Development and evaluation of an experimental platform for steered axles of long combination vehicles

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Abstract— **High Capacity Transport (HCT)-vehicles require different strategies in controlling lateral dynamics of the combinations to ensure optimal paths taken by the trailers. Promising steering algorithms actuating more then one axles of the combination have been developed in previous works [1] and now need to be verified in the field. This work thus developed an experimentation platform incorporating a rapid-prototyping system to provide the possibility of evaluating these algorithms. In this publication the solution is detailed as a Hardware-in-the-Loop (HiL)-platform linking a vehicle dynamics frame-work with two steered axles. In accordance with the automotive development process after the V-model[2], this allows to safely verify the functioning of both software and hardware before performing track-tests of the fully integrated system. This paper outlines the development and capabilities of the resulting experimental platform and gives a short example of its performance in a standard-maneuver, which is also used to proof the validity between simulation and HiL-environment enabling full system testing.**

I. INTRODUCTION

The driving behaviour of HCT vehicles is in many ways different to that of single unit trucks and needs to be researched in great detail to gain an understanding of the vehicle's dynamic properties, that is equally detailed as it is for other vehicle classes. This will lead to development of better safety and assistance systems and thus reduce threat potential, accidents and fatalities involving this emerging mode of transportation.

The research project in which this work is embedded aims to develop an active dolly, meaning that steering of two axles in a HCT-combination will be autonomously conducted based on the driving situation at hand and various vehicle parameters (e.g. speed, steering wheel angle). This control algorithm is a result of previous works and shall now be executed on a rapid-prototyping system which is linked to and controls two axles. To supply this connection between the hardware and control-algorithm implemented in the modeling-environment Simulink is the main-contribution of this work.

The following points will be covered in this paper:

- outline of the development process of the experimental platform and presentation of the utilized hard- and software systems
- evaluation of existing hardware characteristics and delays and implemented measures to eliminate them
- discussion of a standard driving maneuver of a combinationexecuted on the developed HiL-system
- a comparison between these HiL-maneuver and simulation results, which proofs the validity of the platform
- present an outlook over future works

The limitations of for this work are:

- HiL-applications of the system are covered only
- low-speed maneuvers are only to be considered
- all measurements in this work were undertaken with the system being suspended to eliminate friction

II. HARDWARE-SETUP

A. Base vehicle

The hardware base is a dolly manufactured by Parator Industries. The steering system is based around the Electronically-controlled hydraulic Trailer Steering (ETS) developed and built by V.S.E. Vehicle Systems Engineering B.V. (VSE) with two hydraulically steerable axles. It was originally meant to be used in trailer steering as an after-market system and thus does not tie in with any of the truck's communication networks or sensor data. This makes it OEM-independent and very robust. The ETS solely relies on the articulation angle between the leading and following unit and the speed

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of the combination. The articulation angle is gathered via a dedicated sensor mounted on the king-pin of the respective unit, the speed-signal is gathered from the ISO-11992 Controler Area Network (CAN).

B. Rapid-prototyping system (dSpace MicroAutoBoxII (MABII))

To execute the readily developed algorithms[**c27**], that govern the steering of the HCT-combination, they needed to be ported to a platform, capable of interacting with the dolly and the tractor, while ensuring robust behavior during run-time. It was decided to incorporate the MABII by dSpace, a real-time platform for its advantages in automotive environments with a vast selection of in- and outputs for interfacing with vehicular communications systems (CAN, ethernet, FlexLink). It conveniently ties in with Simulink, which was used for algorithm development, for code-generation. Furthermore it physically is very robust and has good logging possibilities.

C. Arduino

To convert from CAN-messages to serial data directly usable in the real-time simulation, an Arduino Due together with a MCP2551 CAN-transceiver was used. This provided the feedback-loop from the hardware-system to the simulation environment during the HiL-testing.

III. Software-Setup

In this section a short overview of the utilized software and its interdependencies shall be given.

A. Virtual Truck Model (VTM)

To evaluate the dynamic performance of the HCT-combination Volvo's VTM came to use. It is a library developed in and for Simulink and permits the simulation of truck dynamics based on a multi-body model for the kinematic relation and a parametrized tire model around the magic formula. Many different HCT-combinations, road-situations and maneuver definitions come pre-defined with the tool-kit enabling a fairly quick implementation of full vehicle simulations.

B. RTI-blockset

dSpace's rapid-prototyping platform's connection with Simulink is centered around a library which provides access to all physical communication ports on the MABII, real-time execution on the target hardware and straight forward code-generation and -download. It was used to implement the CAN-communication with the ETS, the Electronic Brake System (EBS) and will be used to incorporate more signals from the truck's chassis-CAN in the future. Another use of the block-set was to ensure User Datagram Protocol (UDP)-communication within the HiL-testing, as the Ethernet-port on the MABII was used to supply data from the hardware system to the simulated sub-systems.

C. ControlDesk

As the simulation is executed on the MABII it is possible to access representations of all blocks and their values and properties that are part of the abstract Simulink model which was generated to the MABII. It thus is possible to have a user-readable system-state monitor. A number of Graphical User Interface (GUI) creation tools permit fast development. During execution ControlDesk runs on a standard PC, which accesses the MABII's RAM via ethernet connection.

IV. System Architecture

In accordance with the process of the V-model it was deemed necessary and safest to verify both hardware, software and the algorithm in cooperation with the system in a HiL-test.

VTM includes a lot of processing-heavy sub-models (tire models, vehicle parameter sets) which lead to processing power not sufficing to allow for VTM's execution in the dSpace environment on the MABII. To perform HiL-testing it was thus necessary to split the computational load and accomplish real-time data exchange between the hardware controlling-system on the MABII and the rest of the simulation which will be run parallely in Simulink in real-time on a standard PC. Though there are dedicated real-time platforms available to achieve real-time execution it was decided to rely on a standard PC to minimize costs and have a lean work-process without extra steps of code conversion to different platforms. Figure 1 illustrates the distribution of the HiL-setup's different components according to the Volvo GTT functionality model over two computers, the MABII and the actual hardware (axles, hydraulich control system). The Vehicle Motion Management (VMM) consists of the controller previously developed which is executed on the Simulation-PC and the steering interface executed on the MABII. For track-testing it of course is necessary to also port the controller for execution on the MABII to have one closed of system. This was not yet possible to achieve for the tests at hand, as some components used within the controller-algorithm's Simulink structure were incompatible for real-time execution on the dSpace system.

V. Delays and characteristics

Three characteristics mainly influence the behaviour of the system:

1) Around the middle-position the steering does not react towards small changes, the legacy system has a dead-band of $+-2$ degree. For the original application this is useful to ensure a straight path of the vehicle. For this experimental platform however consistent control over the complete range is desirable, also enabling small articulations of the axles which is especially called for at higher speeds.
2) If a constant steering-angle is requested over a certain period, the hydraulic system will slowly fall back to the middle position. This needs to be eliminated because turning maneuvers or shunting-situations often require maximum articulation for longer timespan.
3) The steering system has a response time, composed of the normal inertias of the hydraulic system and an additional delay introduced by filtering and noise-canceling in the legacy system.

Measures to address these issues were:

1) A Pulse Width Modulation (PWM) around the zero-articulation position reaching out of the dead-band was implemented for requested angles lying within this range.
2) If a constant angle is requested over a period of time, long enough to result in the described decline of the articulation, a PWM around this value will be initiated.
3) Exactly determining the delay period made it possible to include it in the calculations for initial testing, where a feedback-loop was not present and the speed was still sufficiently low. A value of 0.26s for the front axle's reaction time and 0.30s for the back axle's respectively are too high for higher speeds.
   A PWM around the desired request value was implemented in order to keep the hydraulic system active and thus eliminating some of the inertia.

VI. Showcase Maneuver

To briefly show the general functioning and to give the reader insight into a practical application of the project, a standard driving maneuver was performed on the platform. As an example the U-turn was chosen, for its relevance in everyday driving and the fact that it shows some of the characteristics of HCT-combinations distinctively. It was executed at a longitudinal speed of $2m/s$, thus resulting in a turning radius of approx. 16m. To eliminate ensure consistent behaviour over all measurements, the steering-angles of the truck were pre-programmed.

Figure 3 shows the be behaviour of the different units of the combination both for the developed platform in its HiL-configuration as well as the performance in the simulation environment. This gives the opportunity to compare between the two different stages of abstraction in the V-model, thus verifying the correct functioning of the actuated axles before executing further testing in the V-model on the test-track.

- explain off-tracking as a measure
- swept path deviation

VII. Results

VIII. Conclusion

A platform which allows the independent steering of two axles in a truck-combination was developed. The correlation between the simulation results and the HiL-tests was achieved accurately enough to continue with field tests.

IX. Related and Future Works

The developed experimental platform has since been used to conduct field tests and successfully performed in an A-double combination consisting of two 40t-semi-trailers towed by a tractor. The two axles of the experimental platform functioned as a dolly steering the first two axles of the second semi-trailer. Results are promising and now need to be researched further to have a fine-tuned setup that correlates simulation, HiL-environment and the vehicle in the field sufficiently well to also allow for safe tests at higher speeds. A variety of different steering algorithms can then be evaluated.

The experimental platform can be taken further by adding wheel-individual propulsion or braking to expand the possibilities of intervention for the tested algorithms. A possibility to have faster response-times by further reducing the delays outlined in section V is to directly control the hydraulic steering system, completely circumventing the legacy Electronic Control Unit (ECU)s.

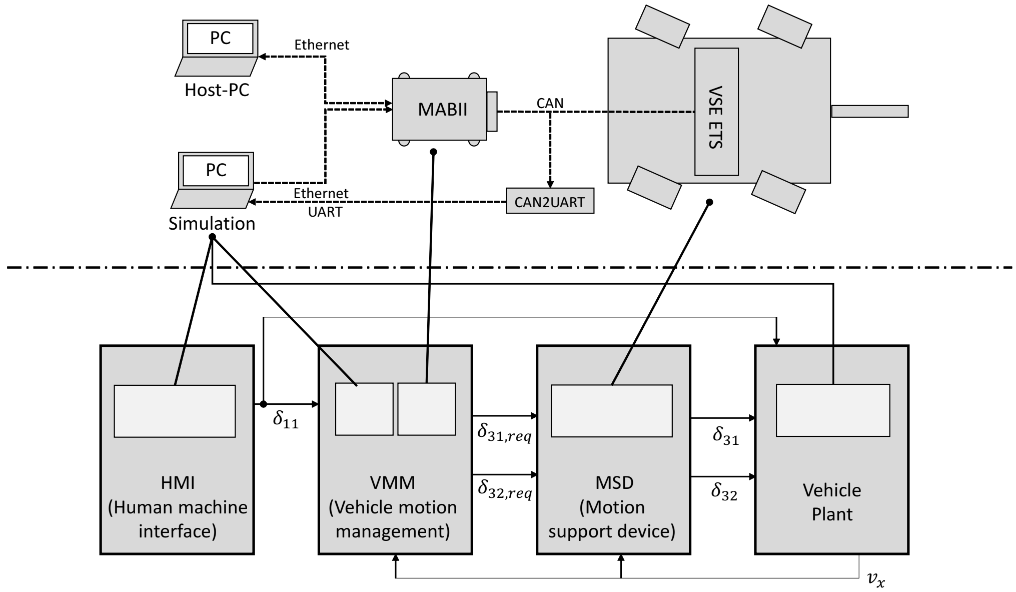

Fig. 1. Overview of HiL-simulation, distribution of sub-functions over different physical platforms (top) and correlation to Volvo functionality architecture (bottom)

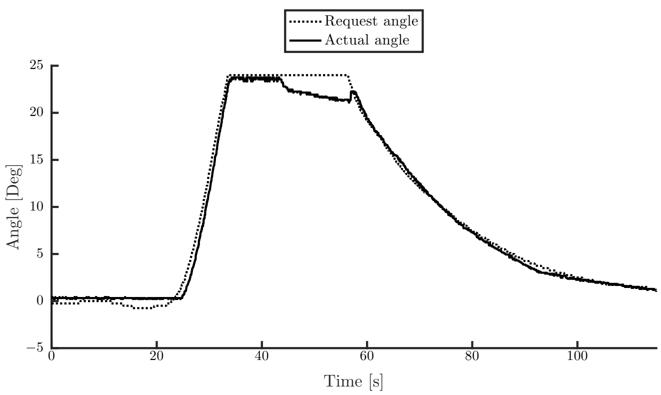

Fig. 2. Requested Angle and Actual Angle

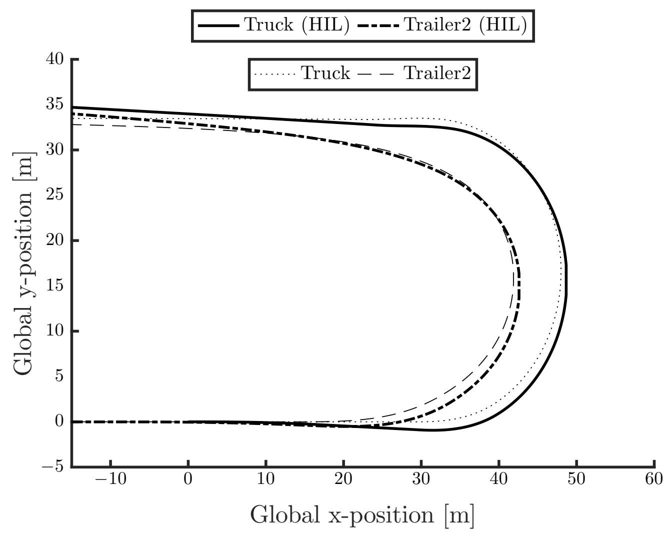

Fig. 3. Path of Tractor and Second Trailer for HiL and Simulation

X. Appendix

XI. Acknowledgement

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