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Observer-based nonlinear control strategies for Hardware-in-the-Loop simulations of multiaxial suspension test rigs☆

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ABSTRACT

The Hardware-in-the-Loop (HiL) simulation is a powerful and well-established approach for the development and testing of mechatronic systems. The specimen is coupled appropriately with mathematical models of the remainder of a larger system that run in parallel on a real-time computer. For test rigs with multiaxial excitation of the specimen, the realization of HiL simulations is a challenging task. The excitation units are serial or parallel kinematic manipulators and the dynamic properties of the specimen vary in different spatial directions. In particular, the interaction forces and torques at the interface between manipulator and specimen have to be considered. Thus, appropriate control strategies are necessary to drive the manipulators enabling realistic and safe HiL simulations. This article deals with the design of motion and force control strategies for a vehicle axle test rig with a highly dynamic hydraulic hexapod used as the excitation unit. The realization of motion and force control for a hexapod requires the knowledge of its current system state. Therefore, sliding mode state observation techniques using super-twisting algorithms (STA) are presented. The developed controllers, observers and HiL configurations are validated with simulation and experimental results.

1. Introduction

Modern mechatronic systems are of increasing complexity. Their design requires effective development and testing methods. In particular, the automotive industry has high requirements on development time and quality of their mechatronic subsystems, which calls for fast and flexible test rigs. Furthermore, the automotive sector has high standards on testing procedures. In this context, the Hardware-in-the-Loop (HiL) simulation is a powerful testing and development method, which gains popularity in industry as well as research projects [1]. HiL test rigs enable the investigation of subsystems or assemblies of mechatronic systems under realistic conditions in the laboratory. The key feature is that the remainder of the larger reference system is simulated in parallel on a real-time computer so that the dynamic behavior of the entire system can be emulated. Hence, the interaction of all components of the mechatronic system, such as the mechanical structure, sensors and the controlled actuators can be examined. Moreover, HiL enables the possibility to develop and validate new control concepts. The usage of HiL test rigs is very attractive in the development phase, in which the product or even certain subsystems of the product solely exist as a prototype. Further advantages are the minimized testing efforts and costs. Also, HiL simulations are applied to consider safety-critical aspects, e.g. by reducing the number of real driving tests. In addition, HiL simulations are flexible, reproducible and more accurate than pure virtual simulations.

The HiL simulation can be realized in different ways. For instance, the number and the type of physically present subsystems in the test rig, e.g. sensors or actuators, can vary in a wide range [2]. However, the key distinction of HiL test rigs is the amount of energy that is exchanged between the specimen and its environment. In classic HiL systems, the interface between the specimen and the virtual subsystems on the real-time computer is signal-based. In the automotive industry, this HiL variant is predominantly used to design and test electronic control units (ECU) [1]. In advanced HiL systems, the test rig can comprise mechanical or mechatronic subsystems which are tested physically, e.g. by imposing real loads in the mechanical substructure of the specimen. The target loads are computed by environment models of the specimen which are implemented on a real-time computer. The realization requires additional coupling systems consisting of actuators, sensors, signal processing devices and local controllers, cf. Fig. 1. In contrast to signal-based HiL simulations, the design of such HiL systems is challenging and high accuracy as well as deep system knowledge

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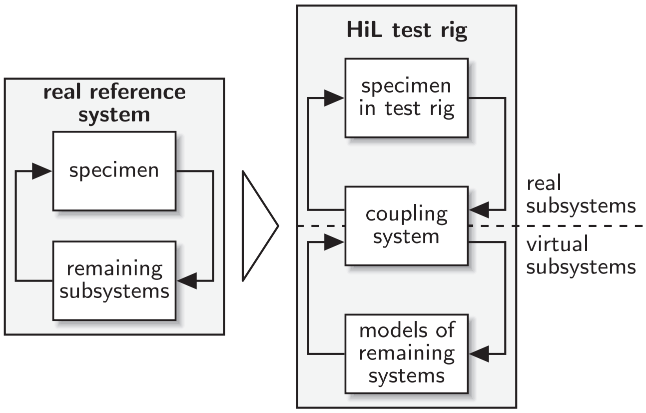

Fig. 1. Subsystems of the reference system and the HiL test rig.

throughout the development process is required [3]. In this article, the second described HiL variant is regarded.

Application examples of such HiL systems can be found in different domains, for example, in automotive / transportation systems [4–7], aerospace [8,9], robotics [10–13], and manufacturing systems [14]. In the automotive sector, generally, HiL systems are realized with simple excitation units, e.g. hydraulically actuated cylinders, which feature uniaxial excitation of the specimen or multiaxial excitation with low dynamics. For the vehicle suspension development, the use of test rigs with a single hydraulic cylinder is still the most common setup for HiL simulations, cf. [4,6]. In this setup, the shock absorber is realized as the physically present subsystem in the test rig while the remainder of the reference system is considered with appropriate vehicle models. The controller design for the excitation units is straightforward and often linear control theory can be applied. Generally, simple position controllers are sufficient. Moreover, the interaction force between the excitation unit and the specimen does not require any additional consideration.

On the contrary, in complex HiL systems which feature spatial or multiaxial specimen excitation, the contact situation between the manipulator and the specimen has to be considered by appropriate force control strategies. In the field of robotics, similar applications exist which focus on the interaction forces [10,12]. The control objective is to mimic a different virtual robot or emulate specific loads. Therefore, serial kinematic manipulators with appropriate motion/force control strategies are used. This setting does not compare to a HiL simulation, because models of the remainder of a larger reference system are not simulated in parallel. The focus is to establish contact stability during simple robotic tasks, whereas high dynamic specimen excitation is not required.

Regarding the general design of complex HiL systems, different research areas exist. For instance, the partitioning of dynamic systems to be applicable for HiL simulations, which is denoted as substructuring, can be mentioned [15–17]. The ideas and methods are presented well, however, they are conceptual frameworks and the considered application examples are idealized HiL systems. Furthermore, the design of appropriate control structures of the excitation units within the HiL system is a main research area as well [18]. In this connection, the terms dynamically substructured systems (DSS), real-time dynamic substructuring (RTDS) or hybrid simulation are often used, which are similar to our understanding of the HiL simulation framework, see [19,20]. There, stability and bandwidth issues of the actuators and the entire HiL system as well as the uncertain dynamic behavior of the specimen are considered. Often, for the validation of the theoretical frameworks, application examples are used that are simple HiL systems, e.g. double oscillators with uniaxial excitation of the specimen, cf. [21–23]. An application example from the substructuring community with multiple in- and outputs is the motorcycle test rig in [19]. However, actuation is done via linear actuators for the two wheels. No spatial excitation is provided that is comparable to the application example in this article. More sophisticated actuation systems can be found in the domain of structural or seismic testing where multiaxial shaking tables are used. An overview about this topic and references to specific examples can be found in [24]. However, multiaxial applications are rare since the stiff coupling between multiple actuators to a specimen presents a challenging task for real-time control of the actuators, cf. [24].

In contrast to the discussed application examples from literature, the vehicle axle test rig considered in this article features high dynamic and spatial excitation of the specimen in all degrees of freedom (DOF) in real-time. Thus, HiL simulations for entire vehicle axles can be realized. Current industrial vehicle axle test rigs do not allow the application of real-time excitation. Due to the structural properties and performance issues of the excitation units, an iterative computation of drive signals is required to achieve satisfactory controller bandwidth [25]. Hence, we are currently not aware of a vehicle axle test rig which can be integrated into a HiL simulation.

This article is an extension of the conference paper [26], where two different concepts of HiL controllers for the realization of HiL simulations for a multiaxial suspension test rig, namely a position-based and a force-based actuation of the specimen, were presented. In [26] the main focus is the general applicability of high dynamic HiL simulations with spatial excitation of the specimen. This includes the identification of appropriate system structures of the entire HiL system with the notion of substructuring as well as basic control concepts. The performance of the identified HiL controllers were compared by means of simulation results. In contrast to [26], this article contains a more rigorous analysis and synthesis framework. Especially, the identified connections to indirect force control are highlighted, since HiL systems add extra feedback-loops besides the existing controller feedback. Additionally, new sliding mode estimation techniques are presented which use super-twisting algorithms (STA) for state estimation. Moreover, an advanced force control strategy with higher controller bandwidth is derived. In this context, a hybrid HiL control strategy is developed.

This article is structured as follows: In Section 2, the HiL test rig for vehicle axles, which is currently built up in the laboratory of the Heinz Nixdorf Institute at Paderborn University, is introduced briefly. In Section 3, by means of a simplified test rig model the general problem formulation in the HiL system design and the control objective are presented. Section 4 deals with the modeling of all components which are necessary for the controller design and the HiL environment. For the state estimation of the hexapod, sliding mode observation techniques are presented in Section 5. Based on the outcomes of the previous sections, the design of appropriate control strategies is demonstrated in Section 6. Section 7 provides simulation and experimental results to validate the HiL system, observation and controller design. This article ends with a conclusion in Section 8.