Highly dynamic control of a test bench for high-speed train pantographs

Keeping Contact at 300 km/h

Electric rail vehicles must never lose contact with the power supply, not even at the highest speeds. But the complex interactions with the overhead contact line pose an enormous challenge for the calibration of pantographs. The Vienna University of Technology (TU Wien) and Siemens are therefore working on a new kind of test bench in order to transfer parts of the usual test runs to the lab. On board with them: tools from dSPACE.

The speed of today's rail traffic is constantly increasing. For example, reaching 300 km/h is no longer a challenge for modern trainsets – but it can be for their power supply. The dynamic interaction between the pantographs and the overhead line is particularly important. This elastic, connected system is prone to vibrations, especially at high speeds. If the contact forces are too weak, the pantograph is separated from the wire, resulting in arcing, which contributes to electrical wear of the carbon contact strips. If the contact forces are too high, they increase mechanical wear and cause strong dynamic loads in the overhead line and the contact strips. The different rail power systems, overhead line setups and national regulations pose additional challenges, especially in international rail traffic. This is why a growing number of modern high-performance pantographs can be controlled actively to optimize the contact forces even at high speeds. Until now, complex dynamic simulations can support these developments and mechatronic design but are not able to replace cost-intensive test runs. The pantograph manufacturer Siemens therefore uses dynamic hardware-in-the-loop tests of real pantographs as early as possible when developing suitable controllers. In these tests, the actual pantograph is the unit under test and is connected to a virtual overhead line. This enables Siemens to combine realistic test results with the advantages of lab-based development, such as reproducibility. Due to the dynamics of the overhead line in particular, it is very difficult to describe its behavior and implement a correct connection to the unit under test. If these tasks are mastered with a high quality, however, such test benches can perform fast, informative tests, in the form of virtual test runs, and give the developers a better understanding of the coupled dynamic interaction of the pantograph and the overhead line on the tracks. Test benches thus help reduce the number of effort-intensive and expensive field tests for newly developed vehicles during the test and evaluation phases.

High Dynamics on the Test Bench

In cooperation with Siemens, the Institute of Mechanics and Mechatronics of the Vienna University of Technology (TU Wien) has enhanced the existing highly dynamic pantograph test bench, which is now able to emulate the complex interactions with a virtual overhead contact line in real time. This means that real

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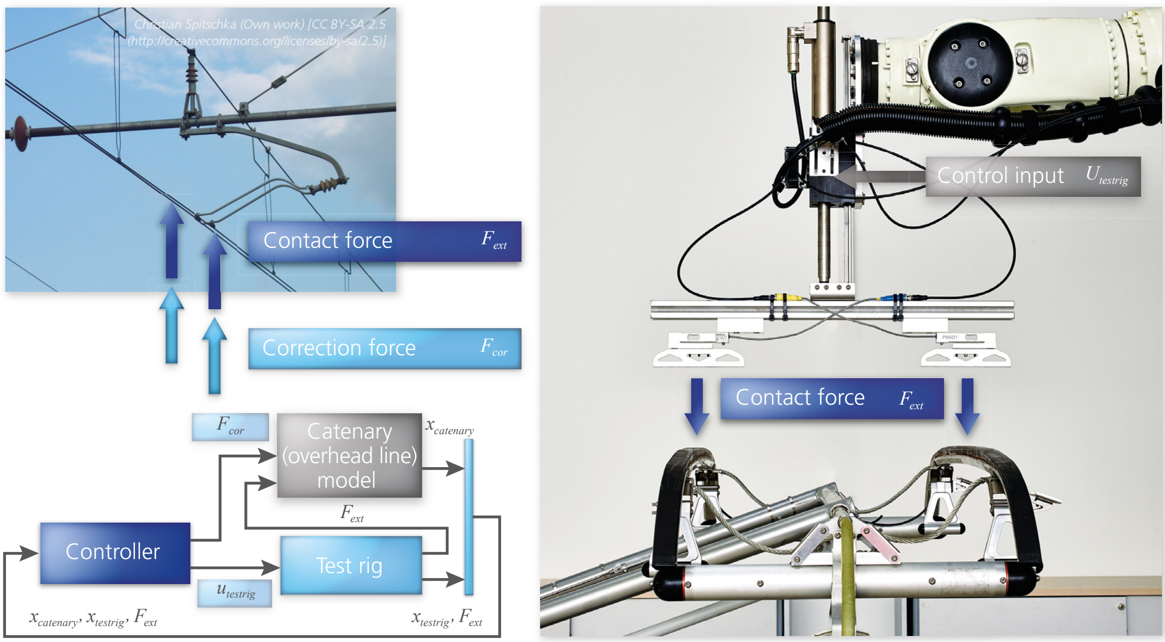
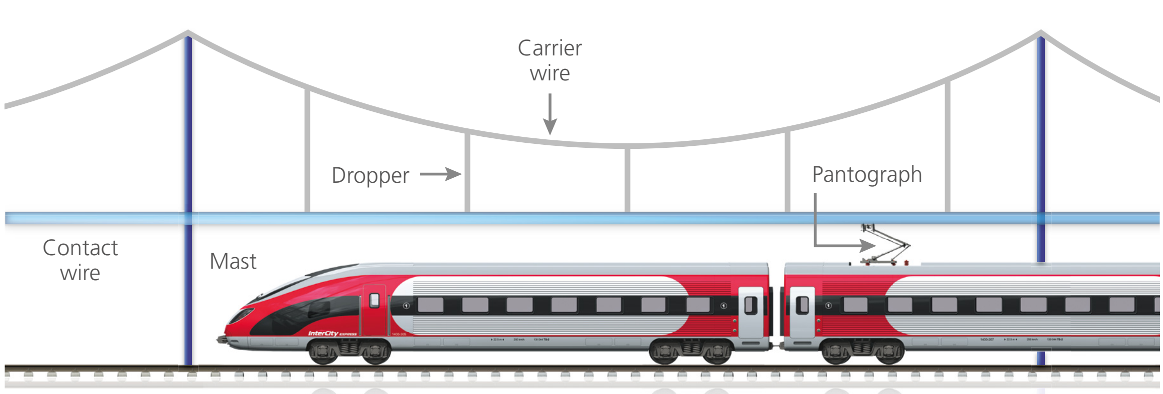


Figure 1: Thanks to the methods developed by TU Wien, realistic high-speed train drives can be emulated on the pantograph test bench from Siemens.

pantographs can be tested realistically and reproducibly in virtual test runs. An industrial robot combined with a linear motor takes on the role of the overhead line. A combined controller enables these two actuators to accurately simulate the behavior of the overhead line at the pantograph's current contact point, while measuring the resulting contact forces (figure 1). The unit under test, the pantograph, is subjected to the same forces that would also occur during dynamic contact with a real overhead line. To make the simulation as realistic as possible, an extremely efficient mathematical model of the dynamics of the overhead line has to be developed first. This model has to consider not only correct mechanical admittance but also wave propagation phenomena. Moreover, it has to be real-time-capable. The main components of the real overhead line are the contact wire and the carrier wire, both interconnected by droppers (figure 2). To create the mathematical model of the wires' dynamic behavior, the developers first formulated the

Figure 2: All components of a real overhead line, simplified in this figure, had to be included when modeling the virtual overhead line.



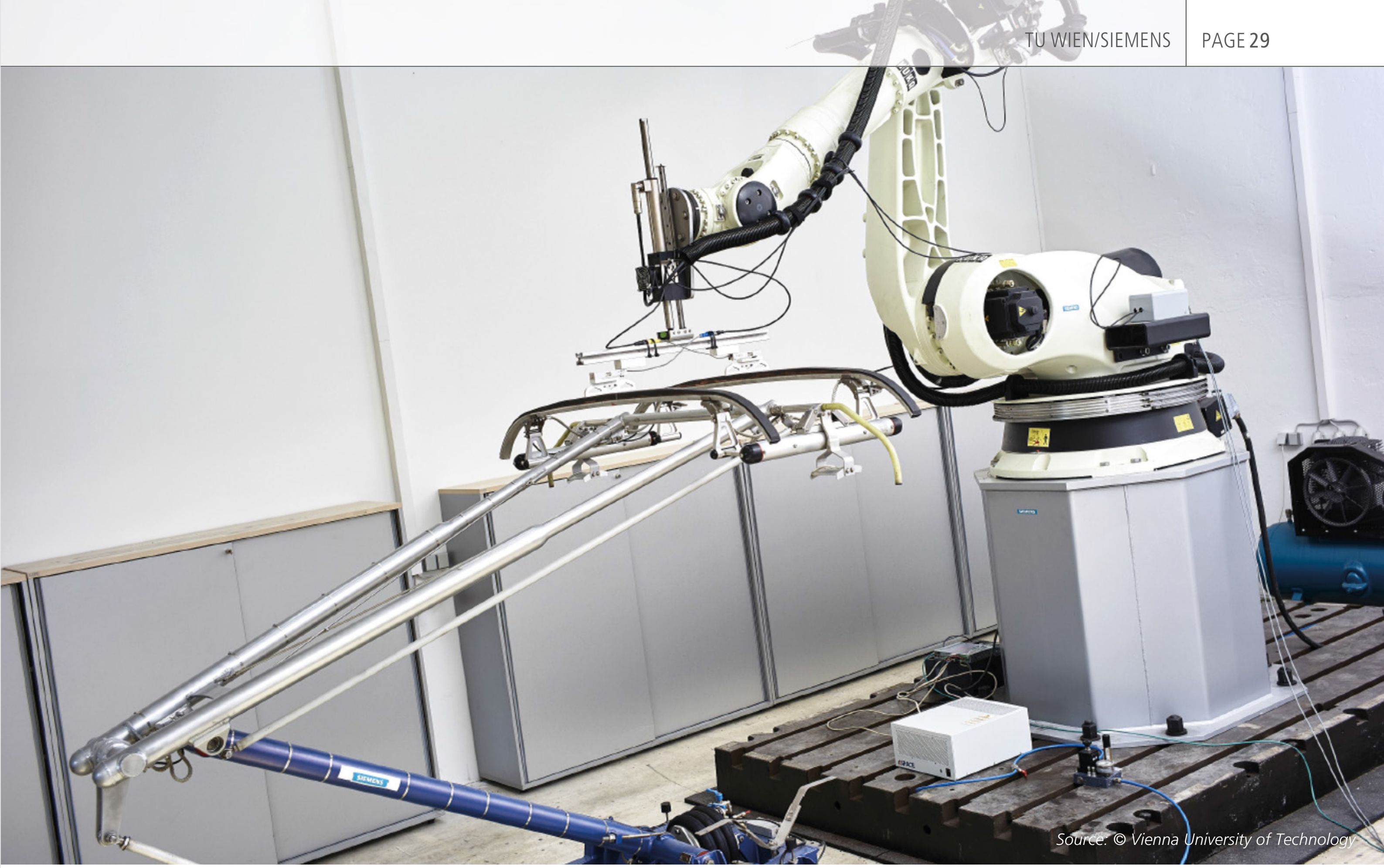


Figure 3: On the test bench system from Siemens, which enables pantograph testing, TU Wien uses a DS1006 Processor Board with numerous I/O extensions.

equations of motion (in this case, partial differential equations). They are formulated in co-moving coordinates so that only the movements of the overhead line close to the contact point of the pantograph have to be considered. These equations can then be solved with appropriate approximation methods (finite differences, finite elements). Special optimized absorbing boundary conditions allow stimulated waves to travel out of the computational domain. This lets the developers consider only a small section of the overhead line while still being able to realistically simulate the complex overhead line dynamics of a larger section. Naturally, the correct relative positions of the droppers need to be included. This results in a time-variant system structure that requires a comprehensive and automated preprocessing of the model data.

Coupling the Virtual and Real Worlds

The test bench control now has to establish a physically correct connection between the virtual power line and the real unit that is currently being tested. To achieve this, the developers use a predictive controller. Together with the precise models of the overhead line and the test bench actuators, the controller predicts the respective behaviors and makes the right control decisions beforehand. Thus, the overhead line can be simulated as realistically as possible on the test bench. This control system also ensures that the controller always observes physical limits, such as the maximum allowed motor current and position limits. To realize this behavior, complex mathematical optimization problems are solved in each sampling interval.
To deliver physically correct results even for difficult, highly dynamic test cases, even if the test bench is not fast enough to follow the virtual overhead line, the research team developed and implemented unique new extensions for traditional hard-

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> "The dSPACE tools not only reliably cover our high demand for computing power, they also give us the greatest flexibility possible and can be used for a wide range of tasks."

Professor Stefan Jakubek, Vienna University of Technology

Figure 4: A MicroLabBox was used to build a smaller demonstrator model of the pantograph test bench. Because it is so easy to transfer the developed control concepts from the test bench to the demonstrator, they can be used as illustrative examples in the classroom.

Figure 5: Test drives can be used to demonstrate how effectively the new pantographs prevent electric arcs.

ware-in-the-loop control concepts. A separate formulation is used to consider the two conserved quantities of impulse and energy directly within the controller. This ensures that the virtual overhead line and the real pantograph consistently exchange these conserved quantities, making the test results even more realistic. Simulating the complex interactions of the virtual overhead line and the real pantograph requires high model precision, while model complexity has to be kept to a minimum so that the model can still be computed in real time. The real-time system also has to prepare the measurement data received from state observers and estimate disturbances such as friction forces. To complete all these tasks in real time, TU Wien needed not only new numeric methods but also an extremely powerful real-time platform.

Flexible dSPACE Tool Chain

TU Wien chose real-time tools from dSPACE. In the course of the research project, the test bench concept was developed on two different dSPACE platforms. The backbone of the test bench that can be used to test life-size pantographs is a DS1006 Processor Board (figure 3). Its 2.8 GHz quad-core processor allows developers to perform complex system simulations and use controls with high sampling rates, because the computation load can be distributed efficiently. For example, one processor core is responsible for the basic connection and control of the test bench (5 kHz sampling rate), while another core performs the predictive impedance control (200 Hz). A third core simulates a precise model of the overhead line (200 Hz). In each sampling step, the test bench controller is initialized according to the model states. For the tailored communication with the test bench components, the developers use a DS4302 CAN Interface Board (linear motor), a

DS3002 Incremental Encoder Interface Board (position sensor), a DS2201 Multi-I/O Board (control variables), and a DS4121 ECU Interface Board (industrial robot). Most of the developed algorithms were implemented in MATLAB®/Simulink® and compiled directly from there. The team also used the easy integration of external libraries for efficiently solving complex mathematical problems. A user interface developed with the experiment software dSPACE ControlDesk® makes controlling the virtual test runs on the test bench highly intuitive. In addition to the life-size test bench, the developers also built a downscaled laboratory test bench for development purposes and for the classroom (figure 4). The laboratory test bench clearly demonstrates the interactions between the pantograph and the overhead line, as well as the basics of impedance control, and makes them easy to understand. For this, TU Wien for the first time used the new compact MicroLabBox. The high compatibility and seamlessness of the dSPACE tool chain allow for an easy transfer of the algorithms from the test bench to the smaller lab demonstrator.

Results and Outlook

The described tools can be used to build a highly dynamic and powerful pantograph test bench. In particular, thanks to the extended overhead line model it is possible to analyze the influence of multiple traction, i.e., a train with numerous pantographs raised simultaneously, already on the test bench. The performance of future pantographs can thus be quantified reliably and early in the development cycle. Siemens' pantograph test bench, developed further in cooperation with TU Wien, is the very first hardware-in-the-loop test bench worldwide that can simulate the system dynamics of partial differential equations consistently in conserved quantities. The realistic, highly dynamic tests that are now possible and their reproducibility significantly improve high-performance pantographs and are therefore a valuable asset for making future rail travel even more efficient. Due to the easy transfer of tests to the smaller demonstrator, the control models can also be used in the classroom for educational purposes and to spark young engineers' interest in railway technology. So it is quite possible that future rail traffic will continue to set new records in speed and efficiency. ■

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This video shows you the Siemens pantograph test bench, developed in cooperation with TU Wien, in action so you can learn more about its new type of highly dynamic control.

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