Next-Cycle and Same-Cycle Cylinder Pressure Based Control of Internal Combustion Engines

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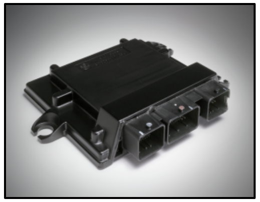

Hardware-in-the-Loop Simulation

Automotive End of Line Test

Test Cell Measurement & Control

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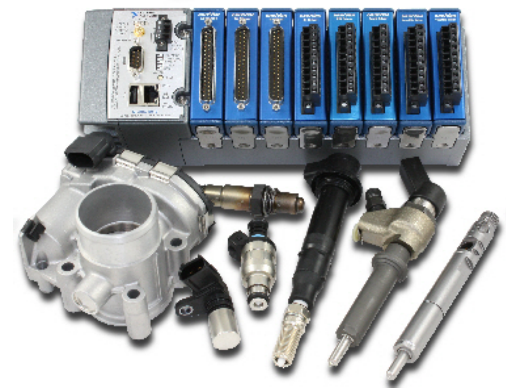
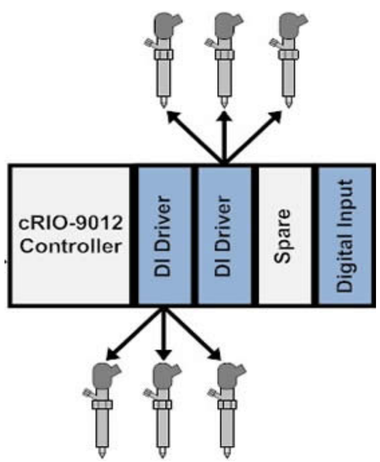
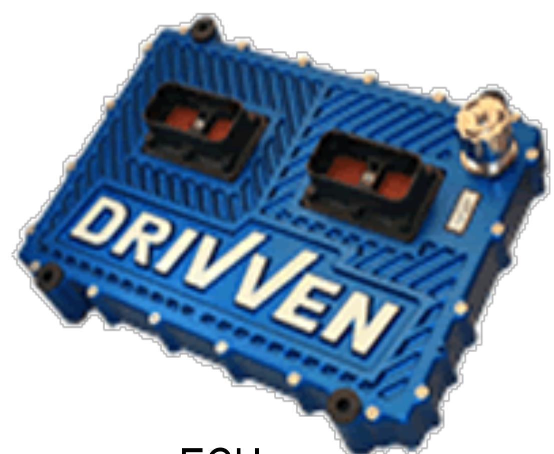
Combustion Analysis System

cRIO Modules for Engine Control





Stand-Alone Kits



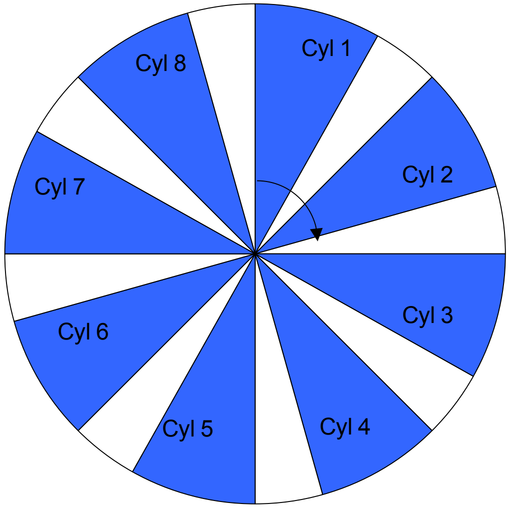
ECUs

Overview

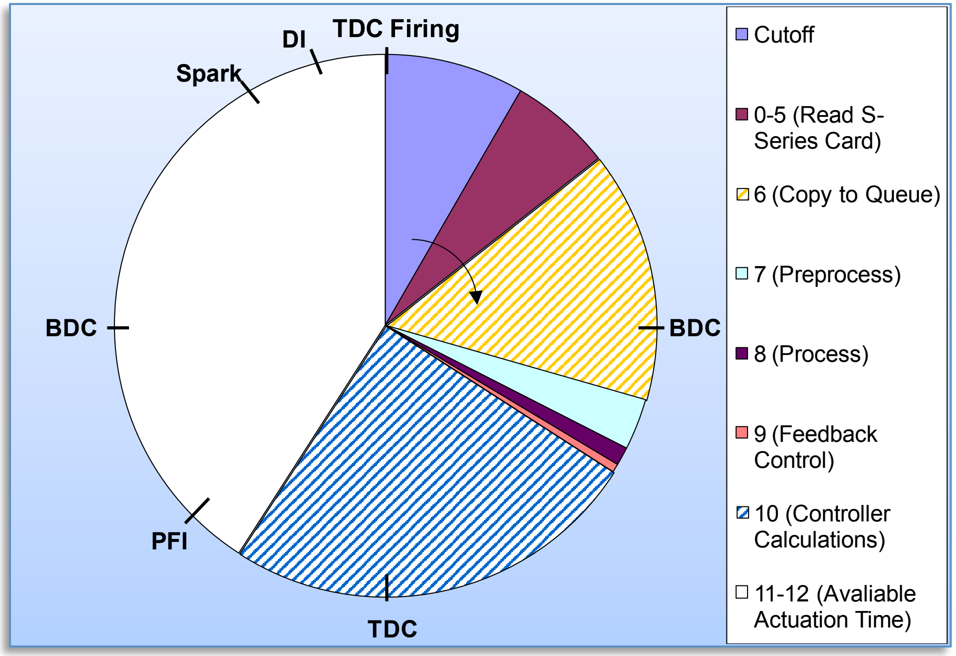
- **Next-Cycle Control**
  - Control based on cylinder pressure derived calculations
  - Calculations are complete before the next firing of the related cylinder
  - Requires <1ms loop time
  - Can be done with dedicated hardware or with interrupts in the main CPU
  - Applications
    - Load balancing
    - Auto-calibration
    - Aid in engine tuning

- **Same-Cycle Control**
  - Control within the same cylinder event
  - Requires ~ 1CAD loop times
  - Done with dedicated computing resources
  - Applications
    - Multi-inject control
    - Misfire re-spark
    - Lean misfire re-inject
    - Dynamic fuel control

Next-Cycle Control timing

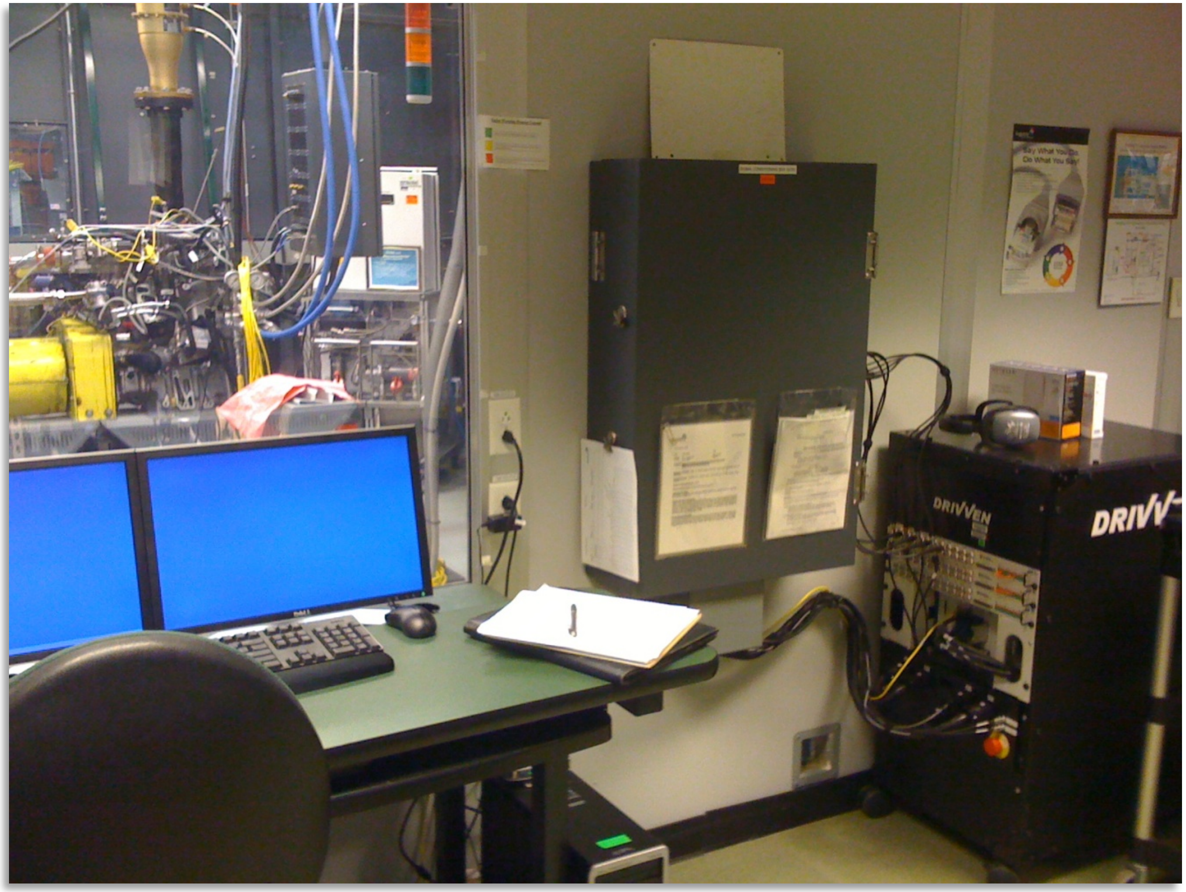


- Data must be available before it is needed in the next cylinder event
- Major timing constraints
  - Type of calculation determines “cutoff angle”
  - CPU availability
  - Actuator type



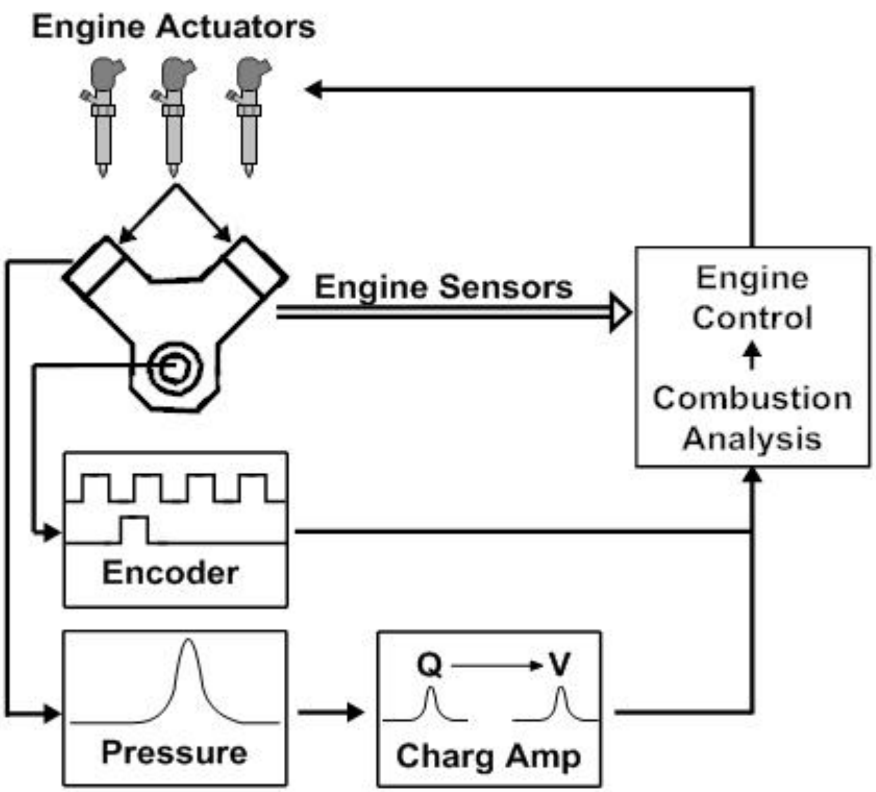
Engine Setup

- GM/Fiat 1.9L engine
  - Bosch Common-rail
  - EGR
  - Turbo
  - Variable Swirl
- 3 cylinders instrumented for cylinder pressure



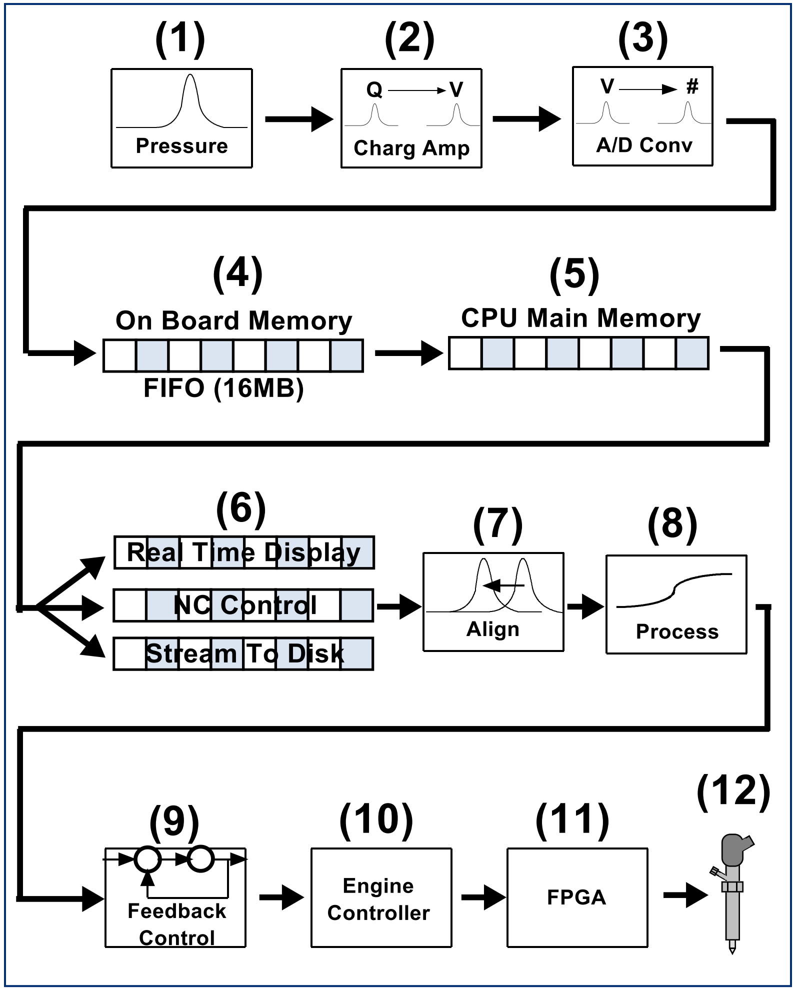
Controller Setup

- COTS Hardware
  - NI PXI-1042 8-slot chassis
  - NI PXI-8106 2.16GHz dual core real-time controller
  - NI PXI-7813R 3M gate FPGA
  - NI PXI-6123 8 channel, simultaneous sampling analog input
  - NI 9215 4 channel, simultaneous sampling analog input
- Drivven Hardware
  - Drivven AD Combo Module
  - Drivven Low-Side Module
  - Drivven DI Module
  - Drivven PFI Module
- Sensors
  - AVL GH-13P Pressure Sensors
  - AVL Micro-IFEM Charge Amplifier
  - AVL 365C Optical Encoder

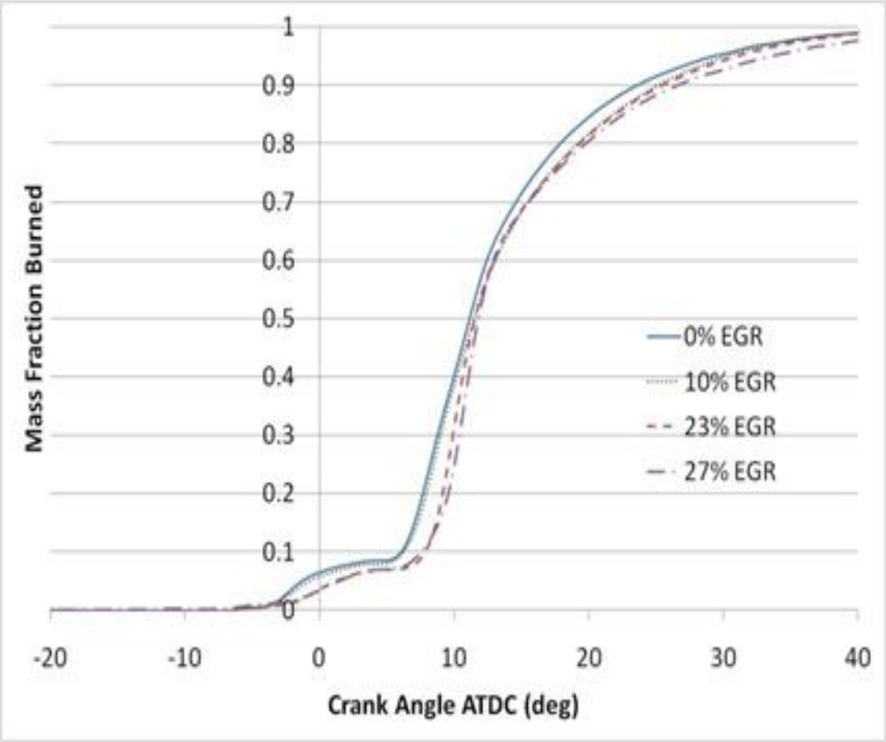


Next-Cycle Control Processing

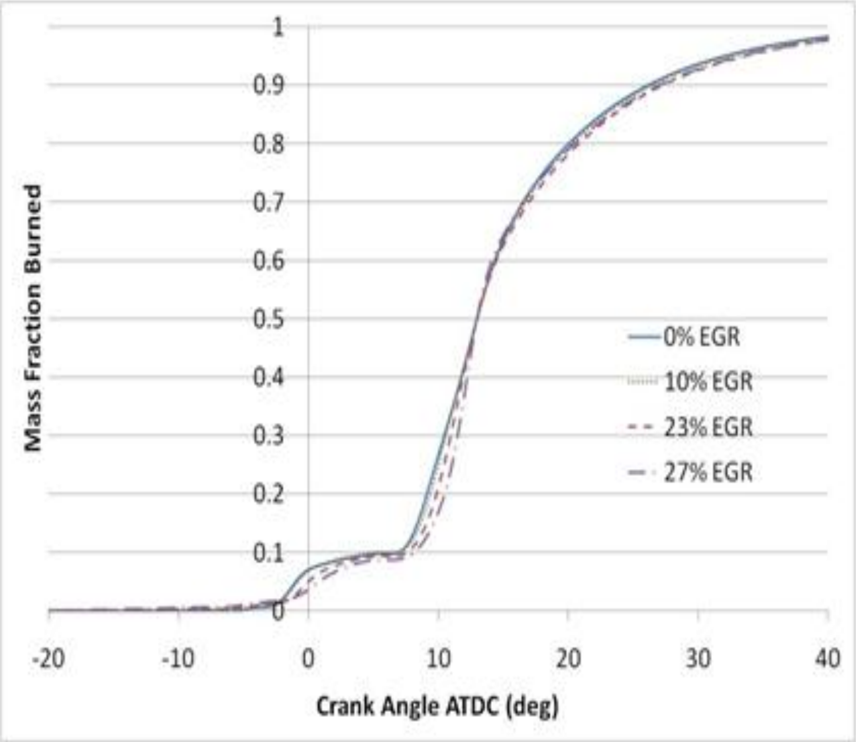
1. Pressure in the cylinder at the sensor
2. Charge amp
3. A/D Converter on the card
4. Buffer on the card
5. Buffer in CPU memory
6. Split copies of data to different memory locations
7. Preprocess data
8. Process data
9. Feedback Control
10. Engine Control
11. Actuator drivers
12. Actuators



Next-Cycle Control Results – MFB50 location



Without feedback

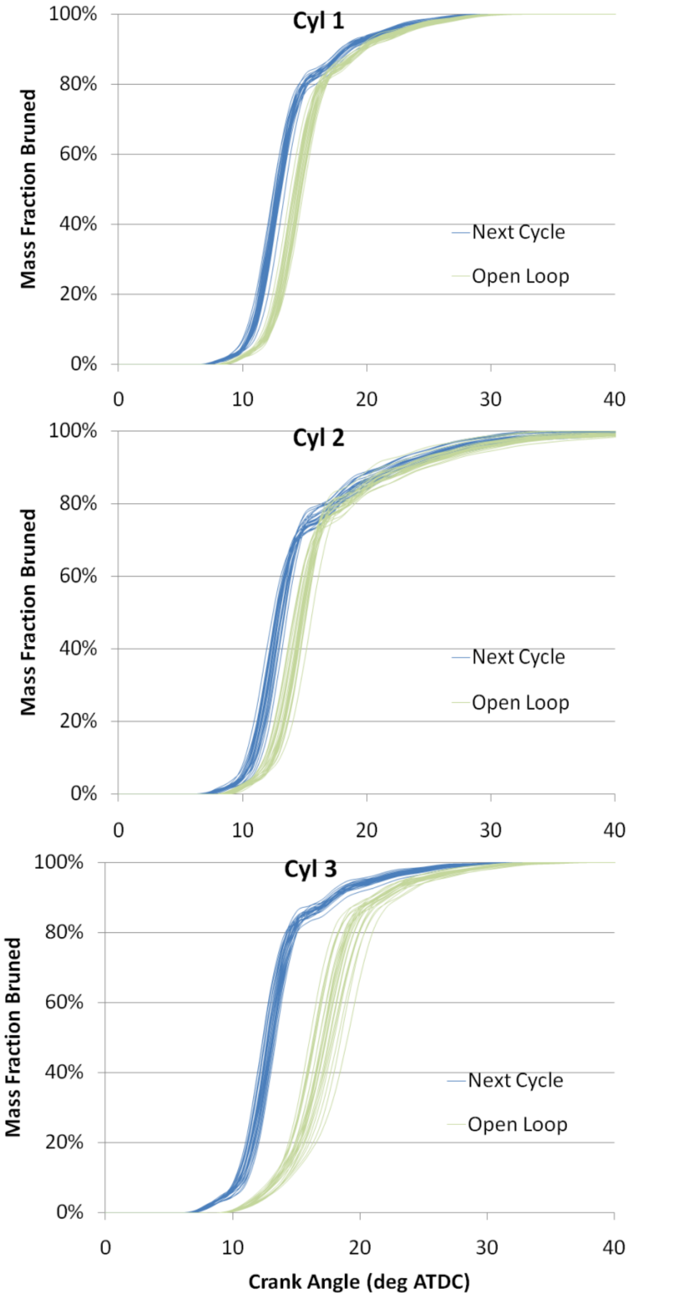


With feedback

100 cycle ensemble and engine global average of MFB

Next-Cycle Control Results by Cylinder and Cycle

10 bar BMEP, 2500 rpm, 10% EGR				
		Cylinder 1	Cylinder 2	Cylinder 3
COV 50% MFB	Open Loop	1.42	1.43	1.12
	Next Cycle	1.03	1.01	1.04
2.25 bar BMEP, 3000 RPM, 18% EGR				
		Cylinder 1	Cylinder 2	Cylinder 3
COV 50% MFB	Open Loop	2.65	2.57	5.10
	Next Cycle	1.73	2.19	2.49
3 bar BMEP, 1800 RPM, 33% EGR				
		Cylinder 1	Cylinder 2	Cylinder 3
COV 50% MFB	Open Loop	2.03	2.40	4.57
	Next Cycle	1.53	1.90	2.64

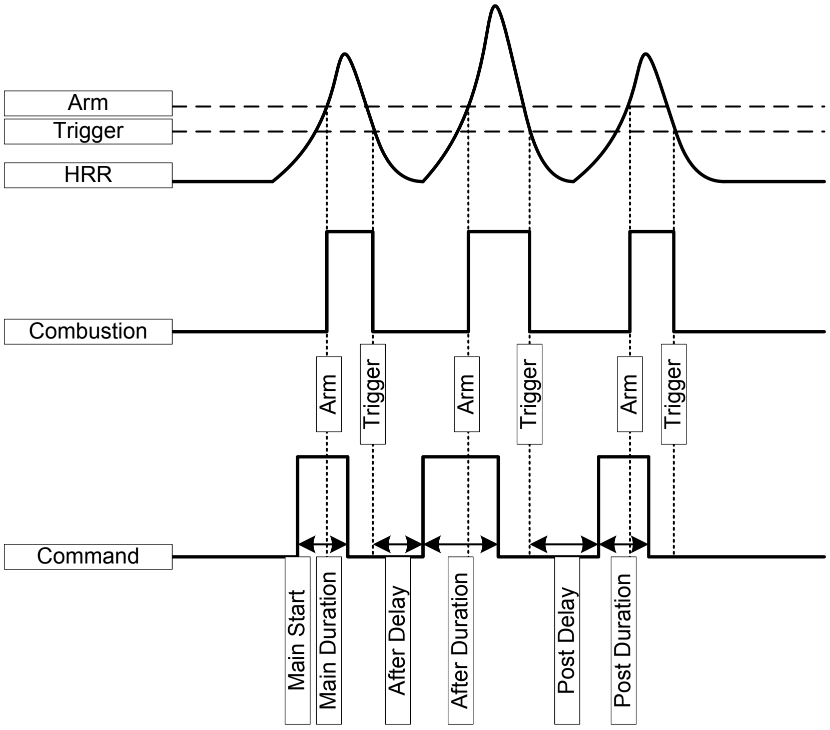


Same-Cycle Control Setup

- Application: Inter-pulse spacing control
- Single zone heat release
- Calculations performed entirely in FPGA

$$\frac{dQ}{d\theta} = \left(\frac{1}{n-1}\right) * V * \frac{dP}{d\theta} + \left(\frac{n}{n-1}\right) * P * \frac{dV}{d\theta}$$

Single Zone Heat Release

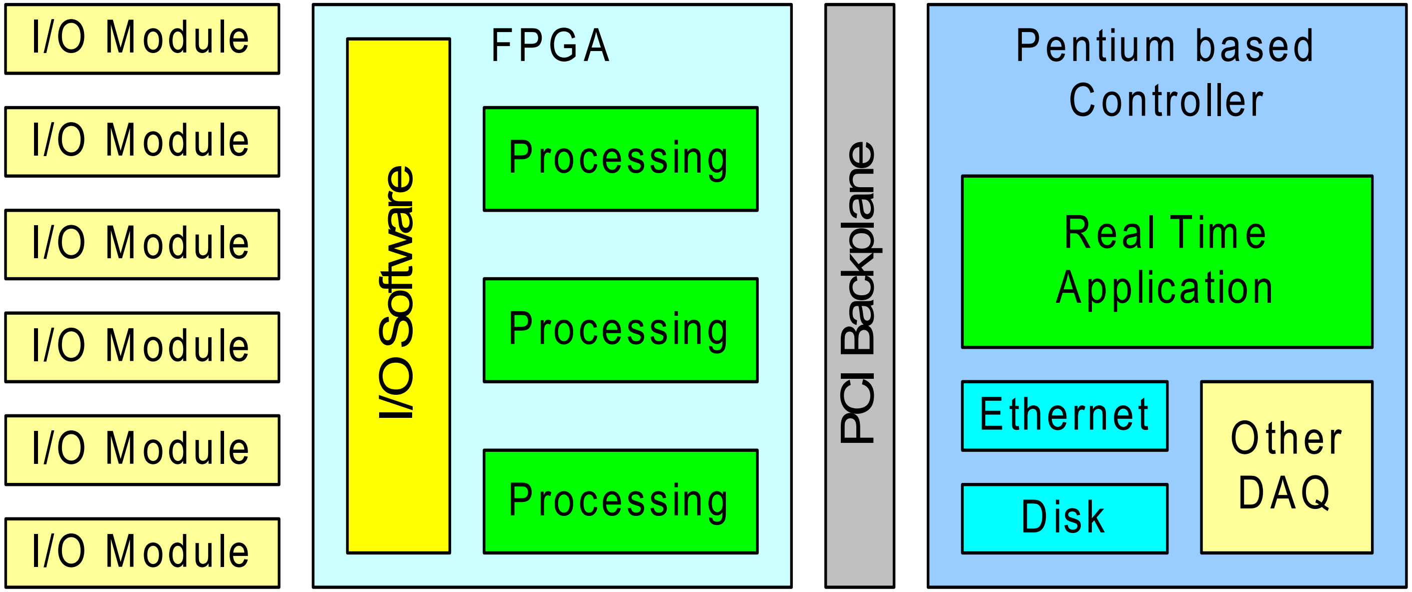


What is an FPGA?

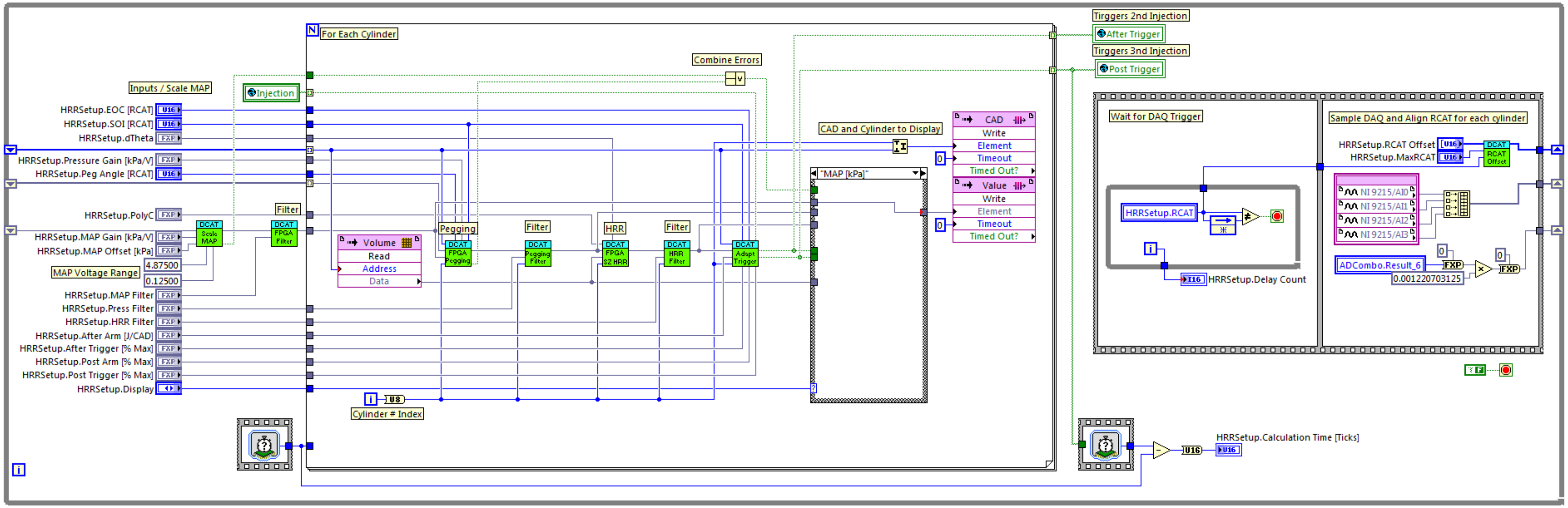
- Field-Programmable Gate Array
- Generic Digital Logic
  - Can implement math (+ - * /), processors, RAM, serial ports, etc.
  - Can not directly do ADC, requires an external A/D.
- Differences from processors
  - Reprogrammable for flexible, dedicated logic
  - Does many simple parallel tasks instead on one complicated task
  - More complex tasks take a larger FPGA, but run at the same speed. As opposed to a processor where they take longer to run but the processor remains constant
  - Programmed in LabVIEW, Verilog, and VHDL as opposed to C, Java, LabVIEW, Matlab, etc for processors
- Can be used in place of ASIC (Application Specific Integrated Circuit)

Detailed NI FPGA Architecture

- The FPGA is put on a board that attaches to the main processor over a PCI bus
- 20MB/s throughput to processor
- Control loops of 200Hz on the Pentium for complex calculation, >40MHz on the FPGA



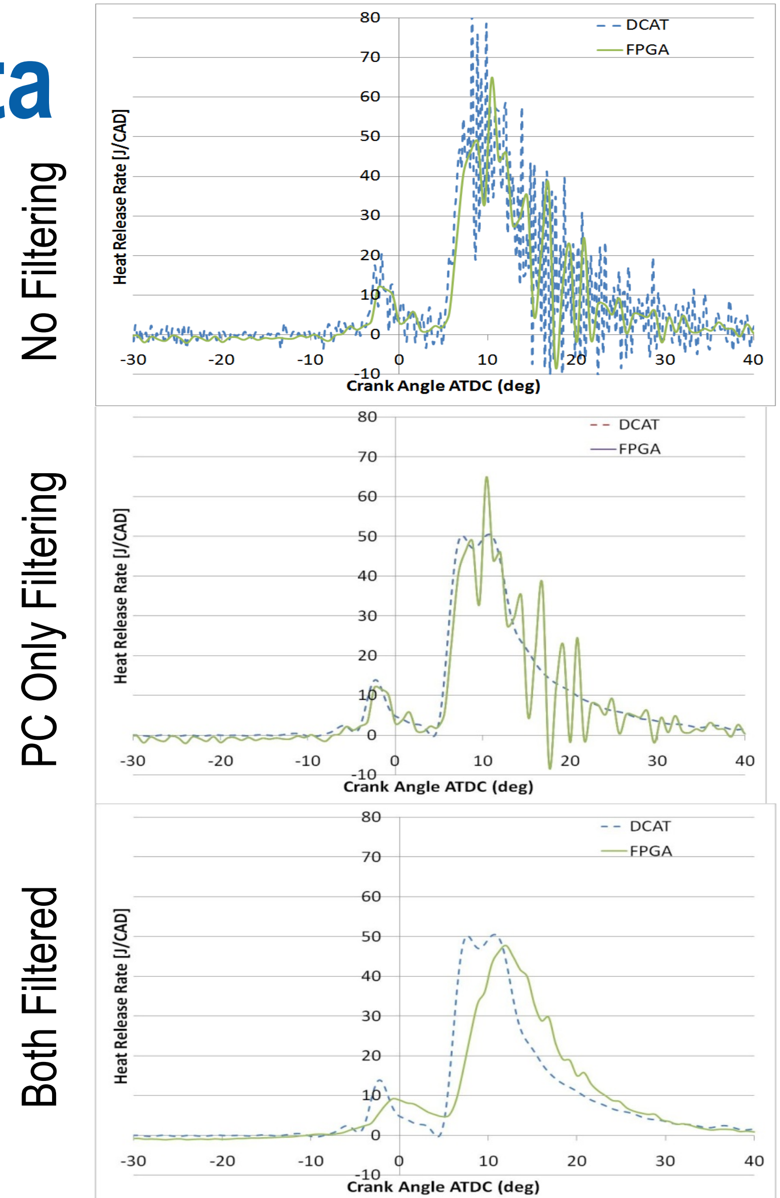
FPGA Code



- Read data from previous loop
- Read control constants from CPU
- Filter
- Peg Cylinder pressure against MAP
- Single zone heat release
- Trigger
- Inject

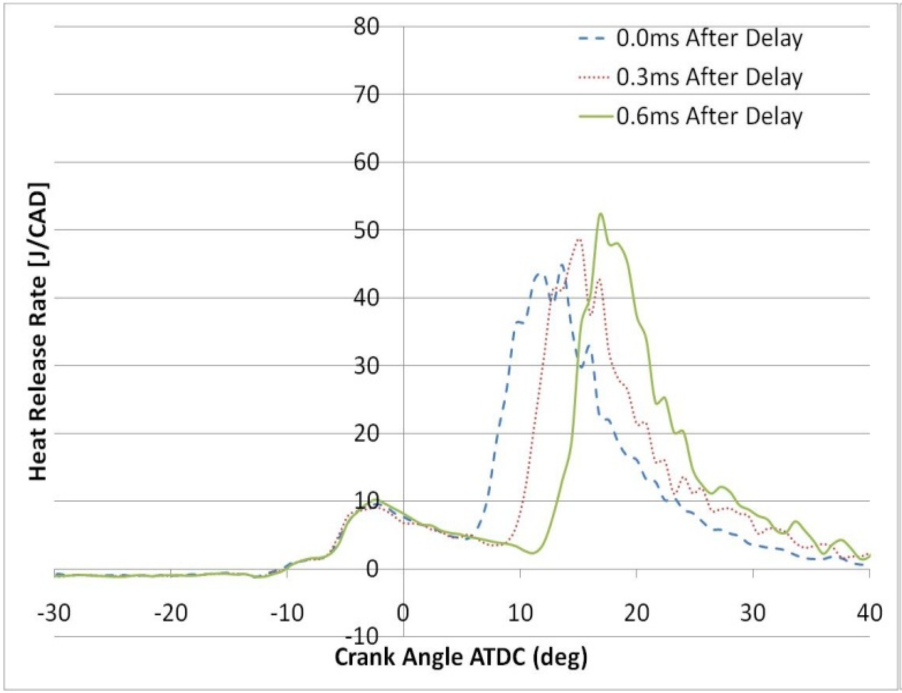
Same-Cycle Control Data

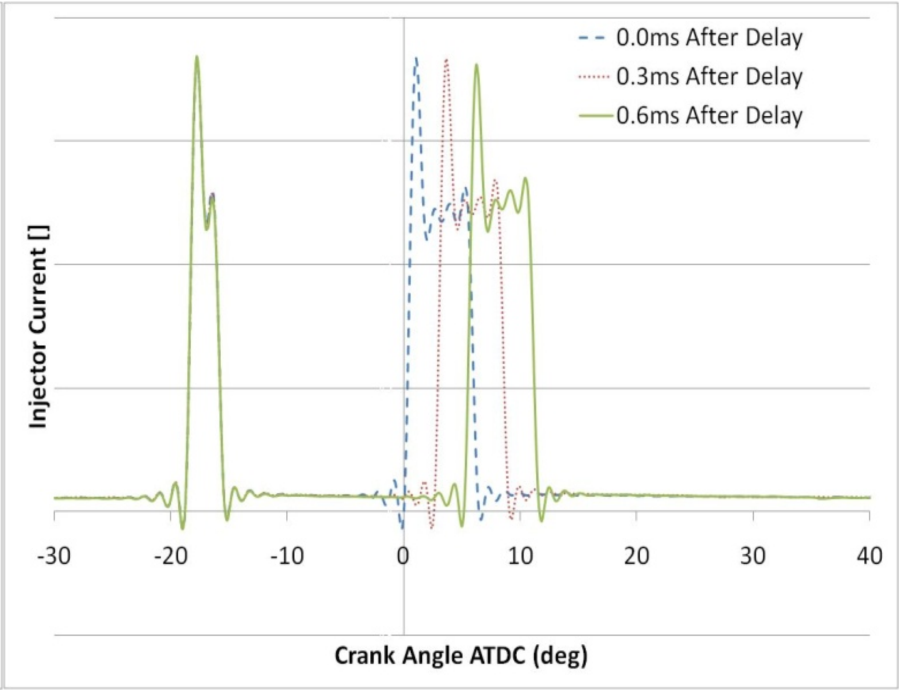
- Raw pressure is noisy
- Filtering induces latency
- Filtering can induce phase shift
- Point-by-point feedback must trade latency for filtering



Same-Cycle Control Results: 2nd Pulse Delay

- Steady state operating conditions
- Sweep trigger parameters

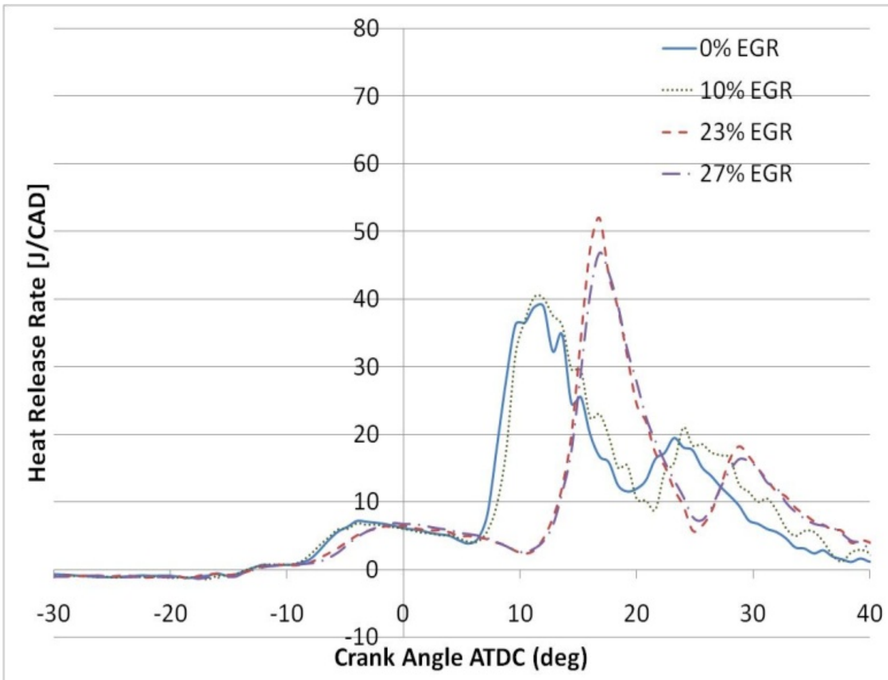


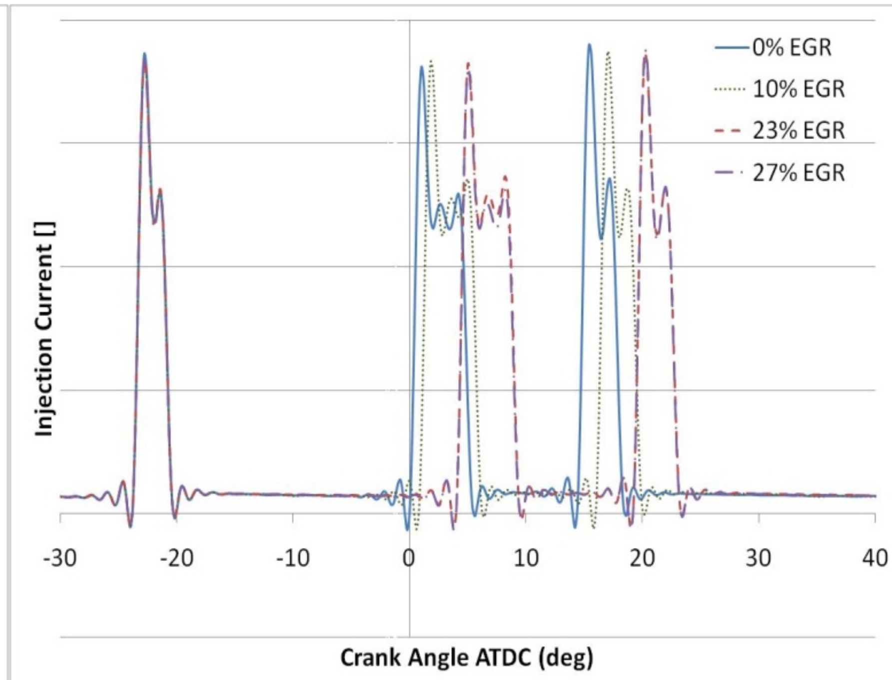


Same-Cycle Control Results: EGR Sweep

- Steady state, just sweeping EGR
- As EGR increases combustion slows

- Inter-pulse spacing increases to keep consistent burn overlap





Future Work

- Restructure the same-cycle control FPGA code
  - Make coding easier
  - Support floating point
  - Build compiler
- Integrate same-cycle and next-cycle control into our upcoming embedded engine control products

Conclusion

- Next-cycle control is a convenient tool for engine tuning
- As more vehicles are equipped with cylinder pressure sensors it will become more mainstream in passenger cars and light trucks
- Standard tools and techniques can be implemented in conventional, but fast, ECUs to handle this in the future.

- Same-cycle control opens up new areas of control not previously possible
- Same-cycle control offers a limited range of capabilities because of limited actuator authority
- Same-cycle controllers will need specialty processing hardware

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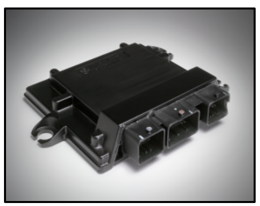

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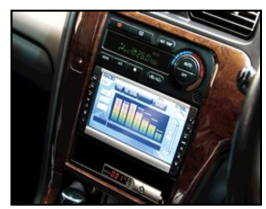

Automotive Infotainment Test