



Development and model-based transparency analysis of an Internet-distributed hardware-in-the-loop simulation platform

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ABSTRACT

This paper summarizes efforts to integrate, for the first time, two geographically dispersed hardware-in-the-loop simulation setups over the Internet in an observer-free way for an automotive application. The two setups are the engine-in-the-loop simulation setup at the University of Michigan (UM) in Ann Arbor, MI, USA, and the driver-in-the-loop ride motion simulator at the US Army Tank-Automotive Research, Development and Engineering Center (TARDEC) in Warren, MI, USA. The goal of such integration is to increase the fidelity of experiments and to enable concurrent geographically dispersed systems engineering. First, experiments with the actual hardware are presented. The concept of transparency is discussed, and the infeasibility of performing a baseline experiment with ideally integrated hardware is presented as a challenge to characterize the transparency of the experimental setup. This motivates the second half of the paper, in which a model-based approach is taken to analyze the transparency of the system. The conclusion is that an observer-free solution is feasible for integrating the two pieces of hardware over the Internet in a transparent manner, even if the nominal delay is increased by four times. It is also found that different signals in the system can exhibit different levels of transparency.

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1. Introduction

Hardware-in-the-loop simulation (HILS) provides a bridge between physical prototyping and virtual experiments by uniquely combining their advantages and allowing for cost-effective, high-fidelity experiments [1,2]. It strongly promotes concurrent system engineering and has therefore become indispensable in many application areas, such as automotive [3–11], aerospace [12–15], manufacturing [16], robotics [17,18], defense [19,20], and structural analysis [21,22].

A natural evolution of the basic HILS idea is to integrate multiple HILS setups to fully exploit their benefits [23]. However, if the setups are geographically dispersed, bringing them together and establishing a physical connection may be infeasible. In that case, a virtual coupling can be created through a communication medium.

Among the different communication media that are available for a distributed HILS setup, the Internet is an attractive choice due to its prevalence. The Internet-distributed HILS (ID-HILS) idea has emerged within the last decade and has found applications in the earthquake simulation [21], telerobotics [24], and automotive powertrain areas [25]. Within the earthquake simulation literature,

the idea of geographically distributing experimental substructures within a network of laboratories linked through numerical simulations using the Internet was proposed by Campbell and Stojadinovic in 1998 [21]. Today, the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) [26] provides an outstanding example of the capabilities and impact of the ID-HILS idea, and the earthquake literature presents many applications of the ID-HILS idea to earthquake simulation [27–32]. Within the telerobotics literature, the possibility of achieving stable force-reflecting teleoperation over the Internet was first explored by Niemeyer and Slotine, also in 1998 [24], and attracted the attention of many other researchers [33–42]. The notion of ID-HILS did not appear in the automotive powertrain systems engineering area until 2006, when US Tank-Automotive Research, Development, and Engineering Center (TARDEC) researchers successfully integrated a ride motion simulator in Warren, MI, USA, with a hybrid-power-system simulator in Santa Clara, CA, USA [25,43,44].

These works highlighted that using the Internet as the communication medium also creates some challenges due to the Internet's inherent delay, jitter, and loss. Much of the delay is related to routing and processing in the network. Jitter refers to the variability of the delay, and loss occurs because not every packet sent through Internet necessarily arrives at its destination. Although loss can be remedied by transport-level protocols like TCP, such protocols increase the delay and are therefore not considered in this work.

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