Adopting Hardware-in-the-Loop for Testing Vehicle Instrument Panel Using Economical Approach

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ABSTRACT
An economical approach for testing Vehicle Instrument Panel is proposed in this paper due to high expenditure of purchasing the available Commercial Off-The-Shelf Hardware-In-The-Loop. Vehicle Instrument Panel is designated as the Device-Under-Test in this paper. The Hardware-In-The-Loop, designated as the test equipment, will simulate the assigned input signals controllable via designed Graphical User Interface. The resulting display is shown on the Graphical User Interface and the Device-Under-Test. The speedometer gauge measurement showed the highest disparity of 4 km/h which is within the tolerance of the pre-determined specification of the Device-Under-Test.
and sophisticated [14]. On the contrary, the economical approach of the proposed system is implemented using a low cost HIL system. The DUT’s pre-requisite is this HIL system’s foundation which eliminates the unnecessary functions and features installed inside the other COTS HIL.

Figure 1. VIP displaying important information to the vehicle real-time condition [3]

Table 1. Previous research using HIL for testing and evaluation purposes [4]–[13]

| Literature Journal | Device-Under-Test | Test Equipment |
|--------------------|-------------------|----------------|
| Wang et al. 2015   | Hybrid Electric Bus Control System | dSPACE TTC200 controller |
| Fasano et al. 2013 | Multisensor Sense and Avoid System | i. Panchromatic and color camera (Allied Vision Technologies Marlin) |
| Chen et al. 2012   | Electronic Control Unit (ECU) of Dual Clutch Transmission Vehicle | i. Data Acquisition card PCL-818LS ii. Control hardware FreeScale MC9S12DP256 |
| Kim et al. 2012    | Light Detection and Ranging Sensor | i. Low Jitter Delay Generator DG535 ii. A321 AOM Driver iii. Acousto-Optic modulator |
| Rad et al. 2012    | Actuation System of a 2-DOF Parallel Robot | i. Development board FiO Std ii. dSPACE MicroAutoBox (MABX) iii. National Instruments PXI |
| Maxwell et al. 2010| GM Two-Mode Hybrid Electric Vehicle | i. MATLAB Simulink ii. dSPACE ControlDesk iii. Fault insertion unit |
| Mouzakis et al. 2009| ECU Diagnostic Software | i. dSPACE Simulink ii. DS2211 HIL I/O Board |
| Huang et al. 2008  | Instrument Cluster | i. dSPACE Simulator ii. DS2210 HIL I/O Board |
| Skjetne & Egeland 2006 | Marine Control Systems | CyberSea Simulator |
| Ramaswamy et al. 2004 | ECU for a Hybrid Electric Vehicle | i. dSPACE Simulator ii. DS2210 HIL I/O Board |

Hence this research aims to adopt HIL system for testing VIP using an economical approach. This paper is outlined in six different sections. Section 2 explains the testing device’s overall design. Section 3

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explains the Graphical User Interface (GUI) applied to run the simulation using either manual as shown in subsection 3.1 or using Speed Profile Selection in subsection 3.2. Section 4 explains the hardware and software framework of the signal generation and Section 5 explains the results of the speedometer testing and the cost expenditure of the COTS HIL. Finally, this paper summarizes the economical approach for testing VIP using HIL system.

2. OVERALL DESIGN OF THE TESTING DEVICE

Figure 3 shows the design architecture of the proposed test equipment. The architecture consists of three main sections which are the Test Input, HIL system and the DUT unit. The Test Input section is where the test personnel inputs the test parameter and performs the test simulations via the GUI designed using Qt Creator.

![Figure 3. Overall Design of the Testing Device](image)

The HIL section consists of two main subsection blocks which are the GUI design software and the signal generator hardware. User interface is where the HIL system receives the test input from the Test Personnel. It is then transferred to the microcontroller which further transmits to the Signal Conditioning Circuit (SCC) for further process and transmits the corresponding signal generation of frequency-based, resistance-based or digital logic. The proposed test system is able to perform testing and verification as required by the DUT with less expenditure compared to the conventional HIL product available in the market.

3. GRAPHICAL USER INTERFACE

User interface which is part of the HIL system is used to launch the testing operation. In this paper, Qt Creator will be utilized as the software IDE to design the GUI via two main modes which are the Design mode and Edit mode.

![Figure 4. Qt Creator’s Edit Mode to input the desired source code](image)
Figure 4 shows the Edit Mode inside the Qt Creator IDE, which contains the source code to program the GUI based on the interaction of the input and output widget. Files directory as shown in Figure 4a is selected and the related source code will be displayed in the Editor’s View as shown in Figure 4b. Figure 5 shows that the design of user interface is conducted inside the Design Mode. It comprises of vast amount of Input / Output widgets such as Push Button, Tool Button and Check Box as shown in Figure 5a. Any action taken towards the input widget i.e. clicking the push button, toggling the radio button, or ticking the check box will be processed according to the source code programmed resulting to the output responded by the output widget i.e. opening a dialog box, rising an analog reading or showing the digital reading.

3.1. Manual Input Test Using Slider Widget

Figure 6 shows how the manual input by the slider widget produces corresponding display at the GUI and transmits frequency data into Arduino IDE. Based on Figure 7, the GUI consists of a slider widget as the input widget used to control the speed reading which will be displayed on the speedometer gauge. The speed range is from 0 to 160 km/h as the test personnel moves the slider from right to left. Besides resulting the speedometer gauge to move, the movement of the slider will also display the corresponding frequency output display which is positioned on top of the slider widget. The frequency output is displayed since the DUT receives frequency signal in order to display the speed of the vehicle in actual condition. The corresponding value of frequency for every speed reading displayed on the speedometer is according to equation 1.

\[ V = \frac{s}{f} F \]  

\[ V \] is the resulting speed value displayed on the Speed gauge and the digital display inside the GUI. \( s \) is the maximum value of the speed on the DUT and \( f \) is the maximum value of frequency required to generate the maximum speed value. \( F \) is the required frequency value to display the desired speed value of \( V \). In this particular case, \( s \) is 160 and \( f \) is 707.78.

\[ V = \frac{s}{f} F \]  

Figure 6. Flowchart of the GUI Manual Input Process

Figure 7. GUI for performing Speedometer testing using Speed Profile simulation or Slider Input widget [3]
3.2. Simulation via Selection of Speed Profile

Figure 7 also displays an option to perform driving profile simulation. 4 speed profiles are introduced for the testing purpose of the speedometer. The test personnel may select one speed profile by clicking at the radio button of the desired speed profiles before clicking the start button. Beside the radio buttons are the speed profile graphs showing whether the speed will be either decreasing, increasing or remain at the same speed.

Speed Profile 1, 2 and 3 consists of 3 stages each with different slope of either increasing, decreasing or constant speed. All three of the Speed Profiles have the similar simulation time. Meanwhile Speed Profile 4 consists of 8 stages and has a longer simulation time. As the simulation of the Speed Profile is performed, the changes in frequency value at the top right and the changes in speed value inside the speedometer are observable.

4. SIGNAL GENERATION FRAMEWORK

This section will explain the generation of the desired signals prior to testing the DUT. As the GUI performs simulation using the speed profile and manual input using the slider widget, this data is then transferred to the Arduino microcontroller which is further conditioned to the desired signal using Signal Conditioning Circuit. The signal generation framework consists of a Personal Computer (PC), PC-to-DUT communication means and Signal Conditioning Circuit (SCC).

4.1. Host PC

The PC is used as the medium to install the utilized software and IDE such as Qt Creator IDE and Arduino IDE. Arduino is an open source physical computing platform based on a simple input/output (I/O) board and a development environment [16]. Qt is a C++ toolkit with an extension for QML and JavaScript [14]. All the testing operation will be conducted by the test personnel using the PC via the GUI explained in Section 3. As the test personnel performs the test either using the speed profile simulation or the slider widget, the value of speed and frequency inside the GUI will be changed and displayed accordingly. Further, the value of frequency output displayed is also be processed by the Qt Creator to obtain meaningful data prior to the signal generation. The data are then converted to character strings before serially transmitted into the Arduino Uno by embedding several lines of source codes and header file to establish the Qt-Arduino connection as shown in Figure 6.

4.2. Device-Under-Test Communication Interface

It is vital to have a communication platform between a PC host and DUT. At this point, the PC host is unable to process further to generate the desired signal input to the DUT. Since the DUT consists of male harness connectors and no USB female ports or any PC-compatible connectors to be linked directly to the PC as shown in Figure 8. Thus, Arduino IDE performs the interconnection between the PC and the DUT via USB connection between the PC and the Arduino USB port. The output pin of Arduino Uno is then connected to the pinout of the DUT via Signal Conditioning Circuit. Arduino IDE is utilized to program the source code to communicate with the Qt Creator and to generate the digital signal via output pins or SPI bus. Arduino is an open-source platform that can be used to build and program electronics, design and invent wide range of mechatronics project [17]. Due to its simplicity and compatibility to communicate with PC, Arduino Uno is chosen from the other Arduino board members.

![Figure 8. Back and Side view of the DUT](image-url)
Source code is developed and uploaded from the IDE into the Arduino Uno board by the means of USB. By using the several commands such as Serial begin(9600), Arduino communication with PC are established and PC will be started transmitting the signal into the Arduino board. This open-source prototyping circuit board will be used to generate a digital logic signal based on the information obtained from the PC. It will generate two types of output: the digital signal and the Serial Peripheral Interface (SPI) signal. This signal generation will then be transmitted to the SCC for further processing.

4.3. Conditioning Signals from Arduino to the DUT

Figure 9 displays the block diagram of the signal generation which is the interconnection of the Signal Conditioning Circuit between Arduino Uno and the DUT. Since some of the DUT gauges and telltale displays cannot be triggered by simply feeding +5 V signals from the Arduino Uno, thus certain signal conditioning process is required to be designed. The circuit consists of two sections of input which is the digital logic with value of 0 V or 5 V, and the SPI bus connection.

![Figure 9](image)

**Figure 9. Signal Conditioning interfacing circuit connecting from Arduino to the DUT**

Digital logic signals representing the tell-tale input signals generated from the Arduino Uno is then processed accordingly. 5 V signal is fed directly, via the DUT pin connection, to the 'Left' and 'Right' Turn tell-tale signal. However, a higher voltage supply requirement is needed for activating the Upper beam headlight. 12 V signal is required to be fed to the DUT and external grounding is required. For both Battery and Hand-Brake signal, a ground signal is required. By using optocoupler for each case, the current flow according to the required standard as above can be achieved. Optocoupler is an optical switch (power electronic switch) which is designed to isolate electrical output from input for the purpose of protection from such intermittent voltage and noise [20].

SPI bus is used for two types of signal which are frequency and resistance. SPI has a simple 4-wire synchronous interface protocol that enables controllers and peripheral devices to intercommunicate [21]. Multiple SPI connections can be achieved by connecting to the respective pins of Master- In-Slave-Out (MISO), Master-Out-Slave-In (MOSI), Clock and Slave Select (SS) to the SPI slave pins of the related IC chips accordingly. Figure 10a shows the multiple slave connection, with the SPI master consists of multiple Slave Select pins to control the desired SPI slave. To select the desired SPI slave, the corresponding SS is pulled low and the master activates the clock signal, hence generates the information onto MOSI line as the slave generates another information through MISO line as shown in Figure 10b [19].

![Figure 10](image)

**Figure 10. SPI configuration and Timing Diagram**

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For generating a frequency with a resolution of 0.01 Hz, the SPI connection from Arduino is connected to the Frequency Signal Generator Board. This board then generates the required frequency output for the Speedometer and Tachometer. A dedicated frequency generator solution will guarantee deterministic square wave signal generation in its own accord avoiding the extra loading on the main microcontroller.

Meanwhile, SPI bus is also connected to the digital potentiometer to generate the resistance output. The value of the potentiometer can be digitally controlled according to the data received from the Arduino Uno via the SPI bus. The lowest available digital potentiometer with an SPI interface is 5,000 Ω with 8-bit resolution (256 steps). To accommodate the range of the resistance signal required which is within 0 Ω to 200 Ω, multiple digital potentiometers are arranged and connected in parallel to enhance the resistance resolution but maintain the number of resolution steps. Thus, the resolution of the resistance value achieved when performing the parallel connection of the potentiometer is up to 3.906 Ω/step.

5. RESULT AND ANALYSIS

In this section, the result of utilizing the GUI and its corresponding signal generation for Speedometer test is discussed.

5.1. Test Result for Device-Under-Test

For this test, the personnel will be using the Slider widget to control the speed reading displayed on the GUI, which also displays the corresponding frequency value. The actual frequency value is also verified (but not as part of automated test process) using Agilent Digital Oscilloscope by probing the frequency output at the DUT Speedometer pin-out. The image of the DUT is also taken and measured to compare the actual Speedometer reading on the DUT compared to the GUI Speedometer reading.

Figure 11 shows the GUI display and the actual speedometer reading on the DUT. The right side shows the manual slider input which controls the frequency that is going to be generated. Meanwhile, the middle side shows the GUI display, which is the frequency of 100 Hz and speedometer value of 22.6059 km/h as calculate from the Equation 1. The left side of the figure is the image captured with the resulting speedometer reading when the frequency signal generated is 100 Hz, which is nearly 25 km/h. Figure 12 and 13 shows the other frequency generation which produce various speedometer reading. The accurate DUT speedometer measurement has been accomplished using image processing and the results are displayed in Table 2.

![Figure 11. GUI and DUT corresponding speedometer reading for frequency generation of 100 Hz](image)

![Figure 12. GUI Simulated Display](image)

![Figure 13. DUT (Actual VIP) Display](image)
Table 2. Speedometer Test and Variation with Actual Result

| Frequency Value (Hz) | GUI Speedometer Value (km/h) | Oscilloscope | Variation | GUI Speedometer Value (km/h) | DUT Speedometer Value (km/h) | Variation |
|----------------------|-----------------------------|--------------|-----------|-----------------------------|-------------------------------|-----------|
| 100                  | 100.15                      | 0.15         | GUI       | 23                          | 23                            | 0         |
| 200                  | 200.30                      | 0.30         | GUI       | 45                          | 46                            | 1         |
| 300                  | 300.45                      | 0.45         | GUI       | 68                          | 69                            | 1         |
| 400                  | 400.64                      | 0.61         | GUI       | 90                          | 91                            | 1         |
| 500                  | 499.96                      | 0.04         | GUI       | 113                         | 115                           | 2         |
| 600                  | 600.91                      | 0.91         | GUI       | 136                         | 139                           | 3         |
| 700                  | 702.18                      | 2.18         | GUI       | 158                         | 162                           | 4         |

Figure 14 shows the graphical representation for speedometer reading for both GUI and DUT. The lower section is the column chart showing the reading of speedometer, while the upper section is the line chart displaying the difference of the speed value between GUI and DUT. It is observed that the difference does not exceed the upper and lower limit of the tolerances pre-defined by the customer, which is the DUTs manufacturer.

5.2. Analysis of Cost Expenditure
The proposed HIL test equipment eliminates the requirements of utilizing costly COTS HIL. At affordable price, less expensive electrical components and microcontrollers were purchased and the test equipment is designed from ground up to meet with the testing requirements. Table 3 shows the cost of the project if the COTS HIL is used on this project. Excluding the charges such as after-sales service and spare parts, using the proposed system is definitely reduces the cost of the project. Moreover, the proposed system maintenance is expected to be much lower than the COTS HIL due to the fact that the knowledge about the system architecture is known to the designer/engineer.

Table 3. Available COTS HIL in market with the estimated budgetary price

| Item  | Specification                                      | Description                                      | Brand  | Price (RM) |
|-------|----------------------------------------------------|--------------------------------------------------|--------|------------|
| 1     | PXI-2720                                           | PXI Programmable Resistor Module                 | NI     | 11,973.76  |
| 2     | PXI-2586                                           | PXI Relay Module                                 | NI     | 6,530.66   |
| 3     | cRIO-9063                                          | 4-Slot Integrated Dual-Core Controller           | NI     | 6,871.98   |
| 4     | NI 9482                                            | 4-Ch SPST Relay Module                           | NI     | 929.62     |
| 5     | NI 9421                                            | 8-Ch Sinking DI Module                           | NI     | 523.64     |
| 6     | sclx fs 100                                        | Failure Simulation for 100 Functions             | dSPACE| 5,842.24   |
| 7     | MOTIONDESK                                         | MotionDesk 3D Animation Tool with USB dongle     | dSPACE| 11,389.68  |
| 8     | ACE SCLX MC                                        | Advanced Control Education Kit SCALXIO MultiCore | dSPACE| 32,124.98  |
| 9     | POWER SUP DELTA                                    | Delta Power Supply                               | dSPACE| 18,008.70  |
6. CONCLUSION

In this paper, the test equipment designed to generate the simulation input for VIP has been described. The frequency generated had successfully displayed the corresponding speed reading inside the speedometer. Minor differences which is 4km/h at most are observed and is within the pre-assigned tolerance. Using Arduino Uno as the microcontroller with the addition of a specifically designated SCC for further signal conditioning, and Qt Creator IDE and Arduino IDE as the software framework, it is possible to adopt a HIL system for testing VIP using economical approach.

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