Determining the Fidelity of Hardware-In-the-Loop Simulation Coupling Systems

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ABSTRACT

Hardware-in-the-Loop (HIL) simulation is a widely used concept for design, rapid prototyping, test and optimization of complex systems. The paper attempts to present a formal approach of determining the fidelity of HIL simulation coupling systems. This approach can help to design and optimize such systems.

Keywords

HIL, Simulation, Modelling, Simulation Tools

1. INTRODUCTION

In a HIL simulation, one part of a real system or the system environment is replaced by a numerical model and interfaced to the remaining hardware via sensors and actuators. The term HIL simulation is often used to describe the interfacing of a real controller to its environment (the plant). This is called a plant simulation ([7]). Within a plant simulation the mathematical model of the control object, called plant, is running on a general purpose computer. The controller is connected e.g. via a data acquisition (DAQ) board. A typical example of HIL simulation is a connection between a complete electronic control unit (ECU) and a simulated car environment (plant model). [8],[3], and [6] are typical examples for this application. The controller behavior simulation inverts the situation. The prototype of a control program runs on a general purpose computer which is connected to a real plant e.g. through a DAQ board. Special simulation computers are sometimes used instead of general purpose computers to run the simulation.

HIL simulation can be also used to replace a component of a plant simulation by the real part, if it is too difficult to model. Formal approaches for the description of HIL systems, especially the coupling system between real system and simulation, are seldom. Many HIL simulators are designed straightforward without deeper analysis of different setups. This paper presents a formal approach to study coupling systems for HIL simulators.

The paper is organized as follows: The next section presents related works to this topic. Section 3 formulates the preliminaries of the approach. Section 4 introduces the fidelity definitions for HIL coupling systems, while section 5 deals with the consequences and the appliance of the given formalism. Application examples are presented in section 6. The conclusion can be found in section 7.

2. RELATED WORKS

The attempt to formulate the problem of the theoretical accuracy of HIL simulations can be found in [1] , [2] and [5]. The authors M. MacDiarmid and M. Bacic wrote in [5] that the “quantification of the accuracy of HWIL simulators presents unique challenges, and remains an open research problem”. The complete system, HIL simulator and real system, is included within the contemplation of the mentioned papers. The authors model the coupled system as two-port network. Especially digital systems and control hardware systems are excluded from the approach.

Our attempt is to formulate the problem for general HIL systems, including the coupling system of an ECU-HIL simulation and similar solutions, like the Chip-Hardware-in-the-Loop Simulation (CHILS) approach we presented in [4]. We focus on the HIL simulation coupling system itself, without modelling the hardware and/or the simulation part.

3. PRELIMINARIES

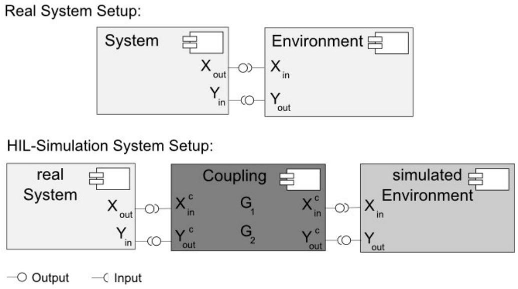

Figure 1: HIL System

The starting point is given by the complete system within its original environment (upper part of figure 1). The system output is the vectorial variable X_{out} corresponding to the vectorial variable X_{in}. The system input is the vectorial variable Y_{out} corresponding to the vectorial variable Y_{in}.

$$\begin{aligned} X_{in} &= X_{out} \\ Y_{in} &= Y_{out} \end{aligned} \tag{1}$$

In the HIL simulation the system remains the same, while the environment will be simulated. The coupling system has the same input and output types as the real system and its environment. The coupling system, as a signal processing system, will transform the output of the real system and the output of the simulated environment. The transformation functions are $G_1(t)$ and $G_2(t)$.

$$\begin{aligned} X_{in}(t) &= G_1(t) * X_{out}(t) \\ Y_{in}(t) &= G_2(t) * Y_{out}(t) \end{aligned} \tag{2}$$

The transformation can be reformulated as follows.

$$\begin{pmatrix} X_{in}(t) \\ Y_{in}(t) \end{pmatrix} = \begin{bmatrix} G_1(t) & 0 \\ 0 & G_2(t)) \end{bmatrix} * \begin{pmatrix} X_{out}(t) \\ Y_{out}(t) \end{pmatrix} \tag{3}$$

An ideal coupling system will not change the transmitted signal, so the hardware "in-the-loop" feels no difference to a connection with the real environment. The term transparency can be used for this purpose ([1]). A design goal of the coupling system would be to design the system as transparent as possible. That means that the transformation functions $G_1(t)$ and $G_2(t)$ are nearly 1 (equation 4).

$$\begin{bmatrix} G_1(t) & 0 \\ 0 & G_2(t) \end{bmatrix} \approx \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{4}$$

The question is how to measure the transparency of the coupling system?

4. TRANSPARENCY AND FIDELITY DEFINITION

The basis of measuring the transparency of the coupling system is a model of the coupling system. Unlike the approach in [1] and [2], it is not necessary to model the real system or its environment. It is feasible to model only the coupling system.

ASSUMPTION 1. *The coupling is assumed to be representable as a lineare time invariant system (LTI system). This is a general approximation that is often used because non-linear system are hard to model. Most of the non-linear systems can be approximated with linear models within their normal working range. Real world system are mostly non-linear.*

For the next steps, we will use the transfer function within the frequency domain. The advantage is that the transfer function directly shows the relation of input and output signal.

DEFINITION 2. *A LTI system can be described by the convolution of the input signal with the impulse response* $y(t) = g(t) * x(t)$.

Assuming that $x(t)$ is the input signal and $y(t)$ is the output signal of a single input/single output system (SISO system). In the frequency domain, the corresponding Laplace transformed signals are $x(s) = \mathfrak{L}\{x(t)\}$ and $y(s) = \mathfrak{L}\{y(t)\}$.

DEFINITION 3. *The transfer function is defined as*

$$y(s) = h(s)x(s) \quad \textit{and so} \quad h(s) = \frac{y(s)}{x(s)} \tag{5}$$

$y(s)$ and $x(s)$ are polynomials of degree m (w.l.o.g. $x(s)$ and $y(s)$ have the same degree).

$$h(s) = \frac{y(s)}{x(s)} = \frac{b_0 + b_1 s^1 + \cdots + b_m s^m}{a_0 + a_1 s^1 + \cdots + a_m s^m} \tag{6}$$

LEMMA 4. *In a complete transparent system, the input has to be identical with the output, so* $y(s) = x(s)$. *The transparency of a signal transformation system can be now defined by the difference of the two polynomials* $y(s)$ *and* $x(s)$ *of the transfer function* $h(s)$.

For the calculation of the transparency, we will first define a $m+1$-dimensional space $\prod^{m}$ over polynomials $\sum_{i=0}^{m} a_i k^i$. The power i stands for the space axis while the coefficients a_i are the values in each dimension i.

Lemma 5. *The difference between two polynomials $y(s)$ and $x(s)$ can be defined as the distance of the polynomials within the $m+1$-dimensional space $\prod^{m}$ over polynomials of the grad m.*

Definition 6. *A weighted distance $d_w(x(s), y(s))$ with $x(s) = a_0 + \cdots + a_m s^m$ and $y(s) = b_0 + \cdots + b_m s^m$ is defined as*

$$d_w(x(s), y(s)) = \left| \begin{pmatrix} a_0 \\ \vdots \\ a_m \end{pmatrix} - \begin{pmatrix} b_0 \\ \vdots \\ b_m \end{pmatrix} \right|_w \tag{7}$$

with the weighted norm

$$|\dots|_w = \sqrt{w_0(a_0 - b_0)^2 + \cdots + w_m(a_m - b_m)^2} \tag{8}$$

.

The weights $w_i \geq 1$ are used to satisfy the influence of the different polynomial exponents on the whole polynomial difference.
For the examples in section 6 $w_i = \sum_{j=0}^{i} i + 1$ is chosen.

The transparency is now defined for SISO systems. Most of the transfer systems are multiple input/multiple output (MIMO) systems (figure 2).

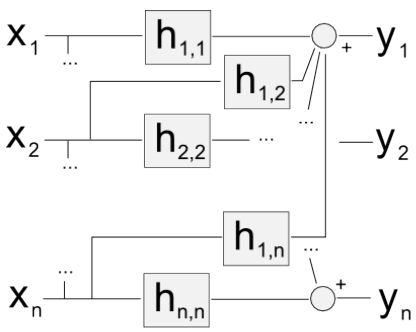

Figure 2: MIMO system

Definition 7. *MIMO systems can be described by a matrix of SISO transfer functions*

$$H(s) = \begin{bmatrix} h_{1,1}(s) & \cdots & h_{n,1}(s) \\ \vdots & \ddots & \vdots \\ h_{1,n}(s) & \cdots & h_{n,n}(s) \end{bmatrix} \tag{9}$$

with

$$Y(s) = \begin{pmatrix} y_0(s) \\ \vdots \\ y_n(s) \end{pmatrix} \tag{10}$$

and

$$X(s) = \begin{pmatrix} x_0(s) \\ \vdots \\ x_n(s) \end{pmatrix} \tag{11}$$

so

$$Y(s) = H(s)X(s) \tag{12}$$

.

Remark The transfer matrix is square because the vectors $X(s)$ and $Y(s)$ have the same size.

The main diagonal elements represent the direct transfer functions between each input x_i and each output y_i. The other elements are couplings between different inputs and outputs (x_i and y_j with $i \neq j$).

Definition 8. *The ideal transfer function matrix has a main diagonal containing ones. The other matrix elements are zero.*

$$\begin{pmatrix} y_1(s) \\ \vdots \\ y_n(s) \end{pmatrix} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & \ddots & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix} \begin{pmatrix} x_1(s) \\ \vdots \\ x_n(s) \end{pmatrix} \tag{13}$$

This means, that no influences between different inputs and outputs exist, while the direct connection between each input and each output does not change the signal ($\frac{y(s)}{x(s)} = 1$).

Definition 9. *A norm $\|h(s)\|_p$ over a polynomial quotient $h(s) = \frac{y(s)}{x(s)}$ can be defined over the distance of $x(s)$ and $y(s)$ in $\prod^{m}$.*

$$\left\| \frac{y(s)}{x(s)} \right\|_p = d_w(x(s), y(s)) \tag{14}$$

This norm can be used as a measure for the transparency.
Remark If $x(s)$ and $y(s)$ are identical the distance is zero, so the system is fully transparent and the transfer function does not change the input signal. In all other cases the distance is larger than zero.

DEFINITION 10. *Additional, the difference between the upper polynomial $y(s)$ and a zero polynomial can be defined as norm $\left\| \frac{y(s)}{x(s)} \right\|_p^0$ over the distance of $y(s)$ and 0 in $\prod^m$.*

$$\left\| \frac{y(s)}{x(s)} \right\|_p^0 = d_w(0, y(s)) \tag{15}$$

DEFINITION 11. *A matrix of transparency can be defined as follows. The main diagonal contains the elements $\|h_{i,i}(s)\|_p$ with $1 \leq i \leq n$, while the other positions are filled with elements $\|h_{i,j}(s)\|_p^0$ with $1 \leq i \leq n$, $1 \leq j \leq n$, $i \neq j$.*

$$\begin{bmatrix} \|h_{1,1}(s)\|_p & & \|h_{j,i}(s)\|_p^0 \\ & \ddots & \\ \|h_{i,j}(s)\|_p^0 & & \|h_{n,n}(s)\|_p \end{bmatrix} \tag{16}$$

An ideal transparency matrix is completely zero.

$$\begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 0 \end{bmatrix} \tag{17}$$

DEFINITION 12. *With a matrix norm we can now define a transparency function $\mathfrak{tr}$ for a MIMO system transfer matrix. The Euclidean norm is chosen in the example in section 6.*

$$\mathfrak{tr}(H(s)) = \left\| \begin{bmatrix} \|h_{1,1}(s)\|_p & & \|h_{j,i}(s)\|_p^0 \\ & \ddots & \\ \|h_{i,j}(s)\|_p^0 & & \|h_{n,n}(s)\|_p \end{bmatrix} \right\| \tag{18}$$

DEFINITION 13. *The fidelity function $\mathfrak{fd}$ of a coupling system can be now defined by the transparency of the transfer function. The value of the fidelity ranges between zero and one.*

$$\mathfrak{fd}(H(s)) = \frac{1}{1 + \mathfrak{tr}(H(s))} \tag{19}$$

The transformation performed by the coupling system (equation 3) is defined as follows.

$$\begin{pmatrix} X_{in}(t) \\ Y_{in}(t) \end{pmatrix} = \begin{bmatrix} G_1(t) & 0 \\ 0 & G_2(t)) \end{bmatrix} * \begin{pmatrix} X_{out}(t) \\ Y_{out}(t) \end{pmatrix} \tag{20}$$

DEFINITION 14. *For better visibility, a symbolic transformation ($\star$) of the input signals can be now defined as multiplication with the fidelity matrix.*

$$\begin{pmatrix} X_{in}(t) \\ Y_{in}(t) \end{pmatrix} = \begin{bmatrix} \mathfrak{fd}(\mathfrak{L}\{G_1(t)\}) & 0 \\ 0 & \mathfrak{fd}(\mathfrak{L}\{G_2(t)\}) \end{bmatrix} \star \begin{pmatrix} X_{out}(t) \\ Y_{out}(t) \end{pmatrix} \tag{21}$$

This can be interpreted as the proportionate information loss of the original input signal caused by the transformation. The fidelity will be one, if the signal is not changed, so nothing is "lost".

An ideal symbolic transformation matrix is now

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{22}$$

.

Remark The system is now defined as a continuous version. The same definitions can be made with a discrete system model (the Laplace transformation will be replaced by the Z-transformation). In real coupling systems, a discrete part often exists, e.g. if the input/output values are exchanged via digital connection.

5. CONSEQUENCES

The fidelity function $\mathfrak{fd}(H(s))$ is an instrument to compare different HIL coupling solutions. Three steps are necessary to use the approach.

- First: model the different coupling systems
- Second: calculate $\mathfrak{fd}(H(s))$ for each system
- Third: compare the symbolic transformation matrixes using a matrix norm

It is also possible to find optimal parameters for a parameterized coupling system by starting an optimization process over the transparency function $\mathfrak{tr}(H(s))$ and the symbolic transformation matrix. The optimization problem can be defined as $min_p(H_p(s))$. p is a set of parameters of the transfer function $H_p(s)$.

6. EXAMPLE

A heat-sensor-HIL simulation is taken as example for a continuous coupling system. To build a heat-sensor-HIL simulation a heating element is needed to transform the simulated heat into real heat for the sensor.

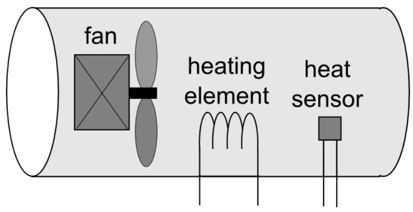

Figure 3: Heat-Sensor-in-the-Loop

Definition 15. *The heating element can be described by the following transfer function.*

$$H_h(s) = K * \frac{1}{1+Ts} \tag{23}$$

The proportional coefficient K and the time constant T are depending on environmental variables like the specific heat capacity, density and velocity of the transfer medium and the heating element.

$$K = \frac{1}{c_m \gamma_m A v}$$
$$T = \frac{c_h}{c_m \gamma_m A v}$$
with

c_m - heat capacity of the medium (air $c_m = 1.01\frac{Ws}{gK}$)

c_h - heat capacity of the heating element (steal $c_h = 0.477\frac{Ws}{gK}$)

γ_m - density of the medium (air $c_m = 1293\frac{g}{m^3}$)

v - velocity of the medium

A - cross section surface of the pipe where sensor and heating element are located

l - distance between heating element and sensor

Heat sensor and heating element are positioned in the distance l from each other. This causes the delay $D = \frac{l}{v}$ in heat transportation. It is assumed that the heat control system corrects the proportional coefficient by adding the correction coefficient $C = \frac{1}{K}$.

The transfer function of the complete coupling system is now.

$$H_h(s) = C * K * \frac{e^{-Ds}}{1+Ts} \tag{24}$$

e^{-Ds} can be approximated by the Fourier series $e^{Ds} = 1 + sD + \frac{s^2D^2}{2!} + \ldots$.

The fidelity function of the system is now calculated assuming an air velocity of $v = 1m/s$, a sensor distance of $l = 0.1m$ and a pipe cross section surface of $A = 0.1m^2$. The calculation (equation 25) is done without units. The result is a system fidelity of $\mathfrak{fd}(H_h(s)) = 0.847$ (the best fidelity would be one).

$$\begin{aligned}
T &= \frac{0.477}{1.01 * 1293 * 0.1 * 1} \\
T &= 0.00365 \\
D &= 0.1/1 \\
e^{0.1s} &= 1 + 0.1s + 0.005s^2 \\
H_h(s) &= \frac{1}{(1+0.1s+0.005s^2)*(1+0.00365s)} \\
H_h(s) &= \frac{1}{1+0.10365s+0.00537s^2+0,00002s^3} \\
\mathfrak{tr}(H_h(s)) &= \left\| \left[\left[\begin{pmatrix} 1 \\ 0.10365 \\ 0.00537 \\ 0,00002 \end{pmatrix} - \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \right|_w \right] \right\| \\
\mathfrak{fd}(H_h(s)) &= \frac{1}{1+\mathfrak{tr}(H_h(s))} \\
\mathfrak{fd}(H_h(s)) &= \underline{\underline{0.847}}
\end{aligned} \tag{25}$$

Increasing the air velocity to $v = 10m/s$ leads to better results of the fidelity function $\mathfrak{fd}(H_h(s)) = 0.982$. Figure 4 shows that the heating systems with increased air velocity follows the control input even better than the other system.

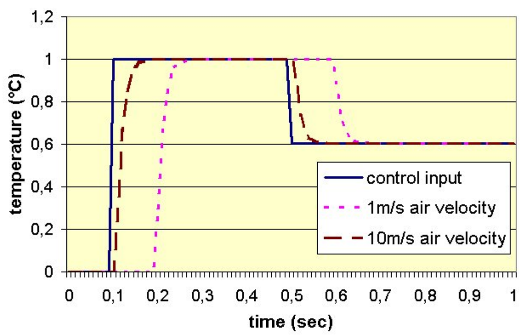

Figure 4: Heating system - different air velocities

It is obvious that the higher air velocity leads to a faster heat transport to the heat-sensor-in-the-loop, but it is not obvious what happens if the material of the heating system itself is changed. The steal heating element in the original system is replaced by a copper heating element and an aluminum heating element. The heat capacity of copper is $c_h = 0.381\frac{Ws}{gK}$ while the heat capacity of aluminum is $c_h = 0.896\frac{Ws}{gK}$. Without a system model it is hard to decide which one is the better material. The fidelity function of the system is calculated assuming the original settings with an air velocity of $v = 1m/s$ and pipe cross section surface of $A = 0.1m^2$. The resulting system fidelity is $\mathfrak{fd}(H_h(s)) = 0.848$ for the copper based system and $\mathfrak{fd}(H_h(s)) = 0.843$ for the aluminum based system. The copper heating element produces a higher system fidelity than the steal heating element and the aluminum heating element, but the delay in heat transportation is even more important for the fidelity. The three materials are leading to nearly the same results (figure 5). The fidelity value reflects this behavior in a very good way.

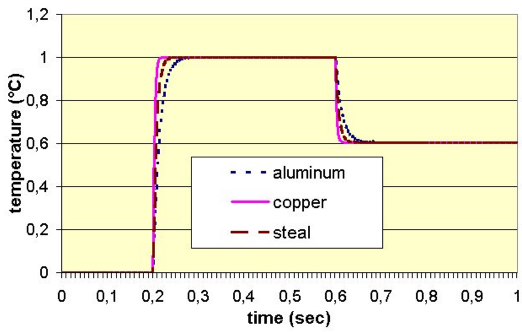

Figure 5: Heating system - different materials

7. CONCLUSION

We presented an attempt to calculate the fidelity of HIL simulation coupling system in a formal way. The calculation is based on the transfer function in the frequency domain of the coupling system. SISO and MIMO systems are covered by this approach. The approach can be used to compare different HIL simulation coupling systems. An optimization process, regarding the simulated coupling systems, can be executed to find the best possible system configuration. This process is based on the presented fidelity value.

8. REFERENCES

[1] M. Bacic. On hardware-in-the-loop simulation. In *Proc. 2005 44th European Control Conference Decision and Control CDC-ECC*, pages 3194–3198, 2005.

[2] M. Bacic. Two-port network modelling for hardware-in-the-loop simulators. In *Proc. American Control Conference ACC '07* [1], pages 3029–3034. no review.

[3] C. Gühmann. Model-based testing of automotive electronic control units. 2005.

[4] C. Koehler, A. Mayer, and A. Herkersdorf. Chip hardware-in-the-loop simulation (chils) - embedding microcontroller hardware in simulation. pages 297–302. IASTED, May 2008.

[5] M. MacDiarmid and M. Bacic. Quantifying the accuracy of hardware-in-the-loop simulations. In M. Bacic, editor, *Proc. American Control Conference ACC '07*, pages 5147–5152, 2007.

[6] M. Plöger, H. Schütte, and F. Ferrara. Automatisierter hil-test im entwicklungsprozess vernetzter, automotiver elektroniksysteme. *AUTOREG (VDI/VDE)*, 2004.

[7] D. Virzonis, T. Jukna, and D. Ramunas. Design of the embedded software using flexible hardware-in-the-loop simulation scheme. *IEEE MELECON 2004*, pages 351–355, May 2004.

[8] P. Waeltermann, T. Michalsky, and J. Held. Hardware-in-the-loop testing in racing applications. *SAE Motor Sports Engineering Conference & Exhibition*, January 2004.