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An Architecture for Real-Time Estimation of Crank-Angle-Resolved Engine Cylinder Pressure

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Outline

- ***Introduction***
- ***Model for Engine Cylinder Pressure Estimation***
- ***Hardware Implementation***
  - *Dual-Fixed Point (DFX) Arithmetic*
  - *DFX Architecture*
- ***Reconfigurable Embedded System***
- ***Results***

Introduction

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- ***Engine Cylinder Pressure Estimation****: This useful information can be used to obtain the instant torque, detect disturbances in the engine operation, compute the optimal spark timing, etc.*

- ***Traditional methodology****: Most modern spark ignition engines use look-up table approach (cylinder pressure values are mapped for different operating conditions). This approach does not scale well with changes in operating conditions, as the amount of required memory can grow very quickly.*

- ***Our method****: We use a model that computes the estimated engine pressure based on specific conditions (e.g..: speed, amount of fuel being used, engine parameters). We can then generate: instant torque, optimal spark timing, etc.*

- ***Hardware implementation****: This model is best suited for dedicated hardware implementation for real-time cylinder pressure estimation.*

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Cylinder Pressure Model

- Relationship among heat release rate, pressure, volume, and heat lost (heat release) for a *closed cylinder engine*:

$$\frac{dQ_{HR}}{d\theta} = \frac{\gamma}{\gamma-1} P \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dP}{d\theta} + \frac{dQ_{HT}}{d\theta}$$ (1st Law of Thermodynamics)

- Discrete Model:

$$\frac{dQ_{HR}}{d\theta} = \frac{\gamma}{\gamma-1} P(n) \frac{dV}{d\theta} + \frac{1}{\gamma-1} V(n) \left(\frac{P(n+1)-P(n)}{\theta(n+1)-\theta(n)}\right) + \frac{dQ_{HT}}{d\theta}.$$

$$P(n+1) = P(n) + \Delta\theta \left[\frac{(\gamma-1)}{V(n)} \frac{dQ_{HR}}{d\theta}\bigg|_n - \gamma \frac{P(n)}{V(n)} \frac{dV}{d\theta}\bigg|_n - \frac{(\gamma-1)}{V(n)} \frac{dQ_{HT}}{d\theta}\bigg|_n\right].$$

- *Empirical model* for the Heat Transfer Rate:

$$\frac{dQ_{HT}}{d\theta}\bigg|_n = \frac{dQ_{HT}}{dt} \frac{dt}{d\theta} = h_{corr}(n) A_{ch}(n) \left(T_g(n) - T_w\right) \frac{30}{N\pi}, N = rpm$$

$$h_{corr}(n) = c \times 0.013 \times V(n)^{-0.06} \times P(n)^{0.8} \times T_g(n)^{-0.4} \times \left(v_p + 1.4\right)^{0.8}.$$

- Model for the Heat Release Rate:

$$\frac{dQ_{HR}}{d\theta}\bigg|_n = \begin{cases} 0, for\ \theta_n \le \theta_0. \quad \theta_0 : spark\ time \\ \frac{\eta_c m_f LHV \alpha(\beta+1)}{\Delta\theta_B(1-e^{-\alpha})} \left(\frac{\theta_n - \theta_0}{\Delta\theta_B}\right)^{\beta} \times e^{\left[-\alpha\left(\frac{\theta_n-\theta_0}{\Delta\theta_B}\right)^{\beta+1}\right]}, for\ \theta_n > \theta_0 \end{cases}$$

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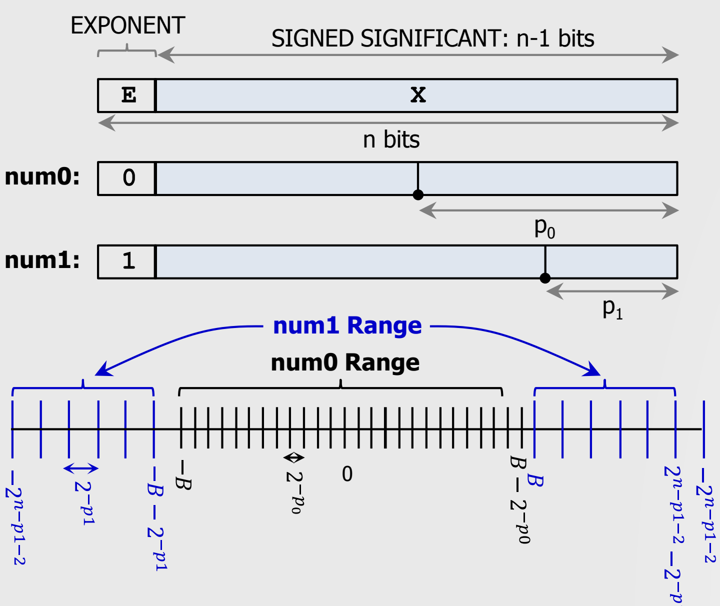
Cylinder Pressure Model

- ***Model Calibration:*** *Heat Release and Heat Transfer models are calibrated based on actual pressure traces.*
  - *Heat Transfer model: Calibrated based on a specific engine type.*
  - *Heat Release model: calibrated for a certain engine and operating conditions, resulting in α, β, c, and $\Delta\theta_B$.*
- ***Covering full operating range of an engine:*** *Cylinder pressure data can be collected that covers the entire operating range of an engine. For a set of specific conditions (e.g.: load, rpm, valve timing), the heat release and heat transfer parameters can be determined.*
- ***Interpolation****: The parameter space can be interpolated to cover the full operating space and then used to produce sets of heat release parameters that cover the full range of speed, load, spark timing, etc.*

Hardware Implementation

Dual Fixed-Point (DFX) Arithmetic:

- DFX is a compromise between Floating Point (high resource usage) and Fixed Point (reduced dynamic range).
- n-bit DFX number: $(n-1)$-bit signed significand and exponent bit E. Notation: $[n\ p_0\ p_1]$.
- It acts as two signed FX formats: it acts as the FX format $[n-1\ p_0]$ $(num0, E=0)$ for numbers representable with this format; else, it acts as the FX format $[n-1\ p_1]$ $(num1, E=1)$.



$$E = \begin{cases} 0, & if\ -B \le D < B \\ 1, & if\ D < -B\ and\ D \ge B \end{cases}, B = 2^{n-p_0-2}$$

- D: decimal value to represented by DFX
- B: boundary value
- $num1$ has a larger dynamic range than $num0$, but $num0$ has better resolution than $num1$.

Hardware Implementation

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DFX Architecture

- We use custom DFX units for arithmetic operations (addition / subtraction, multiplication, division) as well as exponential and powering functions (based on DFX CORDIC). In some operations, LUTs are used. Iterative DFX units require a *start* and *done* signals.

- The DFX format: We tested many variations of *p0* and *p1*, and based on the range of values of the operations, we determined the optimal numerical format to be [32 14 5].

- Hardware: described in VHDL at the Register Transfer Level (RTL).

- Architecture: The discrete model equations were slightly modified to comply with the data units as well as to optimize the hardware in terms of speed and accuracy:

$$\Delta P = \overbrace{\frac{(\gamma-1)}{V(n)}\frac{dQ_{HR}}{d\theta}\bigg|_n}^{A_{term}} .1^\circ + \frac{\pi}{180}\left[\overbrace{-\frac{\gamma P(n)}{V(n)}\frac{dV}{d\theta}\bigg|_n}^{B_{term}} + \overbrace{-\frac{(\gamma-1)}{V(n)}\frac{dQ_{HT}}{d\theta}\bigg|_n}^{C_{term}}\right]$$

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Hardware Implementation

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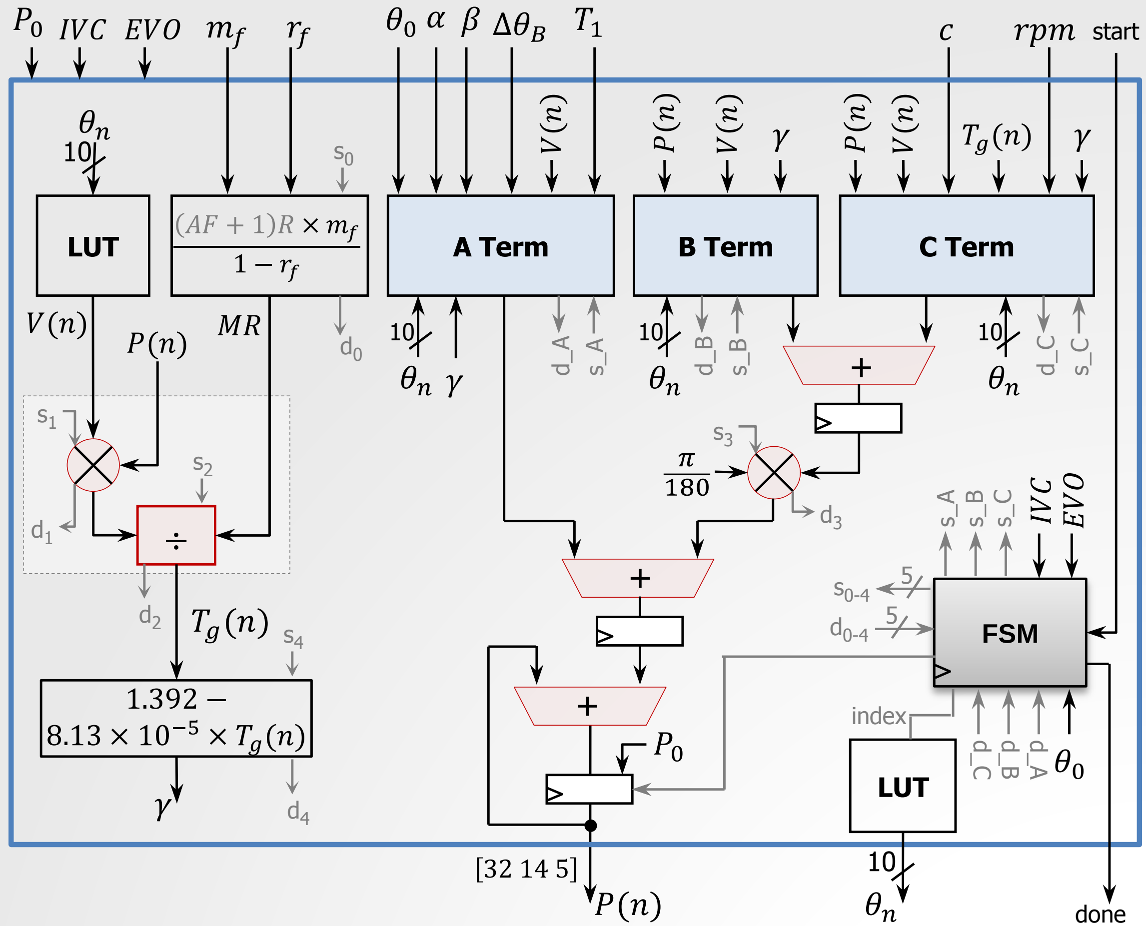
DFX Architecture

- The *start* signal begins the process (data inputs are captured at this time). *done* is asserted each time a new P(n) value is computed.
- Any change in the engine operating conditions is addressed by loading new model and engine parameters.



- The A, B, C terms implement portions of the pressure equation.
- Data transfers are orchestrated by a Finite State Machine (FSM) that controls the start and done signals of every unit.

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Hardware Implementation

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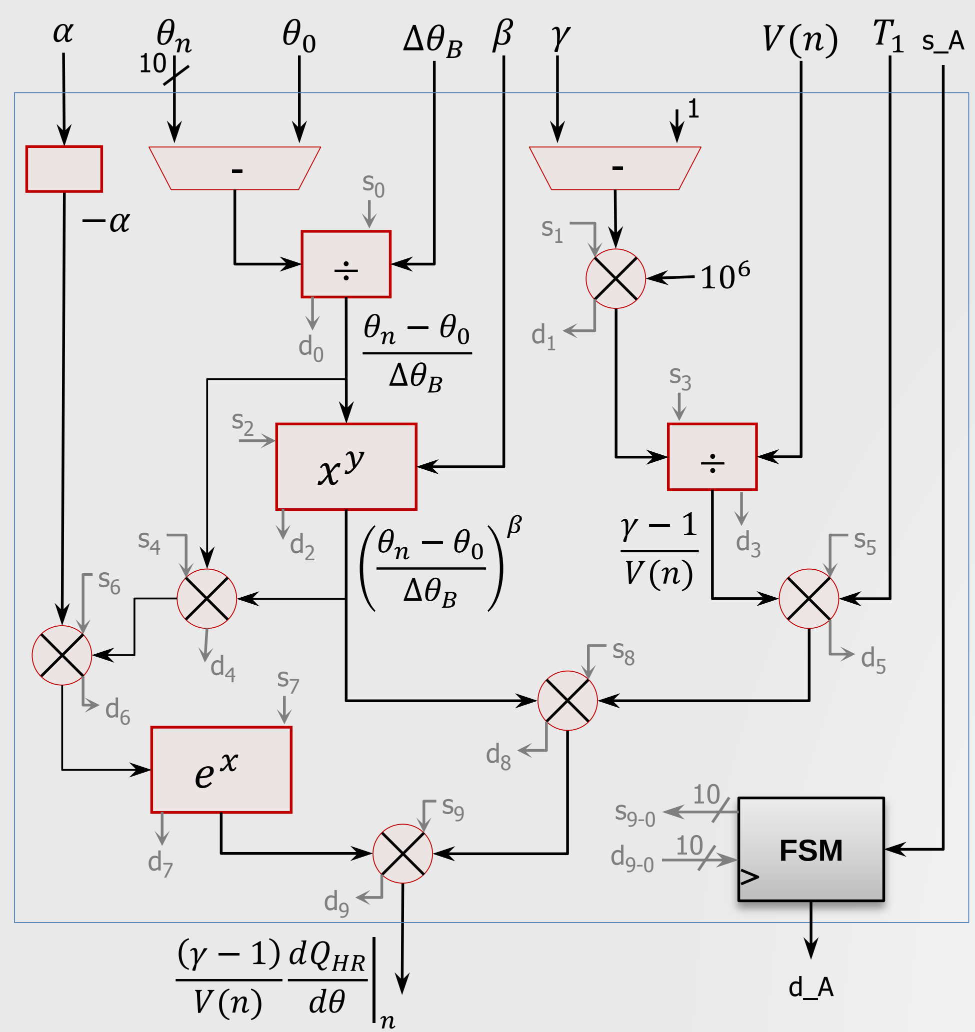
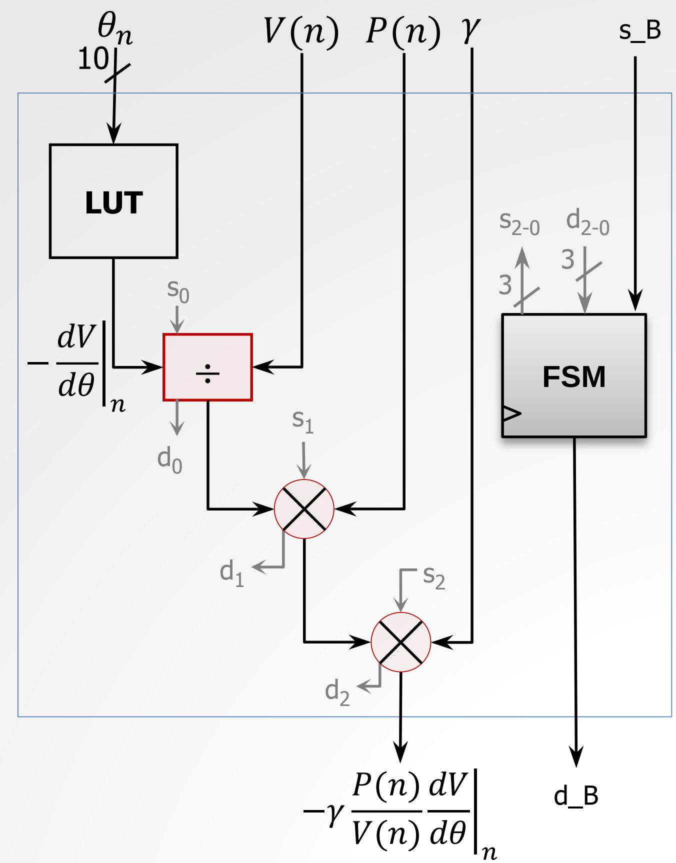
DFX Architecture:

- A and B computation units.





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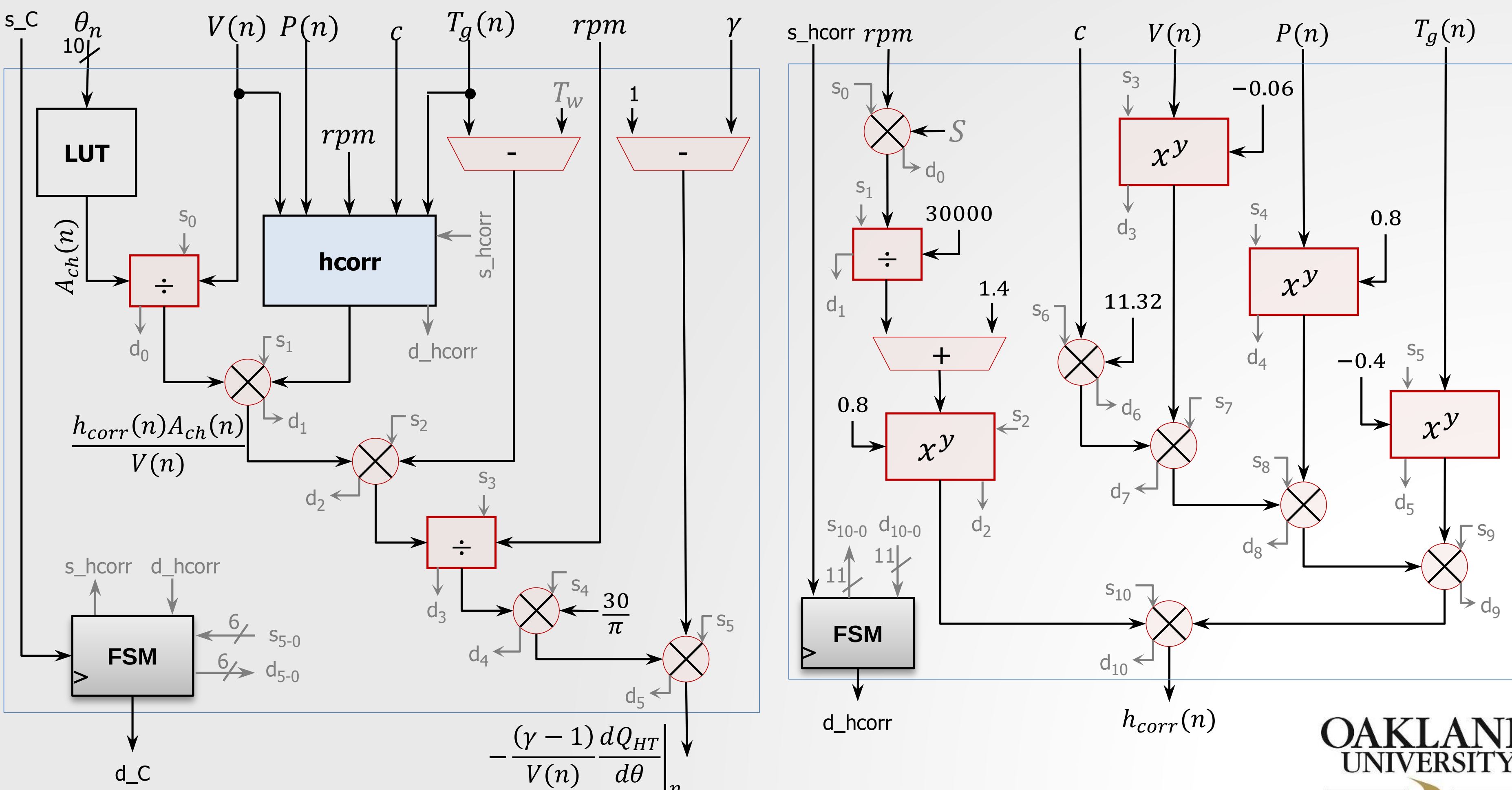
Hardware Implementation

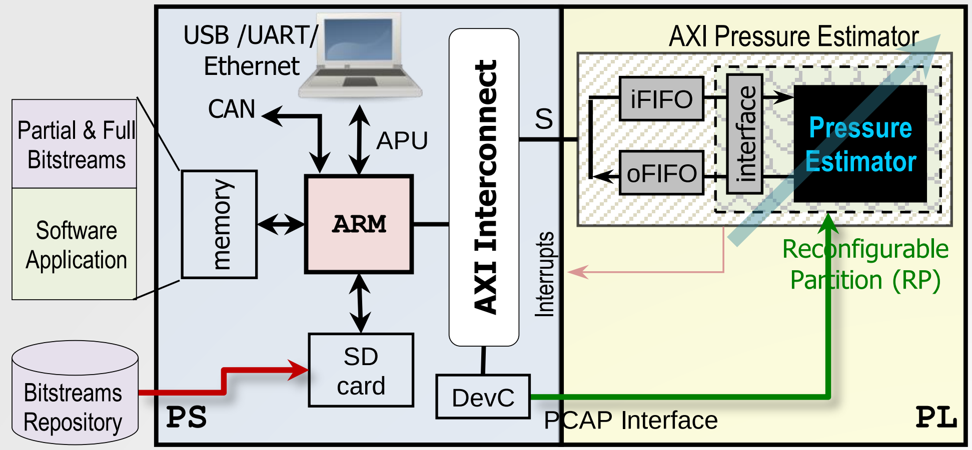
DFX Architecture:

- The C term is shown along with the *hcorr* computation term.
- *hcorr* is the most resource intensive component.



Embedded System

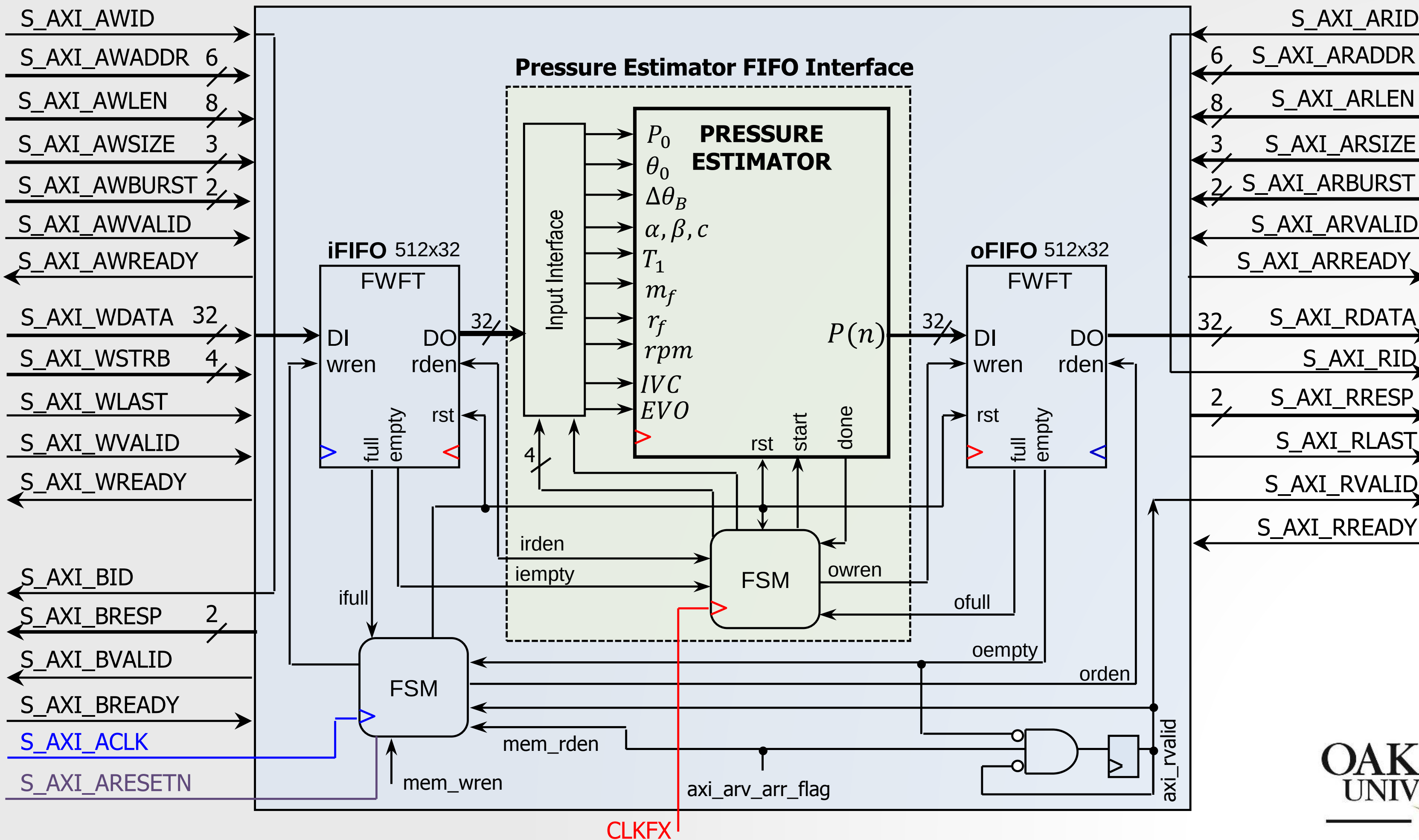
- For real-time hardware validation, the pressure estimator was placed in a reconfigurable embedded system.
- It was implemented on a Programmable System-on-Chip that integrates:
  - Processing System (PS): dual-core ARM® processor and common peripherals
  - Programmable Logic (PL): run-time reconfigurable fabric (FPGA).



- Target device: Xilinx® XC7020 Zynq-7000 All Programmable SoC.
- It was tested on a ZED Development Board.
- The PS feeds data to and extracts data from the Pressure Estimator via an AXI4-Full Interface.
- AXI Pressure Estimator Peripheral: It includes our design. It is located in the PL, and it runs at 50 MHz.

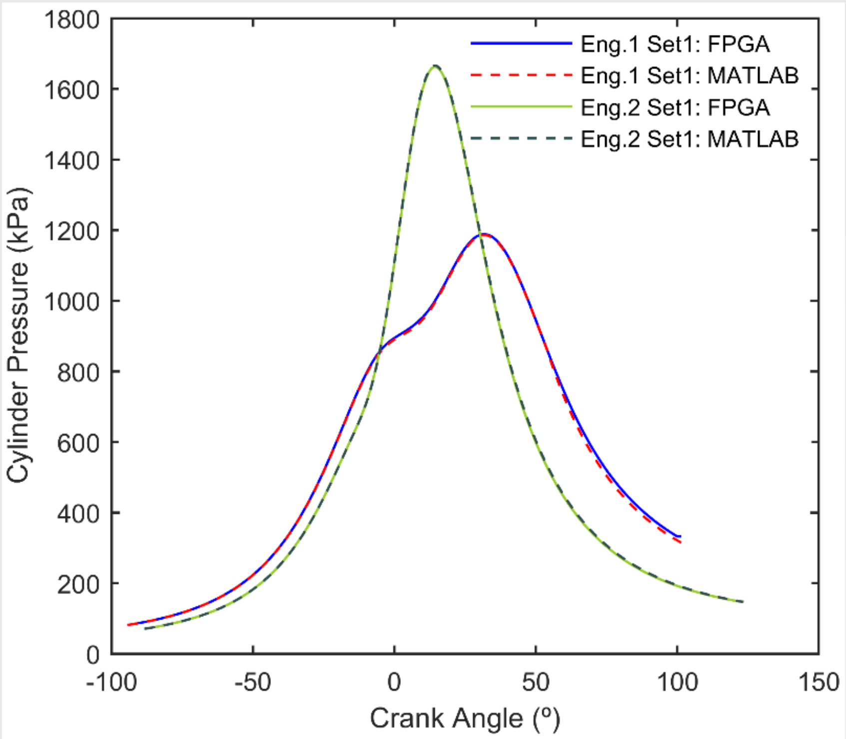
Embedded System

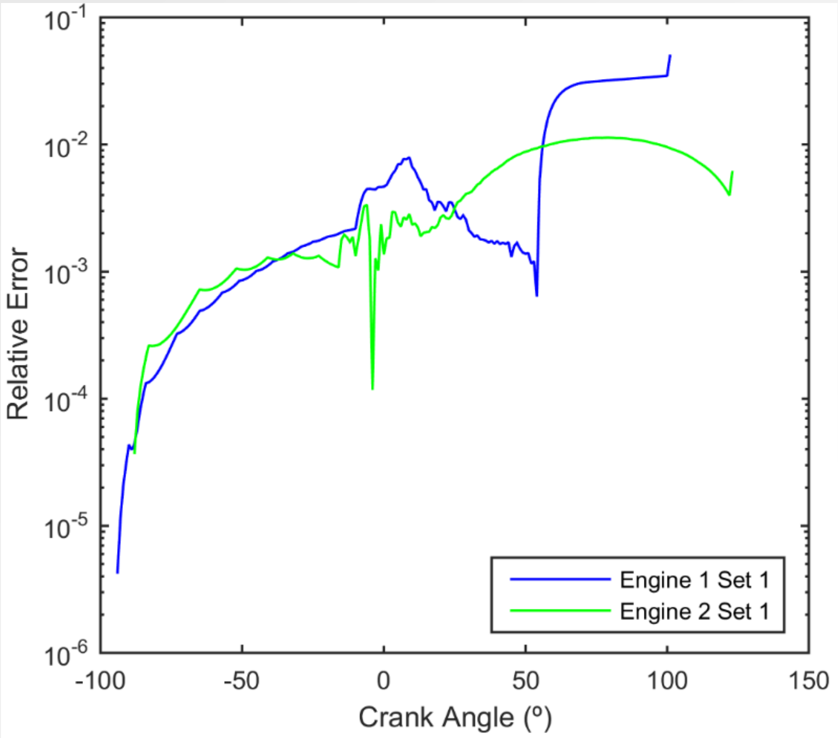
- Pressure Estimator Peripheral: our design + a 32-bit AXI4-Full Slave Interface (2 FIFOs, control, and extra logic).
- With this configuration, we feed the 13 sets of data (from two OEMs) and then retrieve the pressure traces via the AXI4-Full Interface



Embedded System

- We show estimated pressure traces from IVC (intake valve closing) to EVO (exhaust valve opening) for both the 64-bit floating-point MATLAB® model and the 32-bit DFX hardware.
- We also show relative error curves: $Rel.Error = \left|\frac{HW\ value - MATLAB\ value}{MATLAB\ value}\right|$





- We show results for 2 sets (out of 13). Note that the curves are pretty close. This occurs for all the 13 sets.

Embedded System

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- The relative error between the MATLAB® results and the hardware results were shown for 2 sets. The table depicts these relative error results (maximum, average) for all the 13 sets.

- This error is the quantization error between 64-bit floating-point and 32-bit DFX arithmetic. These results suggest that the use of dual fixed-point arithmetic provides results close to those of floating-point without the large hardware overhead of floating-point arithmetic.

Set		Relative Error (%)	
		Avg.	Max.
Engine 1	1	0.86%	4.99%
	2	0.70%	4.02%
	3	1.61%	9.26%
Engine 2	1	0.47%	1.13%
	2	1.15%	6.29%
	3	1.12%	4.97%
	4	0.83%	3.75%
	5	1.53%	6.02%
	6	1.08%	4.31%
	7	1.29%	6.83%
	8	2.41%	7.95%
	9	2.16%	8.45%
	10	1.47%	6.75%

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Embedded System

Execution Time:

- A pressure data point $P(n)$ is computed in a maximum of:

$$T_p = \left(13n \ + 4(p_0 - p_1) + 311\right) \text{ cycles.}$$

  - Note that this T_p is an upper bound as the DFX multiplier takes up to $n + 1$ cycles, but it takes fewer cycles on average.

- T_p=753 clock cycles for [32 14 5]

- Pressure Trace Computation cycles: $(IVC - EVO)^{\circ} \times T_p$ cycles.

- Processing time: It depends on IVC-EVO, crank angle resolution, and operating frequency (50 MHz). For a crank angle resolution of 1º, the pressure trace computation can take up to:
  - 2.951 ms for the Engine 1 sets (IVC-EVO=196º for all sets).
  - 3.192 ms for the Engine 2 sets (IVC-EVO=212º for all sets).

Embedded System

- The hardware can support real-time pressure computation at 1º crank angle resolution and keep up with speeds up to **10000** rpm (at 10000 rpm, the IVC-EVO time duration is 3.26 ms for Engine 1 Sets and 3.53 ms for Engine 2 sets).
- The table shows the actual processing times for the 13 sets, which are shorter than the reported maximum times.

Set		RPM	IVC-EVO (ms)	Proc. time (ms)
Engine 1	1	1300	46.15	2.6671
	2			2.6613
	3			2.6609
Engine 2	1	1250	48.00	2.8800
	2	1250	48.00	2.8959
	3	1250	48.00	2.8988
	4	2000	30.00	2.8833
	5	2000	30.00	2.8979
	6	2000	30.00	2.9083
	7	3200	18.75	2.8967
	8	3200	18.75	2.9033
	9	4000	15.00	2.9068
	10	4000	15.00	2.9260

Conclusions

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- A model for pressure estimation was implemented on dedicated hardware using a non-standard numerical representation that can handle large numerical ranges with reasonable resource requirements.
- Hardware design tested in real-time using a reconfigurable embedded system using 13 sets from 2 OEMs (original equipment manufacturers).
- Numerical results show that the accuracy of the DFX architecture is close to that of a double-precision software realization in MATLAB®.
- The hardware design can keep up with engine speeds of up to 10000 rpm with 1º crank angle resolution.

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