Implementation of Hardware-in-the-loop Simulation (HILS) Method for Control Engineering Education

Wahyudi Martono[*], Riza Muhida

Department of Mechatronics Engineering, Faculty of Engineering
International Islamic Universiti Malaysia, 53100, Selangor Darul Ehsan, MALAYSIA.

Abstract

This paper discusses the development of control systems with hardware-in-the-loop simulation (HILS) method for enhancing the teaching of control engineering. Two control systems based on the HILS approach were developed namely simulated plant HILS (SP-HILS) and simulated controller HILS (SC-HILS) control systems. The SP-HILS control system uses an actual hardware of the controller and the plant is simulated in the computer based on its dynamic model. On the other hand, in the SC-HILS control system, the real/actual plant is used but the controller is simulated on the computer. In general these proposed systems consist of both hardware and software. The software tools of MATLAB/Simulink/xPC Target by MathWorks, Inc and a C++ compiler are used to simulate the physical system (plant) to be controlled and used to simulate the controller in the SP-HILS and SC-HILS systems respectively. The hardware of the SP-HILS includes a microcontroller as a controller and interfacing circuits to allow communication between the simulated plant and the real controller, while the SC-HILS uses a lab-scale gantry crane including its sensors for feedback. The proposed systems are inexpensive and allow students to carry out extensive experimental investigation as well as the design, implementation, performance evaluation and comparative studies of controllers. A case study of the controller design and implementation for an active suspension system in the SP-HILS and PID controller design and implementation for automatic gantry crane in the SC-HILS are presented to illustrate the application of the proposed systems.

Keywords: Control, engineering, education, hardware-in-the-loop simulation, active suspension, gantry crane

1. Introduction

Students taking control systems, for the first time, often find this subject too abstract and theoretical in nature, that is too many mathematical equations as well as block diagrams. It is well-known that the control laboratory experiment is an important way of exposing students to the practical applications of control theory so as to overcome the above-mentioned difficulty. Hence real hands-on experiments or design problems are an alternative way to augment the conventional way of teaching control theory as they can be related to real engineering applications starting from modeling, controller design, and finally, implementation [1,2].

A typical laboratory for control education needs three main pieces of equipment: analysis and simulation software, a target controller and an experimental setup.

The software may include controller design/analysis tools, real-time code generators and a compiler. Moreover, the target hardware for controller implementation may be based on a digital signal processor (DSP) or other low-cost alternatives such as PC-based controllers or microcontrollers, while the experimental setup is the hardware for capturing the real-life of industrial control systems. However, to achieve this requires complex installation and/or machinery, which are both costly and inflexible as well as in some cases potentially dangerous to students. On the other hand, the use of simulation only will not provide an illustration of the real physical application of using the control theory in solving engineering problems.

The above shortcomings and problems can be overcome by adopting the concept of the hardware-in-the-loop simulation (HILS) method [3,4] as an experimental part of control engineering and it has been

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[*] *Corresponding author. Tel.: +603-6196-4469; Fax: +603-6196-4433; Email:wahyudi@iiu.edu.my*

developed at the Department of Mechatronics Engineering, International Islamic University Malaysia. First, the simulated plant HILS (SP-HILS) method is developed. The SP-HILS uses a simulation model of the controlled-object (plant) and a microcontroller as the real target hardware for controller implementation. Instead of using a costly experimental setup, the simulation model in a computer accepts control signal from the microcontroller as well provides all the plant signals in real time which are needed as feedback. By using the SP-HILS system, students would learn how to design a controller and then implement it physically using a microcontroller. Furthermore, the SP-HILS system allows students to use different controlled-objects such as the active suspension system, DC motor control system, temperature control system and gantry crane system as well as selecting the controller such as the phase lag/lead compensator, lag-lead compensator, state feedback controller and fuzzy logic controller without any additional cost. In order to improve the level of illustration in control implementation, the second HILS system is developed namely a simulated controller HILS (SC-HILS) system. Here the SC-HILS approach is use to simulate the controller while the plant is a real plant which is a lab-scale gantry crane.

The paper is organized as follows. In the first section the concept of the hardware-in-the-loop system is explained. Next, the proposed control systems with HILS method are described. Finally, application of the proposed systems to realize a process of modeling, controller design and implementation of active suspension system is discussed.

2. Concept of hardware-in-the-loop simulation

Laboratory sessions are usually included in the control system course to offer the students an environment for a complete design of control systems starting from desired performance specification, plant modeling, controller design, controller implementation and performance analysis and controller re-design, if necessary. The lab sessions attempt to reflect the real industrial applications of the control system. This classical control experiment requires direct connection with the plant as shown in Figure 1. A real plant or its laboratory model delivers physically control output and generates the plant response (output) measured by the sensor. Various plants have been used in the control laboratory such as the inverted pendulum, helicopter model, magnetic bearing and simple robots [5]. However, more complex models of industrial plants are too expensive for control education and in some cases, they are potentially dangerous for the students. In addition, the classical

control experiment often lacks flexibility. Furthermore, it would be costly and consume plenty of time if the lecturer wants to conduct experiments with different plants especially as the lab work is expected to be completed within stipulated time.
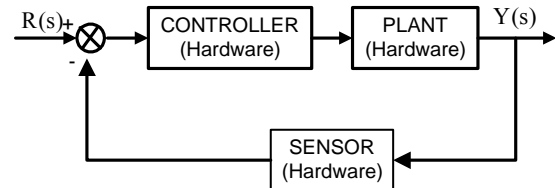

Figure 1. Classical Control Experiment

(a) Simulated Controller HILS

(b) Simulated Plant HILS
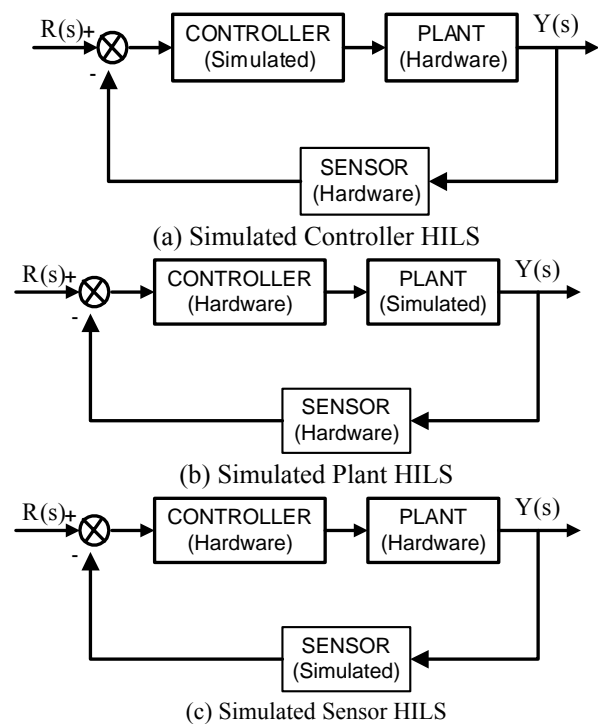

(c) Simulated Sensor HILS

Figure 2. Configuration of HILS Environment

The problem of cost and experimental flexibility can be overcome by adopting the concept of hardware-in-the-loop simulation (HILS). The basic principle of the HILS is that a certain part of the real system (hardware) is replaced by a real-time simulation model. There are many possibilities of replacing the real system (hardware) of a control system by the simulated model for different applications [6] as shown in Figure 2. This figure shows that the simulated model can be used to replace controller hardware, real plant or sensor. HILS based on the real plant replacement is one of the suitable methods for dealing with the problems that arise in many control experiments. The HILS method offers several advantages compared with the classical control experiment. Control system experiments based on the HILS method become less expensive and more flexible.

The plant in the HILS method can be changed easily and timely since one just changes the transfer function of the plant.

3. Development of HILS-based control system

3.1 Simulated plant HILS (SP-HILS) system

The proposed SP-HILS control system is shown in Figure 3 and its schematic representation is depicted in Figure 4. As shown in both diagrams, the proposed system consists of a microcontroller, two personal computers and interfacing circuits. The real system (hardware) of this system is a controller which is implemented using a microcontroller while the controlled-object is replaced by a real-time simulation model which is located in the Target Computer. Another computer, which is called the Host Computer, is needed for generating both the simulation model and microcontroller code development. This arrangement is carried out since the main purpose of the development of the proposed system is to demonstrate to students the real time implementation of the controller design as well as to evaluate its performance.
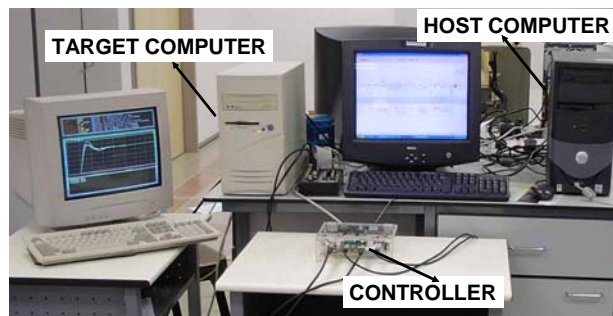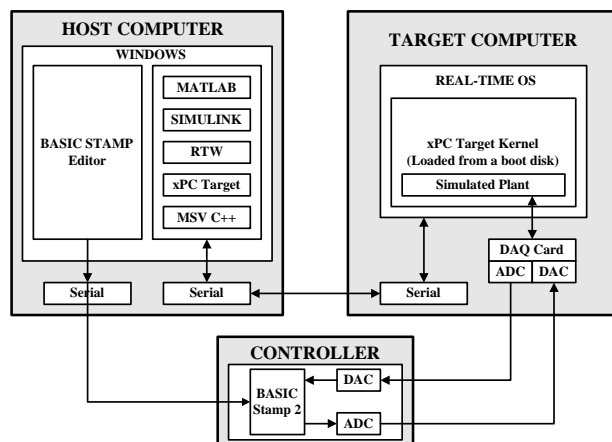
The hardware parts of the proposed systems are a microcontroller and interfacing circuits as shown in Figure 5. The microcontroller used for controller implementation is the BASIC Stamp 2 (BS2) from Parallax Inc due to its availability in the Mechatronics Engineering Department and simplicity in programming. The other hardware parts are interfacing circuits which are used to transfer and convert the signals from/to simulated plant in the Target Computer to/from the controller in the microcontroller. Two ADCs and DACs are required for realizing the proposed system. A unit of the ADC and DAC is built in the data acquisition (DAQ) card of PCI-6024-E from National Instrument [8]. This DAQ card is installed in the Target Computer to receive the control output from the microcontroller and to send the simulated actual plant output to the microcontroller. The other ADC and DAC cards are directly connected to the microcontroller as shown in Figure 5. The ADC connected directly to the microcontroller, is built using 12 bits LTC1298 ADC chip manufactured by Linear Technology. Meanwhile, the DAC circuit connected directly to the microcontroller and used to send the control output to the simulated plant, its design is based on the R-2R ladder network DAC.
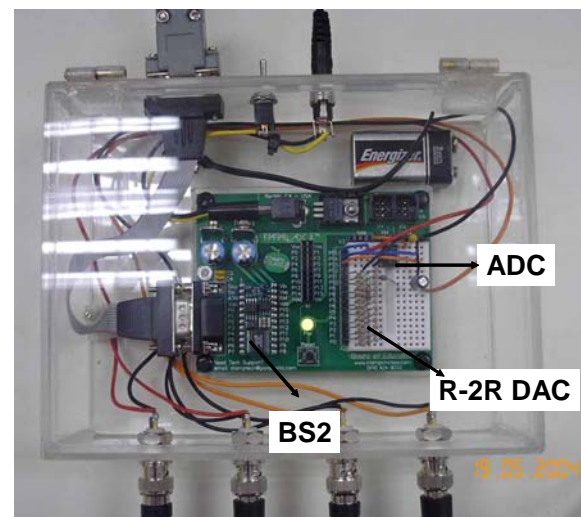

Figure 3. SP-HILS Control system

Figure 4. SP-HILS Architecture

Figure 5. Controller Hardware Part of SP-HILS

3.2 Simulated controller HILS (SC-HILS) system

Figure 6 shows the SC-HILS environment of the developed automatic gantry crane system. The SC-HILS environment shown in Figure 6 consists of the lab-scale gantry crane, two computers and interfacing circuit. The actual hardware part is the lab-scale gantry crane including sensors and actuator while the mathematical model part is the controllers (PID controllers or other controller strategies) which are located in the Target PC. Another computer called as Host PC is needed for generating the controller algorithms. This arrangement is

done since the main purpose of the prototyping phase is to evaluate the controller performances in the real plant namely a lab-scale gantry crane. In order to interface between controllers located in the TC and the lab-scale gantry crane, an analog-to-digital/digital-to-analog PCI-6024-E from National Instrument is used.
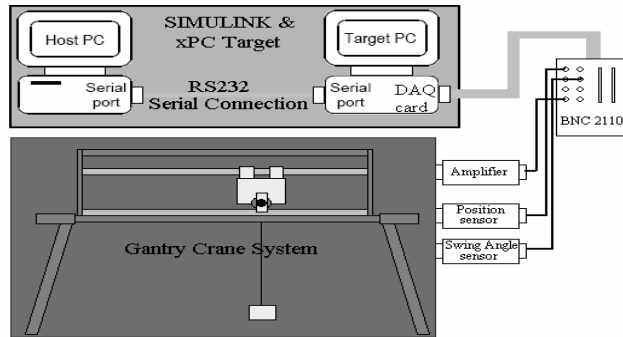

Figure 6. SC-HILS Control System

3.3 Real time implementation software

Both of the SP-HILS and SC-HILS systems have to work in real time. To do so, the MathWork's MATLAB/Simulink/RTW/xPC Target tool is adopted. In the SP-HILS, MATLAB/Simulink is used for realizing the simulated plant based on its dynamics model, while in SC-HILS, it is used not only for designing the PID controllers but also for simulating the controllers. In addition, the RTW environment provides a real-time operation using personal computers and multifunction I/O boards. However, the use of RTW still requires the development of custom interface programs for correct communication with multifunction I/O boards. To overcome this problem, xPC Target is included in the software configuration.

By combining RTW and xPC Target, there is no need to write a low level programming language for realizing a controller and/or accessing other components such as DAQ boards. The PID controllers are developed in Simulink using its blocks, and then it is built so that C code is generated, compiled and finally a real-time executable code is generated and downloaded to the Target PC. In particular, the xPC Target software supports and provides built-in drivers for many industry standard DAQ card [7] including the PCI-6024E DAQ card by National Instrument which is used in the prototype of the automatic gantry crane system. This combination of devices provides a unique and complete HILS environment for rapid prototyping, testing.

4. Results

4.1 Active suspension system with the SP-HILS

In order for students to gain experience in controller design and implementation, an active suspension system is selected as a case study and it is discussed here. The active suspension system is selected because the automotive industry is seriously considering implementation of active suspension systems on automobiles [12]. The suspension system refers to the use of front and rear springs and damper to suspend a vehicles frame, body, engine and power train above the wheels. The main functions of the suspension system are to support the vehicle weight, to isolate the vehicle body from road disturbances, and to maintain the traction force between the tyres and the road surface. Moreover, the suspension system provides the necessary comfortable and safety drive passengers and the driver.

Recently, most vehicles have used a passive suspension system. In passive suspension design, comfort and road handling are difficult to achieve because the design parameters are fixed. Therefore, the performance of the passive suspension is only good under limited conditions. To overcome the problems of the passive suspension system, an active suspension system has been introduced [13]. The goal of the active suspension is to improve comfort and road handling. Comfort and safety improvement using the active suspension systems require a careful control mechanism of the suspension system so that its parameters can adapt to the driving conditions.
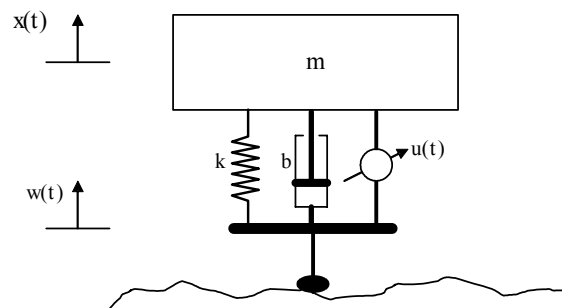

Figure 7. Quarter suspension system and its simple model

Figure 7 shows the simple schematic diagram of a quarter model of the suspension system. In this model, three assumptions are made, i.e. unsprung mass (tyre mass) is negligible compared with sprung mass, the tyre is rigid and a hydraulic actuator is used. Applying Newton's second law, a quarter car model is expressed as

$$m\ddot{x}(t) + b\dot{x}(t) + kx(t) = b\dot{w}(t) + kw(t) + u(t) \quad (1)$$

where

m   : mass of a quarter car body (sprung mass)
k   : spring constant of suspension system

b   : damping constant of suspension system.
u(t) : hydraulic actuator force output
x(t) : sprung mass displacement.
w(t) : road profile displacement.

The actuator force u(t) is simply modeled as directly proportional to the output voltage v(t), that is u(t) = cv(t), where c represents the actuator gain. Hence Equation (1) becomes

$$m\ddot{x}(t) + b\dot{x}(t) + kx(t) = b\dot{w}(t) + kw(t) + cv(t) \quad (2)$$

Taking the Laplace of Equation (2) yields

$$X(s) = \frac{bs+k}{ms^2 + bs + k_1} W(s) + \frac{c}{ms^2 + bs + k_1} V(s) \quad (3)$$

A proportional plus derivative (PD) controller is adopted to control the active suspension system so that

$$V(s) = (K_P + K_D s)E(s) \quad (4)$$

where K_p and K_d are proportional and derivative gains respectively. The PD controller is mainly designed to reject disturbance input due to road profile displacement w(t). The root locus technique [16] which has been discussed previously in the class is used for designing the PD controller. As an example, students are required to design the PD controller to achieve the following criteria:

- Settling time of the closed-loop system is less then 1 second
- Maximum percent overshoot is less than 10 %.

Finally, based on the root locus method, the PD controller parameters K_P and K_D are 1 and 500 respectively.
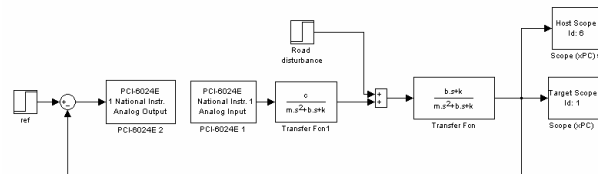

Figure 8. Simulink Model of SP-HILS Active Suspension System

The Simulink block diagram implemented for the HILS-based active suspension system is shown in Figure 8. The Simulink block diagram is used to build the simulated model of the suspension and then downloaded to the Target Computer using xPC Target toolbox. Furthermore, it is necessary to download the designed PD controller to the BASIC Stamp 2 microcontroller. A PBASIC language program is written in the STAMP Editor Environment to implement the PD controller algorithm and then downloaded to the BASIC Stamp 2 microcontroller through serial communication between the Host Computer and the microcontroller. Once the simulated plant and PD controller are on the respective target, some experiments are performed in real time. Parameter changes may be performed from the Simulink

and their effects on the HILS-based active suspension system can be monitored directly.

Furthermore, the performance of the active suspension system controlled by the PD controller is evaluated through the developed HILS-based active suspension system. A simple type of road disturbance profile is used in the experiment namely a 0.1 m step disturbance road profile. Figure 9 shows the result of the preliminary experiment when a 0.1 m step disturbance road profile is applied. The figure shows that the active suspension system results in a lower overshoot and shorter settling time than of the passive system. Hence from the experiment performed using the proposed HILS, one can conclude that the active suspension has better performance than the passive suspension. Figure 9 also shows that an active suspension system is able to recover from the road disturbances with a better performance than the passive suspension one. Moreover, there are slightly different responses between the experimental results obtained using the proposed HILS and simulated one using Simulink as depicted in Figure 9. Such results allow discussion between the lecturer and students respect with respect to solving practical problems in the control system such actuator saturation, noise and the effect of sampling time in digital controller implementation.
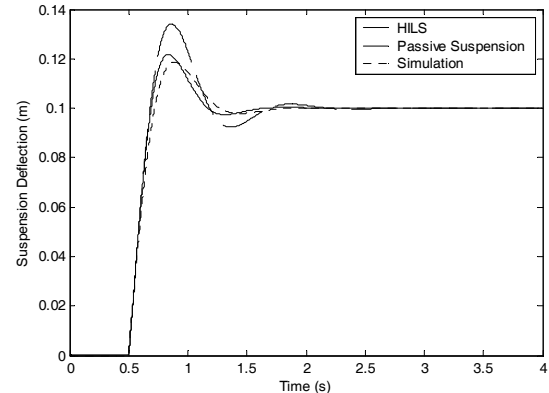

Figure 9. Response to a 0.1m step disturbance road profile

4.2 Automatic gantry crane system with the SC-HILS

An automatic gantry crane system controlled by classical PID controllers is developed in the SC-HILS environment. Two PID controllers are used for controlling both position and swing angle of the load. Students are assigned to design PID controllers based on a specific performance. As an example the PID controller for position control system is designed by considering the following desired specifications:

- Overshoot ≤ 2 %
- Settling time ≤ 1 s

- Rise time ≤ 1 s
- Steady state error $\leq \pm 0.001$

While for swing control system, the PD controller is designed based on the following desired specifications:

- Settling time $\leq$ 5 s
- Amplitude $\leq$ 1 rad.

The obtained parameters of PID and PD controllers were tested in the SC-HILS environment. The performances of the PID and PD controllers were compared with those of the open loop control system. Figure 10 shows the example of responses of the PID and PD controllers when the 10 cm step input references were used respectively. The results for the position control showed that, the PID system resulted in a shorter rise time but larger overshoot and a lower accuracy than the open loop system. Furthermore, for the anti-swing control the PD controller gave faster settling time than the open loop system.
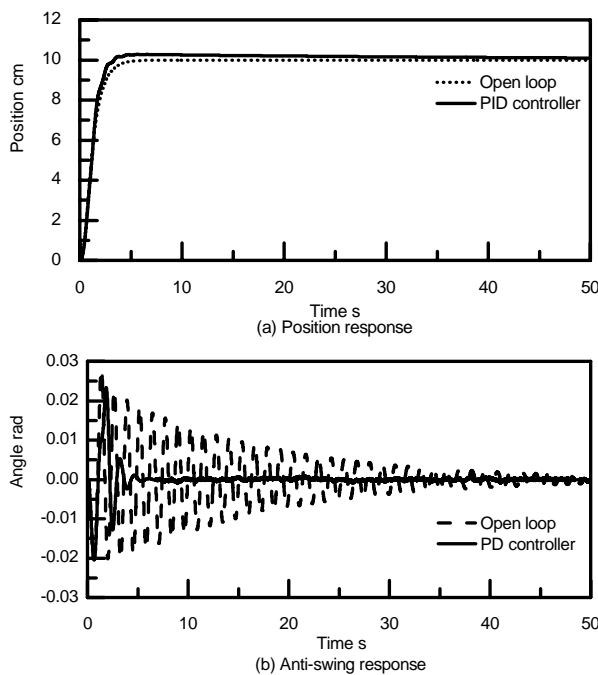

Figure 10. Experimental responses to a 10 cm step input

5. Conclusions

Interactive control systems with the HILS approach have been developed, implemented and demonstrated for educational purposes and especially for the teaching of control engineering. Two control systems based on the HILS approach were developed namely simulated plant HILS (SP-HILS) and simulated controller HILS (SC-HILS) control systems. The proposed systems have been implemented using standard personal computers and data acquisition cards. Examples of student experiment using the both HILS control system have been discussed. The use of MATLAB-based software in the proposed system provides a quick experimentation and performance evaluation. Furthermore, the ease of performing experiments allows the students to focus on the task of understanding, developing and testing control algorithms for many specific industrial applications. document.

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