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On hardware-in-the-loop simulation

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Abstract—**Hardware-in-the-loop simulation is a well established technique used in design and evaluation of control systems. The purpose of this paper is twofold. First it aims to identify research questions related to the design of hardware-in-the-loop simulation. Second it suggests possible measures of assessing the simulation fidelity of hardware-the-loop simulation.**

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I. INTRODUCTION

Basic idea in hardware-in-the-loop simulation is that of including a part of the real hardware in the simulation loop during system development. Rather than testing the control algorithm on a purely mathematical model of the system, one can use real hardware (if available) in the simulation loop. For instance, actuators are notoriously difficult to model and, if available, can be included in the simulation loop to improve the validity of the simulation. Furthermore, the testing and the evaluation of the system are carried out in *real-time*. This ensures that the embedded control system can deliver the control input within the desired sampled period. This is important as the lack of control signal at the end of the sample period can affect stability.

Although hardware-in-the-loop simulation has been used for more than 40 years, there has been no attempt to formalize the approach to the subject. Most of the HWIL design is carried out in an ad hoc fashion specific to the particular application. This paper is the summary of a recent attempt on systematizing the field of hardware-in-the-loop simulation and focusing the research effort[1]. Section II gives a brief historical overview of the field. Section III gives a view on the difference between control system design and the design using hardware-in-the-loop simulation and introduces terms such as *transparency* and *robustness of prediction* in the context of hardware-in-the-loop simulation as means of quantify the simulation fidelity. Finally, Section IV suggests possible measures for *transparency* and *robustness of prediction*.

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II. BRIEF HISTORICAL OVERVIEW

One of the first uses of hardware-in-the-loop (HWIL) simulation was for flight simulation[2]. Hardware-in-the-loop simulation has found widespread use in testing missile guidance systems in the past 40 years[3-6]. The Sidewinder program was one of the first to use HWIL simulation back in 1972 [6]. Soon after, in parallel with missile simulations, NASA was working on the development of highly maneuverable aircraft technology (HiMAT) [7]. The purpose of the HiMAT program was to investigate the use of then advanced concepts such a reduced static stability and fly-by-wire. NASA developed a range of high-fidelity hardware-in-the-loop simulations to enable this research. More recently, within the past 20 years, hardware-in-the-loop simulation has gained popularity in automotive industry [2, 8-12]. There hardware-in-the-loop simulation is used for design of anti-lock braking systems (ABS), traction control systems (TCS), suspension systems and others. Other applications of hardware-in-the-loop simulation are mainly in the fields of power engineering and robotics. For detailed review and taxonomy please refer to [1].

III. HARDWARE-IN-THE-LOOP SIMULATION PROBLEM

Consider first how a typical control system is designed using computer simulation as shown in Figure 1. The system model consists of two components: first, a model of the physical plant, say a UAV; and second, the coupling to the environment, say aerodynamic lift and drag. The two components are normally coupled using a representation such as Bond Graphs, where energy flows are analyzed and, say, a model linearized about some operating point results. The model is subject to uncertainty arising from two sources. First, the physical plant is complex and cannot be modeled precisely. Second, the environmental coupling is uncertain and leads to an increase in uncertainty for the whole system model. The total linearized model might be referred to as $G(s)$, with an additive uncertainty $\Delta G(s)$. The control problem then becomes to design and validate a controller, given this model and its uncertainty. The result is a prediction of stimulus-response pairs, with statements about relative stability under given conditions, step responses, and other relevant properties.

Now consider the situation depicted in Figure 2. The real system is interacting with the local environment, but the actuators in the interface are used to make the system behave as though acting in the global environment.

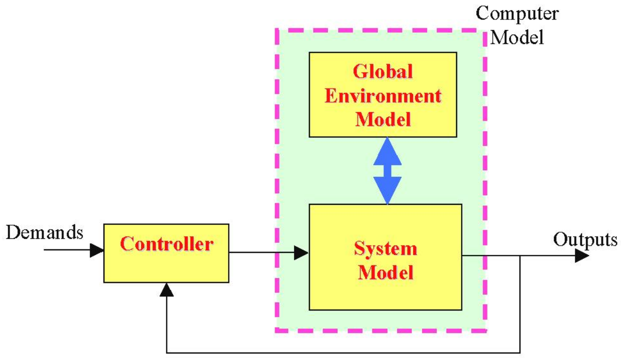

Figure 1 – Abstract model of control system design using computer simulation

As we have the real system, there is no uncertainty here. However, the real system is only coupled to a *local* environment – perhaps the airflow in a wind tunnel, or the accelerations of a flight table. The objective of *transparency* is to couple this local environment to a global environmental model by means of the *interface,* so that the simulation is as faithful as possible. A perfectly transparent hardware-in-the-loop simulation implies that the real system does not feel the difference between operation in the hardware-in-the-loop simulator and the operation in the real environment. To maximize transparency, a transparency controller must be designed. Such a controller must take into account a model of the local environment and the model of the real system. The control problem for HWIL simulation is *robustness of prediction*, not robustness of performance. Given an uncertain system model and an uncertain environment model, how does one design a transparency controller that minimizes the error in predicted response between the real system in its real environment and that within the HWIL simulator? For example, for bounded uncertainty in the model frequency response (the typical assumption underlying all robustness theory), what is the transparency controller that maximizes the *size* of the class of system controllers that are correctly predicted to be stable or unstable within the real system? Current available theory on design for robustness does not address this issue, it not even being clear how to define a measure over a class of controllers. Some of the issues of model uncertainty in HWIL simulation might be overcome by in-the-loop identification, using, say, self-tuning control. But there remains the important question of how to maximize the robustness of prediction.

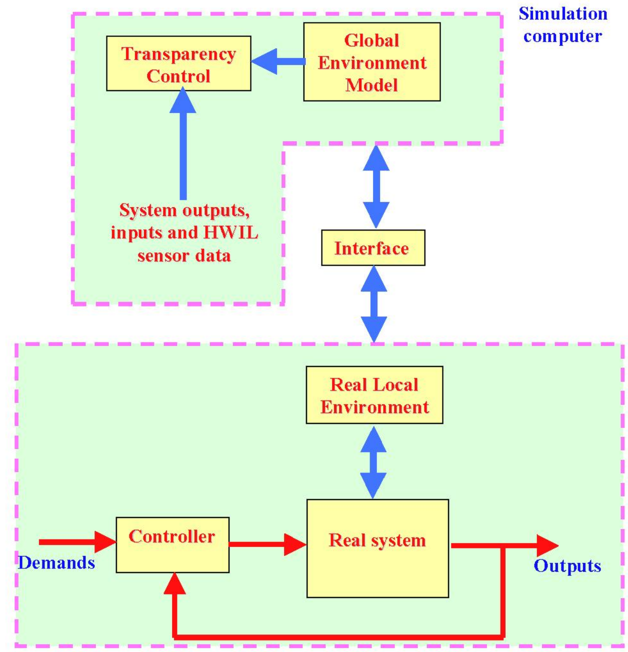

Figure 2 – Abstract view of a HWIL local environment simulator for controller design

IV. POSSIBLE MEASURES OF TRANSPARENCY AND ROBUSTNESS OF PREDICTION

A. Transparency of hardware-in-the-loop simulation

Transparency of the simulation is the measure of how well are the model and the simulation environment coupled. The coupling of the system and the simulation environment is governed by the boundary conditions imposed by the physical laws. Transparency of hardware-in-the-loop simulation can therefore be thought of as a measure of how well the boundary conditions are matched in the simulation environment.

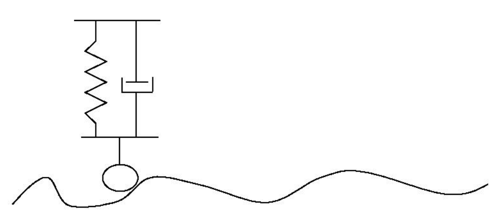

Figure 3. *Car suspension system on the road*

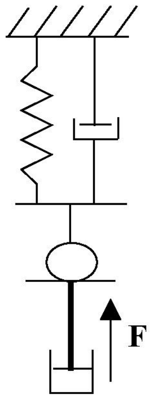

Figure 4. *Labscale simulation of the car suspension interaction with the road*

Consider a hardware-in-the-loop simulation in Figure 3 where we are asked to evaluate the performance of this simple mechanical design to a given road profile. Only the suspension system is present, whereas the rest of the car and the road are not. We use external actuators to exert the force **F** and torque **T** on the system in accordance with the road profile and known car dynamics. We wish to ensure that there is no difference between the response of the suspension system when on the road and its simulated response. The key is to match the boundary conditions between the system and the environment. The boundary conditions for the system in Figure 4 arise from the dynamics of the wheel - road surface contact and the dynamic response of the car to the changing conditions on the road. For simplicity and to a first approximation, assuming perfect contact with the surface, and no slipping the following boundary conditions would apply

$$\begin{aligned} F_{road} &= F_{tyre} \\ v_{road} &= v_{tyre} \end{aligned} \quad , \qquad (1)$$

where v_{road} is the rate of change of curve with respect to time. If the equation (1) holds, the suspension system "will not feel" the difference when interacting with the simulated environment. Dividing (1a) with (1b) leads to impedance matching condition $Z_{road}=Z_{tyre}$. The "feeling" prompts one to consider introducing teleoperation ideas in the world of hardware-in-the-loop simulation.

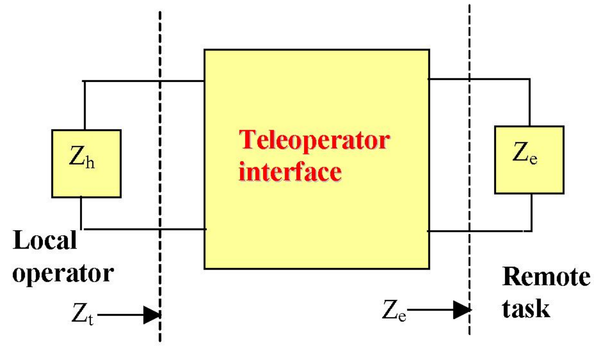

Figure 5 - *General two port model of the bilateral teleoperation system. A human operator is coupled via a teleoperator interface to a remote task as closely as possible.*

In teleoperation, ideal transparency implies that the task impedance as seen from the operator is matched to the actual task impedance as if the operator were performing the task ($Z_t=Z_e$). The remote task is real and so is the local operator. However the local operator is interacting with the remote task via a teleoperator interface that introduces extra dynamics. In practice therefore perfectly transparent teleoperation will not be possible. The issues regarding non-ideal transparency in teleoperation have been thoroughly examined in the research literature[13, 14].

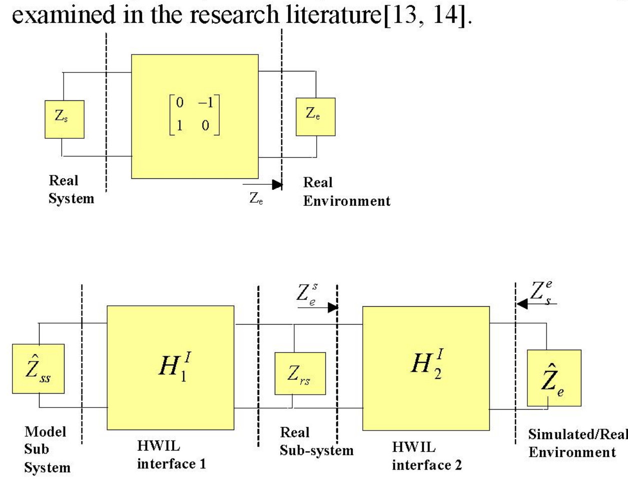

Figure 6 - *Two port network model of hardware-in-the-loop simulation.*

Unlike teleoperation, in the hardware-in-the-loop simulation some parts of the system and/or the environment are not real. A hardware-in-the-loop interface is used to couple numerical models of the non-real components of the system to the set of real components. In addition, the real components are coupled to the local environment (simulated or real) with additional interfaces. For ideal transparency we require that

$$Z_e^s = Z_e$$
$$Z_s^e = Z_s \tag{2}$$

where Z_e^s, Z_s^e are the impedances of the environment and the system as seen by the system and the environment respectively, and Z_e, Z_s are impedances of the real environment and the real system respectively. Equation (2a) implies that the impedance of the environment as seen by the system in the hardware-in-the-loop simulator is the same as if the whole system is real and in the real environment. Similarly, equation (2b) implies that the impedance of the simulated system as seen by the environment (simulated or real) in the HWIL simulation is equal to the impedance of the real system as seen by the real environment.

In practice, perfect transparency of hardware-in-the-loop simulation is unachievable due to:

1) Dynamics of hardware-in-the-loop interfaces
2) Uncertainty in modeling non-real parts of the system and their interaction with the environment

As the perfect transparency corresponds to perfect matching given by (2), a possible measure of non-ideal transparency of hardware-in-the-loop simulation can be established as:

$$\alpha = \left\| 1 - \frac{Z_e^s(j\omega)}{Z_e(j\omega)} \right\|_2 + \left\| 1 - \frac{Z_s^e(j\omega)}{Z_s(j\omega)} \right\|_2 \tag{3}$$

The problem of maximizing the transparency of a given hardware-in-the-loop simulation can therefore be viewed as optimization of the transparency performance index α:

$$\alpha_{opt} = \min_{H_1^I, H_I^2} \alpha \tag{4}$$

It is worth noting that different types of hardware-in-the-loop simulation will have different lower bounds on achievable α_{opt}

Now consider the problem of boundary matching as described in the simple example of the suspension system above. Consider a generate boundary – in the case of an aircraft this would be the boundary around the wing. It is assumed that the HWIL model provides a faithful reproduction of the interaction between the system and the environment at the level of a system partition around the boundary. This partition interacts with the environment to affect the general flow of air, it also interacts with the system to affect its rigid body dynamics. It is the effects on the rigid body dynamics that the 'transparency' controller must optimize. A norm, like one in (3), can be placed on the generalized impedance of the boundary, this in turn will induce a norm on the non-linear dynamics of the system. However, the type and magnitude of induced norm is highly system dependent and is the major challenge for the core theory of HWIL simulation.

B. Robustness of prediction

We have argued that the transparency of hardware-in-the-loop simulation is the primary measure of how realistic the simulation is. Ideal transparency implies ideal prediction of real system's performance in the real environment. Therefore transparency of the simulation can also be regarded as the measure of the quality of prediction. Consequently, the problem of robustness of prediction can be posed in terms of the robustness of transparency. Given a class of controllers $\{C\}$, and the set of modeling uncertainties $\Delta H_1^I, \Delta H_I^2, \Delta\hat{Z}_{ss}, \Delta\hat{Z}_e$, transparency controller should be designed to minimize α.

$$\alpha_{opt} = \min_{H_1^I, H_I^2} \max_{\{C\}} \alpha, \tag{4}$$

Note that the transparency index value α_{opt} obtained through (4) is the upper bound on α for the whole class of controllers. If the above measure can be coupled to an induced norm on the behavior under test, then we have a measure on the robustness of prediction.

V. Conclusions

The purpose of this paper was to highlight open research questions in hardware-in-the-loop simulation. The paper also suggested possible measures for *transparency* and *robustness of prediction* of the hardware-in-the-loop simulation as means of comparing the simulation fidelity of different hardware-in-the-loop simulations.

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