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Catenary emulation for hardware-in-the-loop pantograph testing with a model predictive energy-conserving control algorithm[☆]

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ABSTRACT

Pantograph current collectors, especially for high-speed trains, need to ensure safe contact with the catenary under stringent requirements on the dynamic contact force. A novel, high-dynamic pantograph test rig with accurate virtual catenary emulation is presented that allows for efficient, realistic, and reproducible testing. The complex dynamics of the pantograph/catenary interaction is modeled by a real-time-capable distributed-parameter description in moving coordinates. The proposed test rig controller incorporates model-predictive impedance control to match the desired catenary dynamics. Additionally, it keeps the exchange of the conserved quantities energy and momentum between the real pantograph and the virtual catenary consistent to increase physical trustworthiness of the results, even in high-dynamic test scenarios. The proposed methods are experimentally validated on the full-scale pantograph test rig.

1. Introduction

In recent years, railway current collectors (pantographs) have become a limiting factor when pushing the velocity limits of high-speed trains. They need to ensure a steady contact with the catenary's contact wire to maintain the train's energy supply. Loss of contact must be avoided to prevent arcing (and thus heavy wear). As a result, modern pantographs have to fulfill high requirements: small contact force variations, highly reliable operation, and long life cycles. The main problem in the development process of high-performance, high-speed pantographs is the complexity of the interaction dynamics with the catenary. Therefore, physical trustworthiness of simulations is limited, requiring laborious actual track tests. One way to reduce the need for measurement runs that also allows for reproducible testing is to deploy the pantograph on a test bed and examine its behavior in advance. This concept is called hardware-in-the-loop (HiL) testing whereby the real, full-size pantograph is the unit under test (UUT) that is being put into interaction with a virtual catenary model. The goal thereby is to emulate a real-world train ride already in the laboratory by applying realistic, dynamically generated load patterns that emerge from the coupled interaction of the virtual catenary and the UUT.

Simplified pantograph HiL testing can be realized by exciting the pantograph with a predefined motion trajectory, such as the static pre-sag of the catenary's contact wire [1]. However, the pantograph/catenary interaction is crucial to obtain realistic test results. To consider the catenary's dynamic response, it has to be either modeled in a simplified way by oscillators (ordinary differential equations, ODEs) or by high-fidelity models (based on partial differential equations, PDEs) [2,3].

Controlling the test rig so that it dynamically responds to the UUT in the same way as the catenary model is accomplished by impedance control [4,5], where a dynamic behavior rather than a predefined reference trajectory is tracked. Nowadays, impedance control is not only applied in robotics for handling tasks but also used, for example, in engine testbed control [6] or battery emulation [7]. The closely related field of bilateral teleoperation is reviewed in Refs. [8,9].

Accurate, realistic emulation of the pantograph/catenary interaction needs a real-time-capable model in sufficient details, and so high-fidelity PDE modeling is imperative for accurate dynamics, especially at high speeds. A typical catenary configuration consists of a carrier and a contact wire which are coupled via so-called droppers. The carrier wire is additionally attached to inertia-fixed masts. Each wire can be modeled as an Euler-Bernoulli beam under axial tension, and due to the droppers the resulting equations that need to be solved are two coupled PDEs with constraints [10]. Both wires are weakly damped, and typically a large computational domain is needed in order to capture wave propagation phenomena correctly without distortion by spurious reflections at the boundaries.

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Since the early 2000s HiL pantograph testing has been described, e.g. in Ref. [3]. There, the pantograph has been excited with two hydraulic actuators from the top and the bottom to additionally take the train's vertical displacement into account. The tests have been performed using a passive pantograph at simulated velocities of up to 180 km/h. Facchinetti and various co-authors have published a series of papers showing the progress and newest results of their pantograph test rig from 2004 to 2013 [2,11–14]. The improvements were made in terms of the catenary model's complexity (separate carrier and contact wires, as well as dropper slackening [12]), a novel shifting procedure in Ref. [14], a lateral actuator to incorporate stagger [14], and finally an actively controlled pantograph pan head [13]. In each of the aforementioned contributions a modal approach was used to model the catenary's dynamics. In Ref. [15] an HiL test rig is proposed using two actuators for the vertical and one actuator for the horizontal contact wire displacement. The catenary dynamics is modeled in a simplified way (physical mass-spring-damper system at the contact point and pre-recorded displacement trajectories). A commercial pantograph HiL test rig can be found in Ref. [16], where the pantograph is contacted with a spinning disc actuator enabling wear, arcing and temperature tests of the contact strips. Therein the catenary is modeled as a time-varying stiffness, similar as in Ref. [15].

However, the described test rigs face actuation limits in large-displacement tests, e.g. when emulating tunnel entries, and the measured contact force is directly fed into the virtual simulation environment (VSE; here the virtual catenary dynamics) and the reaction (the contact wire's displacement at the pantograph position) is utilized as a tracking reference. Classical tracking control with its intrinsic phase lag fails to provide state-of-the-art control performance as achieved by, for example, predictive control approaches.

Furthermore, ubiquitous test rig imperfections and limitations are not adequately addressed by classical control designs in terms of physical trustworthiness. It was shown in Ref. [17] that the consideration of energy and momentum balances on an HiL test rig can eliminate systematic errors in test results.

The quality of impedance control is always determined by the quality of the underlying model, and the catenary models used so far are either highly simplified, or require large computational domains or artificial damping to avoid spurious unphysical boundary effects.

The main contributions of this paper solve these issues as follows:

(a) an HiL actuation concept consisting of a high-dynamic linear drive and a six-degree-of-freedom industry robot that allows for high-dynamic maneuvers in a large operating area;
(b) a novel impedance control strategy incorporating energy and momentum conservation, solved by a model predictive control approach to consider constraints and predict the complex catenary dynamics;
(c) an efficient real-time-capable Eulerian approach [18] (a fixed pantograph interacts with a moving catenary) to solve the distributed-parameter catenary dynamics combined with special absorbing boundary layers.

In contrast to the control approaches of existing pantograph HiL test rig designs, impedance control in this work is realized via model predictive control (MPC). The basis of the controller is a model of the underlying plant (the test rig actuator) and the VSE (the catenary dynamics), and the future behavior of both is predicted in each time step, where the upcoming control moves are the decision variables in an optimization problem. This allows to incorporate constraints into the control problem and leads to superior control performance by eliminating the phase lag that emerges in classical state feedback laws. For efficiently solving this optimization problem in real time, the size of the underlying models of the MPC is limited. Hence, the proposed catenary model is formulated in a novel efficient form where a special case of controlled boundaries is used. The computational domains of the contact and carrier wires are extended by small controlled boundary layers that absorb all outgoing waves [19]. The periodic excitation emerging from the train ride in combination with the catenary is modeled as a time-varying periodic system.

The importance of obeying physical conservation laws in an impedance-controlled test rig was already shown in Ref. [17] at a combustion engine test rig. There, the fuel consumption on the real track and in the virtual representation were not consistent because small energy errors emerging from limited control bandwidth accumulated. It was shown that these errors could be eliminated by considering conserved quantities by control.

One major challenge in HiL applications is to establish a robustly stable, yet highly transparent coupling of VSE and UUT. These objectives are conflicting [9], and in Ref. [20] it is shown that causality conflicts result in instability. For haptic interfaces, passivity-based techniques [21,22] have been proposed to ensure stability of VSE/ UUT coupling. Ref. [23] proposes to combine active and passive actuators with a hybrid control algorithm to improve the stable attainable impedance range.

In power-electronic HiL testing the coupling between the VSE and the UUT was already under investigation in recent papers, but not in terms of conserved quantities' consistency. In Ref. [24] different possible interfacing concepts are discussed and it is also stated that the conservation of energy has to be enforced, although this topic is not pursued further there. In Ref. [25] a circuit for electronic power-HiL simulations is described that relies on perfectly controlled voltage or current sources.

In contrast, the method proposed here guarantees the conservation of energy by introducing a correction term (interpreted as a virtual force) acting on the VSE. This allows the formulation of both energy and momentum conservation laws directly as control goals.

The outline of this paper is as follows: In Section 2 the test rig system setup, the VSE and their interconnection are outlined. All relevant signals, the conserved quantities, as well as the general control goals are specified. Section 3 lays the theoretical foundation for impedance control and presents the control in form of a model predictive controller. As VSE model an efficient railway catenary model structure is described in Section 4. Finally, Section 5 demonstrates the functionality of the proposed control concept with experimental results, followed by conclusions.

2. Problem description

2.1. High-dynamic pantograph test rig

The novel high-speed pantograph test rig considered in this work is displayed in Fig. 1.

It consists of a linear drive that is attached to a robot arm. A full-size pantograph current collector represents the UUT. This test rig setup allows for large-scale maneuvers such as to emulate tunnel entries and exits (via the robot's motion) as well as vertical displacements in a broad frequency range (achieved via the linear drive) as needed for high-fidelity catenary emulation. In this work, only the linear drive is considered as actuator.

The available measurements are the position of the linear drive as well as the contact force at the slider's end position where contact with the pantograph is made.

A mathematical description of the test rig dynamics can be obtained by physical modeling approaches where the relevant dynamics are described by the equations of motion. The parameters are either taken from data sheets or obtained by parameter identification based on measurement data. Another possibility is to