August 2003

automotive engineering international

Virtual powertrain, real results

SAE International

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As powertrain control systems require more complex validation testing in less time, Ford is teaming with Concurrent Computer to develop a HIL simulation system that tests real control hardware in the virtual world.

To manage the function of a vehicle's engine, transmission, and related subsystems, almost all modern vehicles make use of an electronic control system. This powertrain control system (PCS) continues to become more complex to meet evolving customer expectations and increasingly strict environmental regulations. Fully validating the PCS is a necessary step in the process of developing a vehicle; however, by using traditional testing environments such as real vehicles or powertrain dynamometers, validation testing is often expensive, time-consuming, and subject to variability.

Business pressures require reductions in testing time and cost while achieving more robust vehicles. To address these concerns, **Ford** Motor Co. is placing an increasing focus on validating a PCS through simulation. Ford has teamed with **Concurrent Computer** Corp. to develop a hardware-in-the-loop (HIL) simulation system that can validate many aspects of a PCS.

A typical PCS consists of multiple microcontrollers (encased in one or more control modules) running embedded control software. HIL testing of a PCS involves interfacing these physical control modules to a simulated powertrain in a manner that is accurate enough to fully exercise the PCS through its entire range of functionality. As the brains of the powertrain, the PCS must control a complex series of events to enable proper engine and transmission function in all driving conditions over the life of the vehicle.

Each time a vehicle is started by turning the key in the ignition, an amazing sequence of events occurs. At key-on, the PCS immediately begins polling the status of a large number of sensors and actuators to determine the state of the powertrain. Once the starter motor begins to crank the engine, the PCS determines engine crankshaft position based on input from the crankshaft position sensor. Then the PCS begins to actuate fuel injectors and spark plug coils at appropriate crankshaft positions to start the engine firing. This initial series of events can occur in less than a second.

Once the engine is running, the PCS continuously monitors sensor inputs to determine the current state of the engine and transmission, while simultaneously controlling numerous actuators to keep the engine running smoothly, minimize emissions, handle gear shifts, and so on. It also continuously performs onboard diagnostics of the powertrain and, if needed, sets malfunction codes and the "check engine" light. Technicians can then access these codes to determine the need for repairs.

Ford's VPACS-HIL lab

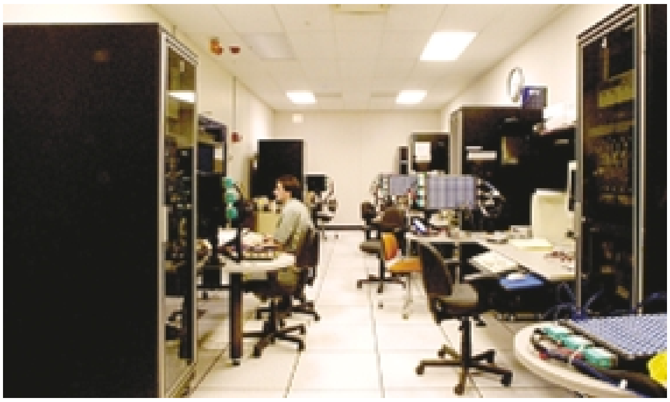
Ford needed a way to fully validate these complex PCS control functions and the associated hardware design while addressing increasing cost pressures, reduced development time, and a desire for improvements in PCS quality. To accomplish this, it worked with Concurrent to create the Virtual Powertrain and Control System (VPACS) HIL Laboratory.

VPACS is Ford's dynamic, closed-loop simulation of all aspects of a vehicle's powertrain (actuators, engine and subsystems, sensors, transmission and driveline, exhaust system and aftertreatment, vehicle, and human driver). VPACS-HIL interfaces this powertrain simulation to a physical PCS by using simulated electrical loads, extensive analog and digital I/O, and modular wiring harnesses.

The VPACS environment allows Ford engineers to run a series of automated tests or interactively "drive" the simulated powertrain by controlling a simulated throttle, brake, gear shift, and other user inputs. At the completion of VPACS-HIL testing, the goal is to deliver a PCS capable of properly running a physical powertrain for additional testing in a powertrain dynamometer and in vehicles. Delivering this "first run" capability to those downstream testing methods greatly reduces the quantity of tests requiring physical prototypes, resulting in significant savings of both time and money.

Current VPACS development is focused on automating comprehensive testing procedures and expanding the application of VPACS to a greater number of vehicle applications. Automated testing, which provides consistent test procedures and standardized results, is being addressed through the development and application of improved test control software tools. To increase the number of vehicle applications that can be supported, Ford developed new VPACS stations that are easy to reconfigure and expanded the VPACS-HIL lab to house more test stands.

The new HIL test station is based on Concurrent's Power Hawk 740 real-time, symmetric multiprocessing system. It contains all of the I/O to successfully communicate with the PCS. Originally, Ford teamed with Concurrent's Professional Services to port a non-real-time version of VPACS to Concurrent's Night Hawk 6800. This product is very useful in testing and calibrating the PCS embedded software but cannot evaluate certain characteristics of the physical PCS—namely, the physical electronics, low-level driver software, and



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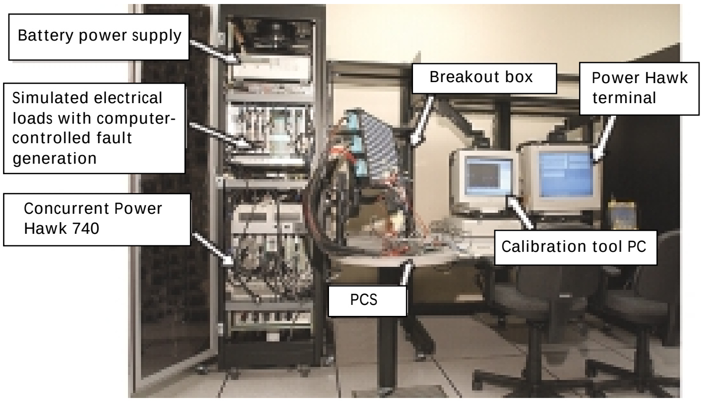

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chronometrics. Concurrent's Professional Services team worked together with Ford's engineers to port the software and add the real-time constructs.

When Ford wanted to upgrade to the Power Hawk 740, it teamed with Concurrent's Professional Services again to move its application to the new platform and integrate the Power Hawk 740 with new third-party products to provide the complete HIL test system to Ford.

How it works

Structuring the virtual powertrain model to interface in real time with a physical PCS was accomplished with several hardware and software technologies that work together to keep the system on a predetermined time frame. The following sections detail each of these technologies.

Time-To-Edge (TTE)—The TTE is a 16-channel I/O board that resides on the VME bus and is capable of outputting edges with a resolution of one microsecond. The TTE receives edge-timing instructions from the simulation software in the form of a data pattern (DP) for the 16 outputs with an associated clock time stamp (TS). These edges are stored in an event queue. When the time stamp of the first data pattern in the event queue matches the TTE's internal clock, it will output the associated data pattern. This internal counter is connected to the VME system clock (SYSCLK). One TTE board is selected as the master for all TTE and change-of-state board counters in the system and disables their counters until it receives the command to start. The TTE master then enables the other board counters, which are then pulsed by SYSCLK. This process keeps all the counters/timers synchronized to the same microsecond value.

For the VPACS application, one TTE board is used to generate all digital pulse trains requiring high-precision edge timing. The TTE board also generates the system "heartbeat," an interrupt pulse each millisecond that controls the real-time execution of the virtual powertrain simulation.

Change Of State (COS)—The COS is a 16-channel I/O board that resides on the VME bus. The COS board is capable of receiving 16 digital inputs; when any of the inputs change state (from high to low or low to high), the COS board will save the data pattern (DP) as well as the internal clock value (TS). This clock has a one-microsecond resolution. The input that has changed and the time of the event are then read by the model simulation and used for the next set of computations. The COS board also supports the use of SYSCLK to strobe its counter.

For the VPACS application, two COS boards are used to record on/off actuators requiring high-precision recording of timing data—namely, fuel injectors and spark ignition coils.

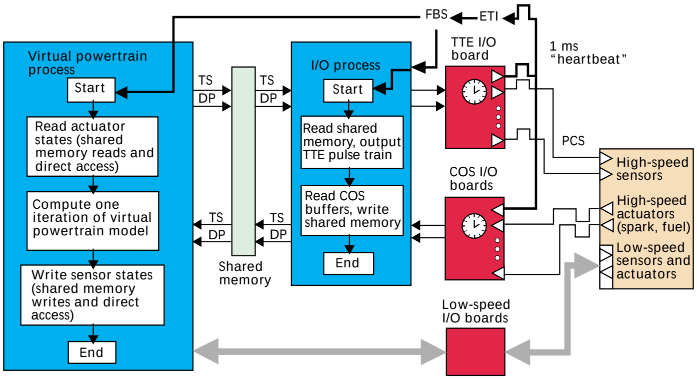
Edge Triggered Interrupt (ETI)—ETIs are standard features of Concurrent's Real-time Clock and Interrupt Module (RCIM). The RCIM is a PCI mezzanine card and installs directly on the Power Hawk 740 central-processing-unit board. The RCIM will accept a TTL signal and, with minimum latency, interrupt the processor to which it is assigned. The processor will then jump to the interrupt routine that is assigned to the interrupt—in this case, the frequency-based scheduler.

Frequency Based Scheduler (FBS)—Concurrent's FBS can accept an external event, such as the ETI being triggered by the TTE signal, and then initiate processes that have been previously scheduled at predetermined times. This product also includes a performance monitor that ensures the processes are completed within the allotted time frame. If the code is not completed in time, a frame-overrun error will be generated.

The two main processes in the virtual powertrain simulation are the virtual powertrain process and the I/O process, which manages and logs high-speed data. Each process is executed on a separate processor. To allow for accurate computations while being able to run in real time, the timing interval for the virtual powertrain process has been selected as five milliseconds, with high-speed values being calculated on an internal half-millisecond time-step. Therefore, the virtual powertrain process receives a wake-up signal from the FBS every five milliseconds. To properly update high-speed signals and avoid excessive buffer sizes, the I/O process is initiated by the FBS every one millisecond.

Run-time scenario

During execution of the virtual powertrain simulation, the virtual powertrain process and the I/O process are running simultaneously, with the I/O process completing five iterations for each complete iteration of the virtual powertrain process. When the I/O process receives its wake-up signal from the FBS, it reads any TTE edges currently stored in shared memory (as provided by the previous iteration of the virtual powertrain process). The I/O program then sorts these edges to ensure that the time stamps are in chronological order and loads the TTE board with



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the calculated data pattern and the corresponding output time. When this time is reached, the TTE board outputs the commanded signal states, which are then visible to the PCS. In addition to outputting TTE edges, on each of its iterations the I/O process reads the buffer of the COS board and deposits any new input edges into shared memory. These COS edges are then available to the virtual powertrain process.

When the virtual powertrain process receives its wake-up signal from the FBS, inputs (including COS edges indicating fuel injectors and spark ignition coils) are processed to determine the state of the powertrain actuators. Based on these states, sensor values are determined and output. Of particular complexity are the high-speed sensor signals (*e.g.*, engine crankshaft position).

It is imperative that the PCS receive crankshaft-position sensor edges with a resolution on the order of one microsecond to accurately simulate crankshaft velocity and acceleration. To generate these edges in real time, the virtual powertrain model predicts the crankshaft position several milliseconds into the future based on current rotational speeds. The model then defines the corresponding pulse train of TTE edge-states and edge-times that will define this predicted position of the crankshaft, and loads these pairs of edge-state and edge-time data into shared memory.

Note that while the virtual powertrain simulation uses shared memory to communicate TTE and COS edges between the virtual powertrain process and the I/O process, it directly accesses the remaining I/O boards, which have less strict timing requirements.

In conclusion, Ford is working to reduce the cost and development time needed to validate a PCS through HIL testing. Concurrent's symmetric multiprocessing computers and real-time programming constructs have provided the high-resolution real-time performance needed to fully interface VPACS to a PCS. This capability, in combination with extensive signal I/O and simulated electrical loads, allows VPACS-HIL to provide an environment for validating many aspects of a PCS.

Tim Cardanha, Ford Motor Co., and **Ken Jackson**, Concurrent Computer Corp., wrote this article for *AEI*.