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Model Predictive Control based Driver Support for Docking of Articulated Vehicles at Logistics Areas

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Bi-directional maneuvering of articulated vehicles at distribution centers is a complex task even for an experienced driver given *(i)* the unstable nature of the vehicle combination whilst reversing, *(ii)* a limited field of view, and *(iii)* a constrained maneuverability space. To support the driver, a novel driver-assist system is established, which consists of a computer vision-based localization module, a vehicle navigation system, and a human machine interface (HMI). This paper focuses on a fundamental module for the vehicle navigation system, that is, the design of a model-predictive-control(MPC)-based tracking controller. This controller is responsible for providing an input for the HMI, based on a known reference path and the actual vehicle pose resulting from driver-vehicle interaction. The controller is validated on a scaled real vehicle and in a virtual reality simulator with human-drivers in the loop.

Topics: Advanced Driver Assistance Systems, Driver-Vehicle Systems, Testing and Validation

1. INTRODUCTION

The volume of cargo in Europe transported on the road has been continuously increasing over the past decade. In the future, it may be expected that more vehicles on the roads will be needed to satisfy the transport demand [1], creating challenges on distribution centers and yards, where the vehicle combination needs to be parked towards the loading dock shown in Figure 1.

Fig. 1 Loading dock at distribution centre

Although the automatization inside the warehouses and distribution centers already took place decades ago, the automation outside, at the parking areas, has not emerged so far. The docking of the vehicle combination towards the loading dock is still done manually by the drivers alike decades ago, even though safety risks exist when operating the vehicle combination.

As confirmed by the measurements with human drivers during bi-directional low-speed maneuvering with articulated vehicle combinations [2], the driver primarily suffers from a lack of view from the cabin, which is limited to the frontal outlook and the rear mirrors. Moreover, the driver is challenged to control the naturally unstable vehicle combination during reversing at an area which is typically limited in space and the parking tolerances at the end position do not exceed ±10 cm. To address these challenges, the VIsion Supported Truck docking Assistant (VISTA) is being developed [3]. The framework consists of a computer vision-based localization module, a vehicle navigation system consisting of a path planner and a path tracking controller, and a human machine interface (HMI) to support the driver [4]. The functionality of the system is being extensively tested in a Virtual Reality (VR) simulator.

Compared to the framework presented in [4], this paper focuses on the design of a novel MPC-based path tracking controller which improves the VISTA vehicle navigation system with driver in the loop but can be also used as stand-alone controller for automating the docking sequence of articulated vehicle being the objective of the 5G Blueprint project [8].

The paper is structured as follows: Section 2 explains the context of the proposed controller in the framework. Section 3 provides the high-level explanation of the MPC controller. Section 4 describes the controller implementation and testing. Finally, Section 5 concludes the paper.

2. PROBLEM DEFINITION

The major role of the path tracking controller is to minimize the tracking error between a reference path (provided by a path planner), which might not be kinematically feasible, and the center of the semitrailer axle group whilst actuating the steering angle of the hauling unit represented by the tractor. Subsequently, the steering angle is being fed as an input for the HMI, which transforms the required steering angle to the audio/visual advice for the driver, who acts as the actuator of the steering angle. In the context of VISTA, the controller should consider the presence of a human driver. In our work, we model the driver as an imperfect actuator introducing noise and delays in the control loop. In addition, the controller needs to be functional bi-directionally (i.e., for both forward and reversing directions).

In this work, we rely on Model Predictive Control (MPC) as the path tracking controller. MPC optimizes the navigation objectives and the behavior of the vehicle over a finite time window by relying on online numerical optimization tools. This allows the controller to compensate for deviations from the reference path due to dynamical limitations. Additionally, MPC allows one to incorporate a driver model directly in the MPC prediction model and consequently to compensate for possible delays in the driver's reactions.

3. RESEARCH APPROACH

MPC is an advanced control technique which can be used to control Multiple-Input and Multiple-Output (MIMO) systems. 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 $\boldsymbol{u_N}$:

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

Only the first element of the obtained control sequence 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 $J(\boldsymbol{u_N})$, 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 vehicle and the driver dynamics $f\big(\boldsymbol{x}(k), \boldsymbol{u}(k)\big)$ and vehicle limitations $h\big(\boldsymbol{x}(k), \boldsymbol{u}(k)\big)$, such as the maximum steering 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 [5]. For modeling of the driver, the McRuerer model [6] is applied in a form:

$$
H(s) = K_p \frac{(T_L s + 1)}{(T_l s + 1)(T_N s + 1)} e^{-\tau_r s}
\tag{2}
$$

where K_p is the static gain, T_L is the lead time constant, T_l is the lag time constant, T_N is the neuromuscular lag, and τ_r is the reaction time delay.

The proposed MPC scheme makes use of the kinematics of tractor-semitrailer and the driver model. The states of this system are given in the following vector: $\boldsymbol{x} = [x_1, y_1, \theta_1, \gamma_1, x_{\text{d1}}, x_{\text{d2}}]^{\boldsymbol{T}}$ which consists of the coordinates of the trailers rear axle, the yaw angle of the semitrailer, the articulation angle and two driver states, respectively. The continuous dynamics of the cascade system (i.e., vehicle and driver) being fully derived in [9] and used by our MPC controller as prediction model are:

$$
\dot{\boldsymbol{x}} = \begin{bmatrix}
v_0\left(\cos\gamma_1 \cos\theta_1 - \frac{L_{0b}}{L_{0f}} \cos\theta_1 \tan\delta\right) \\
v_0\left(\cos\gamma_1 \sin\theta_1 - \frac{L_{0b}}{L_{0f}} \sin\gamma_1 \sin\theta_1 \tan\delta\right) \\
\frac{v_0}{L_{1f}}\left(\frac{L_{0b}}{L_{0f}} \cos\gamma_1 \cos\theta_1 - \frac{L_{0b}}{L_{0f}} \cos\theta_1 \tan\delta\right) \\
\frac{v_0}{L_{0f} L_{1f}}\left(L_{1f} \tan\delta - L_{0f} \sin\gamma_1 - L_{0b} \cos\gamma_1 \tan\delta\right) \\
x_{\text{d2}} \\
-\frac{1}{T_l T_N} x_{\text{d1}} - \frac{T_l + T_N}{T_l T_N} x_{\text{d2}} + \delta_{\text{d}}
\end{bmatrix}
\tag{3}
$$

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 $\boldsymbol{u} = [v_0, \delta_d]^T$ being the velocity of the tractor and the steering angle instruction given to the driver, respectively. The actual steering angle of the truck δ is determined by the driver states as follows:

$$
\delta = \frac{K}{T_l T_N} x_{\text{d1}} + \frac{K T_L}{T_l T_N} x_{\text{d2}}
\tag{4}
$$

The parameters L_{0b}, L_{0f} and L_{0b} are the relevant dimensions of the tractor and semitrailer, while T_l, T_N and T_L are the parameters defining the behavior of the driver. The structure of the control loop is depicted in Figure 2.

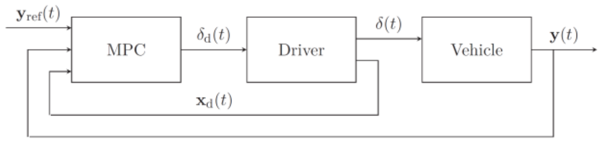

Fig. 2 Control loop layout.

The resulting MPC formulation is nonlinear and requires an efficient numerical optimization algorithm to compute a control action in bounded time. In this project, we use Embotech FORCES Pro software [7]

4. CONTROLLER IMPLEMENTATION AND RESULTS

The performance and robustness of the developed MPC controller is tested in three stages.

In the first stage, the MPC controller is tested directly in the loop with the kinematic vehicle model, initially without considering interaction with the driver, that is, the driver acts as a perfect actuator. Subsequently, the driver is modelled and tested also in the loop with the vehicle model.

In the second stage, the vehicle model is substituted by the real yet scaled vehicle to test the controller robustness against the real-life conditions when the simplified model of the vehicle may not fully hold.

In the last stage, the controller is tested in the loop with real drivers, using the lessons learnt at the first stage. As the test platform, a dedicated VR simulator of the truck is used. More specific description of all three stages follows.

4.1 Model in the loop

The performance of the controller is tested at first purely in simulation using a MATLAB/Simulink-based Model In the Loop (MIL) approach. Herewith, the goal is to examine the controller for two different applications, that are, the *automated docking* and *driver in the loop docking*, which are relevant for the use cases of the 5G Blueprint and VISTA projects, respectively. In both use cases, a representative reference path is provided by the path planner, which generates a ninety-degree bi-directional docking manoeuvre. This is a typical move in every logistic area when the semitrailer needs to be parked perpendicular to the loading dock at the side wall of the distribution centre.

In case of autonomous docking the output of the MPC controller is fed directly to the steer actuator, while disregarding actuator delays and process noises. The reference path is provided as a set of discrete points representing the reference x- and y- coordinates of the rear axle of the semitrailer. The reference path as well as the resulting path for the docking manoeuvre is plotted in Figure 3 with green and blue lines, respectively. Furthermore, in Figure 4 the tracking error is shown along with the applied steering angle.

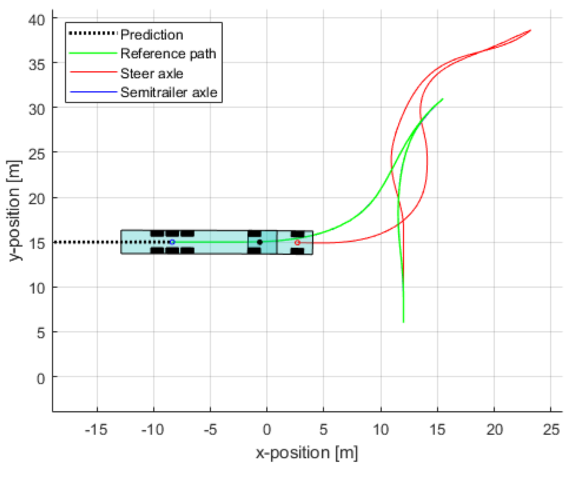

Fig. 3 Reference path tracking MIL – top view

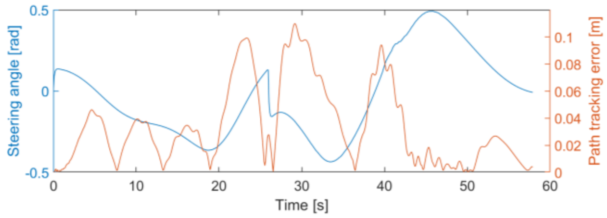

Fig. 4 Path tracking results MIL – steering angle and path tracking error

As the figures show, the actual driven path closely matches the reference path and maximal tracking error yields approximately 10 cm. This occurs nearby the point at which the vehicle changes the direction of movement and where the highest rate of reference path curvature change occurs, making the results acceptable.

The next set of tests includes interaction with a human driver for the use case of driver in the loop docking. The primary goal was to identify the parameters for the generic driver model which can then be incorporated in the MPC so the controller can anticipate the driver behavior and the delays. Therefore, it was required to visualize the instructions and a current overview of the scenario for the driver. Additionally, the driver needs to be able to actuate the simulated vehicle on real-time basis. In this test environment, the driver is only able to see a 2D top-view of the scenario. Here, he or she can see the current location and orientation of the vehicle on a primary screen. An overview of this visualization is shown in Figure 5. Herewith, the vertically oriented vehicle is controlled by the driver, while the other two vehicles represent two parked tractor-semitrailer combinations, representing static obstacles.

Fig. 5 Top view of simulation environment to identify driver parameters

On a secondary screen, the driver sees the steering instructions and the current steering angle, both represented by circular gauges shown in Figure 6. In the simulation, the driver can actuate the steering angle and the velocity of the tractor directly using a Logitech G29 Racing Wheel.

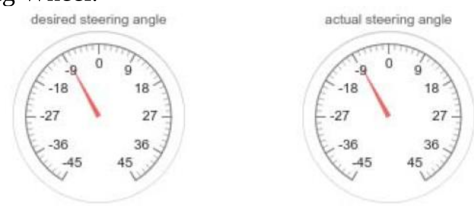

Fig. 6 Driver interfaces in the simulation, left: steering instruction δ_d, right: Steering input from driver δ.

The driver model parameters were identified subsequently by a series of experiments on an iterative basis. Hereafter, we present the results of three sets of tests consisting of: a) MPC fully disregarding the involvement of the driver in the loop, b) MPC characterizing the driver with the set of parameters #1 (see 1st Model in Table 1), c) MPC characterizing the driver with set of parameters #2 (see 2nd Model in Table 1).

The numerical parameters of the driver models are listed in the Table 1, and the tracking errors of the docking manoeuvre are shown in Figure 7.

Table 1 Driver model parameters

Parameter	1st Model	2nd Model
K	1	1
T_L	0.0227	0.0763
T_l	0.3	0.4938
T_N	0.8094	1.164
τ_r	0.2	0.2

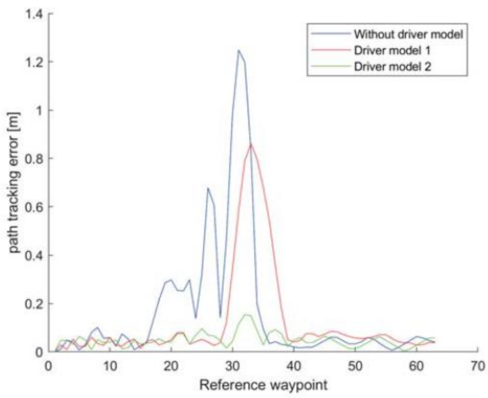

Fig. 7 Path tracking results – steering angle and path tracking error

From the results it noticeable that disregarding the driver leads to mediocre performance of MPC, which results excessive tracking errors. The performance between driver model 1 and 2 also differs considerably. This is mainly due to a big difference in the Lead Time Constant T_L, which is in case of the 2nd driver model approximately four times higher. Since this has positive impact on the tracking error, this model representation is taken as representative for the verification in the VR simulator.

4.2 Hardware in the loop

It is a known fact that MPC heavily relies on upfront knowledge of the controlled plant, and specifically its internal dynamics. As explained in Section 3 the vehicle behavior is modelled as perfectly kinematic, which in general may be questionable, considering excessive slip on the semitrailer axle group during sharp corners. For that reason, it has been decided to verify the performance of the MPC controller in a real life experiment using the scaled vehicle model (1:3) of tractor-semitrailer shown in Figure 8. The tractor's first axle is only steerable, the second axle is rigid and driven, and the last axle is only solid. The semitrailer has solid tridem axle group.

Fig. 8 Scaled model of Tractor-semitrailer 1:3

All the rubber tyres are inflatable, and given the fact the suspension is not pneumatic, an equal load distribution cannot be guaranteed. The weight of the vehicle combination is approximately 290 kg. The tractor can be teleoperated, i.e., controlled on remote basis using a 4G or 5G network connection, in terms steering and driving speed in both forward and reverse direction.

The localization of the vehicle combination is ensured by two high-accuracy RTK-GPS systems which enable to measure position and orientation of both tractor and trailer independently in the local coordinate system centred at the final destination point, representing the loading dock.

The experimental manoeuvre is, as in previous cases, bidirectional docking with the reference path produced by the path planner whilst respecting the real dimensions of the vehicle combination. The longitudinal speed of the tractor is approximately 0.7 m/s forward and 0.5 m/s in reverse direction.

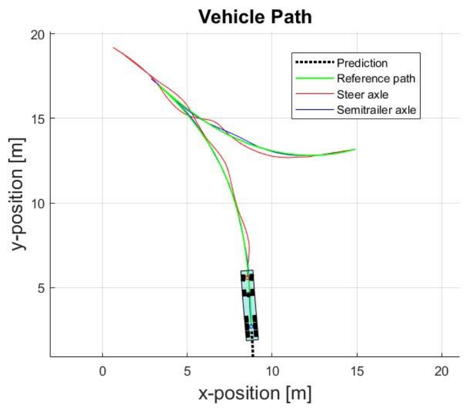

Fig. 8 Reference path tracking HIL – top view

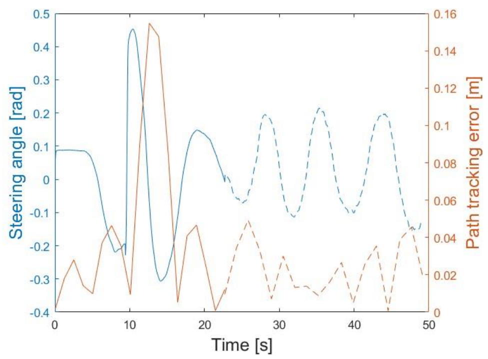

Fig. 9 Path tracking results HIL – steering angle and path tracking error

The results show that MPC-based controller can navigate the scaled vehicle combination along the reference path while maintaining tracking error at an acceptable level during the maneuver. One can notice slightly oscillatory behavior of the steering angle which can be explained by the accuracy of the RTK-GPS which fluctuated during the tests in the range of ±4 cm. The biggest error (~15 cm) occurs due to irregularity of the terrain when the vehicle approached the steep slope. The final docking error is 2 cm which meets the positional tolerances even though the kinematic model has been employed to model the vehicle behavior.

4.3 Human in the loop

The VR simulator is used to test the robustness of the MPC, the effectiveness of different HMI designs and the acceptance of the predefined paths in different realistic situations. The goal is to come to a generic HMI solution and driver model and thus to an MPC design that works for most, if not all, drivers.

To increase realism, a real truck cabin has been transformed into a simulator, where the virtual cabin exactly matches the real cabin. In this way, all controls are at the correct location and the driver can behave as if in a real truck. For example, the driver can hang out of the window to look at the trailer. The drive controls steering wheel, gear selector, accelerator pedal and brake pedal, all read by a microcontroller and communicated to the VR computer. Adjusting the mirrors is possible via keyboard commands. Given the driver inputs, a kinematic vehicle model in MATLAB Simulink is used to calculate the position and orientation of the tractor and semitrailer. This data is sent to Unity where the visualisation in the VR world takes place using an HTC Vive Pro VR glass. The desired steering angle and direction, calculated by the MPC, are also sent to Unity. These are displayed on the HMI, a tablet in the VR world. On the tablet the video stream from the camera system is also displayed, which improves visibility during the manoeuvre. The steering instructions are shown above the video stream with both an arrow and a bar that fills depending on the error between desired and actual steering angle. On the right, a red indicator shows the driver the distance to the dock and on the left an arrow shows the desired direction (forward/backward).

Fig. 11 HMI in virtual reality

The simulator is ideal to quickly test other HMI options that are difficult to implement in the real world, for example LED bars on the mirrors, a heads-up display on the windscreen or audio signals.

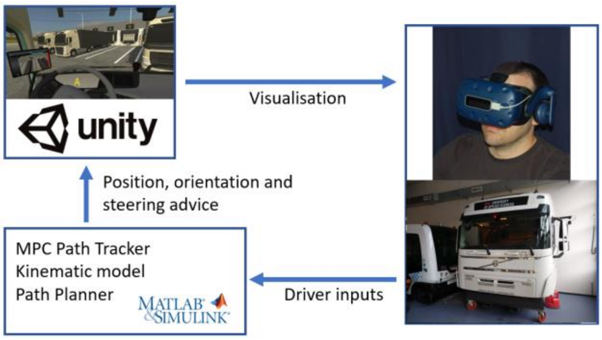

Fig. 12 Simulator functional architecture

Tests with over 40 subjects with varying experience levels and ages ranging from 18 to 62 have been conducted. Not all test subjects were professional drivers. All test subjects were given some time to get familiar with the VR simulator before they were asked to perform docking manoeuvres with and without assistance by the MPC. Half of the test subjects was asked to dock firstly without and secondly with assistance and the other half vice versa. This is done to prevent bias in the results due to the test subjects practicing the manoeuvre on the first attempt.

With assistance the drivers need less changes of direction to successfully dock and the total time of the manoeuvre was decreased.

It was found that the inaccuracy and delay differs greatly between test subjects. This depends on many factors such as the HMI design, vicinity of obstacles near the truck, the stage of docking but also on the age and experience of the test subject. The MPC is robust enough to handle these of delays and inaccuracies.

Typical results can be seen in Figures 13 to 15. Figure 14 shows the path taken by the test subject when not assisted by the MPC, multiple direction changes were made.

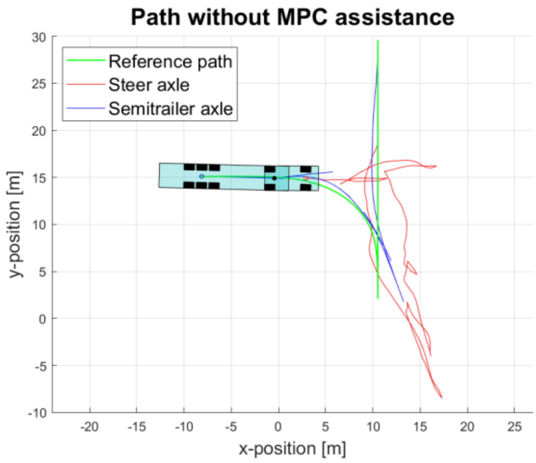

Fig. 13 Path without MPC assistance

As can be seen in Figure 15, when the assistance is turned on, the docking manoeuvre is performed in one try and no change in direction is needed. Resulting in faster and safer docking manoeuvre.

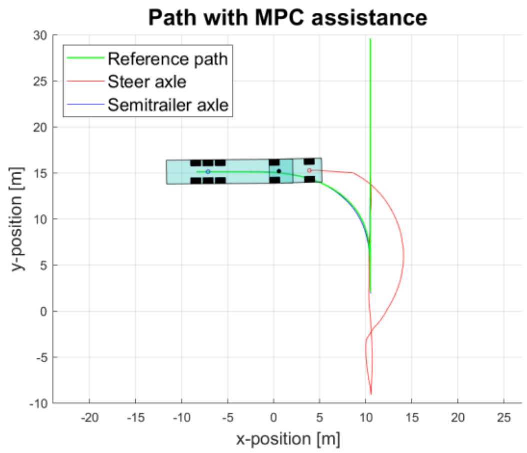

Fig. 14 Path with MPC assistance

During the manoeuvre with assistance the steering effort is higher than compared to the fully automated hardware in the loop test. The driver slowed down when the steering instructions changed rapidly, giving time to react. As a result, the maximum tracking error is 22cm, more importantly the tracking error at the dock is less than 1cm. The manoeuvre without assistance took 385 seconds (6.4 minutes) compared to 217 seconds (3.6 minutes) when using the assistance, a time reduction of 43%. When using the assistance, the distance to obstacles is also larger, decreasing the chances of a collision.

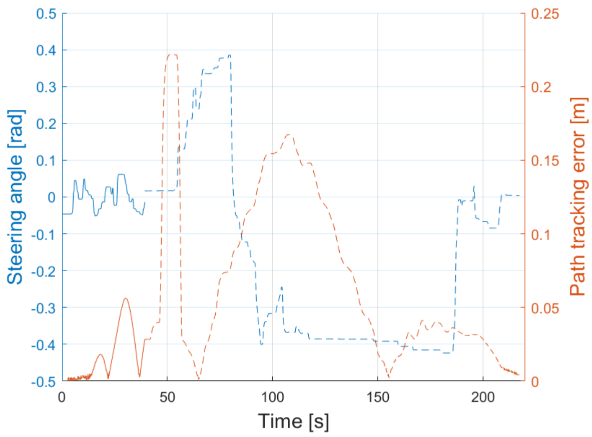

Fig. 15 Steering angle and tracking error

Experienced drivers may have trouble accepting the instructions when deviating from their preferred path, possibly leading to large inaccuracies and the necessity to replan the path because the MPC is no longer able to follow the path given the constraints. In practice replanning the path means an extra forward and reverse movement, something that the drivers also do when not using the assistance. Possible solutions are to allow experienced drivers to choose the forward 'preparing' path themselves and/or to continuously replan the reference path in the background.

5. RESEARCH OUTLOOK AND CONCLUSION

In this paper, a bidirectional path tracking controller for articulated vehicles is developed that can be used for automated docking as well as a docking assistance system, being more complex as it includes driver behavior. The proposed method is based on Model Predictive Control approach which uses a kinematic vehicle model representing the plant dynamics at the low-speed scenarios. The tracking error and the steering effort are considered as the assessment criteria for the performance. The benefits of the proposed control approach are as follows: Firstly, the method proves sufficiently robust when deployed into physical scaled demonstrator and even though a considerably simplified model of the vehicle behavior was used, the parking tolerances can be met. This provides a good foresight for the full-scale implementation. Secondly, when the controller includes the driver dynamics and is tested in the VR simulator, the controller appeared to be more forgiving to driver-introduced steering angle deviations and delays compared to previously developed controllers, i.e. desired steering angle dynamics were perceived as more naturalistic. With MPC assistance the drivers are able to perform the docking manoeuvre both safer and faster.

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