

Innovations In Experimental Techniques For The Development of Fuel Path Control In Diesel Engines

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ABSTRACT

The recent development of diesel engine fuel injection systems has been dominated by how to manage the degrees of freedom that common rail multi-pulse systems now offer. A number of production engines already use four injection events while in research, work based on up to eight injection events has been reported.

It is the degrees of freedom that lead to a novel experimental requirements. There is a potentially complex experimental program needed to simply understand how injection parameters influence the combustion process in steady state. Combustion behavior is not a continuum and as both injection and EGR rates are adjusted, distinct combustion modes emerge.

Conventional calibration processes are severely challenged in the face of large number of degrees of freedom and as a consequence new development approaches are needed.

Our paper will describe the background to a project formulated to investigate the application of Model Predictive Control (MPC) to a Caterpillar C6.6 diesel engine. We outline an innovative experimental facility developed for Rapid Control Prototyping (RCP) for both air and fuel path using Field Programmable Gate Array (FPGA) technology. This utilizes a Drivven FPGA injector driving system coupled with National Instruments™ (NI) hardware (PXI, CompactRIO) and LabVIEW 8.5 software. A detailed review is presented of the development stages from an initial single cylinder open loop fuel path control system through to a full-authority 6-cylinder injection system which replaces the Engine Control Unit (ECU).

The original ECU fuel path control algorithms have been re-written in LabVIEW Real-Time (RT) to emulate the original

ECU function. Drivven's CalVIEW is used for supervisory control and to manage engine maps over a local area network link with the NI RT environment. Two novel techniques are explored for integrating MathWorks™ Simulink based controllers through NI's Simulation Interface Toolkit. Results demonstrate the control of exhaust temperature using MPC.

INTRODUCTION

Fuel path control for a common rail equipped diesel engine fundamentally requires a fuel injection multi-pulse pattern to be varied in terms of both the number of shots per cycle and also the shot distribution (inter-shot time delay) in order to fully optimize engine emissions and performance across the operating range of the engine. This is illustrated in [figure 1](#) which shows the variation of pulse distribution with speed and load in an engine equipped with the Fiat Multijet system.

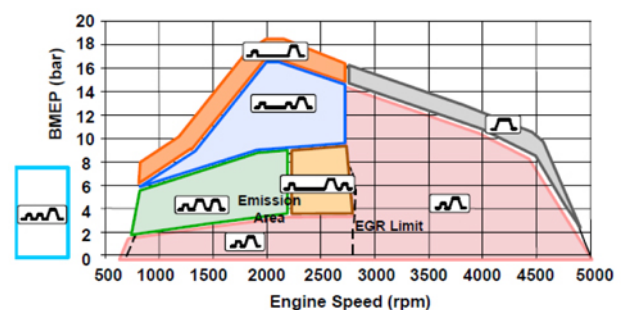


Figure 1. A typical Fiat Multijet calibration for a Passenger Car Application [1]

The term “high degree of freedom” (HDOF) is now used to refer to such an engine which is also equipped with controllable EGR, boost, diesel particulate filter regeneration, selective catalytic reduction and in the future possibly a variable valve timing system. In diesel engine development, the greatest challenge is now the efficient calibration of this

HDOF system in order to enable the engine to meet the competing demands of emissions constraints and low fuel consumption.

The conventional diesel engine control technique is to undertake a large scale calibration program where the system is optimized in real time according to conditions local to the engine like barometric pressure, temperature and fuel quality. The engine is then operated with a combination of open and closed-loop regimes with multiple, often cascading, 1D and 2D maps used to determine such parameters as desired shot number, pilot advance and main duration. This technique affords the engine manufacturer with a reliable, robust and well understood control architecture which accommodates non-linearity across the whole engine speed-load operating range and it has thus dominated.

This methodology, when combined with feed-forward calculations and air-fuel ratio feedback, has proved sufficient even for Super Low Emissions Vehicle (SULEV) controls. However, as the numbers of degrees of freedom expand with new emerging technologies, the required calibration process is rapidly mushrooming into the primary absorber of engine development time and costs. [Figure 2](#) illustrates this for the development of a new Bosch ECU for the GM 3.6L V6 engine in the Cadillac CTS [2].

Here a Design of Experiments (DOE) approach was applied with a fraction factorial design to substantially reduce the otherwise prohibitively large set of mapping points. Other studies have demonstrated in greater detail the significant advantage DOE techniques provide when undertaking engine calibration [3].

In response these issues and others, model predictive control techniques (MPC) are now increasingly being considered in engine control research and development.

Parameter	Number of Variation Steps	Total Number of Mapping Points
Engine Speed	16	16
Engine Load	12	192
Ignition Timing	10	1920
Injection timing	6	11,520
Manifold Pressure	4	46,080
Split Factor	3	138,240
Intake Cam	10	1,382,400
Exhaust Cam	10	13,824,000
Fuel Pressure	5	69,120,000

Figure 2. Bosch Cadillac CTS Motronic MED9.6.1 ECU Conventional Mapping Number of Points [2]

OVERVIEW

Research reported herein confronts the need to innovate in engine control hardware and software capabilities to meet these new challenges. A relatively recent development in Field-Programmable-Gate-Array (FPGA) based hardware for diesel engine control, which has a high potential with regards to meeting current challenges, is investigated. This is combined with a novel integration of Simulink based engine control models into a LabVIEW Real Time (RT)/FPGA software environment.

- The primary aim is to demonstrate the technical achievement of closed loop model predictive multi-pulse fuel path control on an adapted Caterpillar C6.6 engine using National Instruments LabVIEW and Mathworks Simulink software and specialized commercial FPGA hardware. In this set-up, the engine control unit (ECU) has been completely removed from any engine control responsibilities; its function limited to providing an electrical power source for specific engine sensors. There are two stages in this process:

- First: The original ECU control algorithms and maps are faithfully reconstructed in LabVIEW RT and the engine is demonstrated to operate successfully under this 'ECU software emulation' mode.

- Second: The newly achieved closed loop control capabilities are proven with a demonstration of the control of a close-coupled-pilot plus main fuel injection pattern. This involves the closed loop control of fuel rail pressure (FRP), start of injection (SOI), pilot dwell and the ratio of pilot and main fuel quantities. The purpose being the control of exhaust temperature to a narrow operating window of $\pm 10^{\circ}\text{C}$ for a range of engine rpm and loads. (Such a capability provides the prospect for reduced size and cost of SCR/DPF systems.)

- The secondary aim is to illustrate the technical advantages of this software and hardware system configuration. An example being the rapid deployment and testing capability that is inherent in the system's design - benefiting the development of new novel open/closed loop engine fuel path control software and model predictive control algorithms.

ENGINE CONTROL BACKGROUND

Modern production ECUs are turnkey solutions that utilize sophisticated electronics and software. The microprocessor of the latest ECUs used in DI applications can operate at 66MHz and support upwards of 2Mbit of external memory [2]. They are highly specialized devices and incorporate as little hardware as possible to minimize cost. The I/O of a production ECU is also tightly confined with little or no scope for expansion to include supplementary actuators or sensor signals. Thus, the flexibility of ECUs for engine control research and development work is somewhat restricted. For such situations, research orientated ECUs are produced which provide more computing power and greater

I/O flexibility [4]. However, these are usually tightly controlled with regards to availability and then there is the high cost to consider.

In response to these issues, engine control system researchers and developers turn to far more flexible systems often referred to as Rapid Control Prototyping (RCP) systems [5]. These are usually built from combinations of commercially available hardware and software products to provide a programmable real-time I/O architecture [6]. Such an architecture must be able to support both synchronous/non-synchronous input/output from engine sensors/actuators respectively [4]. RCP enables evaluation of control algorithms in real time on an engine, avoiding the need to target the code to an actual ECU. Increasingly, FPGA based technologies are being utilized as part of this process [4,6,9,12,13,14,25,29,33,34,35,36,37,38,40].

Recent developments in diesel engine control have demonstrated the use of closed loop control to reduce the so-called dispersion effects that are the result of small component and operating variations seen in all engines [7,8]. A direct method based on closed loop cylinder pressure feedback is entering the market in the form of the GM CTS engine. Previously, techniques such as those that employ specifically tailored algorithms to monitor engine crank angular velocity down to 10s milliseconds were used in order to detect inter-cylinder combustion imbalances [2, 9]. Cylinder block vibration monitoring has also been successfully used for cycle-to-cycle variation detection [10].

Performance data for the GM CTS engine demonstrates the ability to be emissions compliant simply through the use of closed loop control [47]. The objective is to meet the requirements of Tier 2 Bin 5 regulations and here this is achieved by attaining a 50% burn duration target using EGR, charge temperature and injection timing and duration. Naturally, this capability increases the computational load on the ECU and thus its cost. This can potentially be somewhat offset by the reduction in after-treatment system requirements.

Increasingly, fuel injection is also used to control both mode of combustion and the trajectory of the combustion event. In [12,13,14], fuel injection parameters are selected to guide the development of a homogeneous charge that achieves effective combustion phasing while avoiding loss of efficiency through premature termination of combustion. In [13] the selection of pulse configuration is achieved through the application of closed loop adaptive control. Up to 12 pulses per cycle are selected to balance combustion phasing and the combustion cycle.

The combination of closed loop control [11] and multi-pulse injection control [1] leads to a control system in which multiple control objectives can be supported. In order to

achieve the full potential of such a control system, an optimal closed loop control is needed with an explicit objective function that captures the balance between control goals.

To reduce the number of look up tables, other control methods can be used. Model Predictive Control (MPC) [15] has been investigated to optimize engine system behavior. MPC uses a dynamic model of the system to be controlled and is based on iterative, finite horizon optimization of an engine system model. At a time t the system characteristics of interest are sampled and an algorithm calculates a cost minimizing control strategy step for a short time horizon p in the future: $[t, t + p]$.

The adaptation within the arena of engine control has thus now expanded to encompass new areas such as: mode and trajectory control of diesel engine cycles, diesel particulate trap regeneration [16], selective catalytic reduction [17,18,19], closed loop control [7,8] and MPC control algorithms [20]. This requires substantial changes in both the hardware and software used during research and development, leading each to become increasingly sophisticated and flexible. For instance, the feedback and rapid analysis of cylinder pressure data for next cycle control requires substantial computational resources in addition to an efficient method of software algorithm development and testing.

The product development cycle for an ECU is often described by a V-Diagram, figure 3 [5]. As such, there is feedback between the design and development stages of the left-hand side and the test-stages of the right-hand side. With the increasing number of variables and control actuators of modern ECUs this workflow is very complex and is made more difficult by the common need to use multi-vendor tools [5]. Handling large amounts of data also brings about the issue of data management. Sophisticated systems have to be used to collect, store and share data. Model based testing of ECUs with Hardware-in-the-Loop (HIL) test benches is now being increasingly used [4, 21] to shorten the product development cycle.

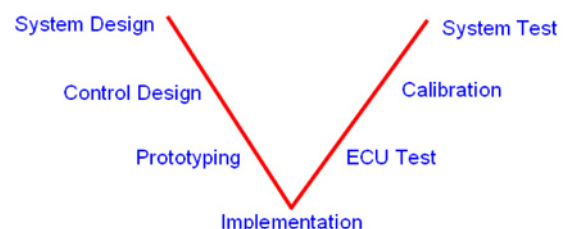


Figure 3. V-Diagram of the ECU Development Process [5]

Thus, a strategy of simply increasing ECU processor throughput and memory to support the ever expanding map



based engine control methodology, is proving increasingly inefficient during engine development [2,21] and is regarded as unsustainable in the longer term. New innovative solutions in hardware and software practices are clearly required.

TECHNOLOGY BACKGROUND

A review of published literature concerning engine control investigations that utilize FPGA has shown that relatively few independent studies exist [4,6,9,12,13,14,25,29,33,34,35,36,37,38,40]. Those based on the LabVIEW derived technique discussed in this paper are even fewer [4,6,12,13,14,29,33,34,35,36,37,40]. Even less consider FPGA for full-authority engine control [4,6,29,33,34,35,36]. As such it is sensible to summarize the key technologies involved.

FPGA AND LABVIEW

A recent Gartner Dataquest study predicts that the revenue from automotive usage of FPGAs will triple to approximately \$312 million during the period 2007 to 2010 [22]. These will be employed in many applications including: driver assistance (safety), navigation, entertainment, adaptive cruise control, next-generation engine electronics and emissions control. Engineers originally familiar with developing embedded applications for microcontrollers are increasingly encountering FPGA and Application Specific Integrated Circuits (ASIC) technologies. This rapid expansion of the utilization of FPGA is the result of the combination of the rapid evolution of the technology, figure 4, coupled with the increasing demand for ever greater bandwidth and functionality [23,24].

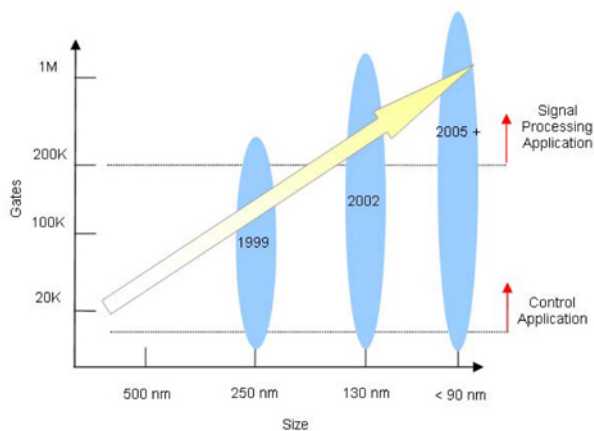


Figure 4. FPGA Evolution [24,25]

FPGA has the advantage over Application Specific Integrated Circuits (ASICs) in that it is reconfigurable and generally provides a faster time to market and lower cost solution for lower volumes [26]. It is estimated some 60% of integrated circuit designs require rework [27], thus the reconfigurable

nature of FPGAs is highly advantageous [28]. Microcontroller obsolescence is a potential major issue for automotive OEMs and of course FPGA is not limited by this issue

Application of FPGA within engine control has so far been for such things as a co-processor for engine controller tasks including knock detection and injector control [26]. Where ASICs are currently used in high-speed applications such as gasoline direct injection and diesel multiple injection, FPGA could expand to replace ASIC as the technology develops [26, 24].

An FPGA is a logic chip consisting of many un-connected configurable logic blocks (CLBs) such as AND, OR gates and flip-flops. To program a FPGA, a user develops a program using software which traditionally is a text based language such as VHDL or Verilog, referred to as hardware description languages (HDLs) [4, 26]. High-level tools are available which can greatly reduce the learning curve at the potential expense of low level code efficiency, these include LabVIEW FPGA and the Simulink HDL coder toolkit for Matlab, amongst others.

With LabVIEW FPGA, a user first develops a program using graphical tools like those of the standard LabVIEW environment. This program is then compiled and from this the logic blocks and interconnections for the FPGA can be determined. An FPGA thus becomes a circuit that performs the logic of the original program directly in hardware. As such, the process of configuring an FPGA is similar to designing an ASIC.

Whereas a logic processor can process only a single complex task at a time, FPGAs are ideal for performing many simple tasks in parallel at high speed. This is because FPGAs can be configured as many custom processors each optimised for the task specified. FPGA computational performance is equivalent to a chip-level hardware solution and orders of magnitude faster than a microprocessor and real-time operating system.

As a technology, FPGA has rapidly advanced in recent years and has reached a good balance of density, speed and cost to be considered for use in automotive I/O control applications. Others have found FPGAs to be far superior to traditional automotive microcontrollers for powertrain rapid control prototyping [29].

In the system presented here, a NI 7833R reconfigurable I/O (RIO) is used. This uses a Virtex-II V3000 FPGA with 28,672 flip-flops. The FPGA can operate at up to 40 MHz with 25ns response for custom timing and triggering logic. LabVIEW is highly suited to high-level programming of FPGA as a consequence of the natural representation of parallelism and data flow [30].

The NI 7833R is fitted in a NI PXI-1042Q chassis and real-time controller along with NI CAN [5] and DAQ cards. An advantage of this system is that it is scalable such that multiple reconfigurable I/O modules can be installed and synchronized.

A vital part of developing the hybrid host PC and FPGA system is determining what tasks should be performed on each piece of the system. All high-speed time critical I/O tasks should be done in FPGA while the real-time program should be as simple as possible with loop times of several milliseconds. Hence, engine control algorithms should be written in the real-time program.

The flexible nature of LabVIEW FPGA means that the system described in this paper can also be easily converted to form the basis of a Hardware-in-the-loop (HIL) test system for ECU or indeed fuel system components [4, 31].

NI COMPACTRIO ARCHITECTURE AND DRIVEN

CompactRIO (cRIO) is an open architecture from NI which is highly suitable for third party developers to create custom modules tailored to industry needs. Drivven Inc [32] have worked closely with NI to develop a series of products specifically for the automotive industry. These include injector drivers (gasoline/diesel), spark drivers, O₂ and NO_x sensor kits and AD combo module kits amongst others.

For the work presented here, three Drivven diesel injector modules and the O₂ UEGO sensor module kit have been utilized. These diesel injector modules are designed for peak/hold solenoid injectors but can also be used with some piezo types. Drivven successfully updated the module firmware and provided modified FPGA software blocks to expend the injector driver module capability so as to drive the high pressure (HP) fuel pump on the engine in this study.

NI SIMULATION INTERFACE TOOLKIT (SIT)

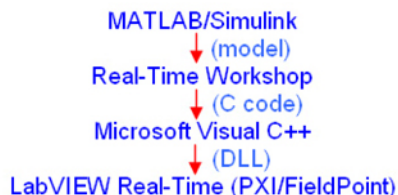


Figure 5. Generating a LabVIEW RT DLL Using Simulation Interface Toolkit

To support individuals familiar with LabVIEW for test and measurement systems who also want to use model-based design for RCP and HIL applications, NI developed the

Simulation Interface Toolkit (SIT) [5]. This LabVIEW add-on enables the incorporation of a Simulink model in a Labview based application. The diagram in figure 5 provides an overview of how SIT works internally to produce a Dynamic link Library (DLL) that can run in the LabVIEW RT environment.

The toolkit first uses The MathWorks Real-Time Workshop to convert a Simulink model to C code. This C code is then compiled into a Windows DLL using Microsoft Visual C++. Finally, the toolkit then produces a LabVIEW Virtual Instrument (VI) wrapper to call the DLL [5]. The toolkit relies upon Application Programming Interface (API) functions provided by Mathworks, Microsoft and NI.

An alternative integration approach, again using API functions, enables a specially configured LabVIEW VI to interact with internal model parameters of a compiled Simulink model [5]. This method has the advantage that a user can modify and monitor internal Simulink model parameters while it is running from the LabVIEW environment. This opens up a very interesting methodology for combining FPGA, LabVIEW, LabVIEW RT and Simulink for engine control research and development and is discussed in detail in stage II of the work presented here.

SYSTEM HARDWARE

The hardware can be separated into three categories.

ENGINE & INSTRUMENTAION SYSTEM HARDWARE

The demonstration of the predictive model based fuel path controller (FPC) system has been conducted using a Caterpillar C6.6 ACERT heavy-duty off-highway engine. The engine is a 6 cylinder, 6.6 liter engine with a Caterpillar common rail fuel system. The engine calibration used for this work produces up to 159kW at rated speed (2200rpm) with peak torque of 920Nm occurring at 1400rpm. The engine has been modified with a high pressure loop EGR system and a Variable Geometry Turbine (VGT).

The engine's original ACERT fuel injection control strategy provides multi-shot injection capability using a number of injection characteristics; start of main injection, shot duration, dwell between each shot, and fuel rail pressure.

The engine is fully instrumented to measure air, fuel and cooling system pressures, temperatures and flow rates. Emissions data is gathered principally from AVL 415 smoke and 439 opacity meters (steady state and transient measurement respectively) and a Horiba 9100 exhaust gas analyzer measuring nitrous oxide, carbon dioxide, carbon monoxide, hydrocarbons and oxygen. The temperature and pressure at the exhaust port, important parameters in the FPC,

are measured for each of the six cylinders. This is supported by exhaust manifold, post turbocharger, pre/post EGR cooler/control valve temperature and pressure measurements. [Figure 6](#) shows the engine and operator station.

Additional instrumentation provides data for items such as turbocharger speed, NO_x via an on-engine CAN based sensor, fast NO_x via an Horiba 1100-FRC and AFR via Universal Exhaust Gas Oxygen UEGO sensors. Cylinder pressure measurements for all six cylinders are obtained using Kistler 6125B ThermoCOMP® Quartz Pressure Sensors mounted in specially designed glowplug adapters. A Kistler 2854A Signal Conditioning Platform (SCP) with three 2-channel 5064B21 charge amplifiers provides the signal conditioning, including drift compensation.

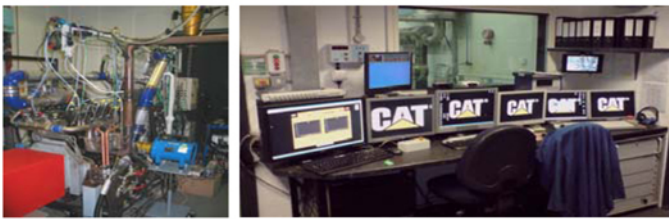


Figure 6, a & b. Instrumented Engine and the Operator Station

All six cylinder pressure signals are analyzed in real-time using a specially developed LabVIEW application with a crank angle resolution in excess of 1 degree. This includes peak pressure, Indicated Mean Effective Pressure (IMEP), Coefficient Of Variation (COV), heat release, Start Of Combustion (SOC) identification, injector current for all six cylinders, plus needle lift and sleeve pressure for one cylinder. Single or multiple cycles can be recorded for later analysis. This is linked with a second LabVIEW application that combines all the temperature, pressure, emissions measurements etc., some 90 plus channels, into a single user interface and logging utility which can record at up to 20 Hz. This very effective solution supports the rapid development of the FPC algorithms.

A specially instrumented injector measures the injector activation current, check lift profile and the injection pressure profile. Needle (check) lift is measured using a Kaman KD-2300-.5SU position sensor machined into the injector body, the injection pressure is measured using a strain gauge fixed to a flat surface machined into the check/needle sleeve. This data provides full understanding of injector behavior and injection characteristics for the FPC.

A CP Engineering Cadet V14 engine/dynamometer control system coupled to a Froude AG400-HS eddy current Dynamometer are used to manage the engine speed and load demand. This combination permits transient testing including

the Non-Road Transient Cycle (NRTC) for the entire engine speed-load range. Specially configured software and hardware sub-systems managed through Cadet regulate key system temperatures including engine coolant and the fuel delivered to the engine. Intake manifold air temperature and the EGR gas temperature (prior to mixing with the intake air) are regulated by separate air-to-water heat exchangers also controlled via Cadet.

All three monitoring/control systems: Cadet, LabVIEW and XPC (air path) require access to the same sensor signals simultaneously. This necessitates the multiple duplication of the majority of engine sensor signals and this is achieved via specially designed electronics optimized to ensure signal integrity. This provides instrumentation system redundancy and permits the Cadet monitoring, alarm and shut down chain to be highly configured to ensure test reliability, repeatability and safety.

AIR PATH CONTROL HARDWARE

For management of the air path, an XPC based system has been developed which permits full authority of both boost and EGR rate. The engine ECU has no control responsibilities for air path and the XPC system is used at all times. Control of the intake manifold boost is achieved using a VGT; a pair of Pierburg valves regulates the EGR rate. A single Simulink model incorporates both boost and EGR control functions and up to seven different open loop/MPC configurations are available. System control capability extends from emulation of the original ECU boost control through to full model based predictive control of boost and EGR utilizing the feedback of opacity and NO_x and other key sensor signals. Further details can be found here [\[41\]](#).

FUEL PATH CONTROL HARDWARE

The multi-shot fuel path control has been developed using a number of FPGA-centric hardware components with associated control software which is based on LabVIEW 8.5. The key elements in the hardware chain are a PXI-1042Q chassis with a PXI-8106 embedded controller, and three Driven Diesel Injector Driver Modules (DI Drivers) which slot into an NI-9151 C-series I/O expansion chassis. [Figure 7](#) illustrates these components in situ.

<[figure 7](#) here>

A full summary of the fuel path control hardware components and their interconnections is presented in [figure 8](#). The following sections discuss the interface between these components and the engine in more detail.

<[figure 8](#) here>