Energy-Efficient Discrete Signal Processing with Field Programmable Analog Arrays (FPAAs)

Yu Bai and Mingjie Lin

UCF
Stands For Opportunity

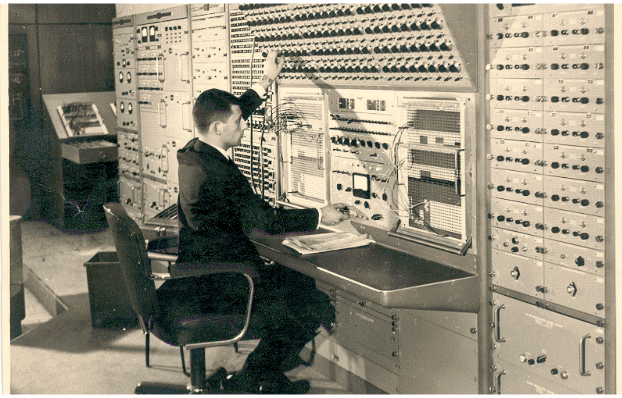
Why Convolution?

- Large-Scale Convolution is the Computing Engine of many CV, AI, and DSP application
  - Image Classification, Edge Detection, …
  - Deep Learning: Convolutional 3D-Network, …
  - Video Object Recognition, …

- But, Computationally Intensive
  - Energy Consumption High
  - Fault Tolerance Low
  - Time Complexity O(n^2) or O(nlg(n)) even with complicated FFT-based method

Analog Computing

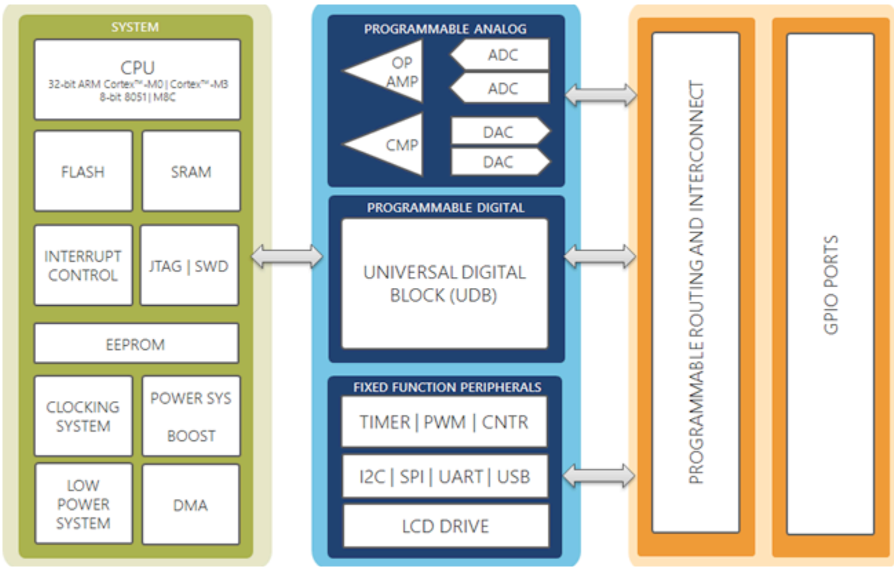
- Digital Computing vs. Analog Computing
  - Energy Efficiency
  - Performance
  - Hardware Effectiveness



- Analog Computing is HARD!
  - Flexible and Effective Prototyping Platform is Lacking
  - Resource Constraints
  - Noise Sensitivity
  - No Unified Computing Framework for Complicated Task

What about Reconfigurable Analog Computing?

Limited Resource Type: No Universal Logic Gate Set, No LUT ….



No Straightforward Design Framework: No Logic Synthesis + Technology Packing ….

Very Sensitive to Noise and Design Parameters: The General Nature of Analog Computing …

Our Idea

Probabilistic-Base Computing

+

Field-Programmable Analog Array

=

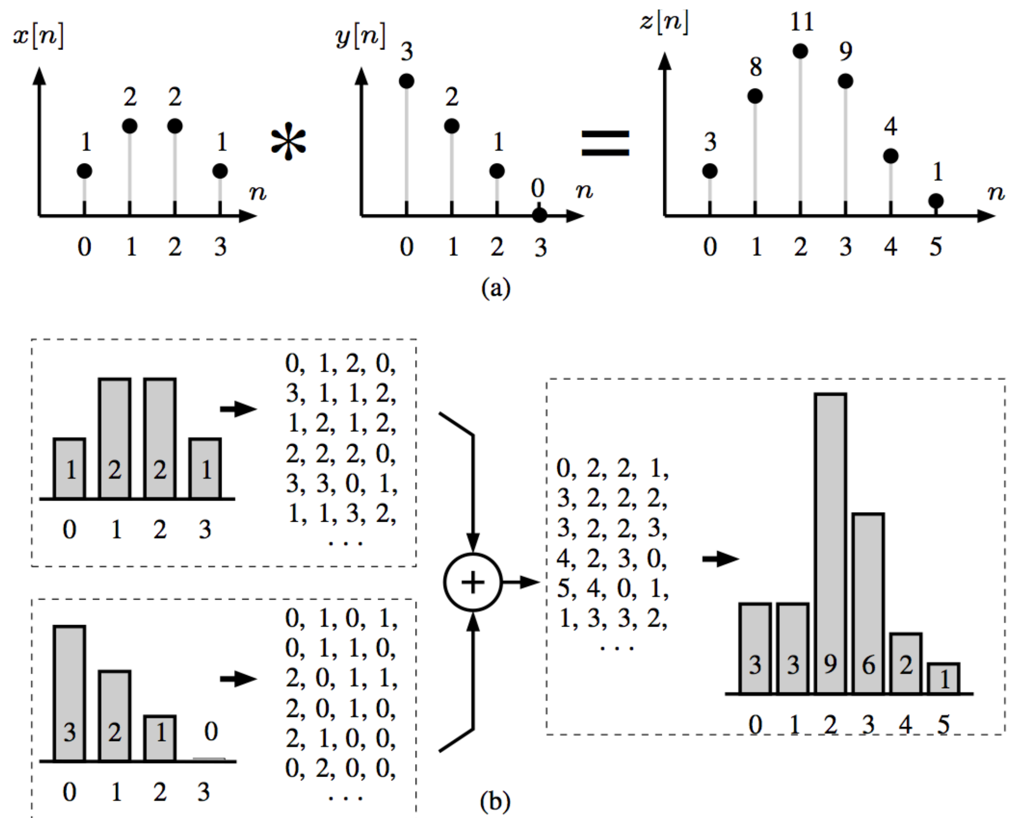
Large-Scale Convolution

- Prototyping
- Resource Constraints
- Noise Sensitivity
- No Unified Computing Framework

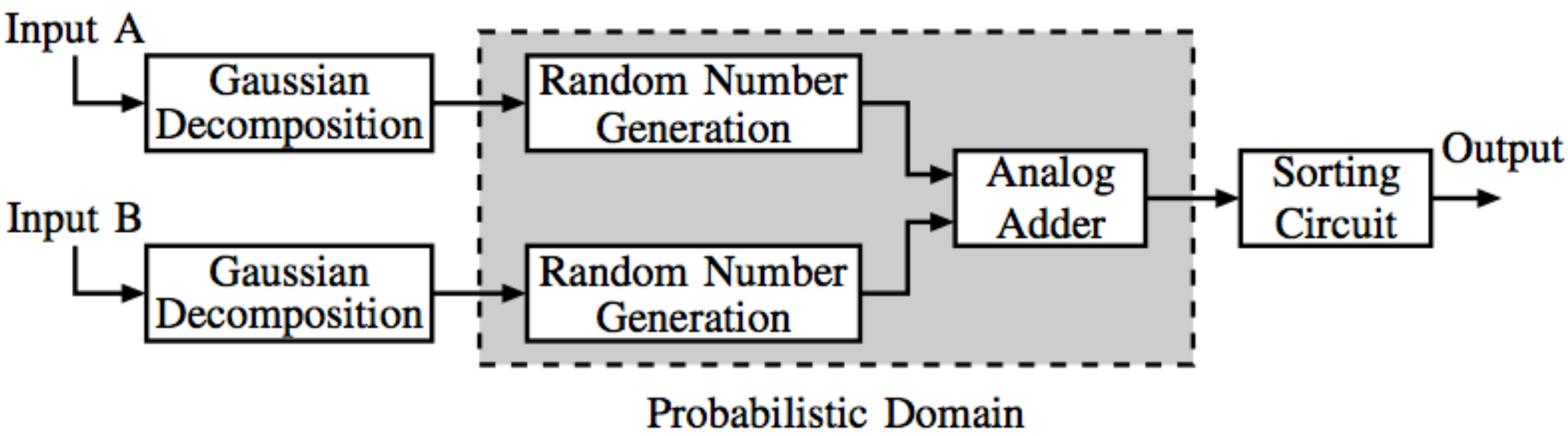
Probabilistic Method for Convolution

- Probabilistic Convolution Theorem

$$f_Z(z) = f_{X+Y}(z) = P(Z = z) = \sum_{x=0}^{z} f_X(x) f_Y(z-x)$$

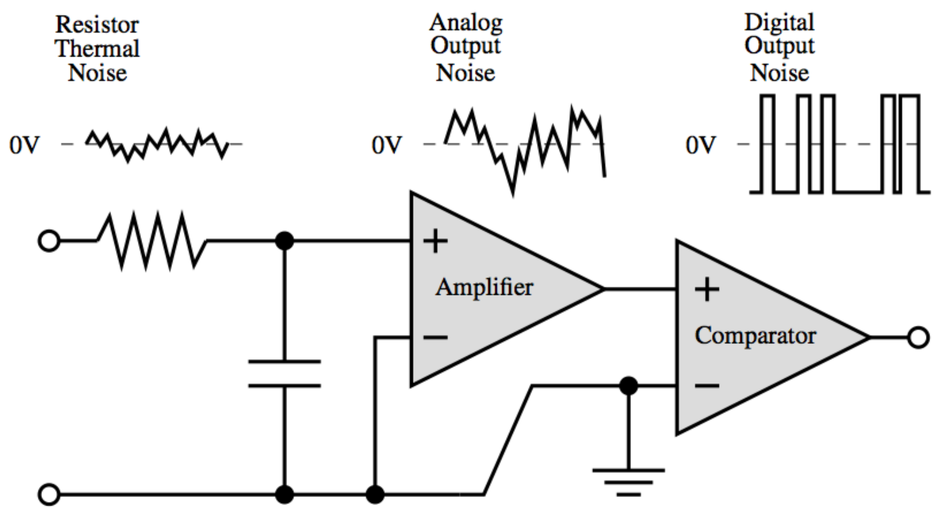


Overall Algorithm Flow

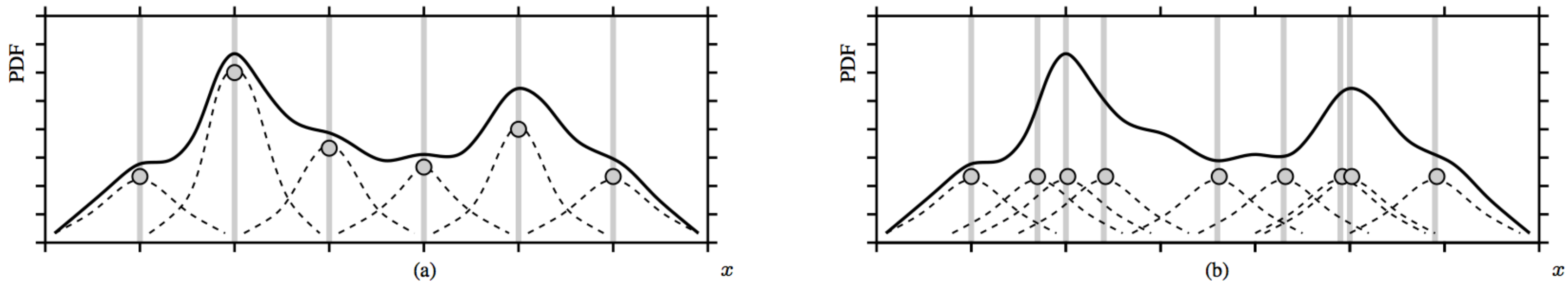


Input → PDF → Random Samples

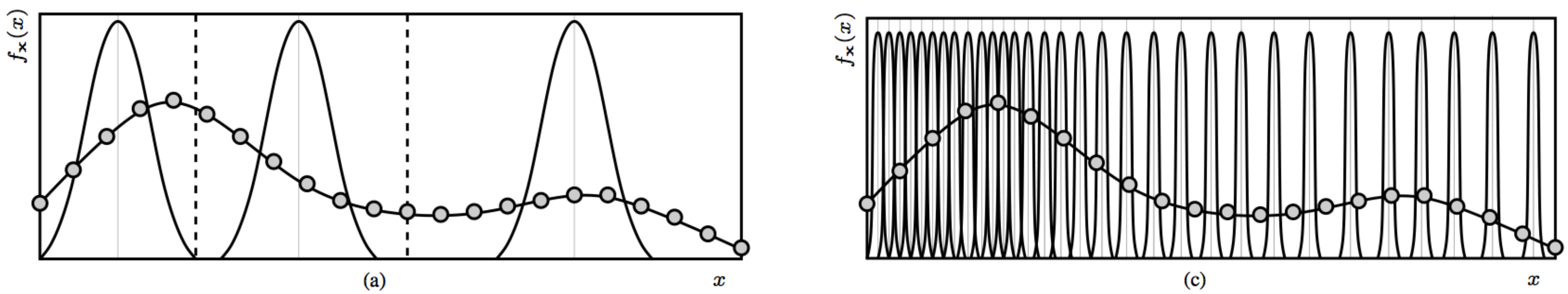
- Direct Implementation too costly
- Objective: Given any form of PDF, efficiently generating a large ensemble of random samples
- Method:
  - Gaussian noise source + Gaussian Decomposition
- Gaussian Noise Random Sample Generator



Gaussian Decomposition: Concept

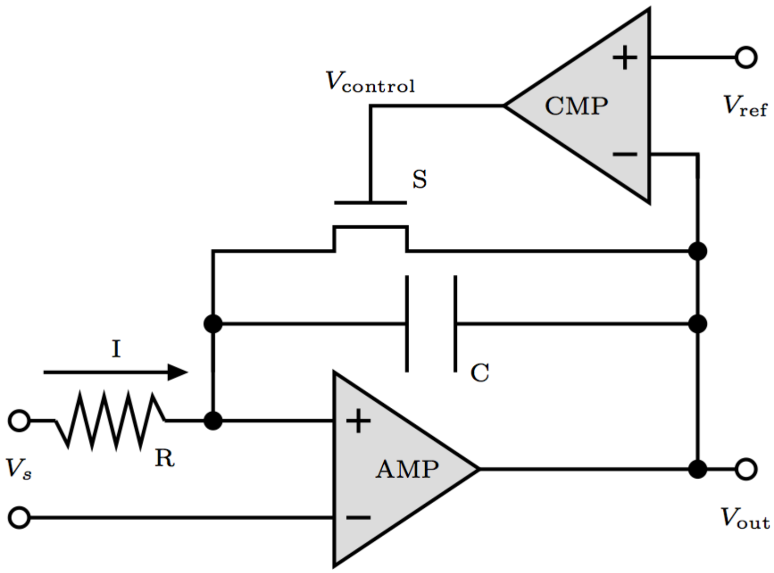


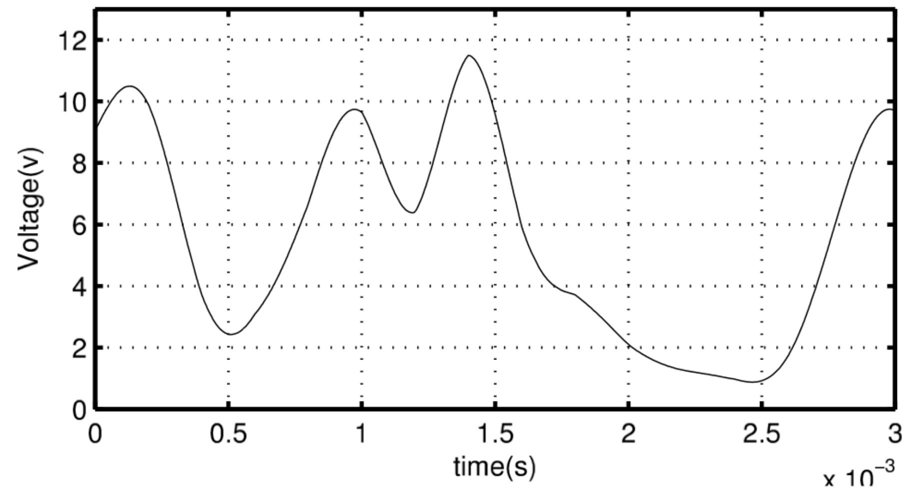
Two Types of Gaussian Decomposition



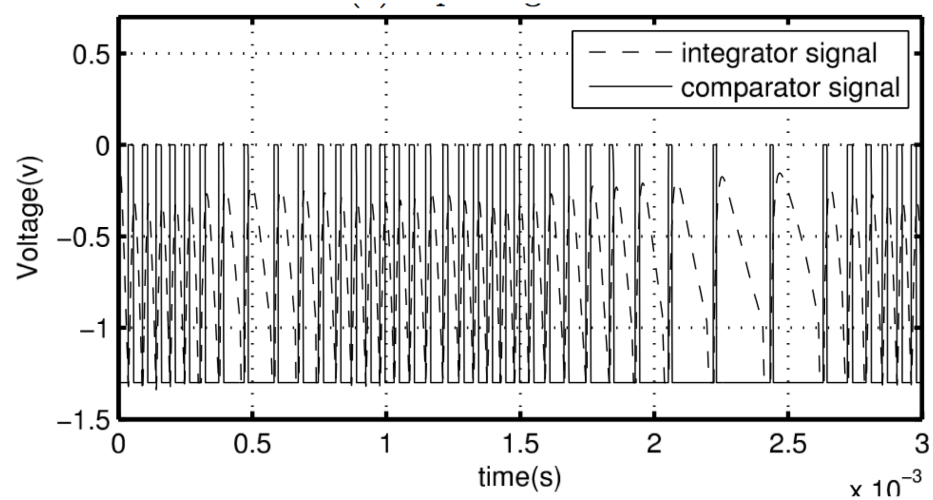
Tunable Accuracy: Number of Gaussian Components

Gaussian Decomposition: Analog Way



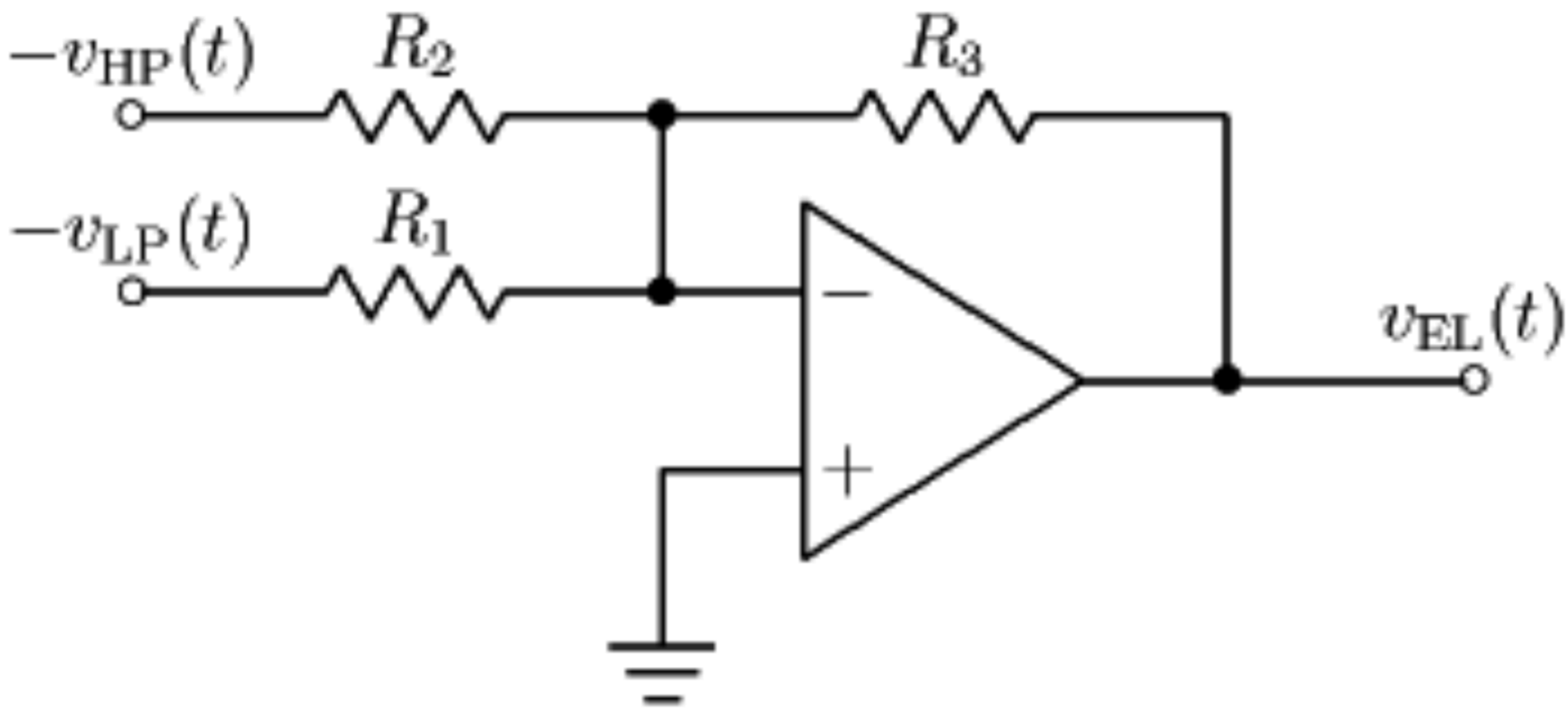


(a) Input signal.

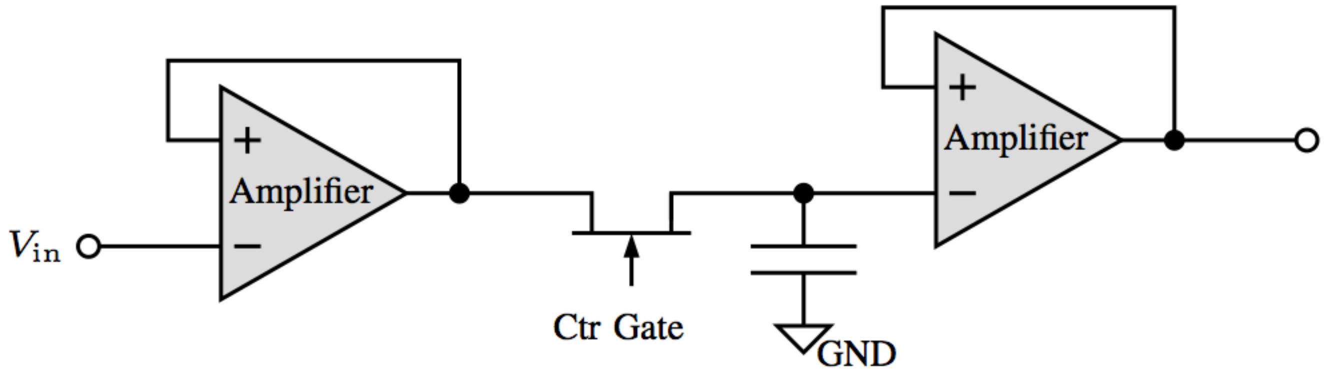


(b) Gaussian decomposition response.

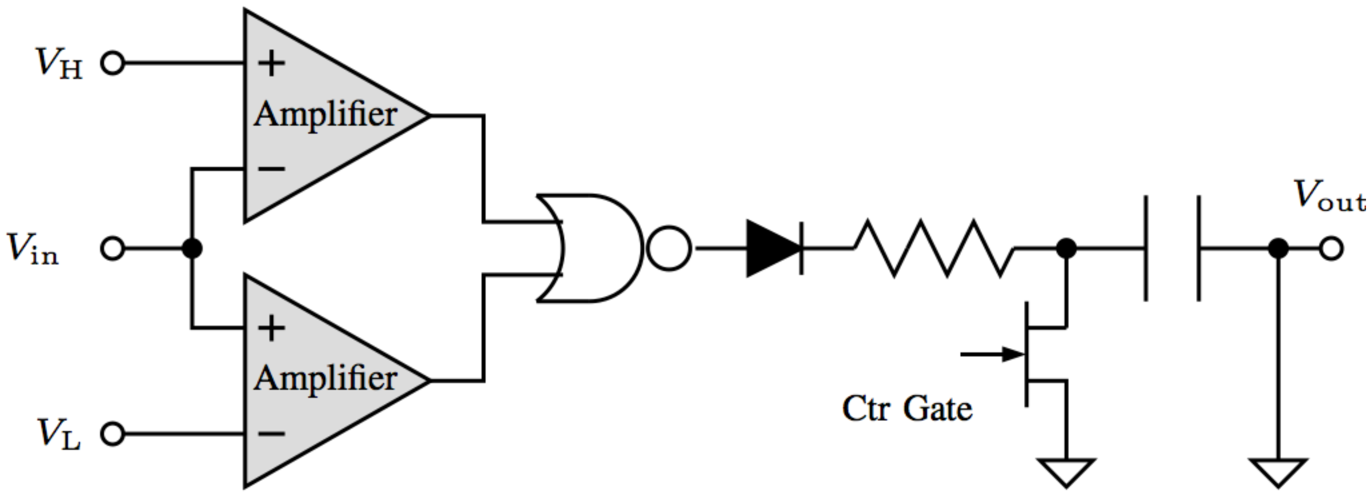
Analog Adder



Random Samples → PDF: Analog Way

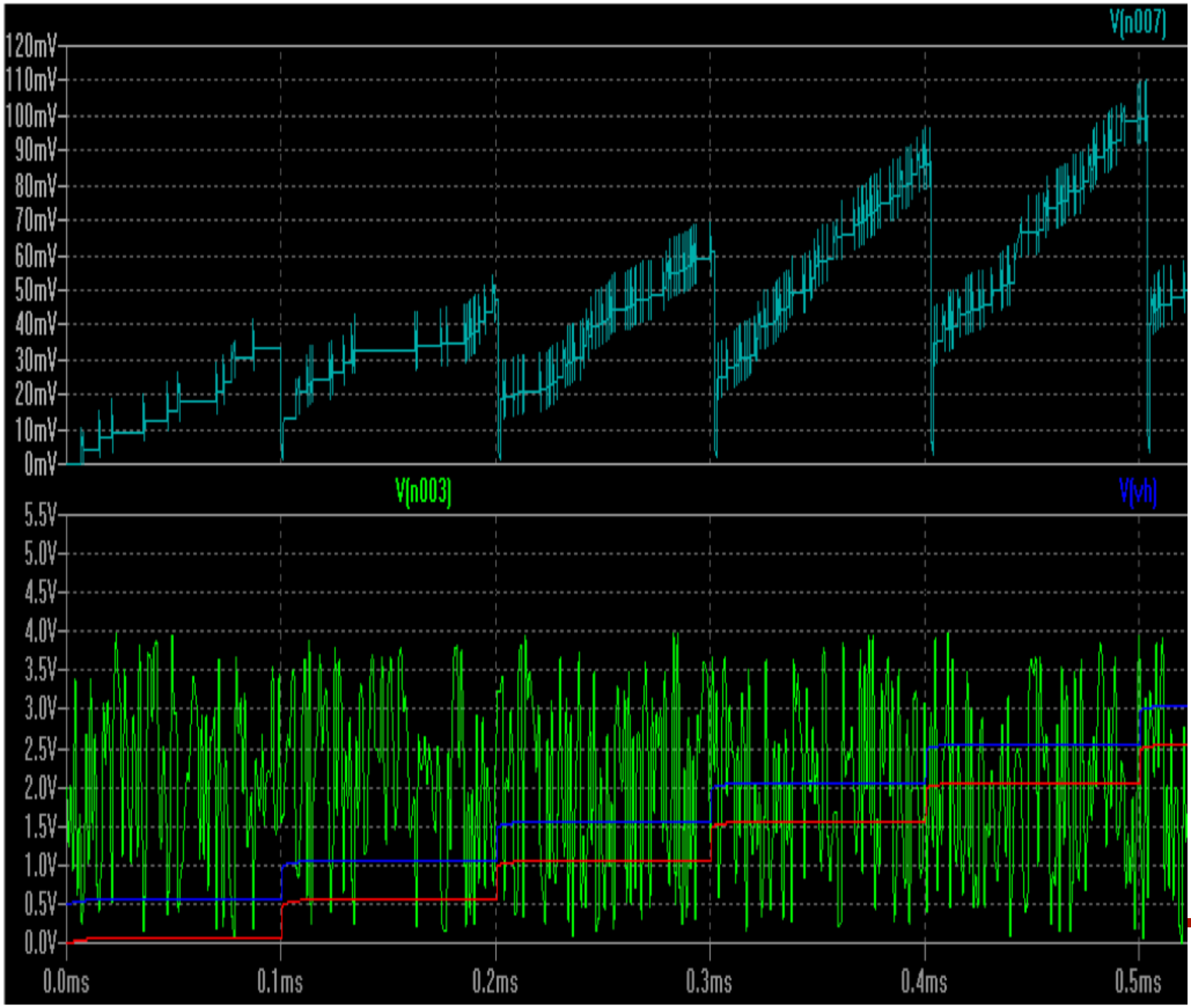


(a)

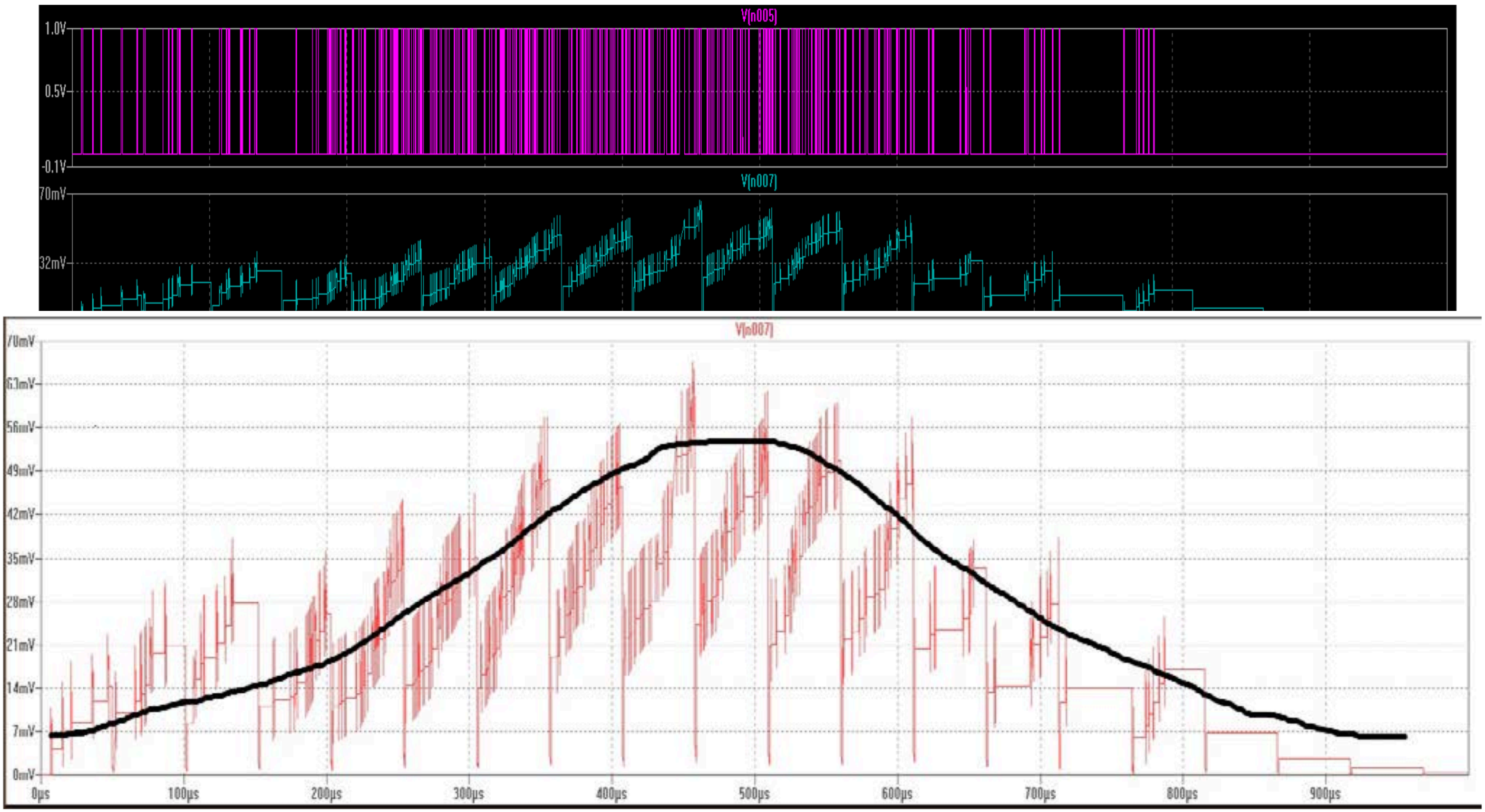


(b)

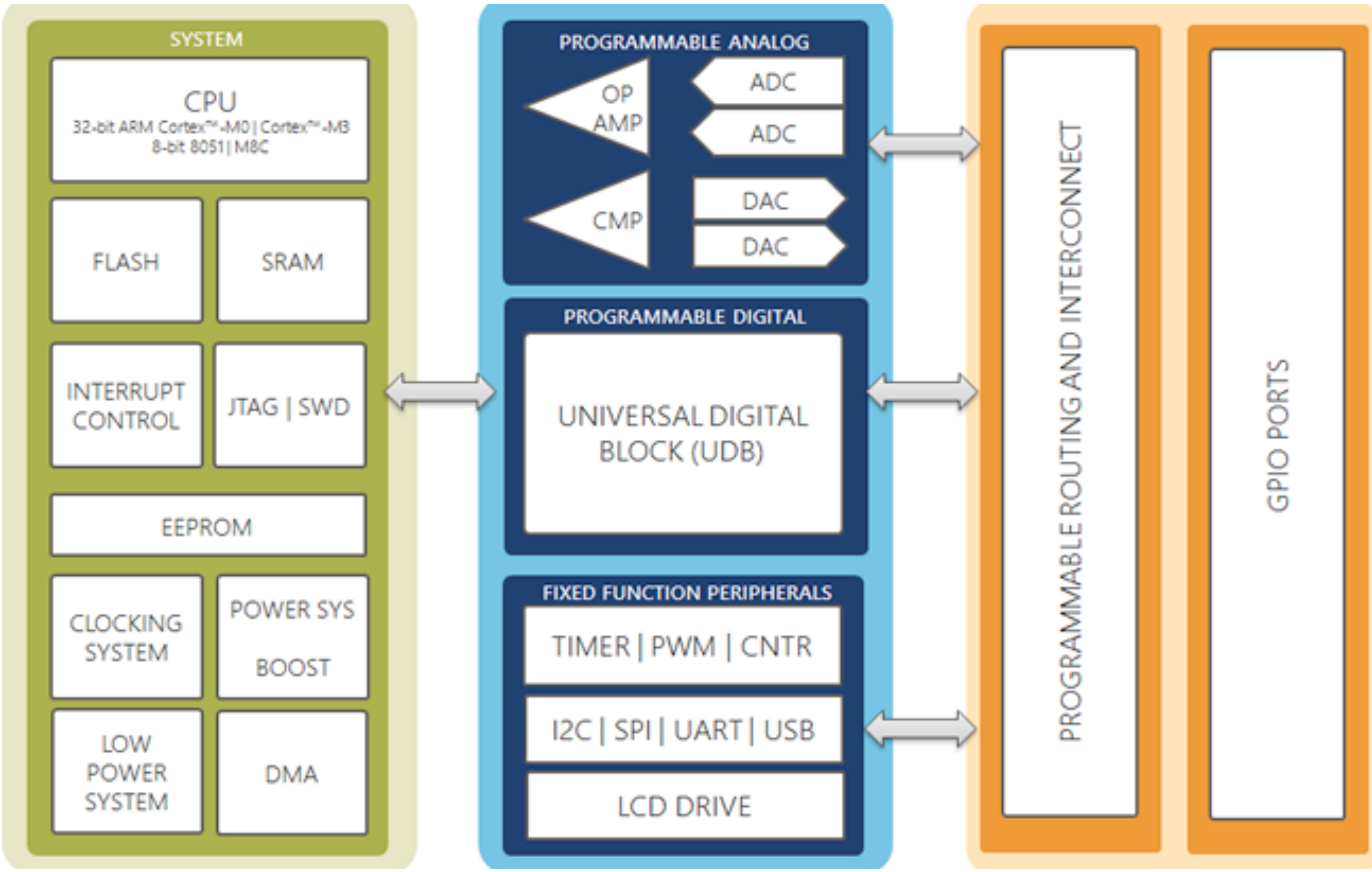
Random Samples → PDF: Results



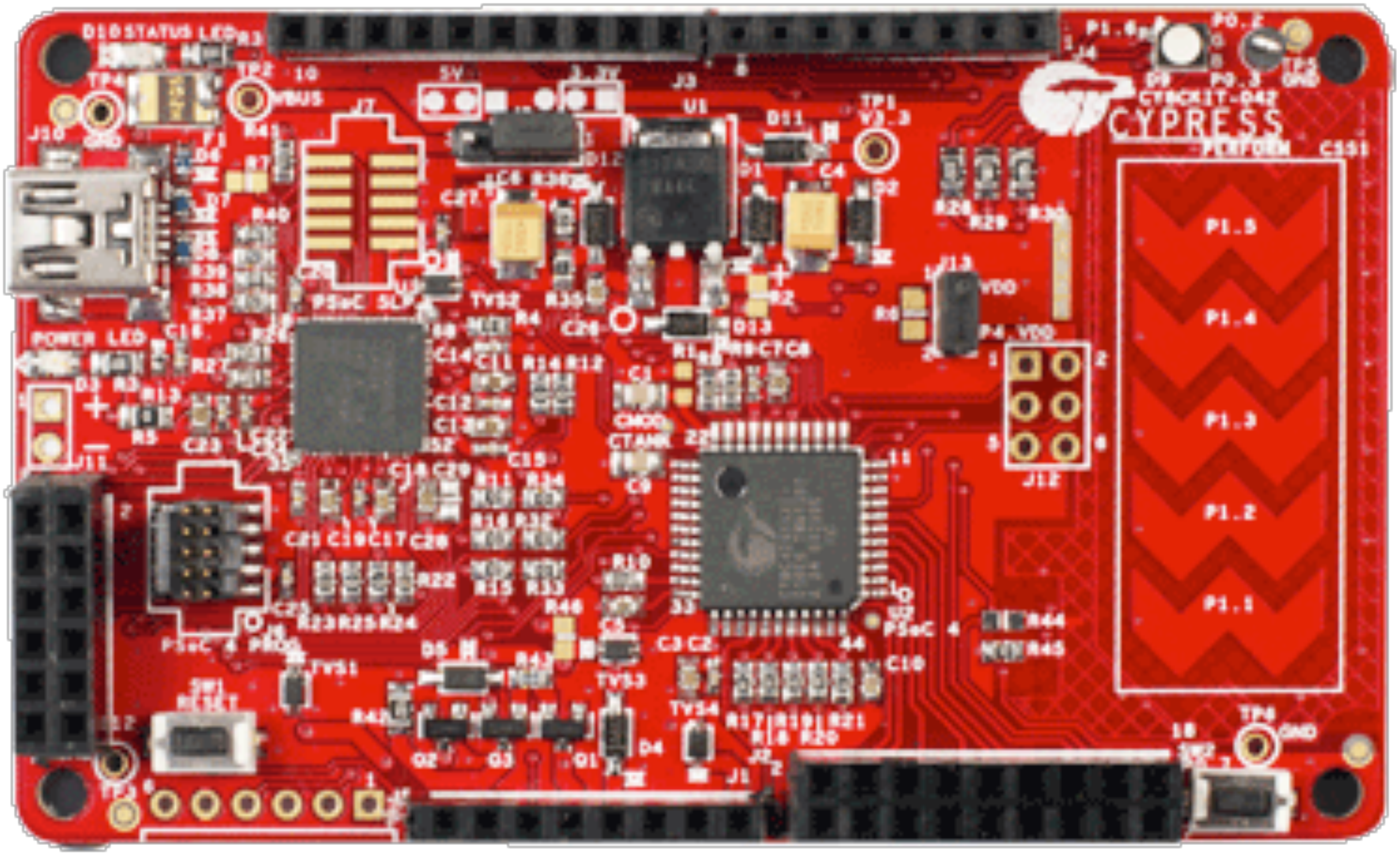
Random Samples → PDF: Results



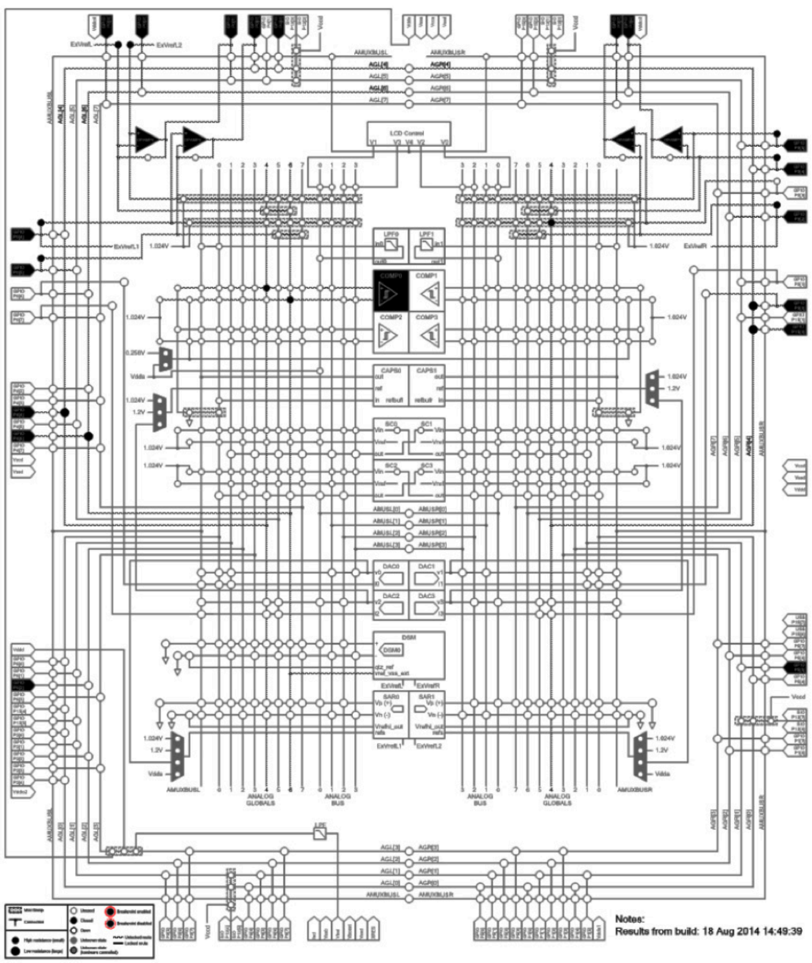
PSoC Platform for Implementation

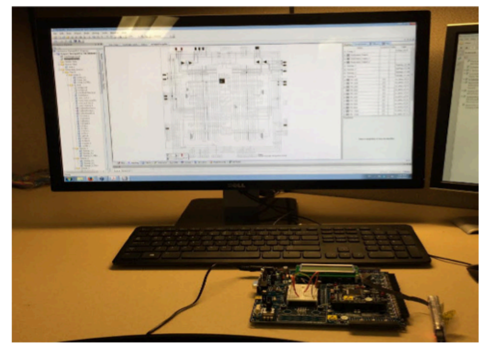


PSoC Board

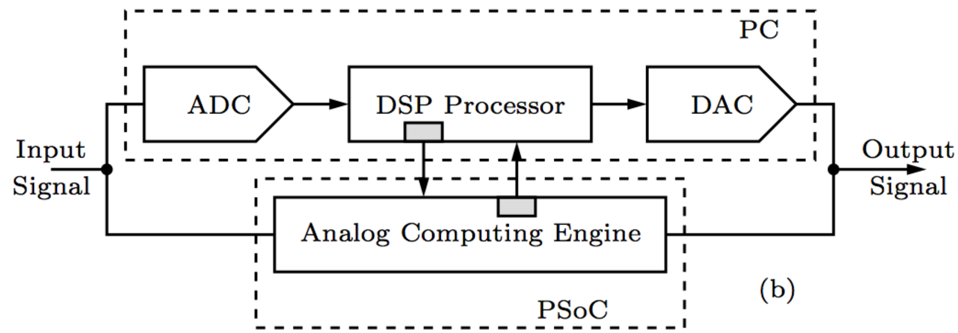


PSoC System Implementation





(a)



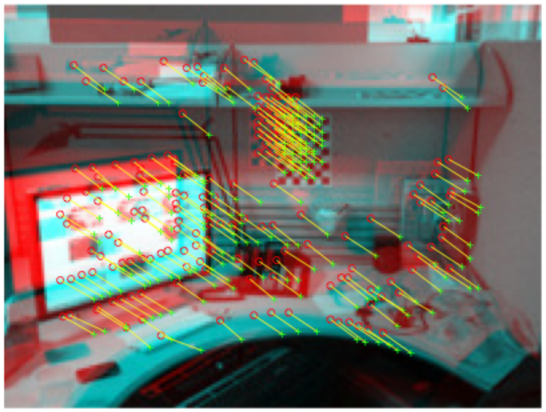
(b)

Hardware Usage and Energy Consumption

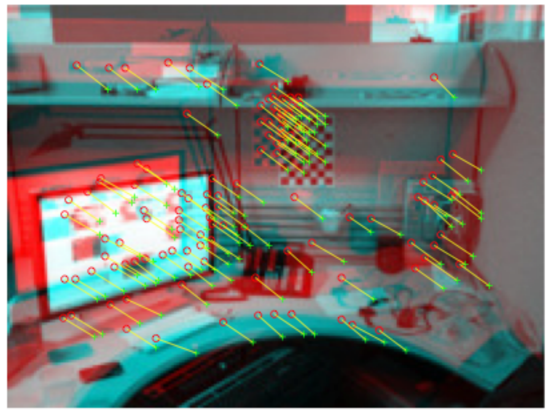
		FPGA-Based			PSoC-Based		
		64	1024	4096	64	1024	4096
Area	Slice LUT	950	3308	13232			
	Slice Registers	426	1436	5744			
	Slice	310	1036	4144			
	Opamp				4	6	8
	comparator				1	1	1
	capacitor				4	8	12
	resistor				5	9	14
	diode transistor				4	7	13
Power	Dynamic Power (mW)	107.82	137.87	186.28	46.66	55.29	64.88
	Energy Consumption (nJ)	1196.80	1098.82	830.81	427.24	392.43	153.86

~1/3 of Dynamic Power, ~1/6 of Total Energy Consumption at 99% accuracy

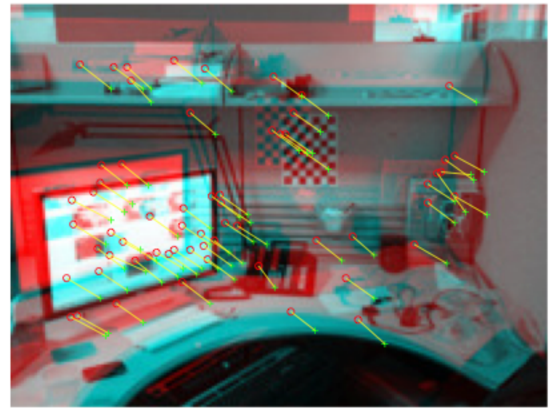
App1: *Finding Corresponding Features*



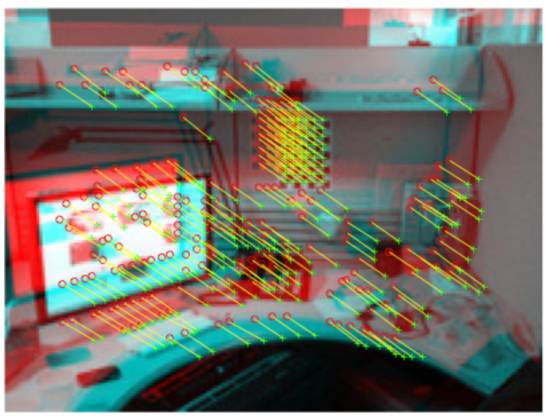
(a) σ=1%, $P = 185$.



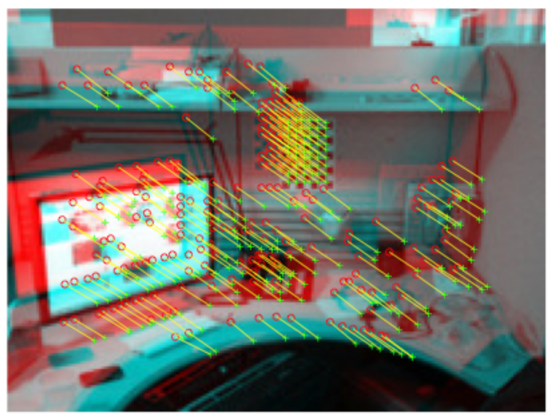
(c) σ=5%, $P = 114$.



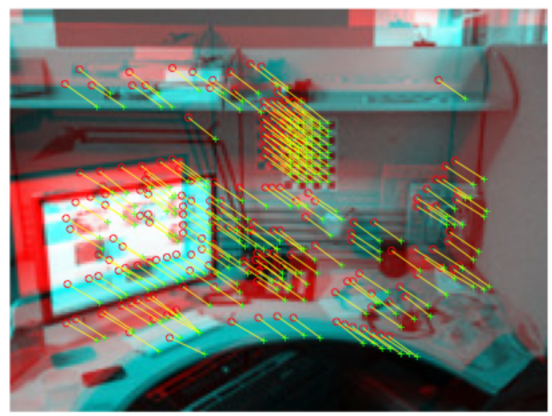
(e) σ=10%, $P = 60$.



(b) σ=1%, $P = 234$.



(d) σ=5%, $P = 230$.

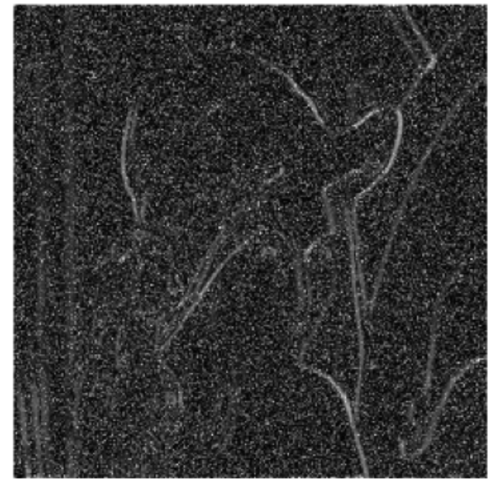


(f) σ=10%, $P = 220$.

App2: *Convolution-Based Edge Detection*

(a) σ=1%.

(c) σ=5%.



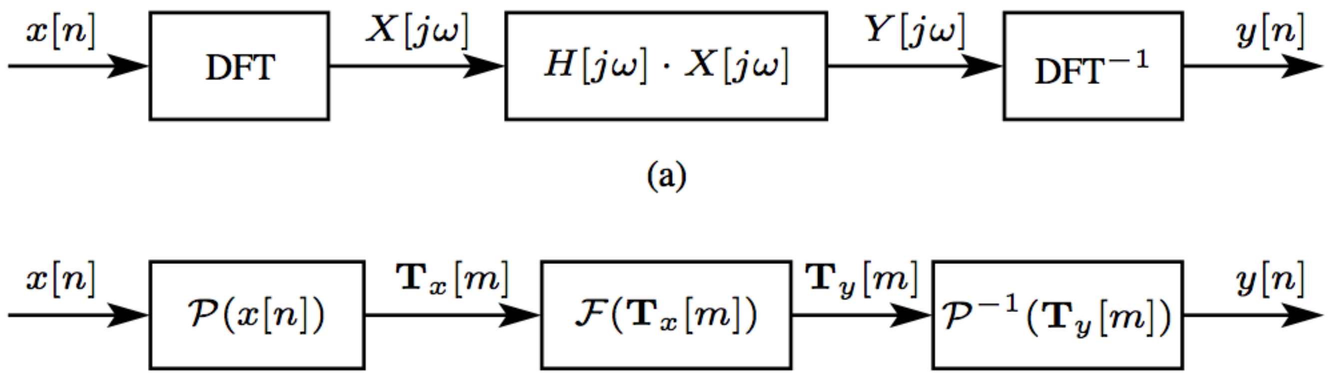
(e) σ=10%.

(b) σ=1%.

(d) σ=5%.

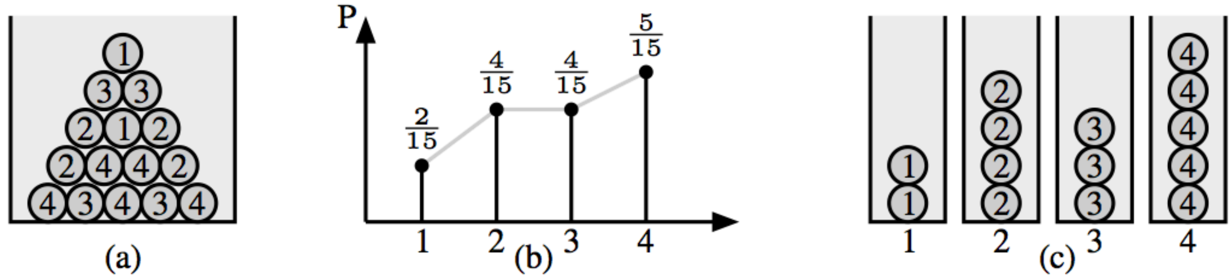
(f) σ=10%.

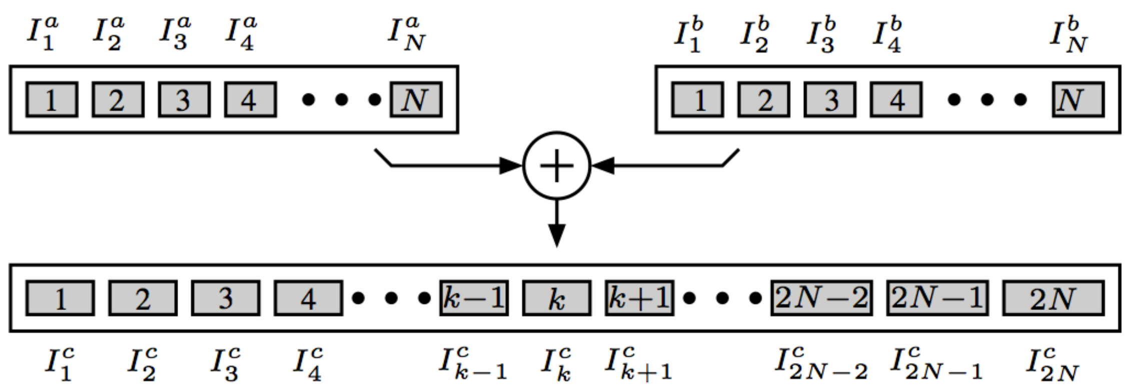
Question 1: How Versatile?



- Computing Framework: Probabilistic Domain Transform
- Perception-Based Computing Tasks
  - Convolution-Like Applications: FIR, Correlation, …
  - Associative Computing, …

Question 2: How Accurate?





$$\Pr(|W_i^c - S \times q_k| \geq \delta \times S \times q_k) < \exp(-\frac{\delta^2 \cdot S}{N}).$$

Chernoff Bound ➔ # Random Samples vs. Accuracy

Thanks! Questions?