

# The Use of Virtual Instrumentation in the Development of the 2005 University of Tennessee Challenge X Vehicle

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## EXECUTIVE SUMMARY

### Vehicle Overview

The University of Tennessee Challenge X entry for 2005 is based on a 2005 Chevrolet Equinox SUV. Team Tennessee is converting the SUV into a highly efficient, low emission, hybrid electric vehicle. The goal is to increase on road fuel economy over the stock vehicle and achieve ULEV emissions status, while maintaining the performance of the stock vehicle. The vehicle will be equipped with an efficient 1.3 liter Fiat turbo-diesel in-line four cylinder engine; and B-20 biodiesel fuel will be used. The electric transaxle from a Ford EV Ranger will be used for the electric drive system. The powertrain will be a through-the-road parallel configuration. A block diagram representation of the powertrain is shown in Figure 1. The system voltage will be 288VDC, with the energy storage system comprised of a Cobasys NiMHax nickel-metal hydride battery system. The control system will be developed using National Instruments LabVIEW RT software and implemented using a host of National Instruments hardware, including PXI, CompactRIO, and LabVIEW Embedded Edition. The control strategy will be charge-sustaining with engine-off operation during vehicle idle periods to increase fuel economy and reduce tailpipe emissions.

### National Instruments and the University of Tennessee

The University of Tennessee is developing the custom control system for the Challenge X competition in a series of stages, which roughly correlate to each year of the competition. The first year is dedicated to the mathematical development of a conceptual vehicle powertrain and controller architecture and is the focus of this document.

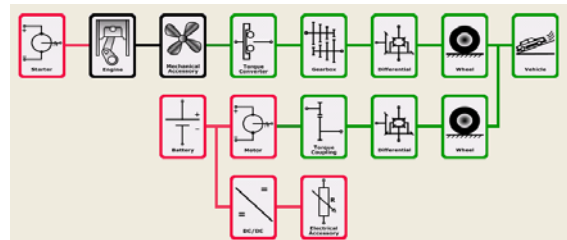


Figure 1 PSAT representation of a through-the-road parallel configuration

The 2005 Challenge X team is making use of PXI, CompactRIO, and Motorola microcontrollers hardware in their application. The PXI system provides a modular framework for developing a vehicle simulator and a laboratory implementation of the vehicle controller for hardware-in-the-loop (HIL) prove out. CompactRIO will be used for initial installation in the vehicle for Year Two of the competition, utilizing LabVIEW RT as the software platform. The final version of the vehicle control system will be developed using LabVIEW Embedded Edition running on a Motorola PowerPC-based microcontroller. This will occur in Year Three of the competition. This progression of hardware integration allows the team to develop and fine tune the control algorithms easily in the preliminary stages (PXI technology) while providing a path for final custom integration with “production” type hardware through the use of existing LabVIEW code running on a microcontroller.

The University of Tennessee has a rich history in utilizing National Instruments products. The 2002-2004 UTK FutureTruck teams relied on the use of Fieldpoint and Compact Fieldpoint hardware. A cFP-2020 network module was the heart of the UTK FutureTruck control system. This system is still in place and functioning flawlessly. It has afforded the UTK automotive program and stable platform for hybrid electric vehicle research and development.

LabVIEW RT was the programming environment during all of the FutureTruck efforts.

### Challenge X Goals versus Implementation

The goal for the UTK Challenge X control system is to implement a robust controller that coordinates the interaction of the heat engine, traction motor, and high voltage battery pack to deliver the power demanded by the driver. The controller should also maintain the integrity of the system by successfully applying the appropriate system limitations. The conceptual implementation of the Challenge X control system will meet these requirements with very little deviation from the set objectives for the project.

## GENERAL DESIGN PHILOSOPHY AND CONTROL STRATEGY

### Design Philosophy

The control system for UTK Challenge X vehicle is evolving around a basic design philosophy. Team Tennessee is adhering to the systems engineering approach to designing their complete vehicle, including the control system. This approach is depicted graphically in Figure 2. The left half of the “V” is dedicated to control system algorithm development and software development/debug. This is performed primarily in a virtual environment utilizing software- (SIL) and hardware-in-the-loop (HIL) principles.

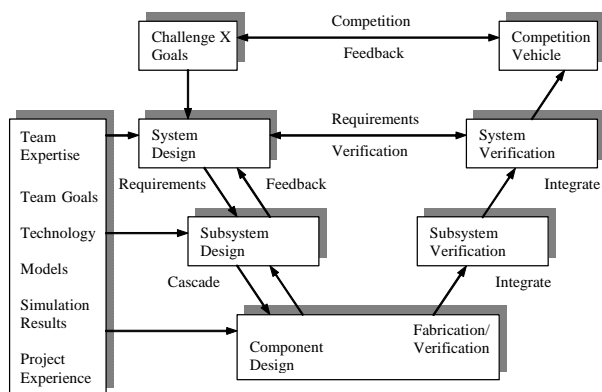


Figure 2 Evolution control system design cycle

The competition has dictated that PSAT (Powertrain Systems Analysis Toolkit written in MATLAB/SIMULINK) be the simulation platform for predicting the performance and fuel economy of the vehicles. Team Tennessee is taking the use of

PSAT one step further by utilizing existing National Instruments tools to integrate its custom LabVIEW controller software directly into the PSAT model for SIL testing. Figure 3 represents the path being taken for this integration. The NI Math Interface Toolkit allows the custom LabVIEW code developed by Team Tennessee to be fully integrated into the PSAT environment. This feature allows the LabVIEW control code to become fully portable among several platforms for simulation purposes (PSAT), HIL testing with the control code residing on NI hardware running in real time, and full vehicle targeting.

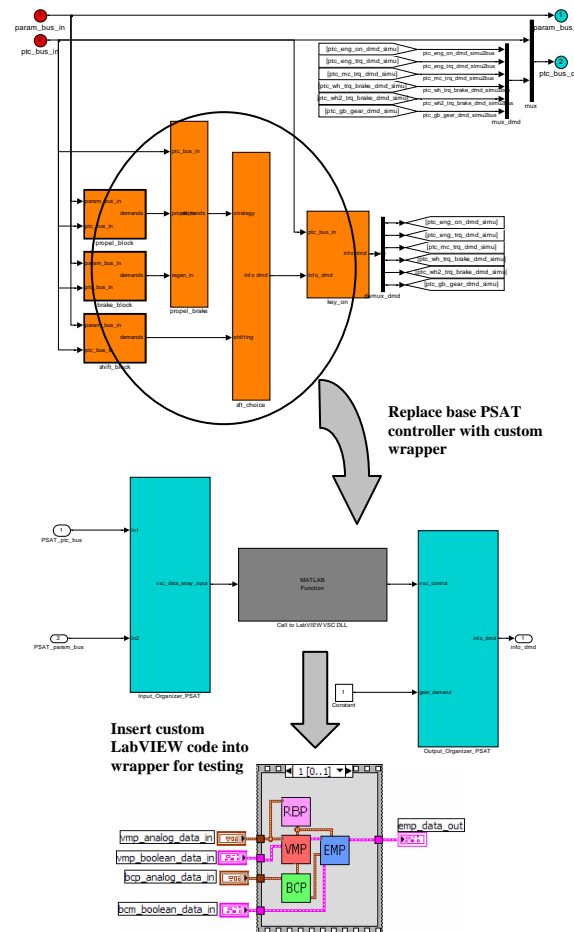
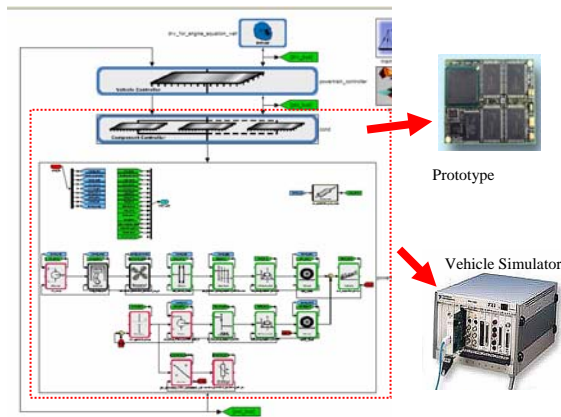


Figure 3 Path for custom UTK VSCM LabVIEW implementation into PSAT

In an effort to further integrate PSAT into the UTK design process, we will use the NI Simulation Interface Toolkit to extract the vehicle model from PSAT for the powertrain architecture we have chosen. Once this has been accomplished, the vehicle model will be integrated into a custom LabVIEW code and targeted to PXI chassis. This

system will be used for the remaining two (2) years of the competition as a vehicle simulator for the purposes of HIL testing. Figure 4 illustrates how this will occur. This application corresponds to the bottom of the right side of the systems engineering “V” shown in Figure 2, and progresses up this side. Team Tennessee plans on making heavy use of the HIL system to develop and debug the control algorithms being developed. Safety is paramount, and it is the goal of the team to have a safe and robust controller completed before it is ever introduced to an actual powertrain or vehicle.



**Figure 4 Diagnostic panel and calibration remote panel example**

The final phase of the design cycle for the UTK Challenge X control system is vehicle testing. The complete control system will be installed in the vehicle along with all of the other components for vehicle level testing. In order to ensure no software glitches or faulty logic has been introduced into the code, the vehicle will be tied down on a chassis dynamometer. Here again, safety is the prime concern for the development of the UTK Challenge X control system.

### Control Strategy

The University of Tennessee Challenge X control system’s overall purpose is to coordinate the interaction of the heat engine and the traction motor. The manner in which the control system carries out this function relies on several factors. The most fundamental of these is to translate the intent of the driver. The control system must interpret what the driver is trying to do, and to deliver what is expected

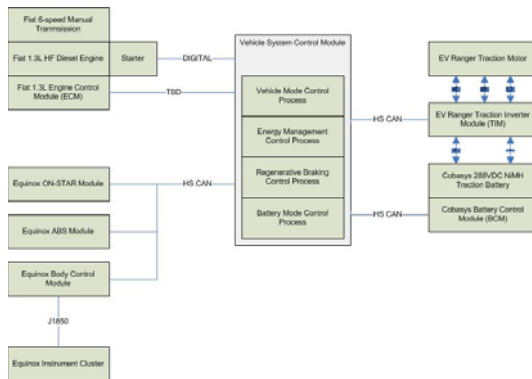
up to the limitations of the entire system. The primary interface for the driver to the vehicle is the accelerator and brake pedals. These inputs are transformed into control signals for the traction motor and heat engine. These two primary motive forces work together to provide the necessary torque to satisfy the demands of the driver.

Since the design philosophy of this control system employs a charge-sustaining approach, the hybrid control system must maintain the state of charge of the high voltage battery pack. This must be integral to the control algorithm and, more importantly, be transparent to the driver. Fluctuations of the delivered torque to the drive wheels are not desired from a consumer acceptability and drivability point-of-view.

There are two (2) basic sources of energy in the powertrain to charge the battery pack. The first device, dubbed regenerative braking, is to make use of the otherwise wasted kinetic energy from a braking event. Regenerative braking can lead to a more efficient drivetrain. Regenerative braking can be applied in two (2) basic versions. The most efficient means of regenerative braking is referred to as series regenerative braking. In this approach, the traction motor absorbs all of the energy from the wheels to slow the vehicle up to a charge limitation on the battery. At this point, the foundation brakes are then applied. While this is the best system to use, it is inherently more difficult to implement. The second approach to regenerative braking is referred to as parallel regenerative braking. The basic difference with this version versus the series approach is the traction motor and foundation brakes work in parallel to slow the vehicle down. For this reason, it is less efficient since less energy is returned to the high voltage battery pack. Parallel regenerative braking is much easier to implement. However, due the overall system efficiency gains that can be attained and the powertrain configuration chosen by the team, the series regenerative braking approach shall be incorporated in to the UTK controls design.

The second device for charging the battery pack is to use the traction motor as a generator that removes energy from the heat engine. Due to the architecture selection of the UTK team, this can only be accomplished when the vehicle is moving. Idle charging of the high voltage battery pack is not possible in this configuration.

One of the key items for HEV durability is the life span of the high voltage battery pack. The vehicle control system should provide a means of limiting available battery power based on the limitations of the pack itself. In order for the battery to survive for a predetermined warranty period, strict adherence to battery pack manufacturer limitations should be obeyed. Such items as charge and discharge limitations, maximum module temp, and state of charge limitations must be taken into account when coordinating the interactions of the traction motor and the heat engine. A high level overview of the UTK Challenge X control system is shown in Figure 3.



**Figure 5 High level overview of Team Tennessee's Challenge X control system**

The heart of the UTK Challenge X control system is the Vehicle System Control Module (VSCM). The VSCM interfaces virtually every other subsystem in the vehicle. The VSCM coordinates which systems are active at any given time instant, and how they interact. The Battery Control Module (BCM) acts as the liaison between the VSCM and the high voltage battery pack. The BCM specifies battery pack limitations, estimates state of charge (SOC), and outputs basic battery physical data (such as voltage and current). The Traction Inverter Module (TIM) acts as the interface to the high voltage traction motor. The TIM is responsible for powering and protecting the traction motor. The scope of this paper includes the development of the VSCM. All other modules are outside the scope of this paper. Most of these modules are self contained from each respective manufacturer.

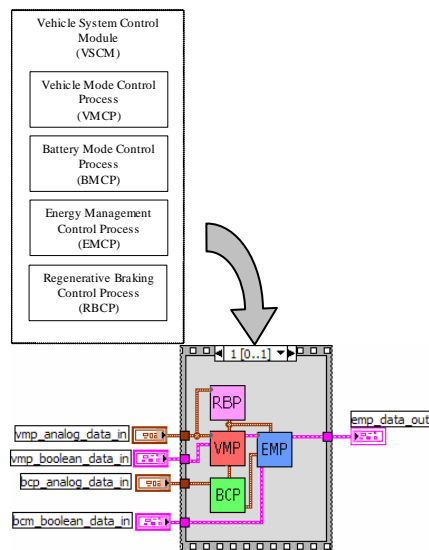
### Hardware Architecture

The hardware used for the implementation of the UTK control system strategy will be a progression of hardware starting with PXI equipment for Year One, the CompactRIO platform for the mule level

vehicle in Year Two, and finally a fully integrated microcontroller running LabVIEW Embedded Edition for Year Three. In addition, a PXI system will be used during all three years of the competition for the purposes of serving as a vehicle simulator for SIL and HIL development.

### Software Architecture

The VSCM is comprised of four (4) basic control processes. These are shown in Figure 4. The Vehicle Mode Control Process (VMCP) is responsible for monitoring the status of the key, translating driver intent, and determining when the engine should run. The Battery Mode Control Process (BMCP) acts as an extension to the BCM. Both the VMCP and the BMCP function in parallel to supply the necessary information to the Energy Management Control Process (EMCP). The EMCP acts as a moderator for the interaction of the traction motor and the heat engine. The Regenerative Braking Control Process (RBCP) is responsible for coordinating all regenerative braking events. The output of the RBCP feeds into the EMCP to modify control of the traction motor based on drive requested braking commands. Figure 4 represents the layout of the VSCM and its corresponding control processes. The VSCM is coded in a modular manner in the LabVIEW RT environment, applying data flow practices.



**Figure 6 Overall VSCM layout and LabVIEW representation**

## Energy Management Strategy

The Energy Management Control Process (EMCP) is the most critical process within the VSCM. The EMCP is responsible for coordinating the interaction of the heat engine and the traction motor. The EMCP must ensure that the driver demanded power is satisfied while at the same time maintaining the state-of-charge of the HV battery pack. The EMCP must deliver these items while also administering overall system limitations for sub-component protection.

The EMCP joins the outputs from the BMCP, the VMCP, and the RBCP to determine what is required of the heat engine and the traction motor. The root output of the VMCP is the driver demanded power, dubbed  $P_{drv}$ . The prime output of the BMCP is the power necessary to maintain the SOC of the HV battery pack, referred to as  $P_{SOC}$ .  $P_{SOC}$  is a calibrateable function of the state of charge of the HV battery pack. These variables together form the total power required of the engine in HEV mode. It is worth noting that  $P_{SOC}$  is ignored in a ZEV mode. The total engine power desired, designated  $P_{tot}$ , thus becomes

$$P_{tot} = P_{drv} - P_{SOC}$$

where,

$P_{SOC} < 0$  indicates power to *CHARGE* battery  
 $P_{SOC} > 0$  indicates power to *DISCHARGE* battery.

The primary function of the EMCP is to deliver the appropriate torque commands to the engine and traction motor that 1) satisfy the driver demand and SOC maintenance demand and 2) apply overall system limitations and constraints. One of the most important functions that the EMCP must include is to protect the high voltage system, particularly the battery pack. The EMCP utilizes the modified charge and discharge power limitation determined in the BMCP and calculates the corrected traction motor torque command, based on the previously determined  $P_{elec\_des}$  (electrical power required of the drive system), to ensure that the current drawn from the battery pack does not violate its maximum system limits. The EMCP offsets the  $P_{elec\_des}$  command by filtering the error of  $P_{elec\_des}$  and  $P_{battery\_actual}$  (actual battery power at any given instant of time) through a PID controller.

## EVOLUTION VIRTUAL INSTRUMENTATION SOLUTIONS

### Integration with other vehicle systems

The control system being developed for UTK Challenge X vehicle not only has to control the key components of the hybrid powertrain, but also has to interface existing and new vehicle systems. The 2005 Chevrolet Equinox SUV contains a high-speed CAN communications protocol that must be interfaced with the VSCM. NI-CAN will be the tool used to bridge the gap. The high voltage system supplied by Cobasys and the electric transaxle both communicate via high-speed CAN. NI-CAN will be used to communicate with these subsystems as well.

### Benefits of implemented Virtual Instrumentation application

The Virtual Instrumentation applications being employed in the UTK Challenge X vehicle control system development greatly enhanced the quality of the control system and reduced prototyping time. Perhaps the greatest benefit of the VI applications that are being used is the ability to run the control strategy in real-time, and to be able to make logic and calibrations corrections while the vehicle is operating. The VI's being developed for this application are structured in such a way so that any variable can be viewed in real-time. This allows spot checks of the functionality of the controller, and the ability to quickly track down faulty logic or coding. In our opinion, this is the very heart of Virtual Instrumentation – viewing data in real-time within a program with no physical sensors or actuators. The application of Virtual Instrumentation to the UTK Challenge X control system makes development quick and painless.

### Enhancing development through Virtual Instrumentation

Team Tennessee is making extensive use of Virtual Instrumentation throughout the design process. Virtual Instrumentation is used to perform measurements during system and subsystem testing wherever possible due to ease of use and rapid turnaround. As an example, we created a VI interface to our Cobasys high voltage battery pack. This pack communicates over CAN. The front panel of this VI is shown in Figure 7. This VI also allows us to read all of the CAN messages coming

out of the battery pack for diagnostic purposes. In addition, the VI was created as a modular program such that it could be integrated into the VSCM later. A similar interface is under development for the electric transaxle subsystem.

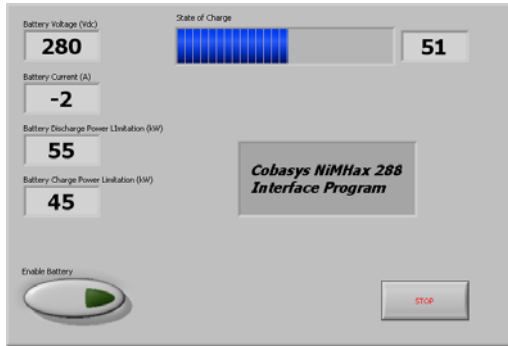


Figure 7 Cobasys high voltage battery LabVIEW interface VI

As a second example, a custom LabVIEW VI was written using the Simulation Module of LabVIEW. The purpose of creating this VI was to allow the controls team to work in parallel to develop battery control algorithms. This VI contains motor, battery, and vehicle models to simulate a zero emission vehicle (ZEV) only mode of operation. Utilizing this model, the team can fine tune the closed loop control of the high voltage battery pack, and to develop new approaches to controlling the electric motor and high voltage battery. Figure 8 represents the front panel and block diagram of this effort.

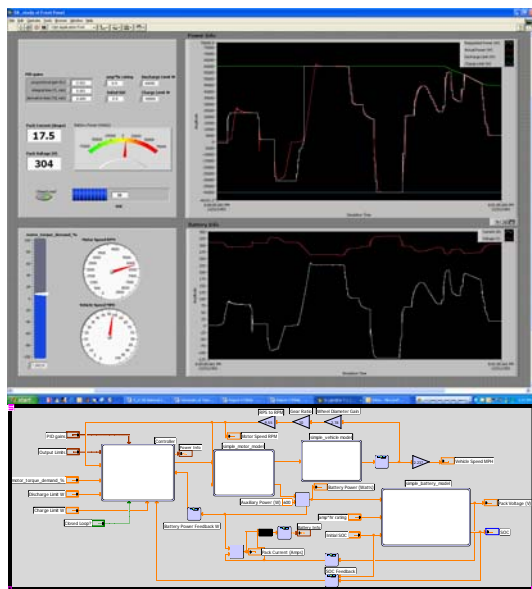


Figure 8 Battery simulation VI utilizing NI Simulation Module

The heart of the UTK Challenge X entry is the control system. A custom LabVIEW RT VI library was put together for this purpose. The top level diagram for the control system is shown in Figure 9. It is clear from the diagram where the benefits of Virtual Instrumentation are evident. Controls and indicators can be directly read during program execution to determine if the VI is functioning as expected.

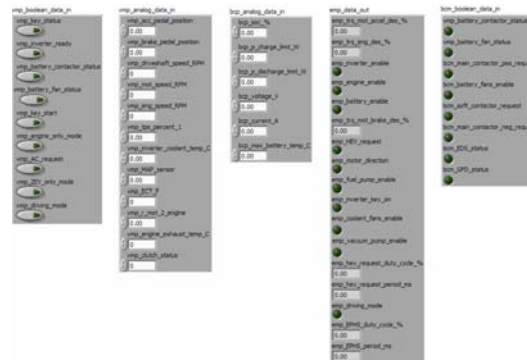


Figure 9 LabVIEW front panel of VSCM code

A calibration VI is being developed in order to be able to change system calibrateables during actual code execution. This VI structure is developed in such a way so that the operator can manipulate these variables “on the fly” while the vehicle is in operation. This functionality is a great boost to tuning the control system in the Equinox. An example of the calibration VI for the BMCP is shown in Figure 10.

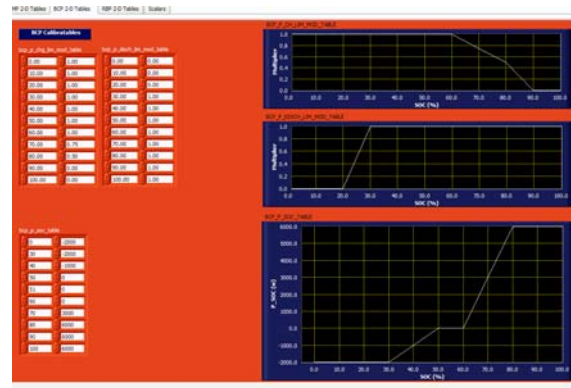


Figure 10 BMCP calibration front panel

Control algorithms are custom made in the graphical programming environment of LabVIEW. The control algorithms are being developed in a modular manner, allowing for the code to be partitioned. This “partitioning” creates a simple yet effective method for sectioning off suspected sections of code

that are not performing adequately. Furthermore, Virtual Instrumentation through the use of LabVIEW allows data that is passed between respective subVI's to be inspected during code execution with no extra programming of setup required. An example of this data viewing is shown in Figure 9 by the front panel of the actual VSCM code. This makes development much faster than by using standard test base programming environments.

Datalogging is another integral part of the control code. Any variable throughout any portion of the code can be tapped and logged for later review. Again, this made programming progress at a very rapid pace.

## **MAIN CHALLENGES FOR VI IMPLEMENTATION**

The implementation of the Evolution control system presented several challenges to the team. The most significant problem the team faced was utilizing the Compact Fieldpoint hardware to control the new electronic throttle body. The loop rate of the Compact Fieldpoint processor proved to be much too slow to accurately control the position of the throttle butterfly. The ultimate solution to this problem was to construct a dedicated electronic throttle controller based on a separate microcontroller running at 20 MHz. This system proved to be successful with no loss of functionality to the main LabVIEW control system

## **CONCLUSION**

A sophisticated control system was developed for the University of Tennessee FutureTruck, *Evolution*. The control system was developed using extensive use of Virtual Instrumentation principles from base software development, to subcomponent testing, to the actual vehicle application. The use of Virtual Instrumentation streamlined the entire controls development process, making *Evolution* a successful hybrid electric vehicle.

## **APPENDIX**

A complete schematic diagram of the UTK Challenge X control system is shown in the Appendix in Figure 11.

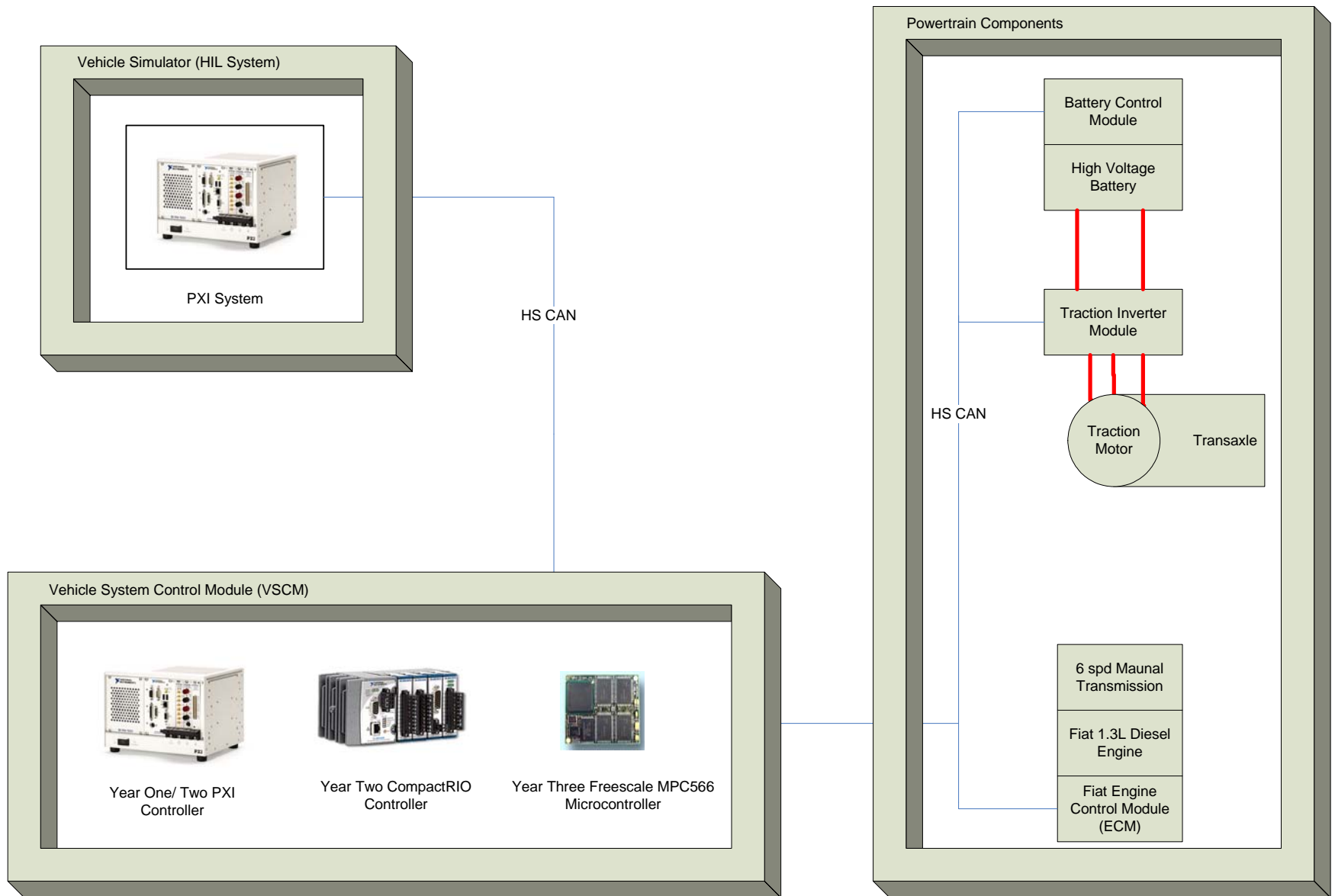


Figure 11. Schematic diagram of UTK Challenge X control system development tools