be seen in the tracking error real time KPI (Table 11), where the real time tracking error of the MPC is 9 centimetres compared to the 16 centimetres for the PPC even though the network quality was much poorer during MPC testing.

- **Smoother Path Following Because of the ‘predictive’ component:**
  MPC generates control inputs by considering future states and the desired path, allowing it to plan and execute control actions more smoothly. It can anticipate upcoming changes in the path and adjust the control inputs accordingly. PPC, on the other hand, often relies on reactive control strategies that may lead to abrupt changes in control inputs when tracking a path. This can result in jerky or non-smooth behaviour, which is undesirable in many applications. This was especially noticeable during the docking manoeuvres where the steering output of the PPC controller is quite oscillatory. The MPC steering control is very smooth with almost fixed steering angles and less fluctuations.

- **Capability to work in tighter areas and make tighter curves:**
  MPC is particularly advantageous when navigating through tight space-limited spaces or when precise path tracking is required, as it can make finer adjustments to control inputs based on its predictive capabilities. PPC may struggle in such situations, as it may not have the ability to plan and execute control inputs as effectively in constrained environments or when navigating tight curves. Especially when reversing a truck, the tractor always needs to counter-steer to get the trailer to the right place. An MPC takes account for this with its predictive capabilities and can therefore counter-steer earlier than a PPC that always is reactive. A PPC controller can therefore be too late to counter-steer and therefore the trailer won’t end up in the desired spot when the area is narrow. This was very noticeable at the IPKW testing. The area there is tighter and the PPC controller had way more trouble to successfully dock the trailer where the MPC controller had no issues at all[4].

[4] When the network quality is good.

In summary, MPC's ability to predict and optimize control inputs over a horizon, its capacity to adapt to changing conditions, and its capability to provide smoother path tracking makes it the preferable choice compared to conventional PPC, especially in applications where precision, adaptability, and smoothness of control are crucial, such as tight and narrow distribution centres for example. It might also be worth mentioning that even though the network quality was poor, the results of the MPC are still impressive and within KPIs. The MPC is therefore way more forgiving than the PPC when it comes to network quality. This is also a very big advantage of the MPC compared to the PPC.

6 HUMAN MACHINE INTERFACE TESTING

6.1 Introduction: short description of the human factors tests

In 5G-Blueprint the technical proof of concept for teleoperation has demanded years of careful research and development. In the course of 2023, researchers of HAN UAS, V-tron and Roboauto have made this technical possibility come true and demonstrated the first live tele-operation of trucks.

In WP4 the aim is to include a first iteration of human factors' tests. In general terms, human factors research aims to optimize system design, improve performance, enhance safety, and increase user satisfaction by considering the capabilities, limitations, and needs of the humans interacting with the system. To this end, the research team created a test set-up for teleoperation of the truck and invited 7 professional (or formerly professional) truck drivers to first-hand experience and evaluate the design of the teleoperation set-up. During teleoperations, there were always one or two researchers participating as safety drivers inside the truck, who were in touch with a researcher at the teleoperation station via phone (see photo 1, below).

During the tests, five types of data were simultaneously collected:

- Video footage using a Go Pro camera registering 'over the shoulder' of the participant.
- Eye-tracking footage using an eye-tracking glasses of SensoMotoric Instruments GmbH (SMI, model ETG 2W AP) and data processing using BeGaze. With courtesy of Dr Kai Essig the Rhein-Waal University of Applied Sciences, Germany, who lend us the equipment for this data acquisition.
- Digital survey using Qualtrics
- Semi-structured interviews; transcribed and coded using ATLAS.ti
- Logs of the vehicle teleoperation inside the truck (speed, throttle, brake)

6.1.1 Test procedure

The tests followed the following template as shown in Table 12:

Table 12: HMI test time schedule per participating professional truck driver.

0h00	Getting settled and introduction to project 5G Blueprint, testing procedure and signing consent form
0h15	Pre-test survey about expectations of the driver on a laptop
0h20	Calibration eye tracking glasses
0h25	Explanation usage of the setup
0h35	3-5 practice laps at slow (turtle mode; max 5 km/h) and moderate (max 30 km/h) speed
0h45	4-6 test rounds: 1) turtle mode (1 lap); 2) moderate speed (3-5 laps); 3) carrying out manoeuvres: reverse straight + reverse at 90 degrees
1h10	Post-test survey about experiences of the driver on a laptop
1h20	Post-test interview
1h50	Wrap up with participant and research team
2h00	Estimated end time

The tests were conducted at IPKW (Figure 52) where the MPC tests were also performed. The 7 drivers that participated in June 2023 were between 29 and 53 years old and had between 2 and 33 years of experience as a professional driver. 3 participants were currently fulltime truck drivers; 3 had been a truck driver until recently but were now active as truck driver instructors (2) and office administrators (1). 1 participant used to drive professionally smaller trucks but is now mostly active as consultant in the automotive sector.

Figure 52: test lap (red) with indication of straight reverse (yellow) and practice area for 90 degree reverse turn (blue).

6.1.2 Limitations of pilot tests

Because of the limited scope of the human factors tests in the 5G Blueprint project, there are a number of considerations to take into account. First, the physical set-up of the teleoperation station consisted of the minimal equipment that is necessary for conducting the study. As can be seen in the photo below, the participating drivers were sitting in a regular chair, with a Logitech G920 setup consisting of a steering wheel, throttle and braking pedal, that were easy to use for the development of the proof of concept but are too basic for professional use. Similarly, the screens that were used in this study were regular 27-inch computer screens. We will reflect on these pieces of hardware, and the impact they have on the performance and experiences of the participating drivers, in the results from the interviews and recommendations at the end of this chapter. Second, based on the limited number of participants it is not possible to provide a conclusive list of dos and don’ts when it comes to the further development of teleoperation for real-life use cases. For this, both the number of participants (7) and the length of the test (30 minutes of driving) and depth of the interviews (max 45 minutes) are not representative. Finally, the pilot tests at IPKW were conducted with the 5G network. However, the type of 5G network available through KPN at these test locations was the NSA (non-standalone) version which operates on the 4G LTE core, contrary to the SA (standalone) 5G network that represents the reduced latency and improved network performance used in the use-case demonstrations sites.

Despite these limitations, the human factors tests that we have conducted in this project have resulted in several findings and conclusions that add new insights to the state of the art regarding teleoperation in real life use cases. These will be discussed below, and several recommendations will propose directions to increase the validity of further human factors tests in the field of teleoperation in the near future.

Figure 53: Teleoperation station during the test with one of the participants.

6.2 Results human factors tests

The results of the tests are first presented per type of data. The discussion and conclusions will cover all the five aspects of the human factors tests that have been conducted for this project.

6.2.1 Results from the Qualtrics survey

About drivers' expectations PRE-TEST:

- When asked about the expected impact of teleoperation on the truck drivers and their jobs, the respondents answered to expect:
  1) increased efficiency in logistics (n=7);
  2) increased traffic safety + extra comfort for drivers + unsafe traffic situations (n=2 for each option);
  3) technology is too new for public roads + less fuel consumption (n=2)
  It is interesting to notice as well that nobody expected no useful impact of the technology.
- With a mean score of 3.57 out of 5, most participants expected that the system would be easy to use. At the same time, all participants expected errors in the system's functioning (mean score 3.71) because the system is still very new.
- All drivers were intrinsically interested in learning to work with a new technological system (mean score 4,57) and are motivated to learn and use all functionalities of a new technological system (mean score 4.14).

About drivers' experiences POST-TEST:

- Participants answered very affirmative (mean score 4.43) to the question "if the set-up had been more realistic, I would have been able to do the work better". This means that further development of the HMI is important. Possible improvements for this will be discussed in the section on results from the interviews.

- Despite the potential for improvements, participants were still positive about the extent to which they were able to fulfil the tasks during the test. They felt like the system was easy to use (mean score 3.71), they had sufficient overview of local traffic situations (mean score 3.43), they would not mind using this system on an everyday basis (mean score 3.43), and using the system felt intuitive and matched the participant's expectations (both mean score 3.29).
- With a mean score of 2.43 and a variance score of 1.67, the participants were most divided about the statement "I found it difficult to find the information I needed". In the interviews several participants substantiated their evaluation of this statement. The results of that reflection follow below.
- In the configuration at IPKW, the participants generally agreed with the distance between the chair and the computer screens (n=5), and also thought that the screens were large enough (n=5). Of the participants who felt that the screen position was too close, one also stated that the screen size was too small. Conversely, the other participant felt that the screen was too close, but still the right size. And finally, one participant stated that the screen was at the right distance, but too small.
  Based on the small set of participants at IPKW, it is not possible to conclude which setup regarding the screens is most optimal.
- All participants experienced glitches in the camera stream; 4 participants stated "yes" and 3 stated "a little bit" when answering this question. Similarly, some participants experienced a delay between their driving manoeuvres and the response of the physical truck. 1 participant answered "yes", 3 participants answered "a little bit" and 3 participants answered "no" to this question. The internal relation between these responses in the survey is as follows:
  - 3 participants experienced disturbed camera view *and* some delay in the truck handling
  - 3 participants experienced some delay in the footage and no delay in the truck handling
  - 1 participant experienced both serious disturbance in the camera view and delay in the truck handling.

6.2.2 Results from the interviews

After the participating drivers had finished the short digital survey, they were interviewed by one of the researchers. During these conversations the drivers had the opportunity to elaborate on their survey answers and expand on their experiences during the test rounds. To analyse this data, we have transcribed and coded the interviews in ATLAS.ti. In total we used 19 subcodes, divided over three main categories: HMI (7 subcodes), driving task (4 subcodes), and teleoperation (8 subcodes).

Before we present the key findings from the interviews, it is interesting to notice the co-occurrence of the three main code categories; see Figure 54. The co-occurrence illustrates how in many of the participants' reflections, various aspects of (this experiment with) teleoperation are interconnected. One example of this is that the reflections on the design of the physical teleoperation set-up (code 'HMI') is connected to the capability of the drivers to execute the driving task (code 'driving task'). We can see that out of the 154 times that the code 'HMI' was applicable, 39 times the participant also referred to one or more issues regarding the driving task. Acknowledging these interconnected relations is important when developing further improvements to the system, because a redesign of one element of the system might affect other parts of the system, which can directly affect the (overall) experience of the human drivers. Such impactful changes to the system may be intentional, but any change to the configuration may also have unintentional or unexpected consequences. Those interrelations should be researched and validated before the system is used at a larger scale.

	Driving t... 71	HMI 154	Teleoperation 117
Driving task 71		39	13
HMI 154	39		21
Teleoperation 117	13	21	

Figure 54: Co-occurrence table of the interview codes, generated in ATLAS.ti

During the interviews, the participants shared many considerations based on their personal experiences and opinions regarding their current jobs, and on the potential of teleoperation for transporting goods. These considerations are summarized and discussed in the sections below. The participants' evaluation of the physical setup and HMI of the teleoperation test will be discussed first (Paragraph 6.2.2.1). After this, the participants' reflections on the driving task (Paragraph 6.2.2.2) will be presented. In this section we will address various aspects of the technical aspects of teleoperation. The results chapter concludes with the participants' opinions on their general opinions of teleoperation, relevant use cases for this technology, and the impact of the technology on the driving profession (Paragraph 6.2.2.3).

6.2.2.1 Regarding the HMI and ergonomics

On a general level, every participant found that the teleoperation station (desk, chair, screens, truck controlling technologies like the steering wheel, throttle and brake pedals) should be up to the basic standards for ergonomics. The set-up during this pilot tests did not meet these criteria fully. The pilot test focused explicitly on the proof of concept, and not yet on the most optimal configuration of desks, screens or chairs. It is therefore not surprising that the participants commented on this during the interviews: there was no high-quality desk nor an ergonomic (driving) chair, for example, which would be important basic requirements when considering teleoperating for a longer period of time.

Apart from these basic requirements, participants asked explicitly for a number of very specific additional elements in the set-up of the teleoperation station. These elements would be useful, they said, to get additional important information from the truck and thereby increase a sense of 'realism' in the teleoperation set-up. In the current configuration of the hardware, participants firstly missed **the turn signal** (the truck's blinker lights were switched on by the safety driver during the test rounds). All participants made a comment on this when they first sat behind the steering wheel, and three participants mentioned missing the turn signal during the interviews again. The following 'missing features' were all mentioned twice during the interviews: **adding warning lights, a tachometer, fuel consumption indication** (or in the future an indicator of remaining battery life), and **Advanced Driver Assistance Systems (ADAS) systems like collision prevention or lane-keeping assistance**. In addition to these sources of information and preferences for in-truck systems, six participants mentioned wanting **a radio** or being able to listen to music if they were to use the system more frequently. Of course, the latter does not have much to do with the act of teleoperating itself, but the fact that six participants mentioned this at their own accord is highly illustrative of the importance of the aural environment of drivers.

The previous paragraph explained the participants' opinions on the physical set-up. The conclusion here is that the hardware of the teleoperation set-up should be improved to meet the basic requirements for ergonomics. The next paragraphs will elaborate on the relation between the physical set-up and the participants' performance of the driving task.

6.2.2.2 Regarding the driving task

At a very basic level, when performing a driving task, the human senses are very important. We drive through our perception of the environment based on our ability to see, hear and feel. The next two paragraphs discuss the visual aspect of driving via teleoperation, the paragraphs after that go into the drivers' discussion of remote haptic and auditory feedback.

Contrary to the normal driving situation, where the driver is physically immersed in their environment, the only source of information in the current configuration of the teleoperation set-up is visual, through the video stream on the screens. Even though there were some problems with the video stream – most participants experienced some pixelated view – the participants still felt they had sufficient overview of local traffic situations (see also mean score of 3.43 in the survey data). Nevertheless, all participants still wanted to change something about the positioning of the cameras and the view of the projection of the side mirrors. This becomes especially important, they argued, in busier traffic situations or when performing manoeuvres. 4 participants mention missing **a front camera**, to see what is directly in front of the cabin and 4 participants wanted to have a better view of what happens directly on the left and right of the cabin for which they would also need **side-facing cameras on the cabin**. 2 participants wanted **a camera at the rear end of the trailer** as well. These additional cameras must support the driver, especially in estimating the position of the truck on the road, or in relation to obstacles or surrounding traffic. One participant illustrated this with the following quote:

> *'You notice that you cannot see depth, especially with driving in reverse. It is harder to estimate how far something is away from you. What they did at Mercedes, is that they put lines in the camera view on the screens. When you are standing still and straight you can calibrate them with the rear of your trailer. The next lines are at different distances from the trailer. This way you know how far something is away from you. These are things to consider, especially when parking.'* (Participant 4, 03-06-2023)

One example of distance indicator lines on the screen can be seen in Figure 55 below.

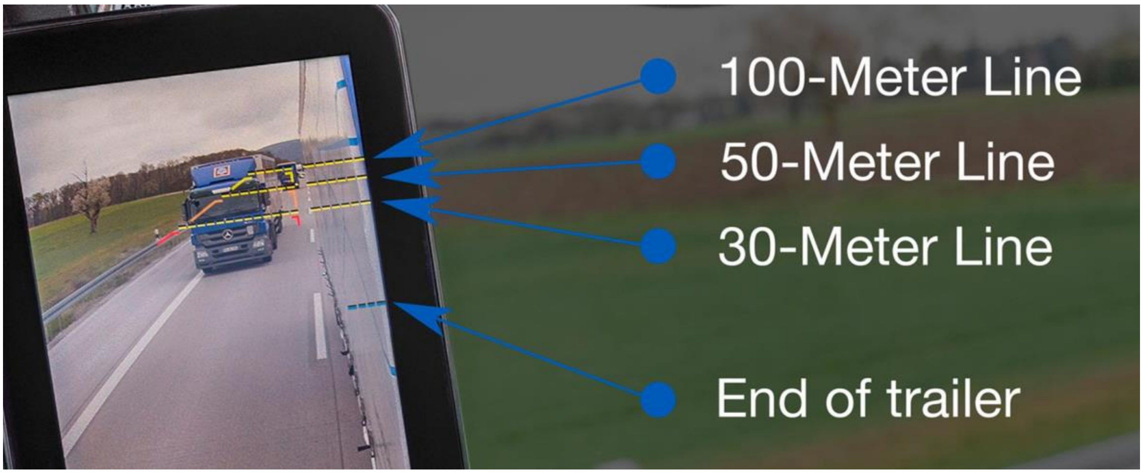

Figure 55: Distance indicator lines Mercedes truck, from https://www.roadtrains.com.au/tech-tips/how-to-operate-mercedes-benz-mirrorcam/.

To get a good sense of the position on the road, it is important to think about the best **position of the camera inside the 'cabin'** of a remotely operated truck. One participant wanted the front view camera to be moved more to the left, compared to the position of the camera during the test rounds. In the existing configuration, the camera was mounted in the middle of the cabin, because of the hypothesis that this would give the most optimal field of view while driving remotely. But many participants really had to get used to this when they started driving, and initially preferred that the position of the camera would be where the truck driver would normally sit inside the cabin.

It is interesting to notice however that, after a few rounds, many participants got used to the different point of view in the teleoperation setup than in a truck. In the interviews they concluded that the point of view is apparently something the driver can fairly easily and quickly get used to. The excerpt below illustrates the opinion of one participant on the topic of camera positioning and the extent to which it takes some practice to get used to operating the truck based solely using camera footage.

Participant 3: *'You have to get used to your position on the street at the start.'*
Interviewer: *'And this is because of the position of the camera?'*
Participant 3: *'Yes.'*
Interviewer: *'And if you could adjust this, how would you do that?'*
Participant 3: '*No, you do not have to adjust it, it just takes some getting used to.'*

The collection of video stills in the Figure 56 visually shows how the drivers were consistently paying attention to the sides of the roads in order to decide on their driving manoeuvres.

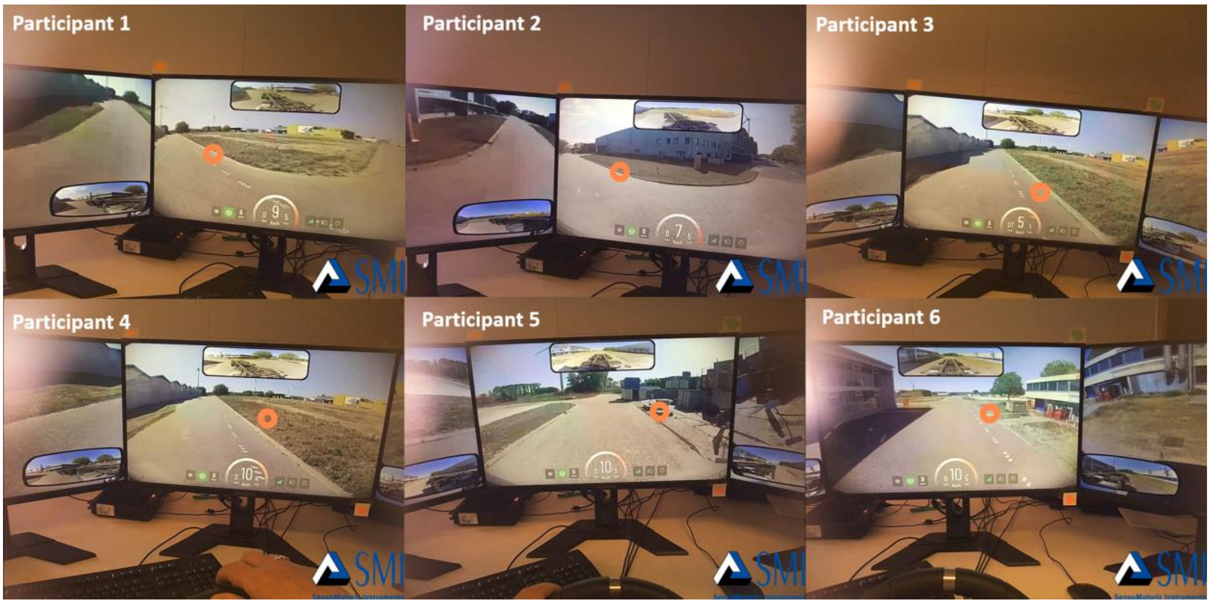

Figure 56: Compilation of stills from eye-tracking device illustrating the drivers' attention to the sides of the road in order to decide the position of the truck.

Next to the point of view of the cameras on the truck, the biggest issue regarding the quality of the video streams, was according to the participants the **colour richness of the video** stream. Or to be more precise, the lack of colour richness and contrast that the drivers experienced while driving the truck remotely. The tests were conducted on days when the weather was clear, and the sun was bright. As researchers, we anticipated this would help with the test because rain or fog are notorious factors that negatively impact the use of cameras to drive a vehicle remotely or autonomously. The effect of the weather on the true-to-life colour representation on the video stream, however, turned out to be more complex. Due to the sun, the differentiation between colours on the video footage was low. It was therefore quite hard for participants, especially at higher speeds, to get a good sense of their surroundings: the environment of the truck became a blur on the video stream. In practice, at higher speeds the camera view contained mostly brown and grey tones, without clear distinctions between the road and its edges or nearby buildings. Consequently, it became difficult for the drivers to see a clear view of the vicinity of the truck or see distinctive features further ahead. This effect became bigger when driving at higher speeds, whereas a good and sharp view of the surroundings is arguably even more important at higher than at lower speeds. This test results requires significant attention in the further development of the technology in the R&D phases that lie ahead.

The difficulty with identifying objects far ahead was exasperated by occasionally **dropping pixel rates due to bad connectivity** during the tests. As we have already stated, all participants experienced glitches and delays in video imaging. Some participants concluded that such delays would be absolutely unacceptable when using this system outside of a controlled test environment. On the other hand, other participants said that dropping pixel rates were "not too big of a problem" (n=1) or something that you can learn to deal with (n=2). The quote below is from a participant who anticipated quick adjustment by the driver when pixel rates would momentarily go down.

> *'But you will get used to the delays, your eyes will adjust. You should not be looking at a very pixelated screen for a long time, but if something happens for a little while you will be able to handle that. I also think your brain will start automatically correcting after a while if the disturbance is only for a split second, like for example with blinking.'* (Participant 5, 03-06-2023)

Based on the current HMI test we have not been able to verify the threshold at which dropping pixel rates become too problematic for tele-operation, or at which speeds or environments this problem is most severe. More research needs to be done on this; see recommendations below.

Of course, in a conventional truck the driving task does not only comprise of responding to visual inputs. Drivers also rely extensively on haptic feedback from the truck and the environment to perform their driving task in a good manner. The comment below illustrates the general reflection on the importance of haptic feedback by one participant.

> *'What I run into is that when you are in the vehicle itself, you can feel the movements of the vehicle, you hear the sound, you have a complete experience. This experience is reduced in here, even though it is fun to do, the experience is less. And this makes it hard for me to estimate, because you step on the gas and you see that the vehicle starts moving, but you do not hear it. The same goes for braking, you miss this experience, this feeling, and I think that it is a very important thing to have.'* (Participant 2, 01-06-2023)

During the interviews, 4 participants talked about a **general disconnect between the haptic feedback of the pedals and the motion of the truck**. In addition, 2 of them mentioned that they did not like the way pressing the **brake pedal** feels. In the hardware that was used during the tests, the braking pedal was very stiff at the start of the braking motion. Once the participant pushed through this stiffness, however, they felt that the push back of the pedal dropped too much compared to the braking pedal in a real vehicle, which resulted in relatively sudden and harsh braking. This was something that the drivers tended to get used to during the test but is of course not very sustainable in professional teleoperation. Three participants also experienced a disconnect between the haptic feedback and the motions of the truck while using the **steering wheel**.

When talking about the general **rocking of the cabin**, 6 out of the 7 participants mentioned missing this, especially during acceleration and braking. The one participant who did not miss the motion of the cabin during braking and accelerating did however mention missing the **sound**, which contributes also to the 'feeling' of how the vehicle moves. In fact, 5 other participants, so 6 in total, mentioned missing the sound of the motor for the same reason. For professional teleoperation it will therefore be important to include transmission of the aural environment of the vehicle in addition to the visual footage that is currently transmitted.

Because drivers can only rely on visual input (and not the sound of the engine or wind) for the speed of the vehicle, they have to regularly check the speedometer. This diverts attention away from the rest of the driving task, and sometimes our participants ended up driving faster than expected. 2 participants suggested an option to limit the speed of the vehicle, to avoid accidentally driving too fast. There were also 2 participants who ended up (almost) off the road after a curve, specifically due to this lack of “a complete feeling” of the speed of the truck and the place on the road. In addition, looking at the speedometer regularly felt for some participants as an extra mental task while driving.

6.2.2.3 Regarding teleoperation as a concept, use-cases and the impact on truck-driving professionals

In this last section of the analysis of the interview data, teleoperation as an integrated part of freight transport will be discussed. The participants gave their opinions on the problems and possibilities they see for the future of teleoperation, and how they think about their own roles as professional truck drivers.

The first important issue raised by the participating drivers about teleoperation, is that of the focus and attention span of teleoperating drivers. One participant said that, because teleoperation intrinsically means that the driver is not immersed in the environment of the truck, the entire concept might end up in a reduction of the sense of responsibility of drivers. 2 other participants also expected to get distracted more easily when using the system for a longer period of time, because the entire experience of **teleoperated driving is less immersive** than in a real truck.

While some participants expected negative effects of teleoperation on the focus of the driver on the driving task, because of the lack of immersion, there appears to be **a tension between the short-term expectations and experiences of drivers, and their expectations of the possibilities for teleoperation in the future**. In our pilot test, 5 participants agreed that (a lot of) practice will negate some of the need for a realistic – meaning: replicating an actual truck – set-up during teleoperation, even though participants answered very affirmative (mean score 4.43) to the question “if the set-up had been more realistic, I would have been able to do the work better”. One participant said he does not need for the set-up to be realistic now, but that he would have needed it to be realistic a few years ago because he used to be less open to new technologies. 2 other participants also said that having realistic features in the set-up is nice, especially for experienced truck drivers, but that after getting used to it, it was not necessary to have all those additional features anymore, like the rocking movement of the cabin or the feeling of handling a large steering wheel. Participant 1 remarked:

> *‘I think the attention span will reduce faster. You do not hear the sound of the truck, you can turn on the radio though. I think als a truck driver, it is not the same feeling as being in a truck. Maybe as a gamer, some gamers are fully focused, looking at my children, they are impossible to disturb.’* (Participant 1, 01-06-2023)

So, clearly, **teleoperating takes practice**. As we have briefly mentioned before, all the participants noticed a substantial increase in their ability to control the vehicle during the test rounds, which took about half an hour in total. This is already a very short period of time. Based on their experiences in this limited timeframe, participants concluded that continued practice will help learning how to deal with the difference between driving a real truck and using the teleoperation system. 4 participants even expressed the hypothesis that there might be a difference between the quality of teleoperated driving by experienced truck driver’s vis-a-vis a new generation of drivers, where the new drivers might get used to using teleoperation more quickly than the more traditional drivers. As one participant explained:

‘The funny thing is, truck drivers used to rely on their hearing a lot more, back in the day. They did not have a tachometer. But the cabins got quieter, so they installed a tachometer to convey what happens with the rotational speed in the motor and when they have to shift gears. Truck drivers have now gotten used to it, but I can imagine that the new generation who never drove without a tachometer does not miss the sound at all. I think there is a division between new drivers and experienced truck drivers, where the experienced truck drivers will miss a lot more components in this [teleoperation] set-up as compared to the new drivers.’ (Participant 4, 03-06-2023)

Nevertheless, 2 participants in our tests would still like the set-up to be as realistic as possible. They did acknowledge that including every kind of haptic feedback into the teleoperation set-up will be difficult to achieve. All in all, based on the sample of 7 participants and the diversity in opinions within this sample, it is difficult to come to validated conclusions regarding the extent to which the teleoperation station should be designed and operatable in a similar way as a conventional truck in order to operate the truck safely and also in a way that the driver-operator will enjoy his work.

On the topic of enjoying the work of teleoperating and reflecting on the impact of teleoperation on their professions more generally, every participant mentioned **the joy of the physical experience of driving in a truck**. This seemingly simple or obvious part of their jobs was for each participant one of the reasons to become truck driver. The lack of this physical experience in the teleoperation set-up is therefore for some participants a large disadvantage of the entire technical concept. 4 participants were very explicit about this, as exemplified in the quote below. 4 of the participants also said that truck drivers would miss their freedom, and the thrill of going places far away from home (despite the drawbacks of such foreign adventures, but that discussion is too much off-topic for this report).

‘You see it [the environment] on a screen, you do not experience it yourself. And I think this is for a truck driver the best part of their job. The contact with their vehicle, the experience of driving it.’ (Participant 2,01-06-2023)

In addition to a pleasurable work experience, the participants are felt a large sense of **responsibility, towards their trucks, cargo and of course their environment and other road users**. This is an important finding, because when the driver is not physically present inside the vehicle, s/he will not have the opportunity to interact very directly with all these elements that regular truck drivers can interact with. Especially in case of an incident, either one-sided (involving only the remotely operated truck) or involving other road users or animals, the driver will also not be there to physically assess the situation or assist any wounded. Several participants said this could cause uncomfortable and undesirable situations, plus there are currently many uncertainties regarding the liability in case of an accident. Participant 7 had most reservations regarding this absence of a driver in case of an accident, or when the potential for hazardous situations is big, for example during bad weather conditions. In his own words:

‘And what happens if you have an accident on the road, huh? And not so much from a legal perspective, but how do you handle that? Because that thing [remotely operated vehicle] is uncontrolled. Or well, from a distance. Who will fill out the claim forms? Just saying. And what about slippery conditions, weather conditions? Are you going… are you going to depart or not? Are you taking off? I've always driven, rain or shine. Watching trucks blow over in front of me. And [those drivers were] not daring to say to the boss: I'm not going. What about situations like that? Weather influences... [1,5 minute later, after mentioning safety braking systems] And that is actually the conclusion of this story. You do a lot of things by feeling, with a car like that. You hear things, you see things, you feel things.’ (Participant 7,03-06-2023)

In the final part of previous quote, participant 7 also remarks upon another downside that participants foresee when introducing teleoperated vehicles in public traffic: the contact drivers have with their environment which contributes to their judgment of the traffic situation. In practice, this also entails a lot of **interactions and exchanges of looks with other road users**. In another part of the interview, participant 7 mentions:

> *'What also comes to mind is, you don't interact with other drivers, behind such a screen, do you? Because very often when you leave a roundabout and cyclists are riding there, they look at you through that mirror. And I already notice that with that camera system, that this is already lost. I also wanted to say that to you.'* (Participant 7,03-06-2023)

In addition to the personal interactions that drivers have with their environment while driving, the drivers are also responsible for their cargo. 2 participants talked specifically about the need to check the load inside the trailer to make sure everything is securely stowed while driving; a risk management task that is not only affecting the truck driver but of course also improves the (financial) reliability of the truck company in case of an incident. This will of course not be possible when the truck is driven via teleoperation. One participant therefore mentioned he would want a camera inside the trailer to be able to check on the load:

> *'Well, if the freight has fallen over or is no longer upright, will the company where you unload solve that? Or is the freight rejected and has to be returned? […] Sometimes the pallets are so damaged that they won't accept it. Then, if there is no one present, there is no one who can say, well, this was already the case or this was not the case. So, yes, in that case [of teleoperation] you don't have that physical checking. Or you should start putting cameras in the trailers as well.'* (Participant 1,01-06-2023)

Next to the issue of securely transporting the goods, several drivers also remarked that part of their job consists of arranging the necessary paperwork and helping with the physical loading or unloading of their loads. Both of these tasks can no longer be done on site, if the driver is not present, which implies that teleoperation not only changes the profession of truck drivers, but also the entire logistics chain more broadly: all communication will be mediated via digital tools or the phone, and on site there might be a need for additional workforce to do the (un)loading of the cargo. Thus, the implementation of teleoperation will require additional **changes in the logistics chain**.

One advantage of teleoperation, according to several participants, would be the **reduction of idle waiting times** at, or near, the (un)loading sites. This would be a positive effect, participants agreed, because waiting around is not a particularly nice part of their work, nor is that time always paid and can be rather lonely, although not every participant had a problem with that part of their job. Participant 3 commented that, despite the upside of reducing idle time at work, he would also miss the contact with fellow drivers on the road. And the prospect of talking only to colleagues in an office environment was not particularly inviting to some of the participants. Moreover, working overtime because of unexpectedly long hours before (un)loading is generally, at least partially, paid. Several participating drivers mentioned that the premiums they earn with those extra hours are a welcome addition to their standard wages. Participant 5 even concluded that it is the extra salary that makes the job financially interesting: "one has to rely [financially] upon paid overtime." (Participant 6, 03-06-2023). He continued:

> *'But for us, a 12-hour working day is very normal. And if you have to go back to 8 hours, you have to give up almost a third of your salary. Well, just ask anyone, who wants that. Who wants to go from 2000 euros a month to 1500? […] If you are a truck driver you don't have to work hard, but you do have to work a lot.'* (Participant 6,03-06-2023)

At the same time, working overtime seems to be a double-edged sword. While the additional income is an upside, having to (frequently) sleep away from home is difficult to combine with a social life and a family. For this reason, working in more standardized shifts and the possibility of taking over the driving shift from one teleoperator to another, is an interesting prospect for some of the participating drivers. Yet three participants also saw a potential negative influence of working in an office environment on the focus that is required for the driving task. They argued that the chit-chat in office spaces could reduce the alertness of teleoperating drivers. As participant 4 concluded:

> '*Yes, I think you should be careful. It can't be that someone taps you on the back of the shoulders and says "Hey, [first name], and you look the other way and... [laughs] […]. I do think that someone would have to sit in some sort of shielded environment. If you are driving 30 km per hour and you look the other way, you have passed the intersection, so to speak. I could see that as a danger, but we are used to talking while driving and such. […] You do get distracted, because I believe that if you call, even though it is hands-free, you are still not 100% focused on driving. But I would like to be shielded [while teleoperating], I think, and not in an office building where there are 30 people sitting behind you.' (Participant 4,03-06-2023)*

Based on this remark, and similar concerns put forward by the participants, we conclude that the further development of teleoperation in road transport not only requires innovations that enable the technology for the remote operation itself, but also necessitates well-considered changes in the working environment of the operating drivers and the larger logistics chain. Based on the interviews, we summarize the most important benefits and downsides, according to the participants, of the concept of teleoperation in the field of road transport in Table 13. The numbers that are mentioned indicate the frequency that the respective issue was brought up during the conversations, after the participants had performed the driving task.

Table 13: Summary of most important downsides and benefits according to the participants.

Benefits	Downsides
- More efficient logistics by switching between vehicles; reducing idle time for the driver/operator (n=5) - less physically straining work for the drivers (n=1) - less commuting time and kilometres when teleoperation is possible from home (n=1) - no reduction of enjoyment of the job itself (n=1) - more time for family and friends because of more reliable working hours (n=3) - possibility of operating 24/7 (n=1) - more flexible working hours (n=2) - becoming a truck driver/operator might be appealing to new types of employees (n=3)	- less direct (sensorial) contact with the environment which inhibits a sharp view on the vicinity and distance ahead of the vehicle (n=5) - less enjoyment of the job itself (n=7) - a sense of motion sickness (n=1) - traffic safety concerns due to lack of sensorial information from the environment of the vehicle, including weather conditions (n=2) - complications in the process of (un)loading cargo; need to revise the entire logistics chain (n=3) - distraction or lack of focus from the driving task when teleoperating (n=2) - uncertainty about maintaining the same amount of salary (n=2) - not having an 'own' truck anymore; not feeling comfortable in the vehicle (n=1) - some parts of the infrastructure, like crowded areas, are not suitable for remote

	operation due to the complex traffic conditions (mixed traffic, narrow roads, etc) (n=1)

6.3 Conclusions and recommendations based on the 5G-Blueprint human factors study

In this small pilot study, we have performed a first, exploratory research on the human factors in teleoperation based on the setup as developed in the 5G-Blueprint project. 7 participants gained some practical experience with the technology during a short driving pilot (30 minutes) during which they drove rounds around a building block at the industrial site IPKW in Arnhem and performed two manoeuvres (straight and 90 degree reversed parking). Next to the driving exercise, the participants filled out a pre- and post-survey, and discussed their experiences with researchers during a semi-structured interview (max 45 minutes).

Despite the small scale of this human factors study, which is clearly a limitation, a number of **findings** stand out. The participants identified several concrete points for improvement regarding the design of the set-up. Some of these are obvious, such as adding handles for the blinker lights or using a proper ergonomic chair when having to do teleoperation for a longer period of time. More relevant findings for the prospects of teleoperation are the need for several more camera streams (front of the vehicle, sides of the vehicle, rear of the trailer, inside the trailer) and the position of the various video feeds should be adjustable on the screens of the teleoperator. Regarding the video feed itself, participants remarked on the low colour richness which results in a monotonous blurring of the environment on the screen. This makes it difficult to see what is happening around the vehicle, especially at higher speeds. This poses a real risk for traffic safety when the teleoperation is taking place in mixed traffic. Moreover, all participants missed the immersive experience of truck driving, where they can use their hearing and tactile senses a lot more to perform the driving task, and do not have to only rely on the visual input to drive safely. At the same time, practice can (potentially) play a (large) role in negating these issues: drivers might get used to the blurring of the environment or occasionally dropping pixel rates due to bad connectivity. The extent to which this is the case, without causing potentially dangerous traffic situations or unacceptance by the teleoperating drivers, needs to be researched further.

Based on the conducted study, we present the following **recommendations** for improving the HMI of teleoperating trucks and **suggestions for additional research on human factors** aspects of research that is being done in the project 5G Blueprint, and that could also contribute to other ongoing research in the field of teleoperation of (large) vehicles.

1) We recommend starting any test using teleoperation on short routes, preferably on (semi)closed-off terrains with multiple buildings, such as production facilities or distribution centres. While drivers may get used to the ‘feeling’ of driving remotely fairly quickly, they need a good sense of the vehicle handling before they can make manoeuvres, let alone drive the truck (or any other vehicle type) on public roads.
2) Improve camera positioning and overall view on the surroundings of the truck. This research did not give conclusive results on which camera positions are best, but the next points could be taken in account:
    a. Prevent blind spots, specifically directly on the left and right of the cabin and in front of the cabin.
    b. Adding a camera at the back of the trailer for precise parking.
    c. Move the front view camera to the left instead of having it in the middle of the cabin, in order to mimic the current seating position of truck drivers. This may be especially convenient for people who are currently driving on the road and who move into teleoperation in a later stage of their career.

   d. Add indication lines on the screens to compensate for the lack of depth in camera views.
   e. Allow different camera combinations on the main display, depending on the driving task (directions, speed, manoeuvres) to allow the driver to focus on the cameras that are needed for a specific task and prevent information overload, e.g., switching between rear and front camera streams on the main screen when reversing.
   f. Improving the colour richness of the video stream, the minimize the blurring effect when driving in very sunny, dark/grey conditions or at higher speed.
3) Making the entire setup more like an actual truck (more 'realistic') can lower the bar for truck drivers to get used to the system and make them more willing to try it out. Points where the setup used in this trial could be adapted to resemble a truck cabin:
   a. Positioning and size of the mirrors.
   b. Size of the steering wheel.
   c. Size of the screens, with the middle screen should be wider to mirror the proportions of the windows in a cabin.
   d. Add handles for the blinker lights to the steering wheel.
4) Look into ways to incorporate sound in the HMI, both from the truck itself and surround sound from outside environment of the vehicle.
5) Improve pedal feeling through another pedal configuration and improve the calibration between haptic feedback and behaviour of the vehicle.
6) Improve calibration of the steering wheel, without a dead point in the middle and change to a more realistic steering wheel with a direction indicator (handles for blinker lights). A full-size truck driving steering wheel might not be necessary, though.
7) Use an ergonomic seating arrangement with high-quality chair, desk, and other basic equipment for desk work.
8) Experiment with visualizing some of the haptic experiences, such as the current steering angles (via a real-time path indicator) or the braking force that is applied. It remains unclear, on the basis of this pilot, to what extent the haptic experiences that drivers currently use as sources of information while driving, must be integrated in the teleoperation setup in order to prevent unsafe traffic situations.
9) Investigate the effect of gaining experience with teleoperation on (the evaluation of) the teleoperated driving task. This can be done by enabling drivers to try teleoperation for longer periods of time, and by including different target audiences (in terms of experience with truck driving, driving different types and sizes of trucks, etcetera).
10) During the conversations with the truck drivers who participated in our small study, the hypothesis was put forward that, maybe, people who are experienced gamers may have less difficulty adjusting to the camera-mediated process of driving a truck compared to professional truck drivers. This may also be an interesting direction for future research.

7 SKID STEER TESTING

Part of Use Case 4.2 is a teleoperated Skid-Steer, which plays a vital role in transporting loose materials (e.g., sand, phosphate, etc.) in warehouses and barges. Like any other material handling equipment Skid-Steers also pose a high risk for the operator and the environment in case of a mishap. Furthermore, Skid-Steers are also, in many cases, used in environments such as high temperature zones, low ventilation spaces and inside barges that are dangerous to human operators. Besides, the goods that are transported may also pose a risk to the operator. Therefore, teleoperation or remote operation could be a solution to these issues. Furthermore, it can make the entire logistic movements more efficient, since operators don't need to go from one machine to another but can directly control different machines from one teleoperation centre.

7.1 Pilot site description

The implementation of the teleoperation aspects and the corresponding tests on the Skid-Steer are conducted in the Verbrugge Scaldia Terminals located in Vlissingen, Netherlands. Figure 57 shows a top view of the Verbrugge premisses and Figure 58 shows an aerial view of the Terminals used by the employees themselves.

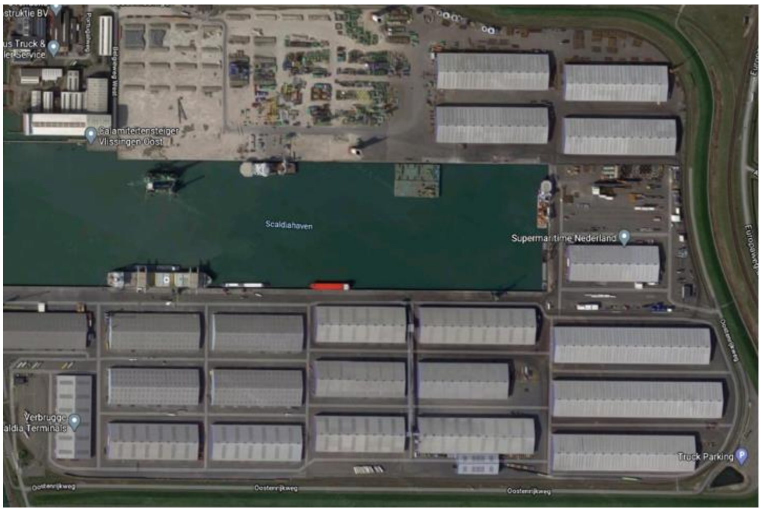

Figure 57: Verbrugge Scaldia Terminals (top view)

Figure 58: Verbrugge Scaldia Terminals (aerial view).

7.2 Equipment and vehicle

This section will give a brief description of the equipment used to accomplish UC4.2b

7.2.1 Vehicle side

The Skid-Steer used for this project is the fully electric “Skid steer loader Elise 900” developed by Firstgreen Industries as shown in Figure 59 (Firstgreen, 2022).

Figure 59: Skid steer loader Elise 900 from Firstgreen Industries, used for teleoperation.

The Skid-Steer is made teleoperated by Roboauto in a similar way as the other vehicles (i.e., the car(s) and truck). It has 4 cameras, one facing forward, two facing left and right respectively and one facing backwards, to provide the operator with visual feedback. The Drive-By-Wire system of Roboauto is connected to the Skid-Steer to be able to control the vehicle. And a Sierra wireless XR90 5G router is used for the communications.

7.2.2 Teleoperation centre

The teleoperation centre is the same set-up as the one used for the autodocking functionality, with some minor changes. The controls are no longer provided via a steering wheel and pedals but by two Thrustmaster TCA Sidestick Airbus Edition joysticks, similar to a regular Skid-Steer. And the displays will show different PoV of the cameras installed on the Skid-Steer compared to UC 4.2a. Figure 60 provides a simplified set-up of this teleoperation centre set-up including the different camera streams POV.

Figure 60: Simplified teleoperation set-up for Skid-Steer driving, including the joysticks & camera streams.

7.2.3 Communication platform

To facilitate teleoperation, a communication link between the operator side and the Skid-Steer side is required. This is accomplished by using a fixed 5G access point in the Verbrugge Terminal Office and a Sierra wireless XR90 5G router on the Skid-Steer. Via this 5G communication link control signals are send and video streams are received.

Since the scope of this work package is to evaluate and demonstrate the capabilities of the 5G networks no further details will be given on the communication side.

7.3 Test plan, Results & Discussion

This chapter describes the tests that were performed with both the electric Skid-Steer, which was controlled teleoperated, and a regular Skid-Steer of Verbrugge, which was controlled manually by an operator, all on the Verbrugge Terminals premisses (See Figure 61). These tests gave various insights in both operation and usability, as well as usable feedback to improve the functionality of teleoperation, like driver's sitting position, quality of the video streams, etc. etc.

In addition, it was tested whether the driver can perform his daily activities properly when he or she operates the vehicle based on teleoperation. This was extensively tested over a period of 2 hours and various measurements were made. In addition, the operator was interviewed about his experiences.

To demonstrate the application value of teleoperation it is necessary to compare the measurements made with the teleoperated Skid-Steer with a regular Skid-Steer. Therefore, the same activities / tests have been performed, with the same operator, in a regular Skid-Steer.

The following pages describe the test procedures, the measurements taken and the results. At the end (subjective) feedback from the operator is included and some discussion is given.

Figure 61: Image of the routes to be driven for test 1.

Note: The red route (office-terminal) goes between terminals 5 & 8! At the end of terminal 8, you turn around, go back, and drive around terminal 8 before reaching the end point.

7.3.1 Tests & Results

First a short description of the performed tests is provided, followed by the results of the described test, which can be found in Table 14 till Table 19.

1. **Warm-Up drive**
    - First, familiarise the operator to the Skid-Steer. Especially if the operator has never operated it before. Do this by letting the operator drive short distances and operate the bucket of the Skid-Steer in the same way as needs to be done in daily operation.
    - Make the tasks more challenging along the warm-up drive. Make sure the driver is really used to the system before engaging the next test / activity.

2. **Moving around 1**
    a. Objective: Follow the indicated route according to Figure 61, i.e., drive from the starting point (Verbrugge Terminal Office) to the end point in Terminal 9[5]. Considering the (traffic) rules of Verbrugge!

Measurements	Teleoperation	Regular Operation
Time in [mm:ss]	11:30	4 min. 48 sec
Number of standstills:	1 (1 minute standstill)	0
Comments about the test / activity:	*For the teleoperation drive, the route between terminal 5 & 8 was blocked and therefore a different route had to be taken. So, the same route has to be driven with the regular skid-steer.*	
General feedback on the teleoperation:	*Operator is happy with the increased speed! Furthermore, the field of view is sufficient, and he can navigate easily on the terrain to the terminal(s). As mentioned before (February tests) the operation feels very natural.*	

Table 14: Results of the “Moving Around” test - 1 both teleoperation & regular operation.

3. **Normal operation light materials 1**
    a. Objective: In the Terminal, scoop[6] <u>five times</u> the light material (poly premium) from the main pile and make a new smaller pile on the floor in front of it (i.e., place each shovel/scoop in the same place). Try to scoop the same amount of material into the bucket each time!

Measurements	Teleoperation		Regular Operation	
	3.a.1	3.a.2	3.a.1	3.a.2
Time in [mm:ss]	06:30	02:40	01:12	01:07
Comments about the test / activity:	*Pile created during 3.a.2 teleoperation was 2x bigger compared to the regular operation pile.*			

[5] Note: The red route (office-terminal) goes between terminals 5 & 8! At the end of terminal 8, you turn around, go back, and drive around terminal 8 before reaching the end point.
[6] Transport 5 buckets of light material with the skid steer to create a new pile.

General feedback on the teleoperation (3.a.1):	*Went well according to the operator. The direct and fast control is good. It feels natural according to the operator. But the perception will always be an issue, especially when it comes to the bucket. It is hard to estimate depth and it is even harder to know when the bucket is (almost) hitting the floor/ground or not. The operator mentioned that some lines on the display which indicate whether the bucket is hitting the floor could really help. And according to the operator he can do the "normal" job almost at the same speed compared to regular, manual operation, but it feels a bit slower.*
General feedback on the teleoperation (3.a.2):	*Well as can be seen the operator becomes much faster. However, he also wanted to be fast and therefore the operation did not always go well and small mistakes were made. Especially going reverse is something that is not ideally configured according to the operator. Pulling the joystick to go reverse is more natural compared to pushing.* *Next to this more material is moved. Which is very comparable to regular, manual operation. Operator says that this is the same as manual operation. He can't do it faster manually.*

Table 15:Results of the "Normal Operation Light Materials" tests - 1.

b. Objective: Move the newly created stack/pile back to the main stack/pile. Do this by sliding the bucket over the floor, and then pushing the material against the main stack! Don't scoop up the little pile! Furthermore, try to clear the stack as quickly as possible, so slide as much material as possible against the main stack at a time.

Measurements	Teleoperation		Regular Operation	
	3.b.1	3.b.2	3.b.1	3.b.2
Time in [mm:ss]	02:00	1:45	00:18	00:14
Number of times pushing:	3	3	2	2
Comments about the test / activity:	*Pile created during 3.a.2 teleoperation was 2x bigger compared to the regular operation pile.*			
General feedback on the teleoperation (3.b.1):	*Same comments about perception. Can do the job well according to the operator.*			
General feedback on the teleoperation (3.b.2):	*Even though the pile created with test 3.a.2 was much larger compared to test 3.a.1, it took almost the same amount of time to shove it back. The operator was happy (except for the bucket perception, as mentioned before)*			

Table 16: Results of the "Normal Operation Light Materials" tests – 2.

4. **Normal operation heavy materials 1 (±5min)**
   a. Objective: In the Terminal, scoop five times the heavy material (phosphate) from the main pile and make a new smaller pile on the floor in front of it (i.e., place each shovel/scoop in the same place). Try to scoop the same amount of material into the bin each time!

Measurements	Teleoperation		Regular Operation	
	4.a.1	4.a.2	4.a.1	4.a.2
Time in [mm:ss]	04:00	04:30	01:03	01:00
Comments about the test / activity:	*Pile created during 4.a.1 & 4.a.2 teleoperation was 2x bigger compared to the regular operation pile.*			
General feedback on the teleoperation (4.a.1):	*Operator is getting more used to the system, so he becomes faster. But still, it feels a bit slower than "normal" operation according to the operator. Main reason is the perception of the bucket. However, operator has the feeling that it will become better when he uses the system more and more. Heavy materials are no problem!*			
General feedback on the teleoperation (4.a.2):	*Not faster than test 4.a.1, but this is due to the fact that more material was taken per time and the operator was dropping it with more precision (on purpose). According to the operator this was perfect!*			

Table 17: Results of the "Normal Operation Heavy Materials" tests - 1.

   b. Objective: Move the newly created stack/pile back to the main stack/pile. Do this by sliding the bucket over the floor, and then pushing the material against the main stack! Don't scoop up the little pile! Furthermore, try to clear the stack as quickly as possible, so slide as much material as possible against the main stack at a time.

Measurements	Teleoperation		Regular Operation	
	4.b.1	4.b.2	4.b.1	4.b.2
Time in [mm:ss]	03:00	02:30	00:30	00:28
Number of times pushing:	4	3	2	2
Comments about the test / activity:	*Pile created during 4.a.1 & 4.a.2 teleoperation was 2x bigger compared to the regular operation pile.*			
General feedback on the teleoperation (4.b.1):	*Same comments about perception, but apart from that the job can be done well. It is of course slower than test 3.b.1 but this is due to the fact that the materials are heavier, and the pile created with test 4.a.1 is larger compared to test 3. a.1*			
General feedback on the teleoperation (4.b.2):	*Not much to tell according to the operator. Went really good!*			

Table 18: Results of the "Normal Operation Heavy Materials" tests - 2.

5. **Normal operation light materials 2 (±5min)**
   a. Objective: In the Terminal, scoop five times the light material (poly premium) from the main pile and make a new smaller pile on the floor in front of it (i.e., place each shovel/scoop in the same place). Try to scoop the same amount of material into the bin each time! (Repetition of Test 3, results can therefore be found in the table of Test 3).

   b. Objective: Move the newly created stack/pile back to the main stack/pile. Do this by sliding the bucket over the floor, and then pushing the material against the main stack! Don't scoop up the little pile! Furthermore, try to clear the stack as quickly as possible, so slide as much material as possible against the main stack at a time. (Repetition of Test 3, results can therefore be found in the table of Test 3).

6. **Normal operation heavy materials 2 (±5min)**
   a. Objective: In the Terminal, scoop five times the heavy material (phosphate) from the main pile and make a new smaller pile on the floor in front of it (i.e., place each shovel/scoop in the same place). Try to scoop the same amount of material into the bin each time! (Repetition of Test 4, results can therefore be found in the table of Test 4).

   b. Objective: Move the newly created stack/pile back to the main stack/pile. Do this by sliding the bucket over the floor, and then pushing the material against the main stack! Don't scoop up the little pile! Furthermore, try to clear the stack as quickly as possible, so slide as much material as possible against the main stack at a time. (Repetition of Test 4, results can therefore be found in the table of Test 4).

7. **Moving around 2 (±10 min)**
   a. Objective: Follow the indicated route according to figure 1, i.e. drive from the starting point in terminal 9 to the end point (Verbrugge Terminal Office). Considering the (traffic) rules of Verbrugge!

Measurements	Teleoperation	Regular Operation
Time in [mm:ss]	06:20	03:09
Number of standstills:	0	0
Comments about the test / activity:		
General feedback on the teleoperation:	*The route was shorter compared to the first drive, so that's why it was faster in terms of time. But the operator said, since he was more used to the system, he was able to drive faster and still felt safe and in control. Furthermore, he had the feeling that this time of driving is comparable to regular, manual operation.*	

Table 19: Results of the "Moving Around" test - 2 both teleoperation & regular operation.

8. **Feedback of tests (±10 min)**

   a. Throughout the tests the operator might have given any feedback, write that down here. Furthermore, try to dive a bit into the given feedback. Did the operator face any remarkable things? What was very different compared to a regular skid-steer. Could the teleoperated skid-steer be used in the same / similar way as the regular skid-steer? What was good? What needs to be improved? Etc. etc.

Teleoperation	Regular Operation
Good points: • *Video quality is good! Except for some short flickering* • *Most of the teleoperation feels very much similar to regular, manual operation.* • *The increased speed and possibilities to change the speed is a good improvement!* • *The field of view is sufficient, and navigating can be done properly. It feels very natural.* • *Transportation time of personnel will definitely be reduced. Instead of walking to a certain machine you can directly log-in.* • *Great solution for certain operations, for example when working with dangerous materials or when working in poorly ventilated areas (e.g., in belly of a barge).* Points for improvements: • *There is no sound feedback.* • *The joysticks positions didn't feel natural. Should be lower / in a more relaxed position, i.e., comparable to a normal skid-steer position.* • *In terms of operation, it doesn't feel natural to push the joystick forward to go reverse. Pulling it will be more logical. And not needing to push a button to go reverse would even be better!* • *Hard to have a clear perception of the bucket. It is hard to estimate the depth, but it is even harder to know when the bucket is (almost) hitting the floor/ground or not. Possible solutions could be markings on the display that inform the operator about this. Or go one step further, driving fast will not be possible when the bucket is too low / on the ground.* Other comments given by operator: • *As an improvement, it is good to show the battery level / fuel level.* • *Have communication possibilities (right now they have walkie-talkies in the cabin) in the teleoperation centre, e.g., via button on joystick.* • *Getting more used to the system makes you faster, more precise and more fluent in operation.* • *Think of a light (G/Y/R) system that indicates*	*Operator felt much more comfortable to be physically present in the skid-steer. The direct feedback received by the machine and having a good depth and/or height perception is unmatchable from a distance.* *Furthermore, when being in the machine the operator can feel direct feedback in terms of resistance when driving into a pile of material or when shoving materials back to a main pile. It is much easier to know when to stop.* *(This feedback is in line with the given feedback when driving teleoperated. The feeling and depth perception are two main factors that are not (well enough) present in the teleoperation environment.)*

whether the load in the bucket is too heavy or not. • *Think of an emergency switch on the joystick as well. Is very common to have that in a skid-steer, also for manual driving!*	

Table 20: Feedback of driving teleoperated compared to regular operation given by the operator.

7.3.2 Discussion

The performed tests give various insights in the use case of a teleoperated Skid-Steer. First of all, by comparing the results it can be seen whether the teleoperated Skid-Steer can have an added value and if it will be possible for an operator to perform its daily activities properly. Furthermore, the feedback given can be used to improve the overall system.

From the results it can be easily observed that the operator is always faster when operating in a regular Skid-Steer and being physically present in the vehicle. But before drawing the conclusion that teleoperation is less efficient some remarks can be made:

- During the Teleoperation tests, except for test 3.a.1, the piles created were much bigger compared to the regular operation tests. Moving more goods will automatically lead to more time. It is therefore hard to compare the time with each other. Since there was no basket (or something similar) available at the time of teleoperation tests it was not possible to perform tests where the same amount of materials could be moved by the operator.
- Next to the previous remark, the location of the created pile was different every time. Resulting in a different travelling distance. However, the difference is within a span of 2 meters maximum, therefore not influencing the results too much.
- Even though the operator has had a warm-up, the time spent in the teleoperation centre is very limited (i.e., neglectable) compared to the time spent in a regular skid-steer. Meaning that the operator might not be trained / skilled enough to perform daily operations in a proper way. Looking at the results it can be observed that the operator becomes faster over time, showing that training will help. This was also mentioned by the operator himself.

Next to the measurement some clear insights are provided by the operator. Usability and driveability of the teleoperated Skid-Steer are very good. The field of view is sufficient, and the operation feels natural to a certain extend. However, when it comes to daily operation the perception of the bucket (depth & height) is the main bottleneck when it comes to efficiency. It takes the operator longer to identify whether the bucket is located correctly. Furthermore, some (small) improvements can be made to make the operation feel more similar compared to a regular Skid-Steer. For example, the location of the Joysticks doesn't feel natural, and eventually resulting in tired arms. Also, the way of reversing is different, and the operator has to think about it instead of operating the Skid-Steer in an unconscious way. All of this will result in less efficiency, but with those improvements and with proper training it can for sure be increased.

To conclude this section, it can be said that teleoperation of a skid-steer can definitely have some great advantages in an environment like Verbrugge Scaldia Terminals. It can reduce the risks when working in harmful environments (e.g., inside the belly of a barge) or when transporting risk to health/dangerous goods. Furthermore, it can make the logistic chain more efficient by having operators changing machines from one place instead of moving them from one machine to another. However, when it comes to daily operation it is hard to tell whether the same (or even higher) level of efficiency can be achieved. Future research is necessary since testing was very limited in time due to the provided availability of the operators from Scaldia terminals, who prioritized the work for terminal over the research activities. Improvements on the Skid-Steer and teleoperation centre (e.g., better perception of the bucket, location of joysticks, reversing, sound feedback, communication possibilities, emergency switch, etc. etc.) are also necessary.

8 CONCLUSIONS

8.1 Use Case 4.2a

In conclusion, the 5G-Blueprint project's Use Case 4.2a has focused on teleoperation and autonomous docking of a truck and trailer combination. Autodocking offers numerous advantages, including precision, efficiency, safety, reduced stress, optimized space usage and better supply chain management. It provides benefits for both commercial and personal vehicle operators, making parking and docking processes smoother and more effective.

Development was done on both software and hardware components. On the software front, critical components such as a high-fidelity model, a path planner, and two path-following controllers, the pure pursuit controller (PPC) and the model predictive controller (MPC), were thoroughly tested and evaluated. The hardware components, including the teleoperation centre, communication hardware, localization hardware, and the actual truck, underwent a well-structured implementation process across three phases: modelling, minimum viable platform (1:3 scaled truck and trailer), and full-scale testing. Defined KPIs like tracking error, final docking state error and overall docking time were established in order to assess the systems performance.

Through extensive testing, it can be concluded that all the KPIs of the autodocking functionality are within the targeted values. Path planning time is not affected by network quality and remains under the target value. Tracking errors during docking are optimized through controller parameter tuning but are sensitive to network quality, especially in tight spaces. Final docking state errors, critical for parking accuracy, were within target values but are impacted by network quality, with potential deviations in narrow surroundings. GPS position and orientation accuracy consistently meet target values, ensuring precise autodocking. While network quality influences some KPIs, the system maintains overall reliability and accuracy in the tested scenarios.

As said, network quality has influence on the overall performance of the autodocking functionality. Particularly latency and fluctuations in latency in the 5G NSA network, significantly impacts the performance of the autonomous docking system. High network delays (>100 ms) lead to undesired vehicle behaviour, affecting the KPIs. To mitigate this, the controller was tuned to prioritize steering suppression in the cost function, enabling smoother and slower steering responses. However, this strategy is suitable for slower tasks like autodocking and may not suffice for high-speed manoeuvres. The study underscores the importance of network performance and the adaptability of the Model Predictive Controller (MPC) to address network-related challenges, offering insights into enhancing system robustness in various network conditions.

In conclusion, despite network quality challenges at the IPKW test site, the Model Predictive Controller (MPC) is the preferred choice for autodocking. MPC offers stability with minimal fluctuations, smooth path following due to its predictive nature, and superior performance in tight spaces. Even in poor network conditions, the MPC remains within KPI limits, highlighting its adaptability and robustness, setting it apart from the Pure Pursuit Controller (PPC). The results underscore MPC's ability to excel in applications requiring precision, adaptability, and control smoothness, making it the more forgiving and effective choice, particularly when network quality is a concern.

In addition to the development, a small pilot study was performed which aimed to study the effects of teleoperating a truck with real truck drivers (7 participants in total). Key findings and recommendations include the need for improved teleoperation setup with ergonomic features, multiple adjustable camera streams, and enhanced sound integration. Participants emphasized the importance of realism, suggesting changes to mirrors, steering wheel size, and screen proportions. Enhancements in pedal configuration, steering wheel calibration, and haptic feedback were also recommended. Additionally, the study pointed to the impact of teleoperation experience and the potential advantages for experienced gamers. Further research is essential to implement these recommendations and enhance the teleoperation interface for trucks effectively.

8.2 Use Case 4.2b

For use-case 4.2b, a skid steer was modified for teleoperation purposes. In conclusion, the tests on the teleoperated Skid-Steer provide insights into its potential. While it's clear that operating a regular Skid-Steer in person is consistently faster, several factors need consideration. The larger material loads and variable pile locations in the teleoperation tests make direct time comparisons difficult. Operator training significantly influences performance, with improvements noticed over time. The operator found the teleoperated Skid-Steer usable but identified challenges related to perceiving the bucket's depth and height. Some aspects need improvement, such as joystick placement and reversing mechanisms. Teleoperation offers advantages in specific environments but may require further research and system enhancements for achieving daily operational efficiency.

8.3 Key Learnings

To conclude this report, the most important key learnings are listed which summarise the conclusions made above. This paragraph can serve as a testament to the next generations that would like to continue on this topic in a comparable project. The key learnings are listed below:

- Model Predictive Controller is the highly suitable control technique for the automation of tasks exerted through the teleoperation thanks to its robustness and ability to deal with unpredictable disturbances both on the side of network and vehicle.
- Network quality has influence on the overall performance of the autodocking functionality. Particularly latency and fluctuations in latency in the 5G NSA network, significantly impacts the performance of the autonomous docking system.
- RKT GPS is a very suitable and robust method for localisation for autodocking. Accuracies are high and very stable. Due to costs of the systems, studying alternatives for localization like Lidar or localization on infrastructure are recommended.
- Training a teleoperator (both for a truck or a skid-steer) significantly improves performance. Over time, all participated teleoperators got more comfortable with the system and therefore the teleoperation performance improved significantly.
- Participants of the HMI study emphasised the importance of realism in the teleoperation centre. A realistic steering wheel, chair and haptic feedback could massively improve the “feeling of driving a truck” and therefore improve teleoperation performance.
- Providing a sound to the teleoperator brings considerably better situational awareness no matter the transport vehicle is considered as confirmed by extensive test campaign in this project.
- Perceiving bucket depth while teleoperation a skid steer is difficult to do through a camera stream which makes teleoperating a skid steer somewhat challenging.
- Teleoperation of skid-steers offers advantages when working in hazardous environments.

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