AUTOMATED DOCKING OF TRACTOR SEMITRAILER WITH DRIVER IN THE LOOP VIA 5G TELEOPERATION

K. Kural, MSc, PhD., Senior Researcher at HAN University of Applied Sciences.

N. Muthakana, MSc. Researcher at HAN University of Applied Sciences.

D. Devasia, MSc., Researcher at HAN University of Applied Sciences

G, van Stekelenburg, MSc, research engineer at V-Tron

B. Hetjes, MSc, Research Engineer at V-Tron.

R. Kusumakar, MSc., Chief Technology Officer at V-Tron.

O.Held, MSc, Project manager at Roboauto

J. Juza, MSc, Chief Execution Officer at Roboauto

Abstract
The logistics sector is continually seeking innovations to improve service productivity and profitability in freight transport, such as reduced fuel consumption and automation in warehouses. However, the road transport sector in Europe currently faces challenges such as a shortage of drivers, unused road capacity at night, and poor digital insight into traffic. Digitalization and enhanced telecommunication, like 5G network connectivity, offer solutions for improvement, including teleoperation where vehicles are controlled remotely by humans from a control center, leading to increased efficiency and comfort for drivers. This paper presents a set of the first results of a pilot project where Automated Docking functionality was integrated in the teleoperated tractor-semitrailer combination. The paper discusses functional architecture, controller design, integration, and the first results of testing on a full scaled vehicle demonstrator.

Keywords: Digital Technology and data, Heavy vehicle design and technology, Intelligent Vehicle System, Driver Support, Low-speed Maneuvering

1. Introduction

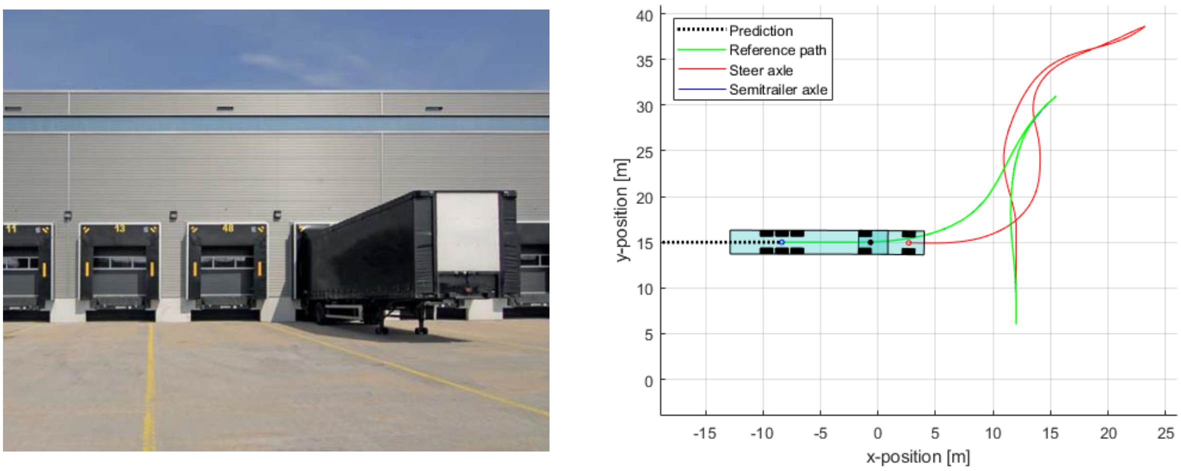
The logistics sector is constantly looking for innovations that can help improve the service productivity level and profitability of the freight transport. These innovations have led to reduced fuel consumption and emissions in recent decades, and the automatization inside the warehouses, among other things. Yet, road transport sector in Europe nowadays faces new challenges such as dynamically growing shortage of drivers, unused road capacity during the night, wasted terminal time due to paperwork and poor digital insight into total incoming and outgoing traffic. Digitalization and enhanced telecommunication offer concrete options for improvement. Where fully autonomous transport is not yet feasible under all operational condition's, teleoperation can add to the next level in road transport.

In the teleoperation, humans still monitor and operate the vehicles but from the distant control center, shown in Figure 1. To make this work, communication between vehicles and control centers needs to be fast, secure, widely available, and reliable at all times, being exactly the promise of 5G network connectivity. This significantly changes the work of drivers while offering more comfort, but most of it makes it more efficient. Instead of waiting for cargo at a terminal and adding avoidable costs, an operator can remotely switch control between several different vehicles. Moreover, additional automated functionalities can be accommodated by teleoperation such as Cooperative Adaptive Cruise Control (CACC) for Truck Platooning or Automated Docking of the vehicle combination when the operator has a purely supervisory role. In this paper we present the latter functionality of Automated Docking combined with teleoperation, which is being developed, integrated into a full scale demonstrator, and tested in the real-life conditions.

Figure 1. Teleoperation visualization.

1.1 Automated Docking Context

Over the past decade, there has been a constant increase in the volume of cargo transported on European roads. This trend may continue in the future, requiring an increased number of vehicles to meet the growing demand for transportation, as identified by European Commission (2011). This, in turn, presents challenges for distribution centers and yards, which must ensure that the vehicle combinations are parked correctly at the loading dock, as depicted in Figure 2.a).



a) b)

Figure. 2 Loading dock at distribution center, and typical docking paths

Although automation has been implemented in warehouses and distribution centers for decades, it has not yet extended to the parking areas outside. The docking of vehicle combinations to loading docks, consisting of low speed forward driving and reversing shown in Figure 2.b), is still done manually by drivers, despite the existence of safety risks. Measurements conducted during bi-directional low-speed maneuvering with articulated vehicle combinations have confirmed that drivers primarily suffer from a lack of visibility from the cabin, which is limited to the front view and rear mirrors. In addition, drivers are challenged to control the naturally unstable vehicle combination during reversing in an area that is typically limited in space, and the parking tolerances at the end position do not exceed ±10 cm due to the tight spacing between the loading docks.

In manual teleoperation mode, docking a vehicle combination can still pose a challenge for the teleoperator driver due to limited visual input, which remains comparable to normal operation. It is therefore expected that complementing teleoperation with automation in this use case would represent high added value for the teleoperators, which would improve both safety and productivity. Furthermore, the majority of recently manufactured vehicles are equipped with advanced X-by-wire systems. These systems enable precise control over steering angle, gear shifting, gas pedal, and brakes from a remote location, eliminating the need for direct driver intervention. This inherent capability makes them an ideal foundation for the development and implementation of auto-docking functionality. In this context, the only requirement is to ensure vehicle connectivity through a 5G modem, eliminating the need for significant investments in vehicle hardware.

1.2 Paper Structure

The paper is organized as follows. At first, we will introduce high-level functional architecture emphasizing the auto-docking path tracking controller, and path planner design, which are most aligned with main themes of the conference. Next, the integration and testing of the full-scale demonstrator at the pilot site are described at next in detail. The paper is concluded with test results, along with the discussion and research outlook.

2. System description

To illustrate the functionality of the complete system representing currently stat-of-the-art, a high-level architecture is depicted in Figure 3. The teleoperator sits in the remote cockpit, where his/her primary input is a Point of View (POV) video stream from six cameras located in the vehicle. This stream is transmitted via a 5G network which is used as well for carrying the control signals. The usage of 5G has key importance here since classical 4G networks do not ensure sufficient bandwidth, low latency, and robustness. The secondary screen displays an Enhanced Dashboard that filters relevant information from enabling functions. These functions may include the detection of vulnerable road users, estimated time of arrival, active collision avoidance, distributed perception, and time slot reservation at intersections. The set of enabling functions improves the teleoperator's situational awareness, contributing to safety, productivity, and user acceptance.

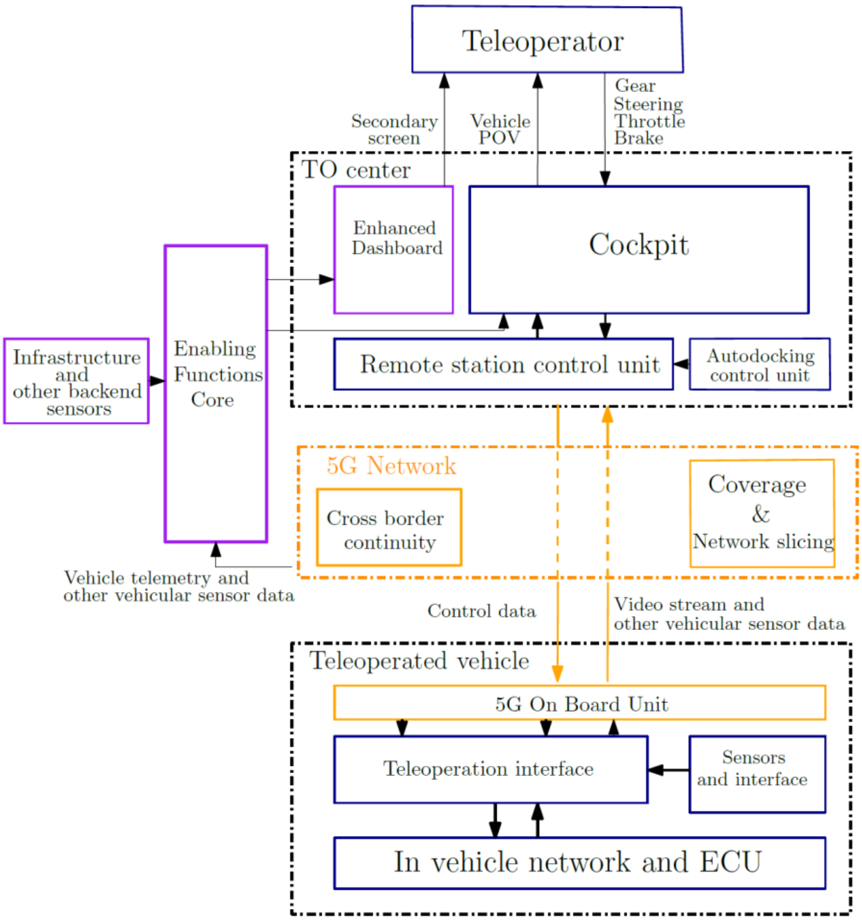


Figure 3. Functional architecture of teleoperated vehicle with Auto-docking function.

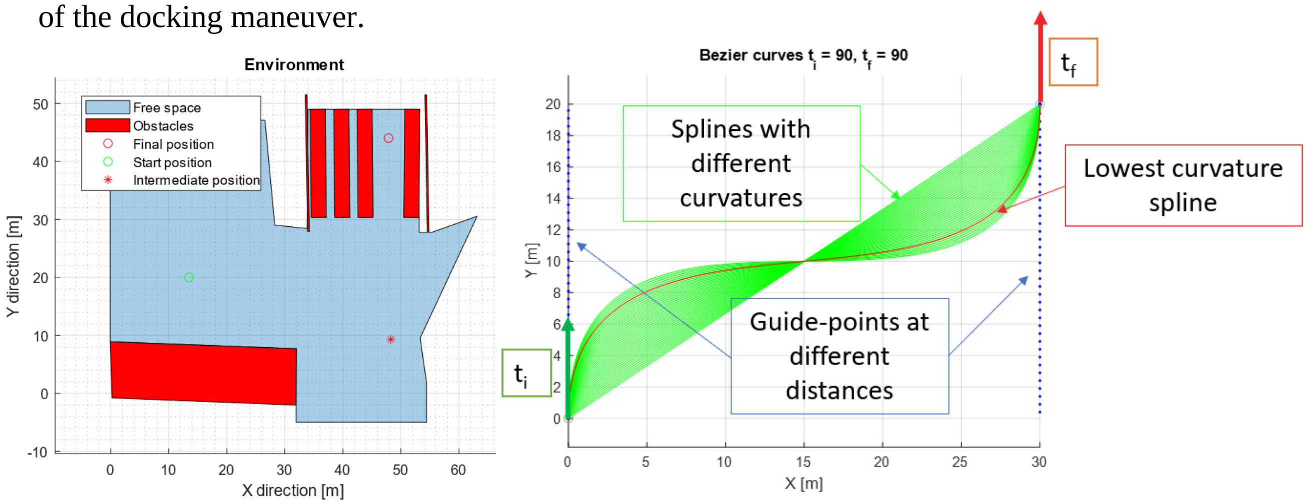
As further depicted in Figure 3, the 5G network offers seamless cross-border handover functionality, ensuring uninterrupted communication during changes in mobile network operators. This handover needs to be swift, occurring within milliseconds, and robust, with sufficient bandwidth, to ensure that the teleoperator does not experience any interruption while crossing national borders, which is though not applicable to autodocking. In addition, compared to 4G the 5G network enables network slicing, allowing for the creation of multiple virtual networks operating on the same physical infrastructure which is essential for scalability. With network slicing, network operators can create separate slices for different types of traffic, such as Internet of Things (IoT) devices, video streaming for teleoperation, or autonomous vehicles. Each slice can have its own specific quality of service (QoS) requirements, bandwidth, latency, security, and other network parameters.

The teleoperator actuates the vehicle by steering wheel, gas and brake pedal, and gear shift based in the remote cockpit. The control signal is being carried by 5G network to the vehicle which has an on board 5G modem unit and teleoperation interface enabling actuation of vehicle key signals on remote basis using X-by wire systems. The vehicle is also equipped with sensorics cluster which provides the vehicle dynamic states data, such as positions, orientations, velocities, and accelerations to the autodocking control unit through the 5G network.

When actuated by the teleoperator, the Autodocking Control Unit (ACU) takes over the control and plans the optimal path between the current location and loading dock position (obtained through enabling function) using the path planning module which we describe in detail hereafter. Subsequently, the path tracking controller (being also part of ACU) is engaged and calculates in real time the required steering angle and speed profile to keep the vehicle combination on the planned path for both forward and reverse moves. These signals are being sent to the remote station control unit which communicates with the vehicle teleoperation interface through 5G signal, which executes the commands in same spirit as if the driver would be physically sitting in the vehicle. Since the operation of docking is automated, not autonomous, the driver remains still in control and has an ability to overrule the system anytime he finds important or in case the operation does not stay within prescribed limits of tracking error.

2.1 Path Planner

The main functionality of the path planner is to generate a bi-directional reference path for semitrailer axle group connecting the start position and orientation delivered by the GNSS localization with the final position and orientation at the destination dock, which is determined by Warehouse Management System. The path also includes the intermediate point, where the vehicle combination will change the speed from forward to reverse, designated by the red asterisk in Figure 4.a). The exact position and orientation of the intermediate point is determined empirically with respect to known practice observed by professional drivers, who tend to minimize the steer effort mainly due to the reversing phase of the docking maneuver.



a) **b)**

Figure 4. Example of path planner environment basic layout.

As can be further seen in Figure 4.a), the environment is modelled by using polygons designating accessible space for maneuvering, depicted by blue color, and the red colored polygons representing the static obstacles or restricted areas being prohibited for trespassing.
The main goal of the path planner is to design the path such that resulting path will be kinematically viable for the vehicle combination (eliminating the side slip of the axle groups), will not result in excessive tyre slip by applying extensive curvatures, and is collision free. In real-life deployment, it is essential that the algorithm delivers the reference path and initiates the execution of the maneuver within 15 seconds from the moment the teleoperator activates the autodocking. From the functionality perspective the path planner employs two stage process involving a Bezier (1977) curve generator and a kinematic path follower model for articulated vehicles by Kural (2019). More specifically, the forward and reverse path are being constructed using Bezier curves shown in Figure 4.b). As an input to the Bezier curves the poses of the start position, intermediate point, and the final position in the local coordinate frame are used. Each pose t_i is described by a x-coordinate, y-coordinate, and the orientation. Since there exists a vast number of Bezier curves enabling to connect aforementioned points, a criterion is established selecting the spline with the absolute minimal curvature, while curvature of the curve is defined by the equation:

$$K = \frac{1}{R} = \frac{\left|\frac{d^2y}{dx^2}\right|}{\left(1 + \left(\frac{dy}{dx}\right)^2\right)^{3/2}} \tag{1}$$

Such a spline may be then expected favorable for minimizing the tyre slip, nevertheless it is not guaranteed that such a spline can be negotiated by the vehicle combinations since it may not satisfy the kinematic constraints. Therefore, in the second stage we will employ the kinematic vehicle model with the path follower model to drive in simulation along the chosen Bezier splines in both forward and reverse direction, while recording the executed paths. By this the Bezier splines are filtered, and new paths can be guaranteed to be kinematically viable. Resulting set paths can be seen in Figure 5. by black color.

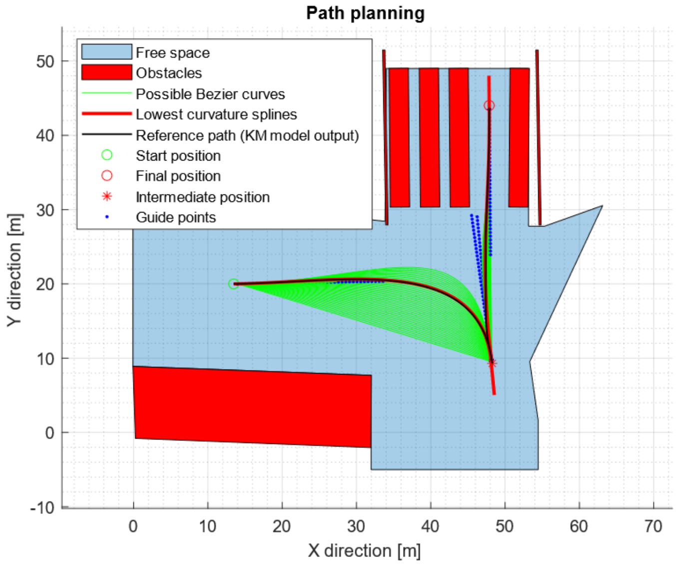


Figure 5. Example of path planner final output.

In this method the path planning is deterministic and complete. Computational time is also predictable as the identical loop of computation is carried out every time. The computation time on a laptop with Intel(R) Core (TM) i7-8750H CPU @ 2.20GHz processor and 16 GB of RAM is approximately 1.5 secs, satisfying the requirement.

2.2 Path Tracking Controller

The tracking controller plays a crucial role in ensuring that a vehicle combination remains on the reference path. In this research project, we have implemented an advanced control technique known as Model Predictive Control (MPC), which is capable of effectively controlling Multiple-Input and Multiple-Output (MIMO) systems. The MPC algorithm optimizes the navigation objectives and vehicle behavior 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. 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 $\boldsymbol{x}$ of the vehicle over a finite time horizon N. At each time step, when new measurement $\boldsymbol{x}_{\text{init}}$ are provided by the sensors, an optimization problem is solved to compute the optimal sequence of control inputs $\boldsymbol{u}_{\boldsymbol{N}}$:

$$
\begin{aligned}
&\min_{\boldsymbol{u}_{\boldsymbol{N}}} \ \sum_{k=t}^{t+N} J(\boldsymbol{u}_{\boldsymbol{N}}) \\
&\text{s.t.} \quad \boldsymbol{x}(\mathrm{t}) = \boldsymbol{x}_{\text{init}} \\
&\boldsymbol{x}(k+1) = f\big(\boldsymbol{x}(k), \boldsymbol{u}(k)\big) \qquad \forall k \in [t, N-1] \\
&g\big(\boldsymbol{x}(k), \boldsymbol{u}(k)\big) = 0 \qquad \forall k \in [t, N] \\
&h\big(\boldsymbol{x}(k), \boldsymbol{u}(k)\big) \leq 0 \qquad \forall k \in [t, N]
\end{aligned}
\tag{2}
$$

Only the first element of the obtained control sequence input $\boldsymbol{u}_{\boldsymbol{N}}$ is applied to the system in closed loop. The rest of the predicted control action is discarded, and a new sequence of actions is recomputed when new sensor measurements are available. In our MPC formulation, the objective is to minimize the sum of the stage costs $J(\boldsymbol{u}_{\boldsymbol{N}})$, while considering the dynamics of the vehicle and possible constraints. In our context, the 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 $f\big(\boldsymbol{x}(k), \boldsymbol{u}(k)\big)$ and vehicle limitations $g\big(\boldsymbol{x}(k), \boldsymbol{u}(k)\big)$, $h\big(\boldsymbol{x}(k), \boldsymbol{u}(k)\big)$, such as the maximum steering rate and articulation angles, as constraints. The vehicle behavior is considered perfectly kinematic, and thus disregarding the slip on the tyres, load distribution or inertial effects. The proposed MPC scheme makes use of the kinematics of tractor-semitrailer. The states of this system are given in the following vector: $\boldsymbol{x} = [x_1, y_1, \theta_1, \gamma_1]^{\boldsymbol{T}}$ which consists of the coordinates of the trailers rear axle, the yaw angle of the semitrailer, and the articulation angle, respectively. The continuous dynamics of the system being fully derived by Fardanian (2022) and used by our MPC controller as prediction model are:

$$
\dot{\boldsymbol{x}} = \begin{bmatrix}
v_0\left(\cos\gamma_1 \cos\theta_1 - \frac{L_{0b}}{L_{0f}} \cos\theta_1 \tan\delta\right) \\
v_0\left(\cos\gamma_1 \sin\theta_1 - \frac{L_{0b}}{L_{0f}} \sin\gamma_1 \sin\theta_1 \tan\delta\right) \\
\frac{v_0}{L_{1f}}\left(\frac{L_{0b}}{L_{0f}} \cos\gamma_1 \cos\theta_1 - \frac{L_{0b}}{L_{0f}} \cos\theta_1 \tan\delta\right) \\
\frac{v_0}{L_{0f}L_{1f}}\left(L_{1f}\tan\delta - L_{0f}\sin\gamma_1 - L_{0b}\cos\gamma_1 \tan\delta\right)
\end{bmatrix}
\tag{3}
$$

Where the constants L_{0b}, L_{0f} and L_{1f} are the relevant dimensions of the tractor and semitrailer representing tractor fifth wheel overhang, tractor wheelbase, and semitrailer wheelbase, respectively. Notice that our MPC formulation can accommodate systems with more complex dynamics at the cost of requiring additional computational resources. Nevertheless, for the considered application, the kinematic vehicle model is sufficiently accurate since the vehicle operates at low velocities. The control inputs to the system reads $\boldsymbol{u} = [v_0, \delta]^T$ being the velocity of the tractor and the steering angle to be applied at the steered wheels, respectively. The structure of the control loop is depicted in Figure 6.

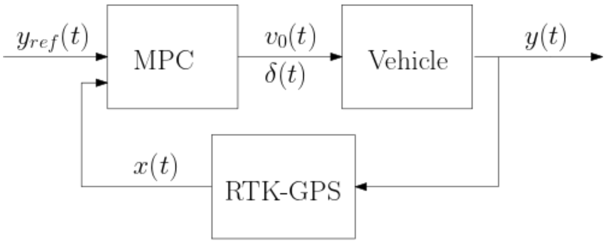


Figure 6. Control Loop Layout.

The resulting MPC formulation is nonlinear and requires an efficient numerical optimization algorithm to compute a control action in bounded time. In this application, we use Embotech (2023) FORCES Pro software. Furthermore, the vehicle dynamical state measurements are delivered by the OXTS (2023) Real-Time Kinematic Global Positioning System (RTK-GPS).

3. System Integration

To evaluate the functionality of the complete system, the components from the framework are described in Figure 3. were integrated into a vehicle and teleoperation center, and subsequently tested in the real operation environment of the distribution center.

3.1 Teleoperation vehicle

The vehicle combination comprises of a two-axle tractor and a three-axle semitrailer, as depicted in Figure 7a. To enable teleoperation of the tractor, several actuators have been mounted on the brake pedal, gear shifting knob, and steering wheel, as shown in Figure 7b. The gas pedal is actuated through CAN bus. Additionally, a 5G onboard modem unit has been installed to ensure the connectivity of the x-by-wire box with the 5G network. This allows the vehicle to be operated remotely, as if someone were physically present on board. To provide the teleoperator with a complete field of view, a set of six cameras has been installed on the vehicle. This includes two side view cameras, two side rear mirrors, main frontal view, and rearward view, which are typically not available in normal vehicles. Finally, both the tractor and the semitrailer are equipped with a high-precision localization system (OXTS 2023), providing position and orientation of the vehicle in the local coordinate frame at a sampling rate of 50Hz.

a) **b)**

Figure 7.a) Test vehicle combination, b) Tractor modified cockpit enabling teleoperation

3.2 Teleoperation center

Via the teleoperation center, an operator can control the vehicle combination by providing inputs. As can be seen on Figure 8a). the teleoperation center consists of three screens, steering wheel with knobs, and a set of pedals. The operator inputs go to the computer and modems which send them via 5G signal to the router based at the tractor.

a) **b)**

Figure 8. a) Teleoperation center, b) Teleoperator view.

The visual signals from tractor on board cameras are presented to the operator and consists of 6 video streams as in Figure 8b). The resolution of each stream is dynamically scaled depending on the uplink speed of the network, while the main frontal view camera has always priority. As can also be seen in Figure 8b) the teleoperator is provided with the speed indicator, as well as number of icons showing engaged gear, lights, or 5G signal quality.

3.3 Test conditions and objectives

The autodocking controller in the full-scale demonstrator has been tested in the premises of the real distribution centre where the loading docks were partially submerged under the nominal road level (there is downslope heading towards the loading dock). The initial pose of the vehicle combination was always chosen randomly, so the path planner is responsible to create the reference path leading to the dock. The maximal speed during the docking manoeuvre was set to 5 km/h for both forward and reverse trajectory. In order to evaluate the effectiveness of the integrated autodocking function, a set of Key Performance Indicators (KPIs) has been established. Table 1 outlines these KPIs, along with their corresponding units and target values. It should be noted that these targets values are valid for the initial full-scale testing to evaluate controller and path planner performance and does not apply for eventual final deployment.

Table 1 - Key Performance Indicators of the Autodocking Functionality.

No.	Name	Definition	Target value(s) [unit]
1	Path Planning Time (PPT)	The time it takes the Path Planner (PP) to plan the desired path	< 15 [s]
2	Tracking Error Real Time (TERT)	The mean average value of absolute lateral difference between the actual position of the axle of the trailer with respect to the generated reference path during manoeuvring. Measured for both Forward and Reverse trajectory separately.	< 0.5 [m]

3	Final Docking State Error (FDST)	The difference between the actual end position and the planned docking position after the docking manoeuvre is performed. It consists of: A) Lateral (Y) deviation B) Orientation (θ) deviation	A) Lateral Error < 10 [cm] B) Orientation Error < 1 [deg]
4	Elapsed time / total docking time (ET)	The time between the start of the manoeuvre and the final stop at the end position.	< 150 [s]

4. Test Results

The tests which are presented in this paper cover one day of testing which included a repetition of sixteen autodocking tests to create a dataset of minimal viable statistical relevance. The mean median of the 5G network latency during these tests was 24 milliseconds and 90th percentile maximum was 89 milliseconds which is sufficient for the stability of the control loop, and which can not be guaranteed with 4G networks.

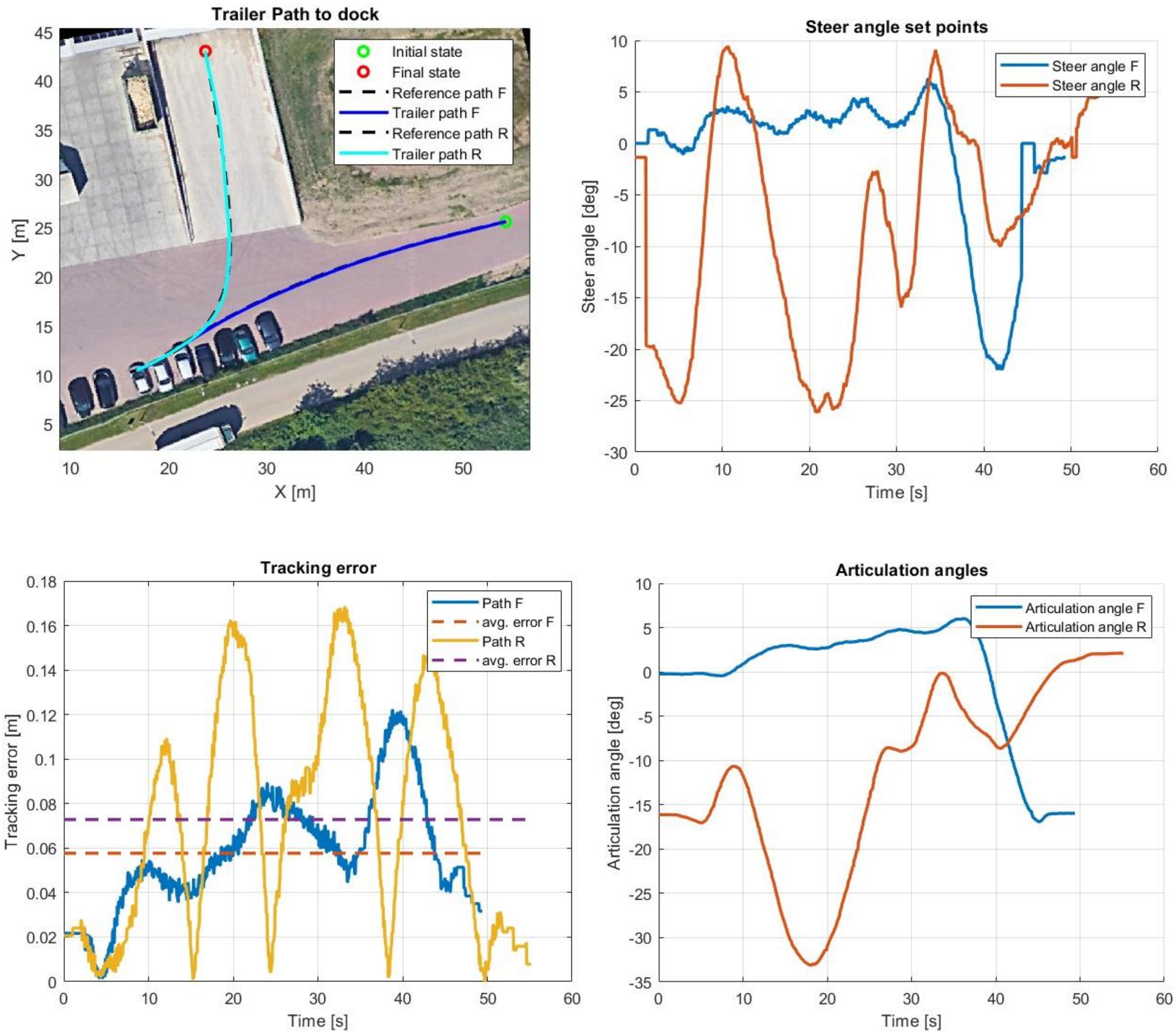


Figure 9. Test #15 results.

Table 2 – Summary of test results.

Test no.	PPT [s]	TERT F [m]	TERT R [m]	FDST LAT [cm]	FDST Angle [deg]	ET [s]
1	11.3	0.06	0.15	15	0.43	102.0
2	10.8	0.08	0.11	10	0.11	100.0
3	10.6	0.07	0.13	10	0.11	97.0
4	10.9	0.05	0.23	7	0.61	100.0
5	10.4	0.07	0.12	1	0.20	101.0
6	10.5	0.06	0.12	2	0.21	98.0
7	10.2	0.08	0.11	13	0.93	96.0
8	10.4	0.07	0.11	13	0.06	98.0
9	11.6	0.05	0.19	4	0.47	112.0
10	10.5	0.05	0.13	5	0.35	94.0
11	10.8	0.09	0.42	2	0.68	104.0
12	10.9	0.05	0.07	2	0.28	99.0
13	11.5	0.05	0.07	13	0.25	106.0
14	11.2	0.05	0.05	2	0.26	104.0
15	11.5	0.06	0.07	0	0.54	105.0
16	11.3	0.06	0.06	2	0.08	102.0
Average->	**10.90**	**0.06**	**0.13**	**6.31**	**0.35**	**101.13**

The test results quantified in KPIs are summarized in Table 2, along with Test #15 in Figure 9, where the path tracking error and the number of relevant vehicle states are plotted as an example. Herein, it can be observed that the absolute value of the path tracking error oscillates between 0-16cm, with an average tracking error of 6cm and 7cm for the forward and reverse paths, respectively. Additionally, it can be seen that the articulation angle reaches up to 35 degrees, which is a consequence of the reference path designed to avoid high articulation angles that can cause excessive tire slip on the first and last non-steerable axles of the semi-trailer. Since the articulation angle at the end of the forward path is suboptimal for initiating the reverse path, the steer controller needs to significantly act at the beginning of the reverse phase to minimize the tracking error. This can be observed in the amplitudes of the steering angle.

In principle, all the tests were successful, but four of them resulted in a slightly exceeded target value of the final docking state (FDST) lateral error, which was larger than 10 cm. The tolerance for this KPI is rather small, making it highly dependent on the accurate localization of the vehicle combination in the local coordinate system. To achieve the required level of accuracy, we relied on real-time kinematic (RTK) GPS localization, which was provided by OXTS (2023). The best guaranteed accuracy of the RTK-GPS localization falls in the range of ±4 cm. However, the accuracy of the localization can be affected by varying weather conditions, particularly during cloudy skies or rainfall, which was our case. These conditions can reduce the accuracy of the system and may result in deviations from the target values for the FDST lateral error.

Hence, it is important to continuously monitor the accuracy of the RTK-GPS localization system, especially during varying weather conditions, and when the antennas get closer to the areas which may cause the signal reflection, such as containers or steel parts of the buildings.

Conclusions and Research Outlook

In this paper, we presented the first results of the concept of automated docking for the tractor semi-trailer in logistics centers, where the driver serves as a supervisor. The automated functionality is enabled through the 5G network, which provides the driver/teleoperator with all the relevant information displayed in a remote-control station, where the driver is located.

Moreover, this concept utilizes a path planning algorithm that uses Bezier Curves and a path tracking controller that uses a nonlinear Model Predictive Controller. All these modules have been integrated into a full-scale demonstrator that has been tested repeatedly in real-life conditions. The concept has proven to function well and operate within established key performance indicators (KPIs). However, it has shown high dependence on the accuracy of absolute localization. Therefore, in upcoming research, we plan to improve accuracy by incorporating an extended Kalman filter, given the fact that the main input to the system is known.

Additionally, more tests are planned to optimize controller performance with the emphasis on mapping the impact of the cost function scaling weights to the controller performance. Furthermore, the goal is to implement a longitudinal position controller, which will improve the overall efficiency of the system. By continually testing and refining the concept, we aim to achieve the highest level of accuracy and reliability for automated docking in logistics centers. This will help reduce human errors and increase efficiency, ultimately leading to safer and more productive operations.

5. Acknowledgment

The research in this paper is conducted as a part of project 5G Blueprint funded by the European Union’s Horizon 2020 research and innovation program under grant agreement No 952189.

6. References

- European Commission (2011), Impact Assessment – accompanying document to the White Paper, pp. 137, Brussels.
- https://www.5gblueprint.eu/
- Dekker, A. (2022), et al., Model Predictive Controller based Driver Support for Docking of Articulated Vehicles at Logistic Areas, 15th International Symposium on Advanced Vehicle Control (AVEC’22), Tokyo, Japan.
- Bezier, P. (1977). Essai de définition numérique des courbes et des surfaces experimentales: Contribution à l'étude des propriétés des courbes et des surfaces paramétriques polynomiales à coefficients vectoriels (Thesis). Diss. Universite Pierre et Marie Curie (Paris VI).
- Kural, K. (2019), Analysis of high-capacity vehicles for Europe: application of performance-based standards and improving maneuverability. PhD thesis, Eindhoven University of Technology.
- Fardanian, R. (2022), Implementation of Robust Model Predictive Control (MPC) for Automated Truck Docking over 5G, Master Thesis, HAN University of Applied Sciences, Arnhem, Netherlands
- OXTS (2023), https://www.oxts.com/products/rt3000-v3/
- Embotech (2023), https://www.embotech.com/products/forcespro/overview/