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# Emulator-based control for actuator-based hardware-in-the-loop testing

P.J. Gawthrop[a], D.W. Virden[b], S.A. Neild[b], D.J. Wagg[b,*]

[a]Centre for Systems and Control and Department of Mechanical Engineering, University of Glasgow, Glasgow G12 8QQ, Scotland
[b]Department of Mechanical Engineering, Queens Building, University of Bristol, Bristol BS8 1TR, UK

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**Abstract**

Hardware-in-the-loop (HWiL) is a form of component testing where hardware components are linked with software models. In order to test mechanical components an additional *transfer system* is required to link the software and hardware subsystems. The transfer system typically comprises sensors and actuators and the dynamic effects of these components need to be eliminated to give accurate results. In this paper an emulator-based control strategy is presented for actuator-based HWiL. Emulator-based control can solve the twin problems of stability and fidelity caused by the unwanted transfer system (actuator) dynamics. Significantly EBC can emulate the inverse of a transfer system which is not causally invertible, allowing a wider range of more complex transfer systems to be controlled. A robustness analysis is given and experimental results presented.


*Keywords:* Hardware-in-the-loop; Feedback control; Robustness; Automotive engineering

## 1. Introduction

Hardware-in-the-loop (HWiL) is a form of component testing where physical components of the system communicate with software models which simulate the behaviour of the rest of the system (Brendecke & Kucukay, 2002; Faithfull, Ball, & Jones, 2001; Zhang & Alleyne, 2005). Typically the hardware components being tested are control systems and the method has particular applications in the automotive industry (Hong, Sohn, & Hedrick, 2002; Isermann, Schaffnit, & Sinsel, 1999; Kendall & Jones, 1999; Lin, Tseng, & Tseng, 2006; Misselhorn, Theron, & Els, 2006; Rulka & Pankiewicz, 2005) and a range of other applications (de Carufel, Martin, & Piedboeuf, 2000; Ferreira, Almeida, Quintas, & de Oliveira, 2004a, 2004b; Ganguli, Deraemaeker, Horodinca, & Preumont, 2005; Jezernik, 2005; Lambrechts, Boerlage, & Steinbuch, 2005; Mansoor, Jones, Bradley, Aris, & Jones, 2003). In a typical hardware-in-the-loop test, the hardware component consists of a box of electronic components which can communicate with the software models via electrical signals exchanged using a data acquisition and control system such as dSpace. Extending the HWiL technique to test mechanical components has been an area of interest for some time, for example, for use in suspension development, see Misselhorn et al. (2006) and references therein. The main difficulty is that connecting a mechanical component to a software model requires the transfer of forces and velocities, and to achieve this an additional dynamic *transfer system* (Wagg & Stoten, 2001) must be included in the loop. Typically the transfer system is a set of actuators, which will have dynamic characteristics which need to be compensated for if the test is to be carried out in real time.

Mitigating the effect of transfer system dynamics has been studied in detail in the context of the related testing technique of real time dynamic substructuring (RTDS) (Blakeborough, Williams, Darby, & Williams, 2001; Darby, Williams, & Blakeborough, 2002; Gawthrop, Wallace, & Wagg, 2005; Horiuchi, Inoue, Konno, & Namita, 1999; Reinhorn, Sivaselvan, Liang, & Shao, 2004). The topic of real-time dynamic substructuring is the subject of a recent issue of Philosophical Transactions of the Royal Society, within which Williams and Blakeborough (2001) give an excellent introductory review. Real

*Corresponding author. Tel.: +44 117 928 9736; fax: +44 117 929 4423.
*E-mail address:* david.wagg@bristol.ac.uk (D.J. Wagg).

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time dynamic substructuring is an actuator-based HWiL technique (AbHWiL), which so far has primarily been considered for civil engineering systems. As a result instability is a frequent problem because the systems being modelled usually have lightly damped resonant behaviour, and any small delays in the transfer system have the effect of negative damping (Horiuchi et al., 1999; Wallace, Sieber, Neild, Wagg, & Krauskopf, 2005a).

The effect of transfer system dynamics can be mitigated by reformulating the problem as a feedback control problem, so that the techniques of robust control design can be applied to ensure stability (Gawthrop, Wallace, Neild, & Wagg, 2007), but at the cost of reduced accuracy. In a small number of cases, the dynamics of the transfer system can be removed from the closed loop by using an inverted model of the transfer system dynamics—for example, using the virtual actuator approach (Gawthrop, 2004, 2005; Gawthrop et al., 2005)—in most cases, however, the transfer system is not (causally) invertible. One of the most commonly considered examples of a non-invertible transfer system is that of a pure time delay. A number of approaches have been suggested to compensate for a pure delay including polynomial extrapolation (Darby et al., 2002; Horiuchi & Konno, 2001; Wallace et al., 2005a; Wallace, Wagg, & Neild, 2005b), adaptive forward prediction (Darby et al., 2002; Wallace et al., 2005b) and Smith's predictor (Agrawal & Yang, 2000; McGreevy, Soong, & Reinhorn, 1998; Reinhorn et al., 2004). In the automotive suspension systems studied by Misselhorn et al. (2006) the damping levels are significantly higher than in most RTDS tests, such that phase margin instabilities can be avoided. In fact the approach is to use PID control, and operate in a frequency range where actuator phase lag is seen to be acceptable. However, for mechanical components with lower damping, it is believed that the delay compensation techniques developed for RTDS will be of significant benefit for actuator-based HWiL. This will also apply to applications where electro-mechanical devices or complex circuitry are used as transfer systems, with the result that the effect of their dynamics may be significant (Driscoll, Huggins, & Book, 2005; Zhu, Pekarek, Jatskevich, Wasynczuk, & Delisle, 2005). It will also be useful for the development and techniques such as model-in-the-loop (Plummer, 2006; Zhu et al., 2005) and engine-in-the-loop (Fathy, Ahlawat, & Stein, 2006) testing which are further extensions of the HWiL technique.

In this paper, the use of an emulator-based control strategy is proposed for actuator-based HWiL. Emulator-based control (EBC) gives a novel and effective solution to the twin problems of stability and fidelity caused by the unwanted transfer system (actuator) dynamics. In particular EBC can emulate the inverse of a transfer system which is not causally invertible. Moreover, the approach can be used with more complex models of transfer system dynamics than have previously been studied. This means that more accurate coupling can be obtained, leading in turn to a higher degree of accuracy for the complete test. This will be demonstrated using an example of the lightly damped mass-spring-damper system previously considered in Wallace et al. (2005b).

## 2. Actuator-based HWiL as a feedback system

This section shows that the actuator-based HWiL (AbHWiL) approach introduced in this paper has a feedback interpretation and that standard frequency domain results (for example as discussed in the textbook of Goodwin, Graebe, & Salgado, 2001) can be used to analyse the resultant feedback loop.

AbHWiL involves having a model in two parts, one to be tested as a hardware component and one to be implemented as a software model. In this paper, the analysis is accomplished in the continuous-time domain thus regarding not only the tested component but also the software component as a physical system. The implementation of the software component (including choice of integration method and sample time) is an important issue which is not, however, covered in this paper.

Because the complete system being modelled is a physical system, each of the two subsystems has the special mathematical property of passivity (Willems, 1972) which can be expressed in bond graph terms (Gawthrop et al., 2005). The software subsystem is connected to the hardware subsystem via a computer digital to analogue interface driving a physical actuator; the connection is referred to as the transfer system.

Gawthrop et al. (2007) showed how RTDS (and hence AbHWiL) can be viewed as a feedback system, represented in conventional block diagram form in Fig. 1, where $P(s)$ is the transfer function of the hardware component, $N(s)$ and $N_r(s)$ the transfer functions representing the software model (which is driven by the reference signal $r(s)$ as well as the physical subsystem output $y(s)$) and $T(s)$ the transfer function of the transfer system. For the case where interface displacement is passed from the software model to the hardware component, $u(s)$ is the interface displacement calculated by the software model, $x(s)$ is the displacement imposed on the hardware component, $y(s)$ is the force required to impose the displacement $x(s)$ on the hardware component and $r(s)$ is the external excitation. In the ideal situation, $T(s) = 1$ so that the software model output matches the hardware component input exactly (and hence the AbHWiL system perfectly replicates the full physical system). In this ideal case the closed-loop system of Fig. 1 has the closed-loop transfer function

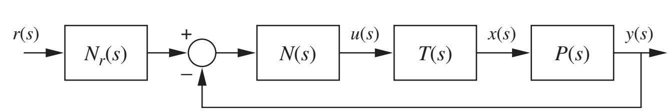


Fig. 1. Substructuring as a feedback system. $P(s)$ is the hardware component transfer function, $N(s)$ and $N_r(s)$ are the software substructure transfer functions and $T(s)$ is the transfer system transfer function.