Prototyping and Deployment of Real-Time Signal Processing Algorithms for Engine Control and Diagnosis

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IFP

Outline

- Introduction
- Rapid prototyping platform for real-time signal processing algorithms
- Algorithm implementation for combustion analysis
- Deployment on industrial DSP based target
- Conclusion

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Introduction

Today issues :

- Increasing legal requirements (tailpipe emissions, fuel consumption) while keeping engine performances
- Development of innovative combustion concept: LTC, HCCI, CAI
- More sensitive combustion processes according to
  - initial conditions (BGR, temperature, pressure) and fuel properties
  - injection system drift
- No direct control of the start of ignition

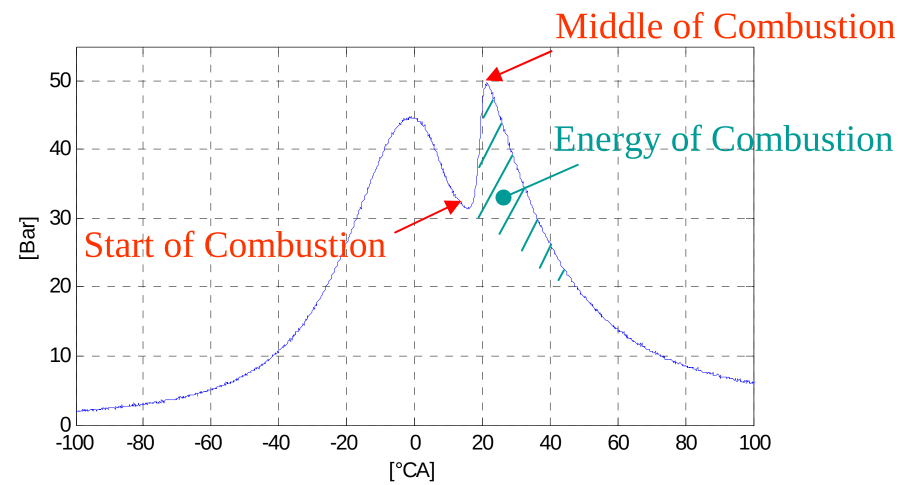
A closed loop combustion control is needed to ensure fuel loop robustness

- Combustion indicators (closed loop variables) can be computed from :
  - cylinder pressure
  - instantaneous engine speed
  - ion current
- Need for higher sampling rate and suitable rapid prototyping platform

Real-time combustion analysis issue

- Need of relevant combustion parameters to characterize
  - combustion phasing (efficiency, emissions)
  - combustion noise
- In-cylinder pressure analysis provides significant information
- Acquisition and processing of in-cylinder pressure signals
  - cycle to cycle
  - cylinder to cylinder
  - engine synchronously

in-cylinder pressure



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Platform specification

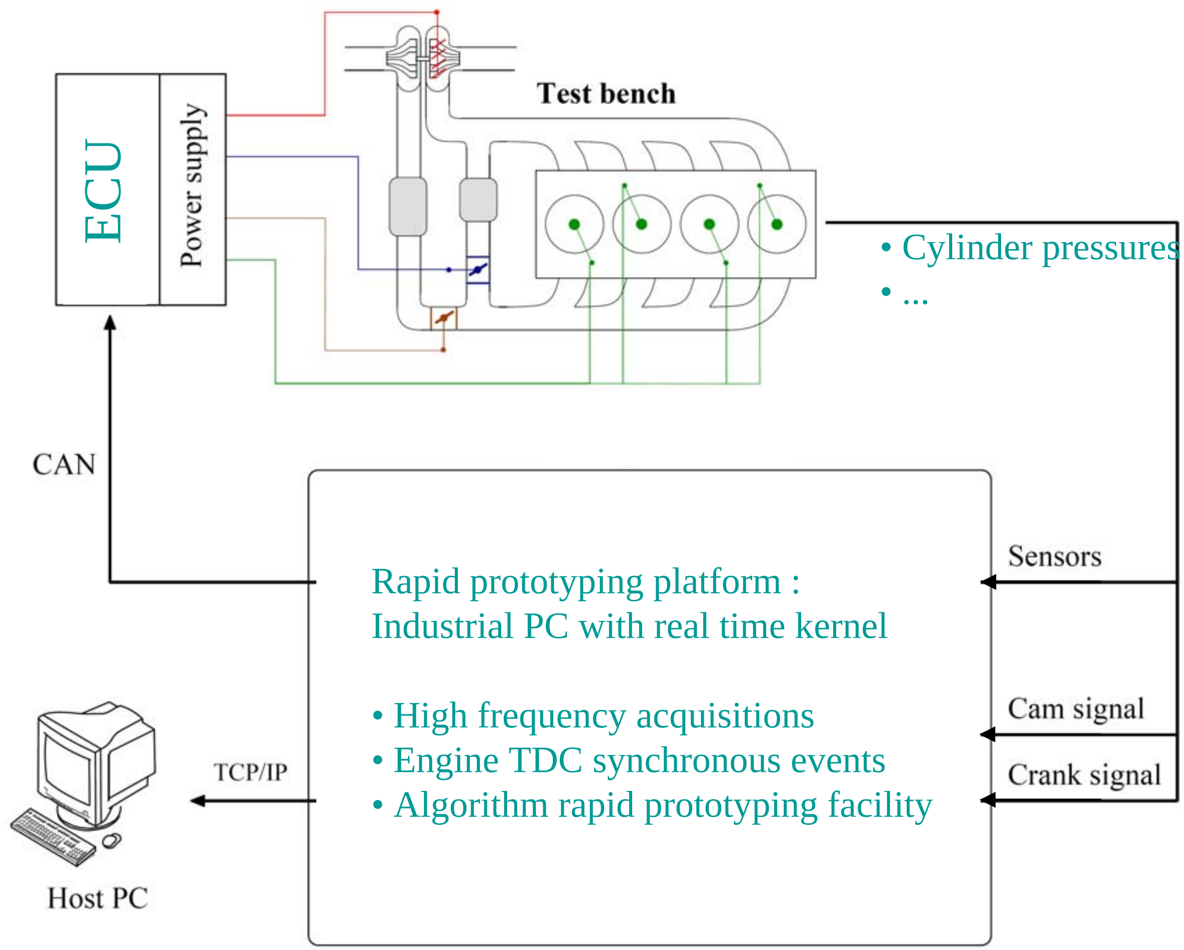
IFP has developed a real-time platform for engine-synchronous algorithms prototyping.

It fulfills the following specifications:

- engine events synchronization (TDC or 6°CA)
- eight continuous or multiwindowed acquisition channels
- acquisition at fixed frequency (400 kHz) or at fixed angular resolution (0.1°CA)
- cycle-to-cycle and cylinder-to-cylinder data availability for online signal processing and combustion analysis algorithms
- data recording for database acquisition and post-treatment purpose (over 1000 consecutive cycles)

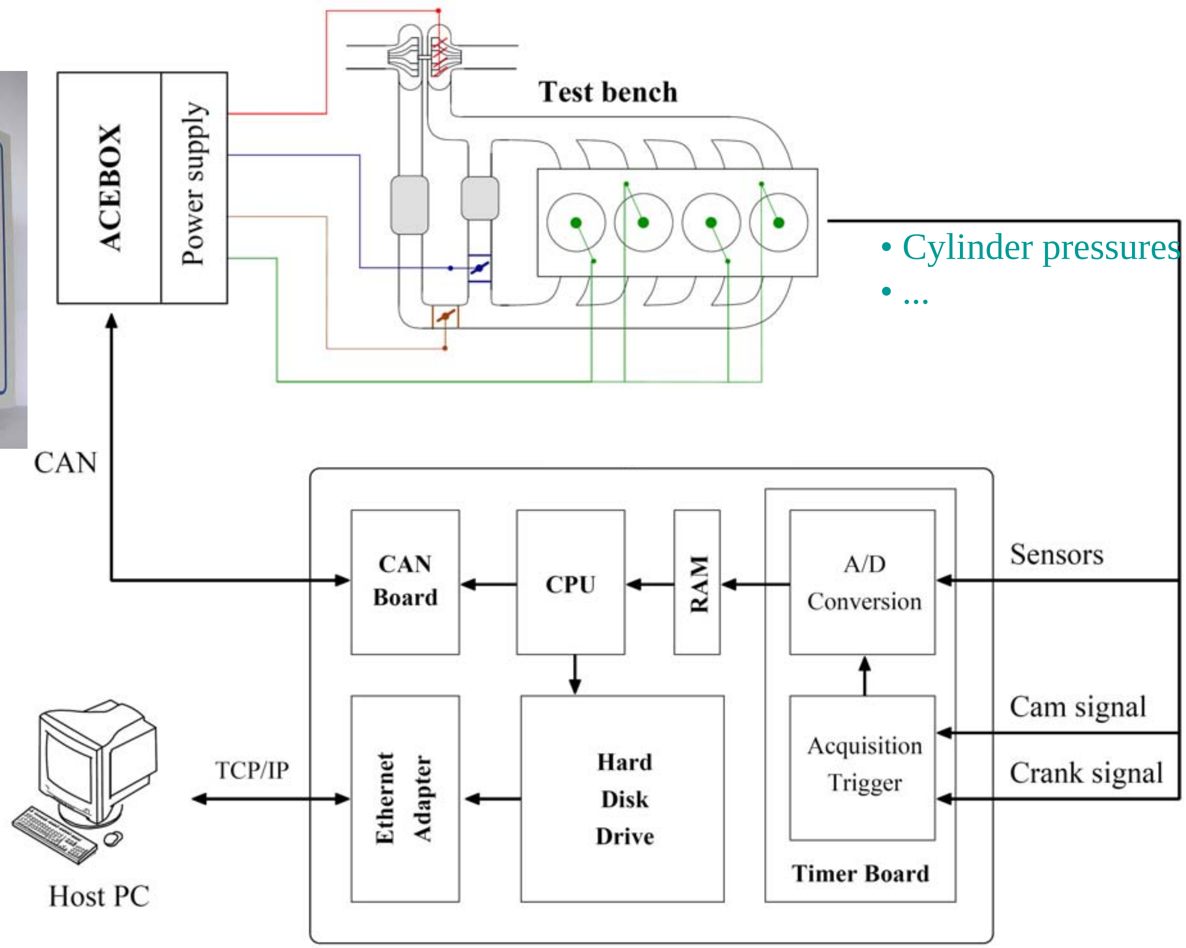
Platform description

- Industrial PC based acquisition and rapid prototyping platform

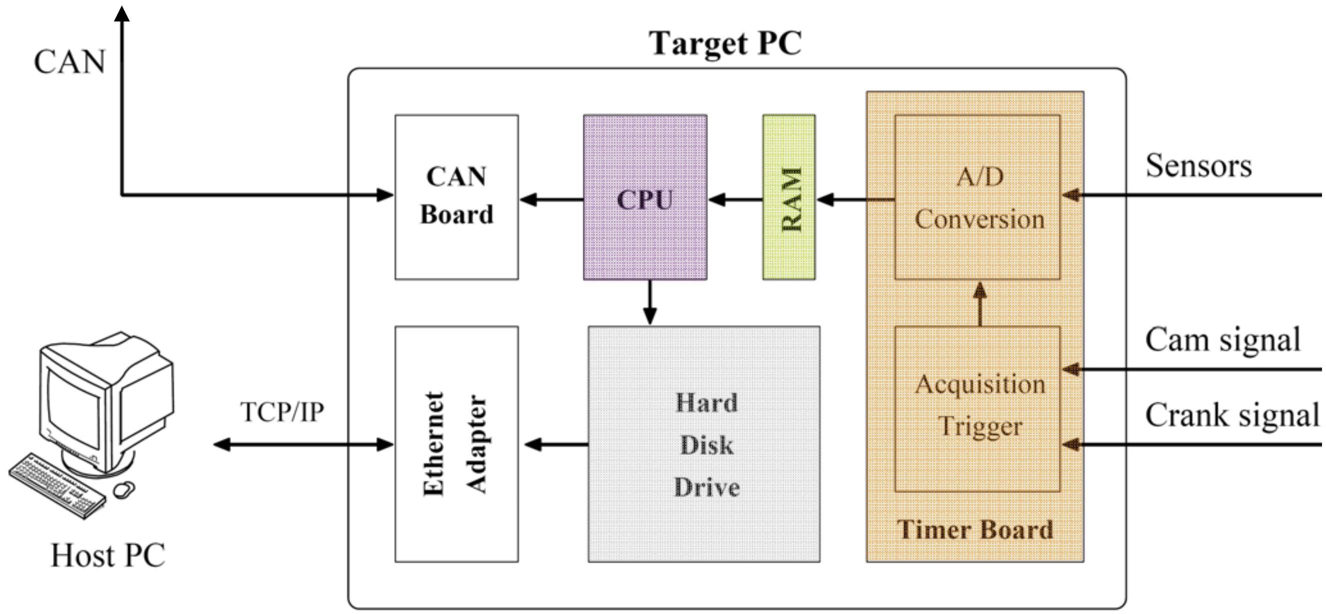


Platform description

- Industrial PC based acquisition and rapid prototyping platform



Platform description : Hardware architecture



- CPU (xPC real time kernel)
- RAM (online data storage)
- HDD (data recording)
- *IFP* Timer board (PCI) : FPGA (ALTERA Stratix)
  - Initially designed for generation of ignition and injection signals driven by ACEBox control system
- *IFP* Daughter acquisition board
  - maximum sampling frequency : 400 KHz
  - minimum sampling period : 0.1 °CA
  - 16 bit resolution (+/-10V with tuneable gain)

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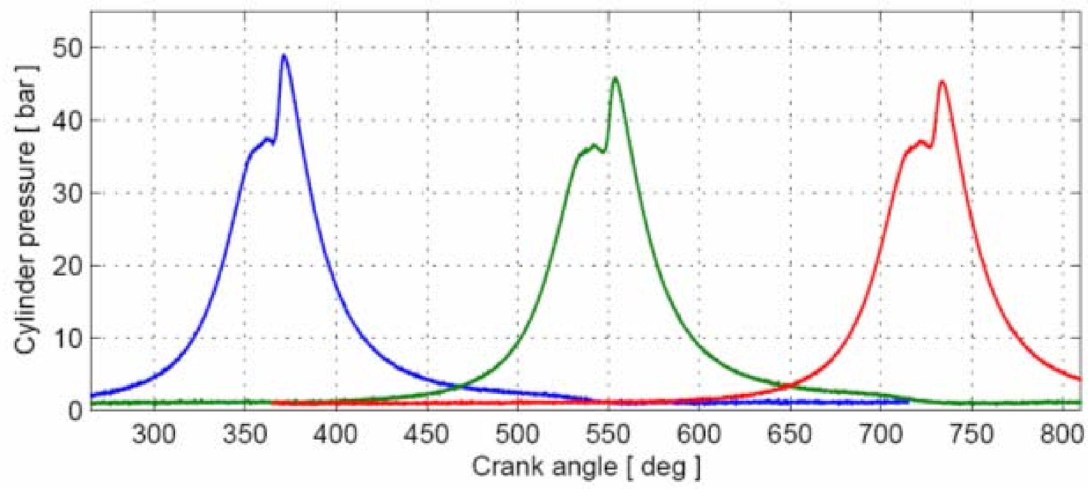
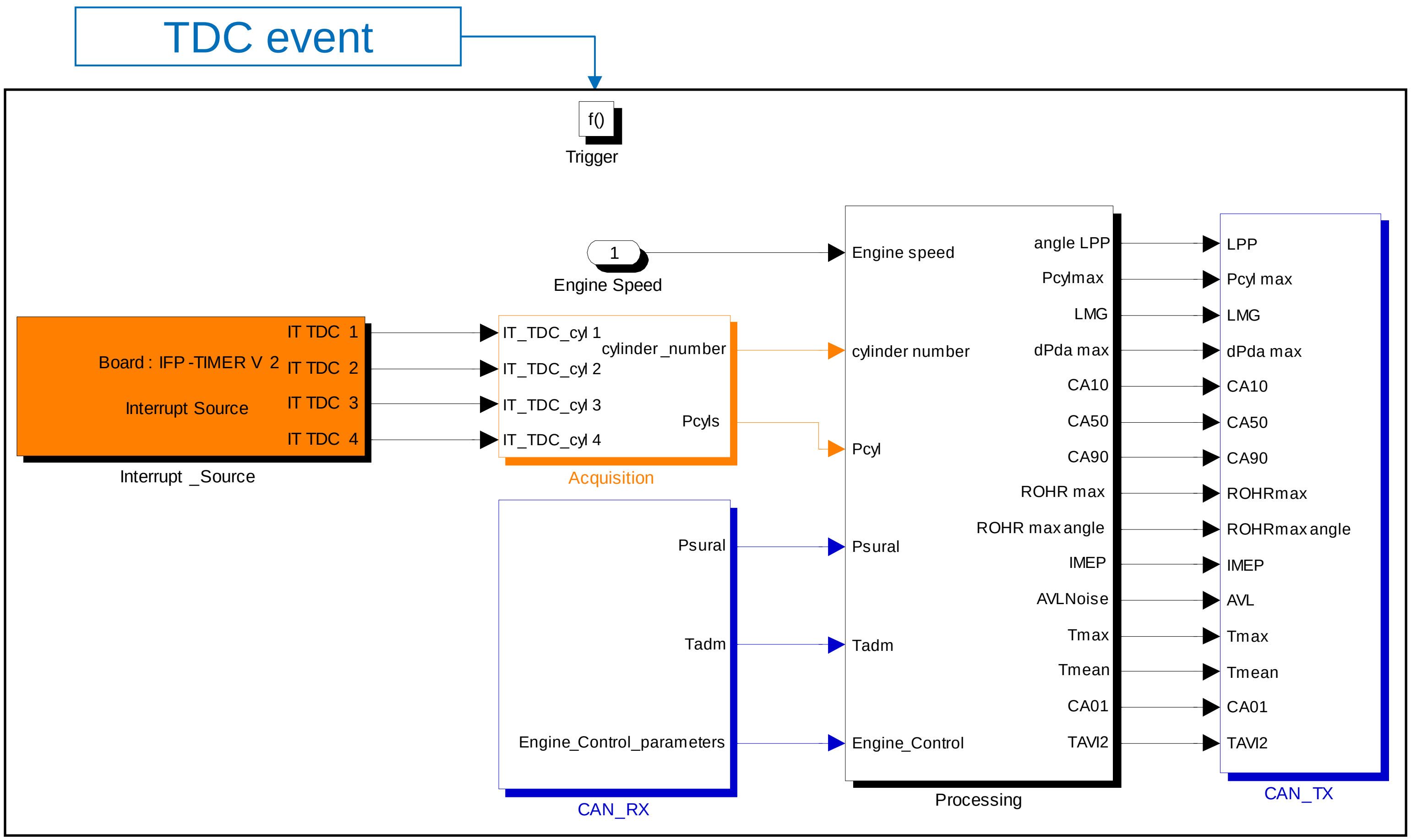
Platform description : acquisition functionalities

- Acquisitions frame-based, continuous or windowed in engine cycle
- Acquisitions in time or angle
- Acquired data frames updated engine synchronously (cylinder-to-cylinder and cycle-to-cycle)
- Acquired data frames available for processing with fast recursive algorithms
  - TDC synchronous results sending to external devices (bench supervisors, ECU)
- Data can be saved on PC hard disk drive for a specified number of consecutive engine cycles
  - post-processing purpose



Platform description : software implementation

TDC synchronous task implemented in Simulink



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Combustion parameters computation

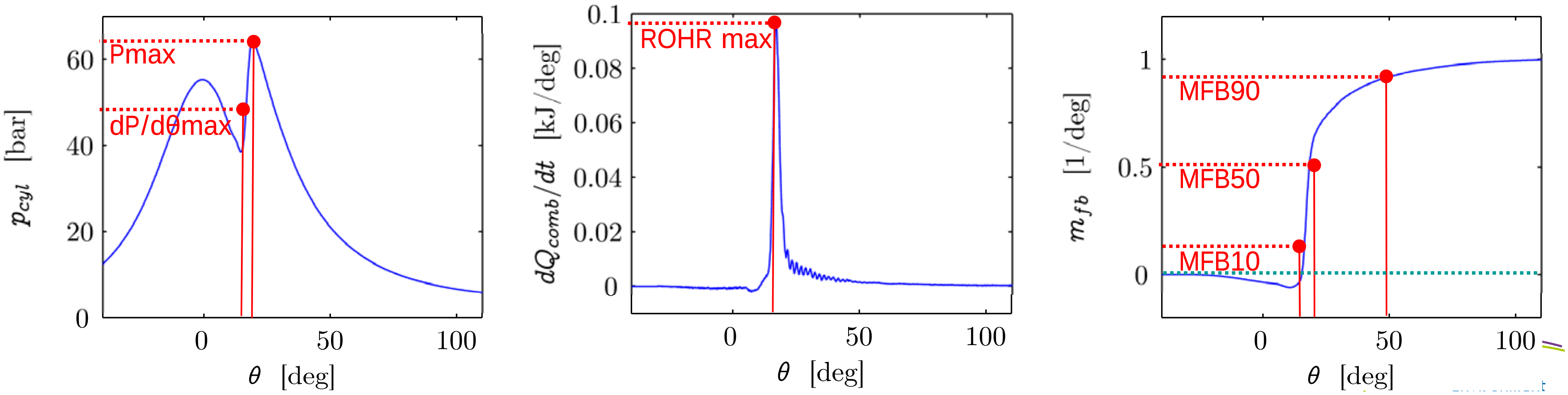
- Online TDC synchronous computation tasks include combustion analysis :
  - indicated mean effective pressure, indicated Torque
  - maximum pressure gradient and its location
  - peak pressure and its location
  - maximum rate of heat release and its location
  - locations of 10-50-90% of mass fuel burnt

$$\frac{dQ_{comb}}{d\theta} = \frac{\gamma}{\gamma - 1} p_{cyl} \frac{dV_{cyl}}{d\theta} + \frac{1}{\gamma - 1} V_{cyl} \frac{dp_{cyl}}{d\theta} + \frac{dQ_p}{d\theta} = f(p_{cyl}, \theta)$$

Cylinder pressure

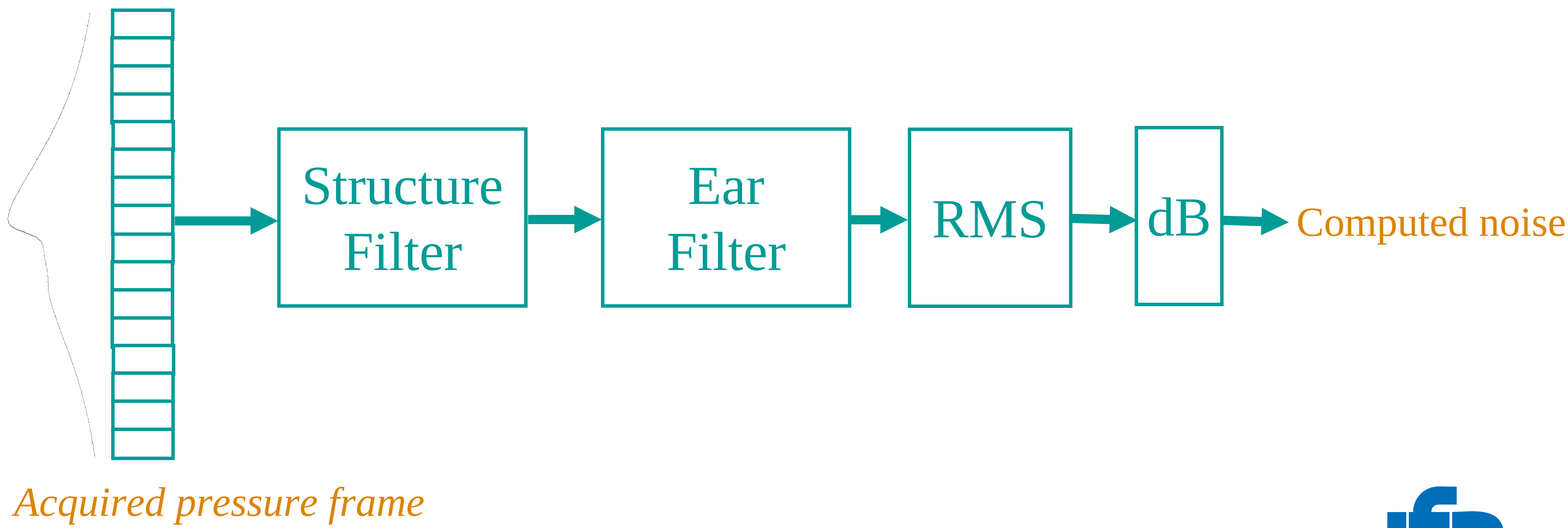
Rate of heat release

Mass fuel burnt



AVL noise computation

- Noise computation algorithm is implemented using AVL Noisemeter specifications for engine structure filter shape and human ear filter shape
- Root mean square value is computed on filtered frame
- Modeled noise is obtained in dB



AVL noise computation: filters implementation

- Fixed angular resolution with varying engine speed give varying sampling frequency
- Filters coefficients updated every TDC, in order to maintain absolute bandwidth
- Approximation : engine speed considered constant during a cycle

$$H(z) = H(s)\big|_{s=\frac{k(z-1)}{z+1}}$$

where $k = \dfrac{2\pi f_c}{\tan\left(\pi f_c / F_s\right)}$

and F_s is the sampling frequency.

Denominator coefficients

$$a_1 = \frac{-4k^4 - 2\alpha\omega_c k^3 + 2\alpha\omega_c^3 k + 4\omega_c^4}{k^4 + \alpha\omega_c k^3 + \beta\omega_c^2 k^2 + \alpha\omega_c^3 k + \omega_c^4}$$

$$a_2 = \frac{6k^4 - 2\beta\omega_c^2 k^2 + 6\omega_c^4}{k^4 + \alpha\omega_c k^3 + \beta\omega_c^2 k^2 + \alpha\omega_c^3 k + \omega_c^4}$$

$$a_3 = \frac{-4k^4 + 2\alpha\omega_c k^3 - 2\alpha\omega_c^3 k + 4\omega_c^4}{k^4 + \alpha\omega_c k^3 + \beta\omega_c^2 k^2 + \alpha\omega_c^3 k + \omega_c^4}$$

$$a_4 = \frac{k^4 - \alpha\omega_c k^3 + \beta\omega_c^2 k^2 - \alpha\omega_c^3 k + \omega_c^4}{k^4 + \alpha\omega_c k^3 + \beta\omega_c^2 k^2 + \alpha\omega_c^3 k + \omega_c^4}$$

Numerator coefficients (LP)

$$b_0 = \frac{\omega_c^4}{k^4 + \alpha\omega_c k^3 + \beta\omega_c^2 k^2 + \alpha\omega_c^3 k + \omega_c^4}$$

$$b_1 = \frac{4\omega_c^4}{k^4 + \alpha\omega_c k^3 + \beta\omega_c^2 k^2 + \alpha\omega_c^3 k + \omega_c^4}$$

$$b_2 = \frac{6\omega_c^4}{k^4 + \alpha\omega_c k^3 + \beta\omega_c^2 k^2 + \alpha\omega_c^3 k + \omega_c^4}$$

$$b_3 = \frac{4\omega_c^4}{k^4 + \alpha\omega_c k^3 + \beta\omega_c^2 k^2 + \alpha\omega_c^3 k + \omega_c^4}$$

$$b_4 = \frac{\omega_c^4}{k^4 + \alpha\omega_c k^3 + \beta\omega_c^2 k^2 + \alpha\omega_c^3 k + \omega_c^4}$$

Numerator coefficients (HP)

$$b_0 = \frac{k^4}{k^4 + \alpha\omega_c k^3 + \beta\omega_c^2 k^2 + \alpha\omega_c^3 k + \omega_c^4}$$

$$b_1 = \frac{-4k^4}{k^4 + \alpha\omega_c k^3 + \beta\omega_c^2 k^2 + \alpha\omega_c^3 k + \omega_c^4}$$

$$b_2 = \frac{6k^4}{k^4 + \alpha\omega_c k^3 + \beta\omega_c^2 k^2 + \alpha\omega_c^3 k + \omega_c^4}$$

$$b_3 = \frac{-4k^4}{k^4 + \alpha\omega_c k^3 + \beta\omega_c^2 k^2 + \alpha\omega_c^3 k + \omega_c^4}$$

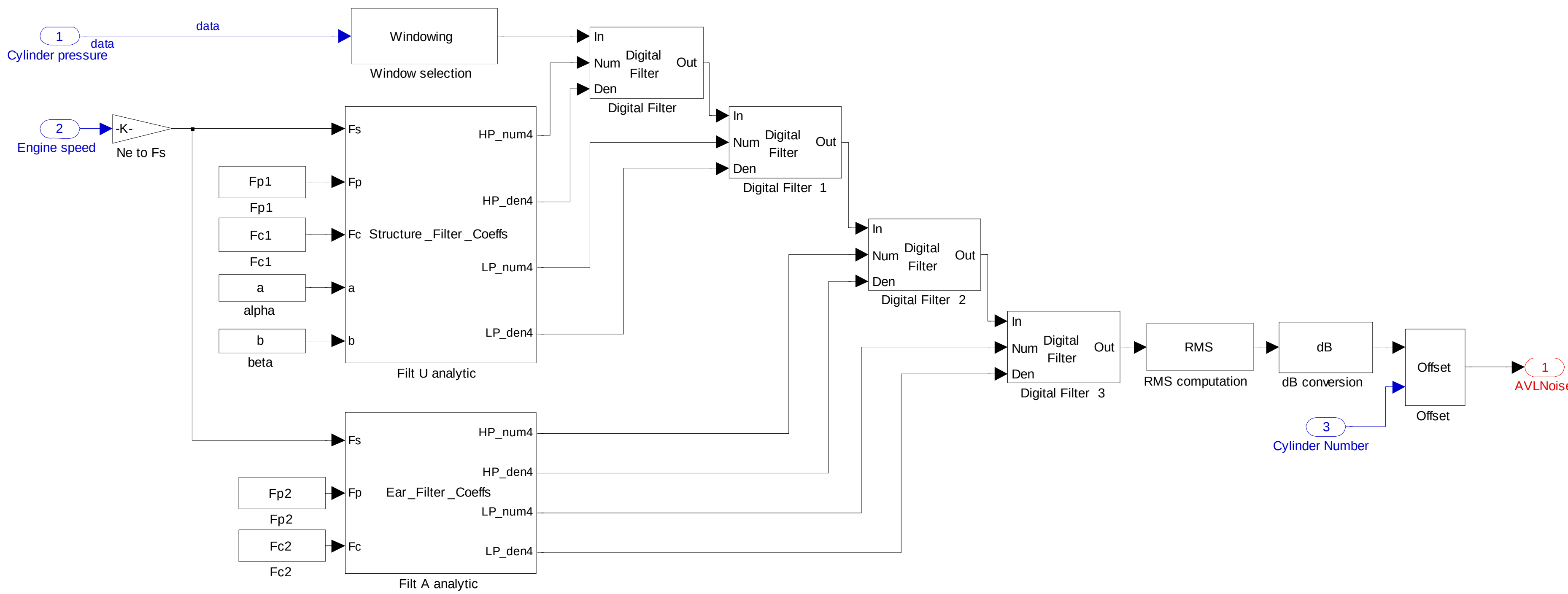
$$b_4 = \frac{k^4}{k^4 + \alpha\omega_c k^3 + \beta\omega_c^2 k^2 + \alpha\omega_c^3 k + \omega_c^4}$$

where $\alpha = 2\left[\cos\left(\frac{\pi}{8}\right) + \cos\left(\frac{3\pi}{8}\right)\right]$,

$\beta = 2\left[1 + 2\cos\left(\frac{\pi}{8}\right)\cos\left(\frac{3\pi}{8}\right)\right]$

AVL noise computation: filters implementation

- Implementation in Simulink, using Signal Processing Blockset and Embedded Matlab functions



AVL noise computation: filters implementation

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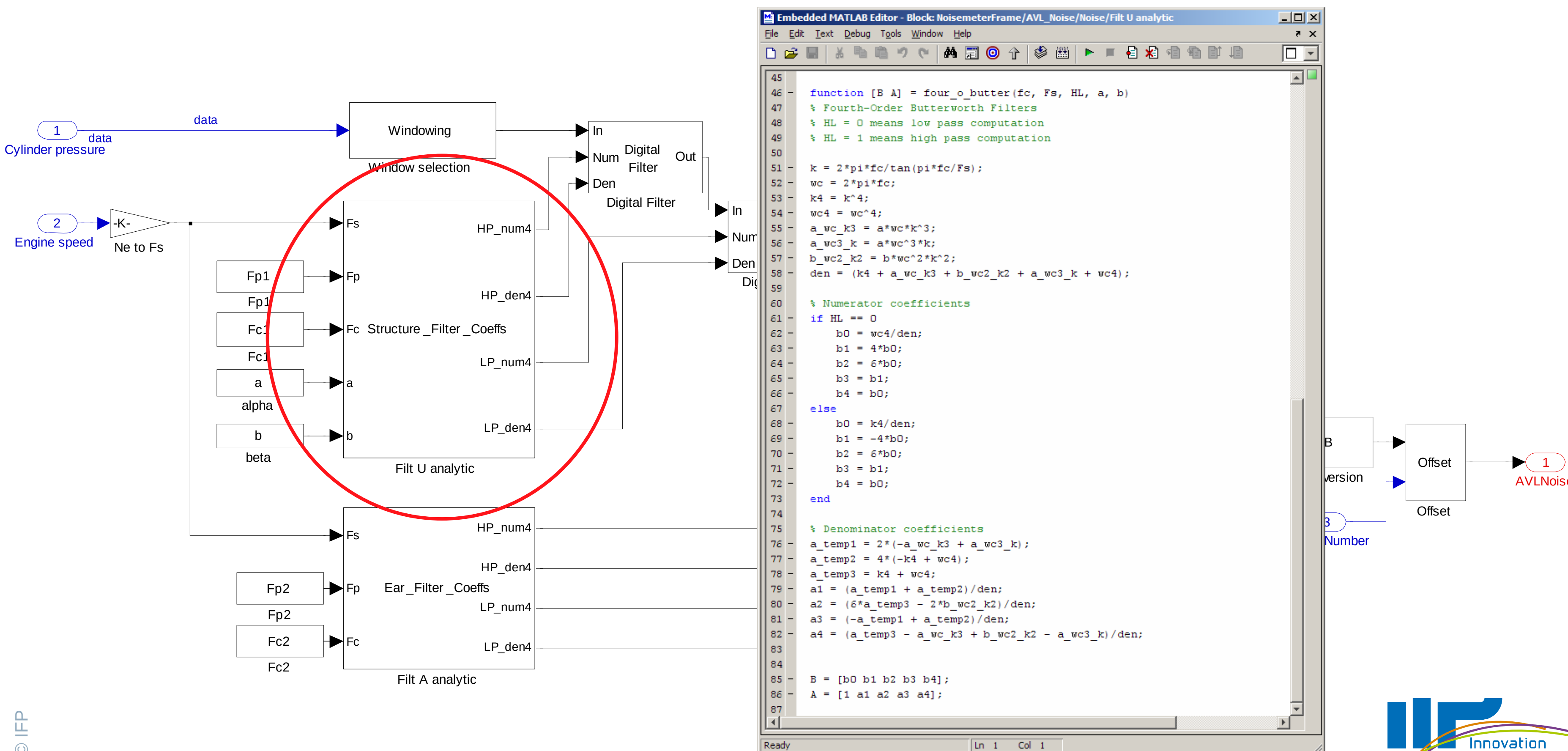


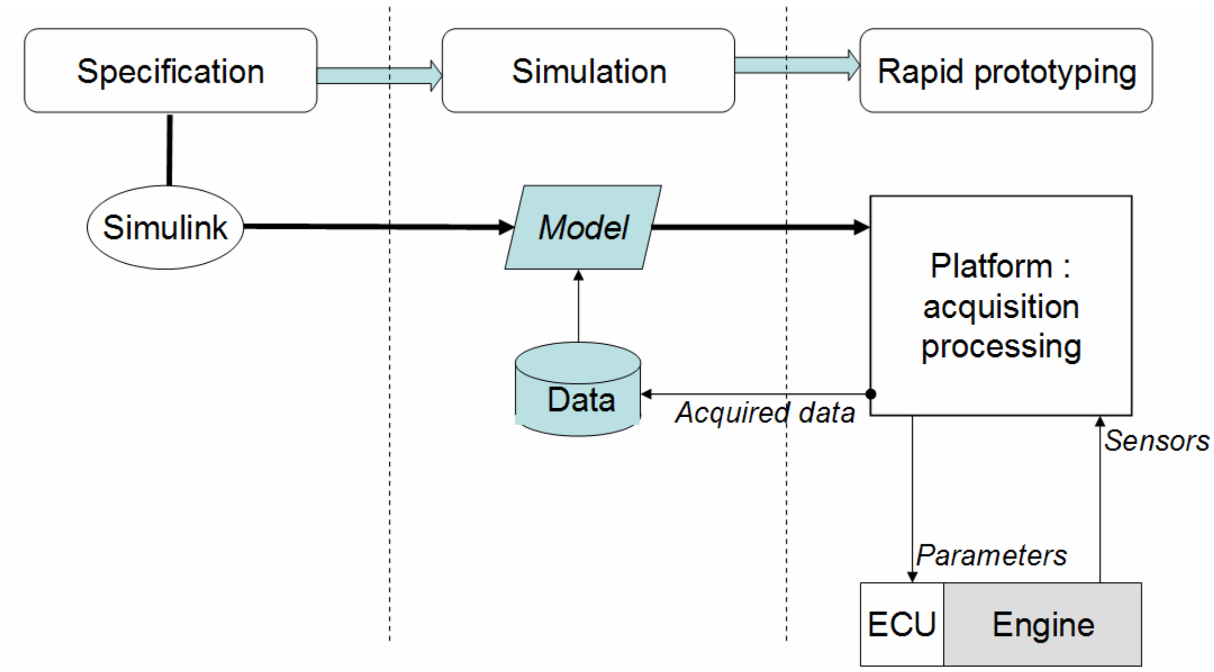
Model-based design, implementation and integration

Use of same Simulink model along all development process

- Specification and Simulation
  - Simulink is the receptacle of the functionalities to be developed
  - Simulink allows to test algorithm reliability offline, using simulation
- Development and test of the platform's drivers
- Integration with algorithms in a whole system model
  - system testing in real time, on xPC Target environment
- Validation of the final executable application
  - system validation in HIL conditions, with an engine signals simulator
  - functional validation on a test bench or in a vehicle
  - calibration online, using Simulink external mode or GUIs

Model-based design, implementation and integration

- Acquired data exploitation in model-based design
  - The platform's data storage ability permits to feed a full database with a complete engine mapping
  - With an offline analysis of this data, computation algorithms can be tested and pre-tuned from the early development and simulation phases



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Issue and functionalities

- Need of an embedded industrial and energy-cost effective solution
  - to deploy developed algorithms rapidly on vehicles and test benches
  - to provide efficient standalone tools for combustion closed-loop control achievement
- Cost and time effective achievement
  - Minimize modifications while moving validated application from prototyping platform to deployment hardware
  - Exploit existing targets and IDE

Issue and functionalities

- IFP has developed an industrial solution based on FPGA-DSP (TI C6727) hardware
- The functionalities to be embedded are:
  - in-cylinder pressure acquisition and sampling
  - combustion analysis and noise computation
  - cylinder-to-cylinder and cycle-to-cycle updating of combustion parameters
  - result availability to external devices
  - algorithm parameterization from external devices

Hardware description

This device is composed of:

- A customized timer board
  - includes an FPGA, which manages:
    - engine and angular coder signals, such as cycle trigger and 0.1°CA trigger
    - acquisitions
    - communication protocols with external devices (mainly CAN)
    - memory mapping
- An 8-channel acquisition board
  - 8 dedicated 16-bit ADCs
  - high-frequency acquisition (800 kHz or 0.1°CA)
- A TI C6727 DSP module
  - targeted by Real-Time Workshop to execute a Simulink modeled application

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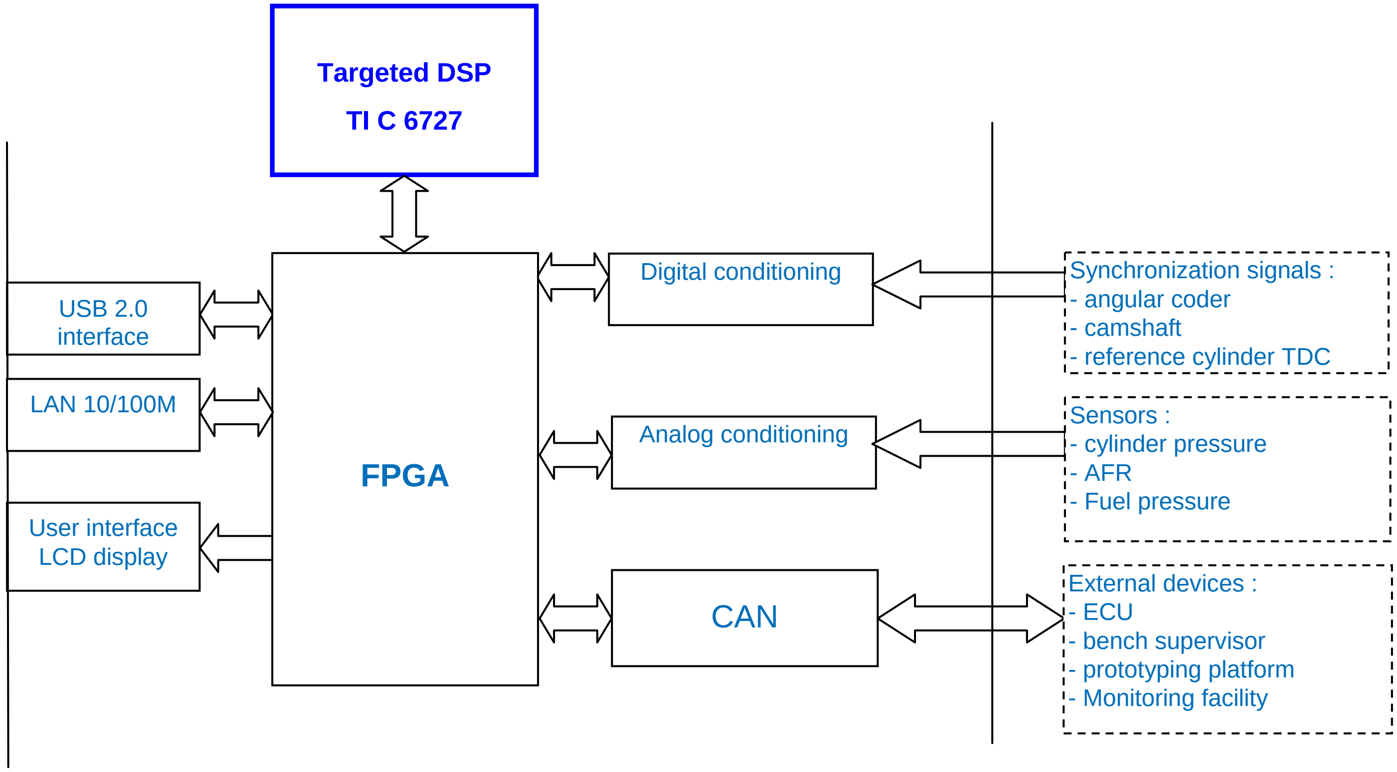
Hardware description

- Deployment platform scheme

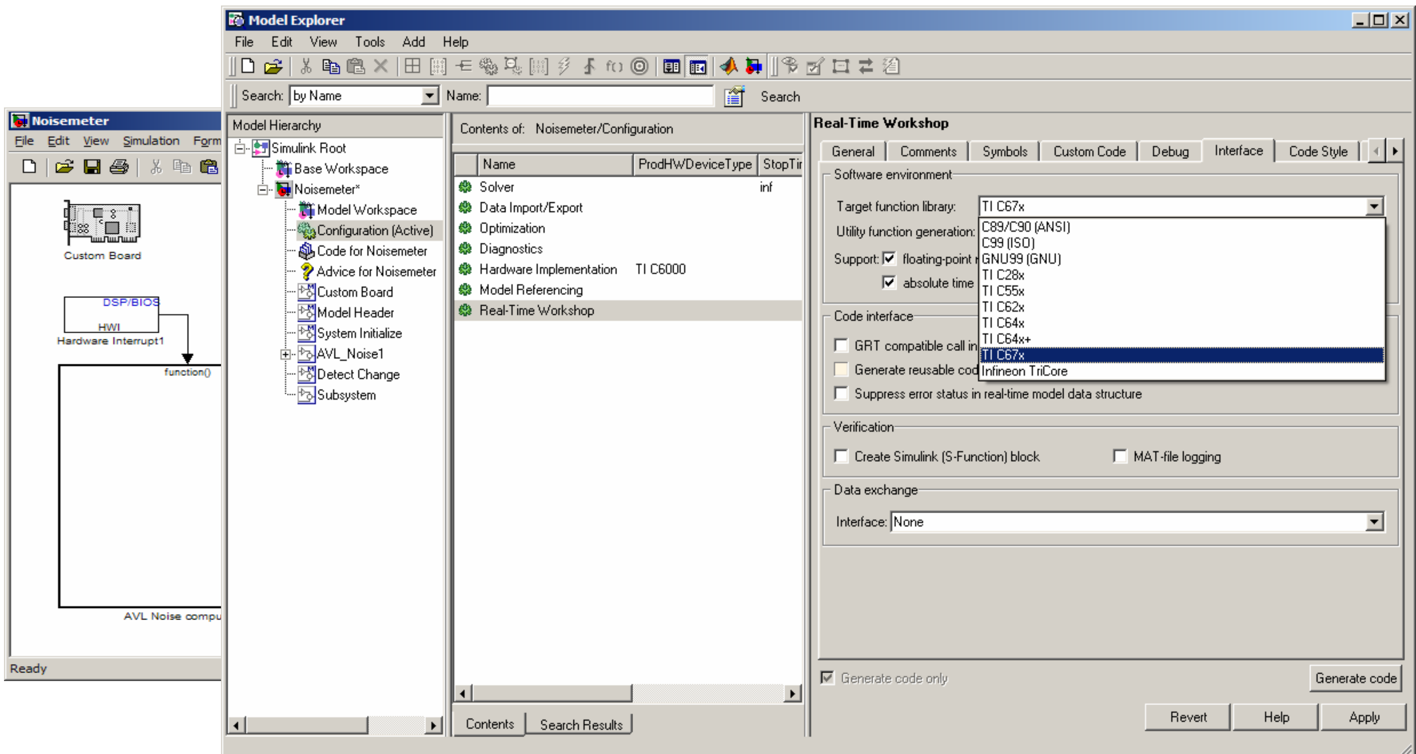


Software implementation

- Aim: bring the application from a PC-based rapid prototyping environment to an industrial DSP-based target
- Direct use of the Simulink code implemented on prototyping platform
- Additional tools exploited in the code generation process:
  - Real-Time Workshop® Embedded Coder™
  - Target Support Package™ TC6 (for TI's C6000™ DSP) and its corresponding target function library (TFL)
  - Embedded IDE Link™ CC (for TI's Code Composer Studio™)

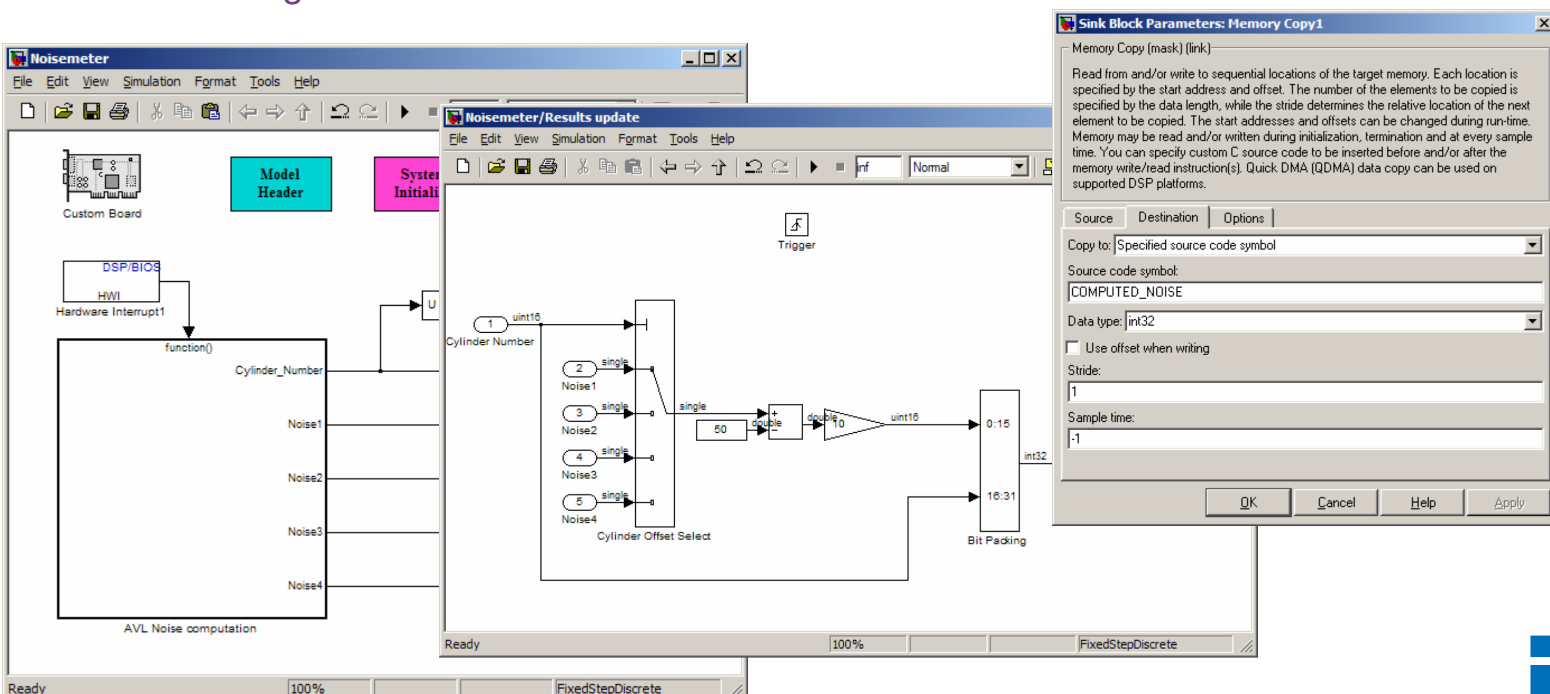
Software implementation

- Real-Time Workshop Embedded Coder configuration using TI C67x library
  - Using TFL instead of complete ANSI C code generation has improved code execution performance by a factor of 5, for frame-based AVL computation algorithm



Software implementation

- The application embedded in the DSP gets acquired data and gives computation results
  - Data accessibility management by mapping DSP memory
  - Memory addresses specified by code variables
  - Add of specific headers and initialization code in the model and in the custom target configuration.



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Conclusions & Perspectives

- Future engine technologies applying new combustion systems require a closed loop combustion control
- IFP has developed a rapid prototyping platform for high frequency data acquisition and signal processing algorithm development
- By acquiring in-cylinder pressures, online analysis is possible in real-time TDC synchronously, allowing for the estimation of combustion phasing and noise
- Validated algorithms are being deployed on a standalone industrial DSP-based solution developed at IFP
- Other issues addressed with signal processing platform :
  - Fuel pressure measurement for diagnostic and control purpose
  - AFR rapid measurements for control purpose
  - Instantaneous engine speed measurement for torque estimation
  - CAI applications

- Implementation, integration, and calibration phases of processing algorithms have been simplified and accelerated thanks to the use of The MathWorks toolchain and model based design approach

Thank you!

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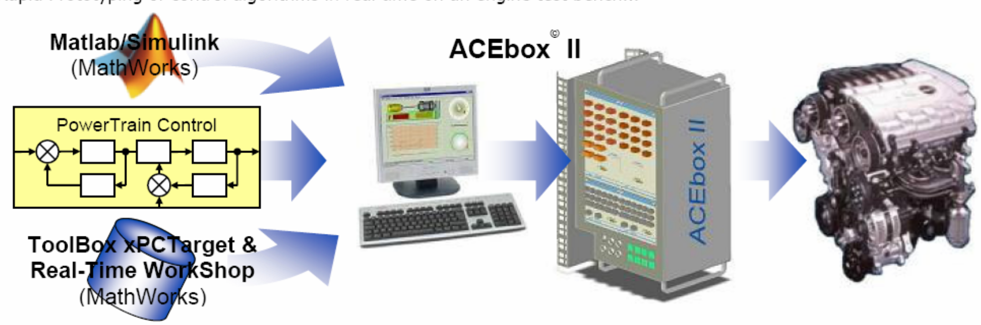
Annex : ACEbox Control System

Rapid Prototyping based on Mathworks xPC Target©

Rapid Prototyping of control algorithms in real time on an engine test bench...



The ACEbox II system includes all the necessary software components for rapid prototyping of control algorithms. The system integrates a gasoline and diesel torque structure with all Simulink's drivers allowing to configure and modify control parameter in only one Drag & Drop.

Main Characteristics of the ACEbox© II System

- Operation of gasoline or diesel engines from 1 to 6 cylinders.
- Multiple injection & Spark events (from 1 to 8 events per engine cycle).
- Accurate operation of solenoid valves and motored throttle valves.
- Engine synchronisation on :
  - 2 AAC inputs of any type (with measuring the out of phase),
  - the engine crank by a captor of vehicle's target 60-2 or by a crank angle encoder with different resolutions.
- OMERE© user interface with Windows XP on PC supervisor linked by TCP/IP 100Mbits with central unit ACEbox© II.
- ACEbox© II based on PC architecture with timer card dedicated to engine applications.
- Optimised overall dimensions and fitted to its industrial integration on an engine test bench.
- Easy connection with captors and actuators cables of engine by separate connectors including power pins for all input.
- ACEbox© II powered by 220VAC/50Hz and interface's modules with captor and actuators cables of engine powered by 12VCC.

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