AC 2010-1409: INTEGRATING HARDWARE-IN-THE-LOOP INTO UNIVERSITY AUTOMOTIVE ENGINEERING PROGRAMS

Michael Wahlstrom, Argonne National Laboratory

Frank Falcone, Argonne National Laboratory

Doug Nelson, Virginia Tech

Integrating Hardware-in-the-Loop into University Automotive Engineering Programs Using Advanced Vehicle Technology Competitions

Abstract

With the recent increase in complexity of today's automotive powertrains and control systems, Hardware-in-the-loop (HIL) simulation has become a staple of the vehicle development process in the automotive industry. For university vehicle design and engineering programs to stay relevant, the industry development process must be mirrored in a low cost, efficient manner. HIL has been outside of the realm of possibility at universities due to the complex modeling techniques and information required, as well as the prohibitive cost. Supplying universities with low cost, function development-based HIL systems reduces the vehicle development time by parallelizing the process while educating students on cutting-edge vehicle design techniques.

Reducing the complexity of the hardware reduces the overall utility however lessens the cost associated with networking Electronic Control Units (ECU). Also, developing simpler, lower fidelity models reduces required computing resources and cost.

This paper will explore the required system configuration as well as the optimal fidelity of the models to allow for function development at the university with a low overall cost. As well, the paper will focus on the introduction of the HIL system into the university vehicle development process and the benefits of utilization.

Introduction

As the need for more efficient, cleaner vehicles increases, so does the need to educate the future workforce to be ready to deal with the current environmental issues. The United States Department of Energy (DOE) has been sponsoring Advanced Vehicle Technology Competitions (AVTC) at the university level since 1988. The most recent competition, Challenge X: Crossover to Sustainable Mobility came to a conclusion May 2008, in Washington, DC. The follow up competition, EcoCAR: The NeXt Challenge has now commenced its three year cycle, with competition events occurring each year. The scope of the AVTC's has changed over the years, influenced by current social concerns such as petroleum reduction, greenhouse gas emissions reduction and increased fuel economy, and the inclusion of advanced technologies such as Ethanol, Biodiesel, Hydrogen, Grid Electric energy.

The complexities of the powertrain systems in EcoCAR have forced the universities to become much more involved in component control than past competitions. For example, previous competitions would typically couple an engine with a transmission that was designed to work with that engine. As the powertrains become more diverse, many schools need to make an engine work with other transmissions or motors that were never designed to be integrated together. Taking this step forward in powertrain design enables greater efficiency benefits, but is coupled with a large increase in system level control capabilities. These capabilities are not typically available at the academic level.

EcoCAR uses HIL to enable teams to do off-board control design and simulation that was not previously possible. This increased control testing and development time gives teams the required time to complete complex powertrain control in a tight timeline at the university.

Hardware-in-the-Loop Simulation

The use of HIL simulation to validate vehicle control systems has recently become an industry staple. HIL system setups tend to vary greatly depending on the required accuracy and utility of the system as well as balancing the complexity and cost of the system. Typical vehicle HIL simulation methods vary from single Electronic Control Unit (ECU) testing to testing of a network of ECUs on Distributed Control Systems (DCS). Powertrain control systems are typically distributed across several ECUs. As the number of ECUs under test increase, the cost and complexity of the overall system also increases.

HIL Simulation in AVTCs

EcoCAR is utilizing HIL as a controller validation tool to further the advancement and enable control strategy innovation in the university environment. The typical AVTC Vehicle Development Process (VDP) has included waiting for the mechanical integration of the vehicle prior to control validation and verification (Figure 1). The need for this delay stems from two barricades:

1. The lack of sufficient tools for completing controller hardware validation and verification, and
2. The lack of sufficient models for testing real time control validation and verification.

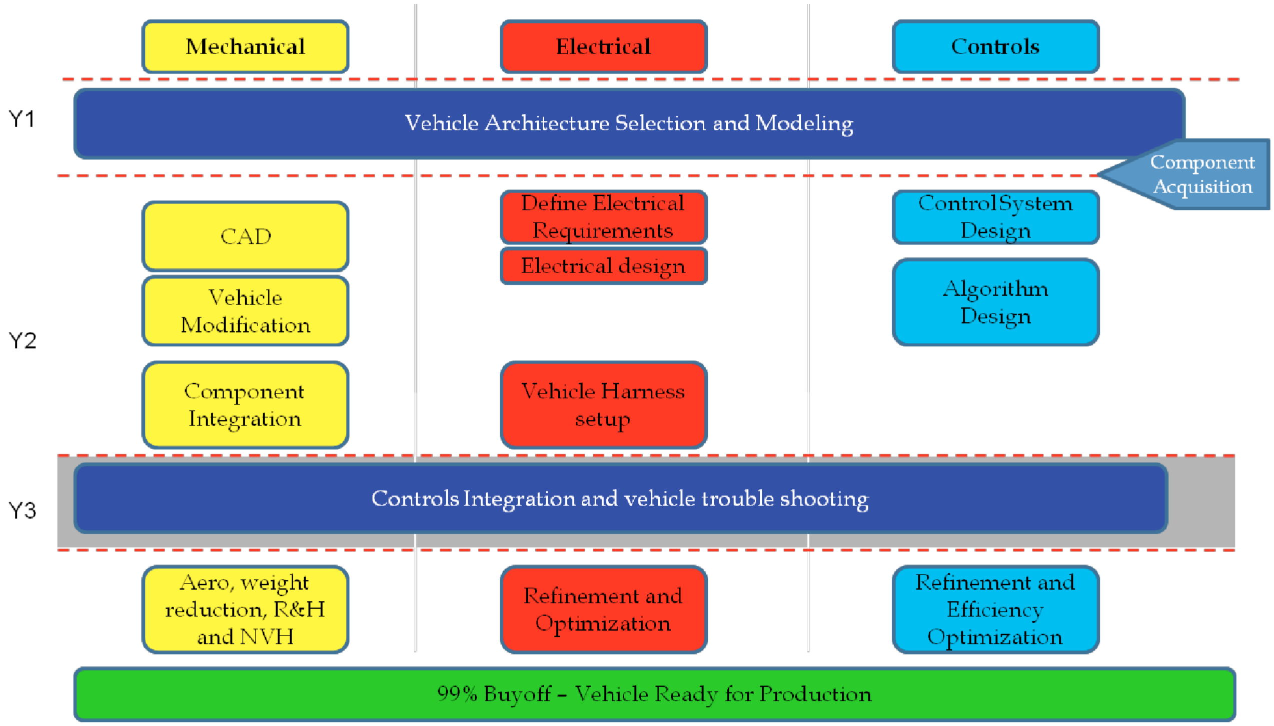

Figure 1: Challenge X VDP

Typical control architectures in AVTCs include a supervisory controller communicating with several embedded system controllers. The result is a hierarchical control system as seen in the example in Figure 2.

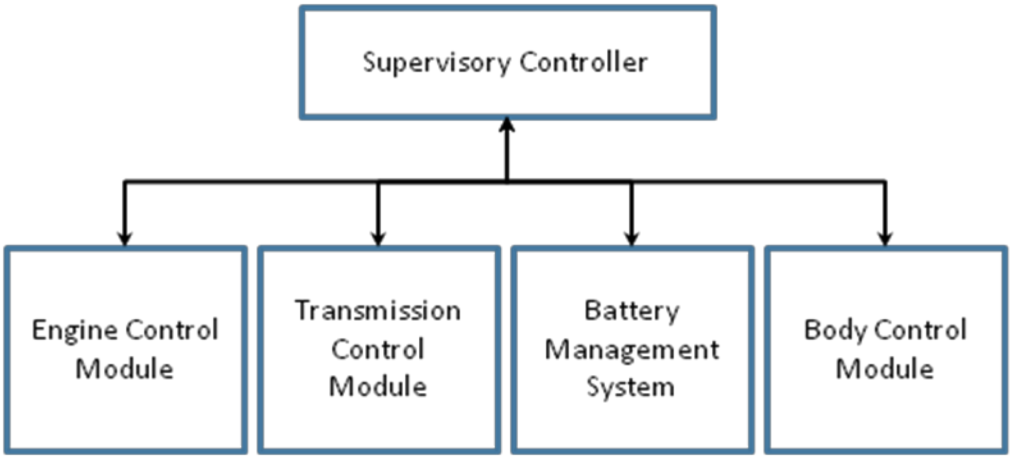

Figure 2: Example of a Supervisory Controller Architecture in EcoCAR

Often the powertrain subsystems are production variants calibrated to standards set forth by each Original Equipment Manufacturer (OEM). The EcoCAR HIL system needs not to revalidate the powertrain subsystems, however it needs to adequately validate the overall system control strategy. This important distinction allows for a reduced cost, reduced complexity system that can be standardized for the competition based on a review of past AVTC supervisory control systems.

The new EcoCAR VDP has been designed to include HIL testing and simulation (Figure 3). This offers many advantages including:

a. Safety
    i. Enhanced initial vehicle safety
b. Architecture design
    i. Educated designs based on upfront development
c. Fault mitigation
    i. Design Failure Mode and Effects Analysis (DFMEA)
    ii. Failure Insertion (FIU)
d. Enhanced innovation
    i. Decoupled controls development
e. Shortens vehicle development time

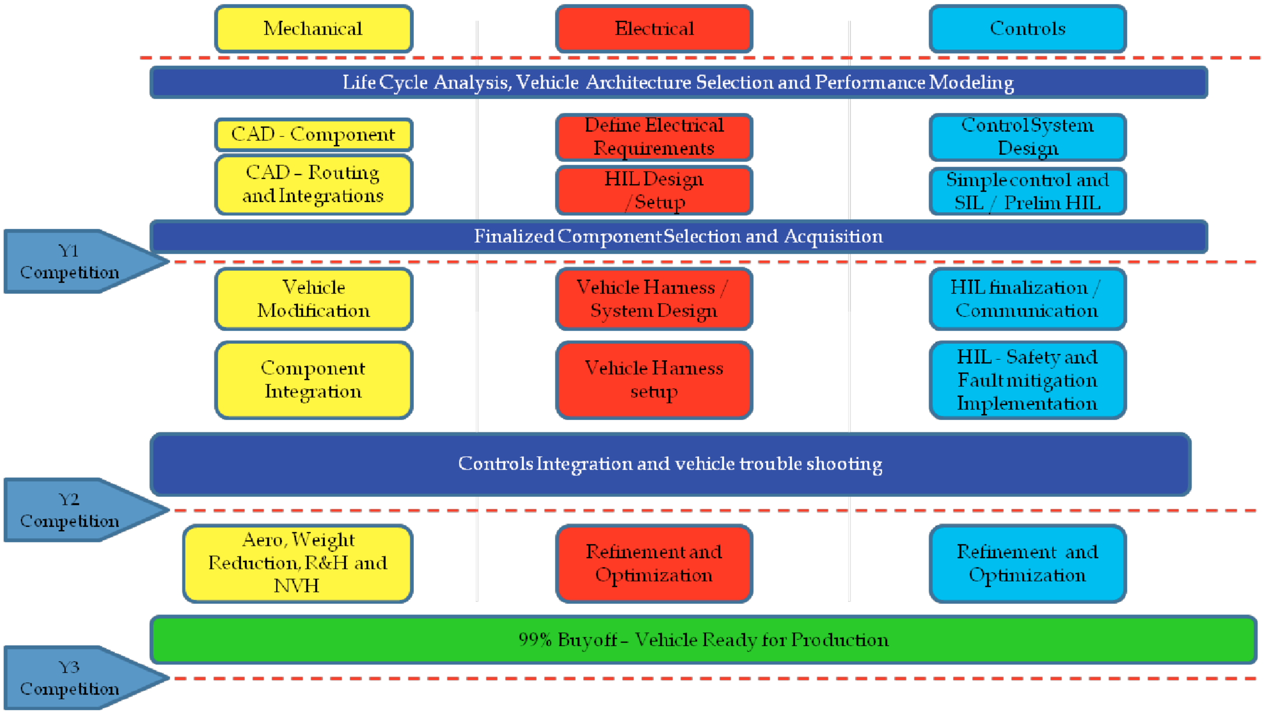

Figure 3: EcoCAR VDP

Notice that a lot of control design and implementation can now happen in year 1 and the start of year 2. This will inherently shorten the control integration and troubleshooting prior to the year 2 competition finals.

Model Considerations

The models required for the simulation methods must be sufficiently complex to represent behavioral characteristics while not being so complex that they require unattainable computing power to execute in real time. HIL models with an acceptable level of fidelity generally involve having intimate knowledge of the components. In order for the students to be able to utilize the HIL system quickly, baseline models have been provided to the teams in Simulink and Stateflow. Models can then be customized to meet the need of each school. Model structure, modularity and simplicity will be evaluated to ensure real time operating characteristics and accuracy. A main model consideration is the use of fixed step solvers to ensure that each integration step is within the specified simulation time.

The models supplied to teams include:

1. Powertrain System Analysis Toolkit (PSAT) simulation model
2. A Simulink-based baseline real time vehicle model
3. Simulink real time models of donated GM components

The modularity of models is of paramount importance. The ability for the teams to integrate their new component models relies heavily on the ability to identify and separate specific component control, actuators, plant and sensor models. Also, during model development, all models must conform to a standard model structure as it will be important to calibrate the models to each component and in collaboration with the real time vehicle model.

The vehicle and component model fidelity varies by component and by vehicle architecture. Ultimately, each team will need to justify the complexity and fidelity of their models as related to required transient responses and ability to execute in real time. For example, a team using a series hybrid powertrain may require a less dynamic engine model for control development due to the intrinsically steady engine operating points that a series vehicle may have. Alternatively, a powersplit hybrid vehicle team may require a much more dynamic engine model due to the transient nature of the engine especially during shifting events.

Teams were supplied with Powertrain System Analysis Toolkit (PSAT) as a donation from the US Department of Energy and facilitated by Argonne National Laboratory. PSAT is a forward-looking, empirical model database that evaluates fuel economy and realistic performance characteristics.

The vehicle model is separated into several components:

1. Driver model
2. Engine model
3. Transmission model
4. Driveline model
5. Chassis model
6. Electrical system model

Each model is controlled by its own low level controller and includes the required sensors and actuators to enable successful simulation. However, the fidelity and complexity of each model varies depending on the intended utilization. The driver model is a standard PI (proportional – integral) model and will not be discussed in this paper as it is simplistic and should be modified for each team.

Engine Model

The engine model is a 0-dimensional, mean-value model that utilizes a response surface model to determine engine torque output as a function of engine speed, input and exhaust cam positions, air flow per cylinder and spark timing. It also uses a response surface model for volumetric efficiency as a function of engine speed, input and exhaust cam positions, and intake manifold pressure. There are simple air flow dynamics considered during the cylinder charging through the intake manifold and throttle body. Fueling dynamics are also modeled through a simplistic transfer function. The model is calibrated through the calibration of the volumetric efficiency and torque response surface models using engine dynamometer data.

Transmission Model

The transmission model is a 0-dimensional, mean-value model that includes dynamics of the torque converter, and the controller utilizes a lookup table for the selection of the gear ratio based on throttle pedal position.

Driveline Model

The driveline is modeled as a rigid driveline with a gear ratio for the consideration of the final drive. The driveline was originally not rigid, however, including the compliance of the shaft caused the model to slow down drastically during simulation. For the purposes of EcoCAR, it is assumed that a rigid driveline will suffice.

Chassis Model

The chassis model is a road load model that accounts for rolling resistance, mass and aerodynamic drag. It does not include a suspension model or steering effects.

Electrical System Model

The electrical system model is assumed to be a constant alternator load on the engine.

Utilizing this kind of torque based modeling makes the models modular and easily transferrable. Moving from the production engine to another engine requires little integration time.

HIL System Considerations

There are several considerations for determining the required HIL system:

1. Real Time Processing
2. Networking capability; specifically Controller Area Network (CAN) enabled
3. Sensor and Actuator conformity
4. Data capture
5. Real Time Target simulation timing
6. Adequate input/output (I/O) counts

Each consideration must be optimally met to increase system utility while decreasing overall system cost.

Real Time Processing

Real Time Processing is integral to the HIL simulations. The real time controller must be able to capture transient system behavior to maximize available system utility. The models must in turn use fixed step solvers to ensure that integration happens at each fixed time interval as specified. The real time ability of the system is complicated by the fact that the model fidelity must be such that it allows the system to operate in real time. Utilizing empirical models constructed from available component and vehicle data will reduce the complexity of the models and will allow reduced processor power of the real time controller. The deterministic execution of the empirical models, however, must be tested at data boundaries to ensure extrapolated behavior is reasonable and rational.

Communication Networking Capability

CAN bus dynamics must be sufficiently tested to ensure bus loading, error handling, and overall network management, and requires real time operation to accurately analyze system behavior. CAN protocol is highly utilized in vehicles as a distributed control system (DCS) communication network. Flex Ray networking is not widespread enough that the system must be able to support it for the purposes of EcoCAR. A study was completed of Challenge X vehicles to determine the required CAN network requirements. The number and speed of CAN networks are important for the utilization of development components from various sponsors and suppliers. The number of customized CAN networks on a vehicle varied between 2 and 4 in Challenge X.

Sensor and Actuator Conformity

The system must have accurate system and actuator conformity to enable the controller to communicate as if it was connected to the vehicle. Each sensor output from the HIL chassis and actuator input must have the same time factor, range and sensitivity as the physical sensors and actuators.

Data Capture

Data capture can be either integral to the HIL system or external, but must be able to provide sufficient feedback for further controls development. Real Time Target simulation timing must be sufficient for real time systems to execute accurately. For example, some power electronics operate at loop rates up to 1000 Hz. To ensure accurate model feedback, the HIL system must be able to provide feedback fast enough. Adequate I/O must be present on the system to represent typical AVTC supervisory control utilization.

Analog and Digital I/O Requirements

Studying the previous AVTC vehicles will provide a baseline for the proper I/O counts required. The Challenge X vehicles were surveyed for an understanding of the typical supervisory controller input and output requirements. It’s important to note that the requirements are based on the supervisory controller. Therefore the HIL system must be able to sink or source the necessary inputs and outputs.

The Challenge X teams fell into one of two categories. The first category used fewer I/O due to the fact that the powertrain subsystems they utilized were heavily CAN controlled, meaning the sensor and actuator interfaces were not very many. The second group utilized subsystems that required low level control, such as custom power electronics, custom battery pack integrations, non-CAN enabled components, etc. The results are shown in Table 1. Since EcoCAR is supporting controller models for all competition sponsored powertrain components, it is reasonable to assume that if the system can handle most of the Challenge X vehicle supervisory controllers, it will be able to handle the EcoCAR teams as well. It is, however, desirable to source systems that can be expanded in the case where there isn’t enough I/O for a certain team.

Table 1: Challenge X I/O Requirements

High I/O Utilization (8 Teams)		Low I/O Utilization (9 teams)	
I/O		I/O	
Analog Input	20-30	Analog Input	5-6
Digital Input	3-5	Digital Input	3-5
Low Side Driver	15-20	Low Side Driver	7-11
High Side Driver / H-Bridge	3-5	High Side Driver / H-Bridge	2-3
PWM	5-10	PWM	2-5

HIL Hardware

EcoCAR has pursued and acquired support from two HIL suppliers, dSPACE and National Instruments(NI). Each supplier has suggested a system and will supply roughly half the field. Teams wrote proposals for which system they would like to use. Each system was evaluated for the above considerations using the production vehicle model to ensure the system utility meets required needs.

National Instruments System Specifications

Teams were able to request customized systems from National Instruments, however, the baseline system included:

1. NI-PXI Chassis
2. NI-PXI Controller
3. PXI-8464 CAN Cards
4. PXI-6229 FPGA Board

dSPACE System Specifications

The baseline dSPACE system donated included:

1. dSPACE mid-size HIL simulator
2. dSPACE 2202 I/O Board
3. Failure Insertion Unit

Both systems meet the requirements set forth from the competition and both systems can be customized and expanded.

HIL Demonstration and Evaluation Events

The team’s HIL simulation systems are demonstrated and evaluated at two events. The first event was part of the year 1 competition finals in Toronto, Ontario, Canada (June, 2009). The second evaluation of the HIL systems came in Daytona Beach, Florida at the EcoCAR 2010 Winter Workshop (January, 2010).

The teams were judged by a panel of industry experts in categories including:

1. Dynamic System Demonstration – demonstrated functionality through test cases

2. Hardware Walkthrough – demonstrated that hardware interfaces functioned, and unique features including usability, functionality and test efficiency
3. Software Architecture – Final model architecture, and model interactions
4. Model Limitations – demonstrated model limitations and discussed the tradeoffs of using simplified models
5. HIL Test Plan
6. Design Failure Mode and Effect Analysis
7. High Voltage Stability Analysis
8. Test Coverage
9. Documentation

After the second evaluation and demonstration event, 14 of the 17 teams were able to show full functionality of their HIL systems and the others demonstrated slightly less functionality. All teams evaluated showed CAN based communication between their supervisory controller and HIL simulator as well as met minimum system hardware requirements. Of the teams that showed full functionality, several teams had made advancements including updating to more dynamic models, including peripherals such as throttle bodies and automatic shifting mechanisms, automated failure insertion.

Conclusion

The use of HIL simulation in EcoCAR has been facilitated by the sponsors and organizers of EcoCAR. HIL simulation has become an integral part of this and future Advanced Vehicle Technology Competition Vehicle Development Processes. This process has enabled cutting edge HIL simulation tools and techniques for the EcoCAR competition and will enable shortened control integration time, safer control strategy implementation and vehicle commissioning, and innovation on the advanced technologies that the schools are integrating. By reducing the complexity of the systems and increasing the scope of the models, the system cost has been greatly reduced so that it is feasible for the two companies to sponsor HIL systems for all of the schools.

Recommendations and Suggestions

The use of HIL can be very useful in research situations that require vehicle control. It is recommended that universities that are doing either vehicle system research or vehicle component control research (engines, motors, fuel cells, etc) explore the usage of HIL in their labs. Developing an HIL simulator is a great research project in itself and will enable many future projects in a much shorter timeframe yielding significant results in laboratory experiments.

Bibliography

1. Hanselmann, Herbert, "Hardware-in-the-Loop Simulation Testing and its Integration into a CACSD Toolset", Proceedings of the 1996 IEEE International Symposium, 1996.
2. Kohl, Susan, et al. "How to Do Hardware-in-the-Loop Simulation Right" SAE 2005-01-1657, 2005.
3. Dhaliwal, et al. "Hardware-in-the-Loop Simulation for Hybrid Electric Vehicles – An Overview, Lessons Learned and Solutions Implemented" SAE 2009-01-0735
4. Long, et al. "Open Architecture Solution for Hardware-in-the-Loop Testing" SAE 2008-01-2711