Smart Meter SoC with Adaptive Calibration for Smart Cities

Ji-Soo Seo, Jae-Lim Lee, Dong-Sun Kim
Department of Semiconductor Systems Engineering, Sejong University

Introduction

- Smart meters require accurate sensor measurements for reliable smart grid operation.
- Environmental factors introduce sensor errors, making calibration essential.
- Progressive Polynomial Calibration(PPC) is effective for calibration but suffers from exponential polynomial complexity.
- This work proposes a Smart Meter SoC based on 2D Simplified Progressive Polynomial Calibration(SPPC) and its segmented extension for efficient sensor calibration.

Calibration Algorithm

Ⅰ. Progressive Polynomial Calibration (PPC)

PPC constructs a calibration function by progressively adding polynomial terms at each calibration point. Its repetitive structure is suitable for hardware implementation.

$$f_n(x) = f_{n-1}(x) + a_n \prod_{i=1}^{n-1} (f_i(x) - y_i)$$

a_n : calibration coefficient
y_i : reference value

However, the exponential polynomial degree growth$\left(deg(f_n) = 2^{(n-1)}\right)$ leads to high computational complexity and increased processing latency.

Ⅱ. 2D Simplified Progressive Polynomial Calibration (2D SPPC)

To overcome the exponential polynomial degree growth of PPC, SPPC updates the calibration function using residual errors rather than expanding the entire polynomial structure at each calibration point.

$$f_n(x) = f_{n-1}(x) + a_n \prod_{i=1}^{n-1} (x - x_i)$$

a_n : calibration coefficient
x_i : calibration point

By utilizing residual errors, SPPC achieves linear polynomial degree growth ($deg(f_n) = n - 1$), reducing hardware complexity and execution time.

2D SPPC extends SPPC using both sensor output (x) and cross-sensitivity variable (z).

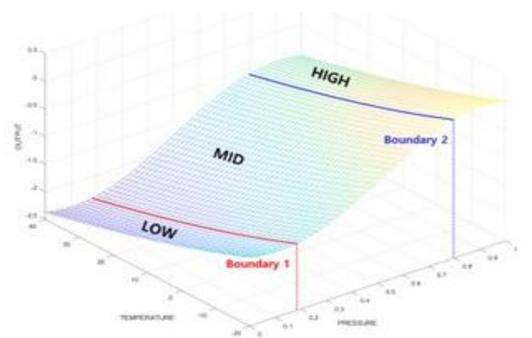
$$f_{n,m}(x,z) = f_{n,m-1}(x,z) + a_{nm} \left(\prod_{i=1}^{n-1} (x - x_i)\right)\left(\prod_{j=1}^{m-1} (z - z_j)\right)$$

a_n : calibration coefficient

Simultaneous compensation of sensor nonlinearity and environmental variations.
Linear polynomial order growth is preserved ($deg(f_n) = n \times m - 1$).

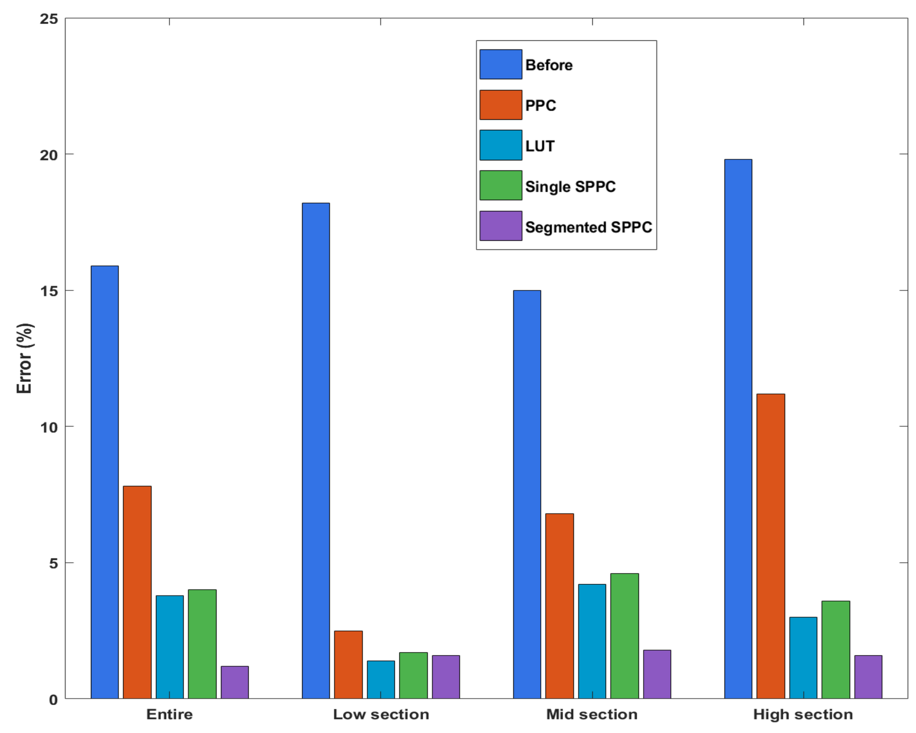
Ⅲ. Segmented SPPC

Segmented SPPC divides the sensor input range into multiple regions and applies independent SPPC functions to improve local calibration accuracy.



Experimental Results

Ⅰ. Calibration Accuracy



- Segmented SPPC achieved the lowest error among all calibration methods.
- The overall error(MAE) was reduced from 7.66 (PPC) to 1.75 (Segmented SPPC).
- Independent calibration functions for each segment improved calibration accuracy by reducing localized nonlinear errors.

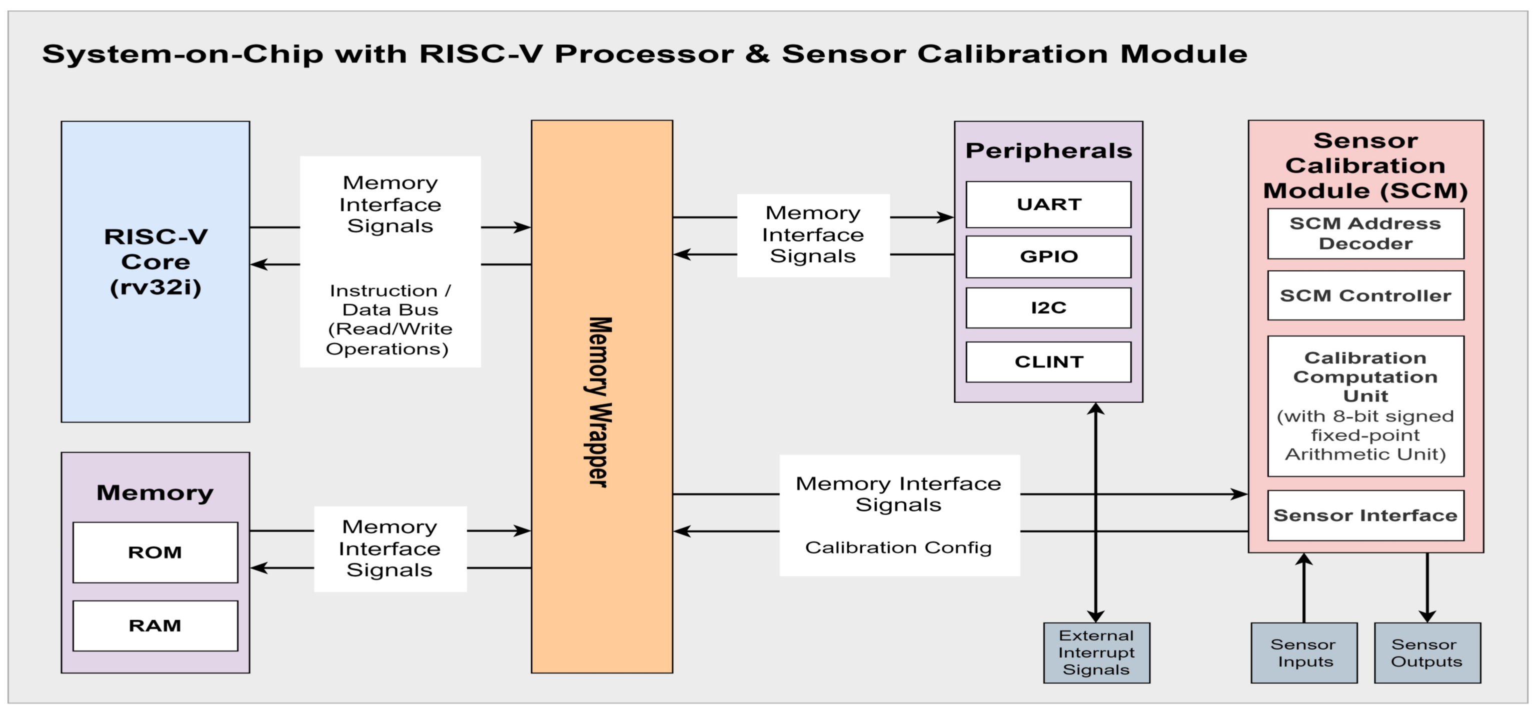
Ⅱ. Computational Efficiency

Mode	PPC	SPPC
Calibration	18.2 µs	10.58 µs
Normal	2.18 µs	0.45 µs

- The proposed SPPC significantly reduced processing latency compared with conventional PPC.
- Processing time was reduced by approximately **42%** in Calibration Mode and **79%** in Normal Mode.

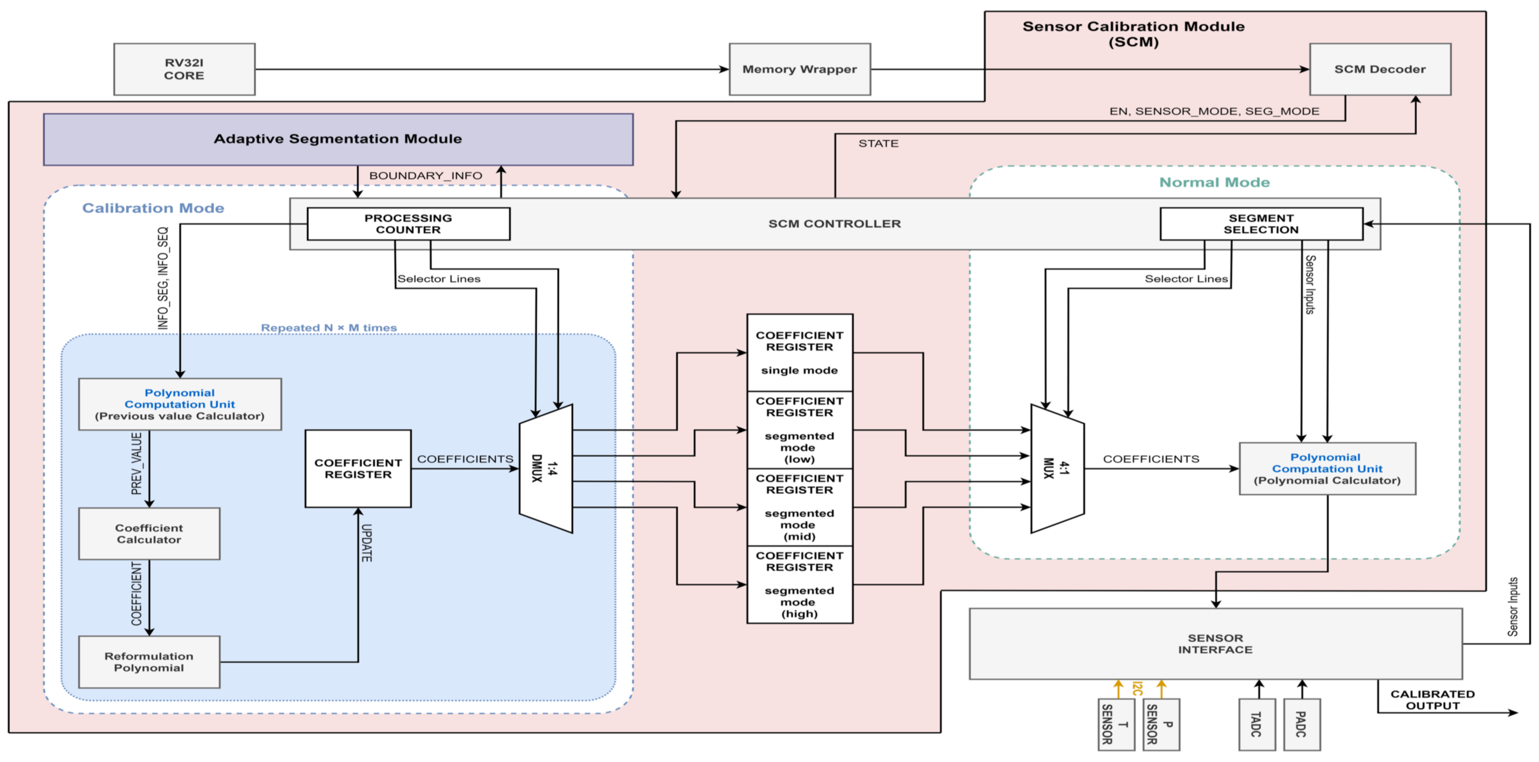
Hardware Architecture

Ⅰ. Overall Architecture



Input sensor data are processed in Calibration Mode, where the ASM determines optimal segment boundaries and the SCM computes SPPC calibration coefficients. In Normal Mode, the stored coefficients are applied to incoming sensor data to generate calibrated outputs in real time.

Ⅱ. Sensor Calibration Module (SCM)

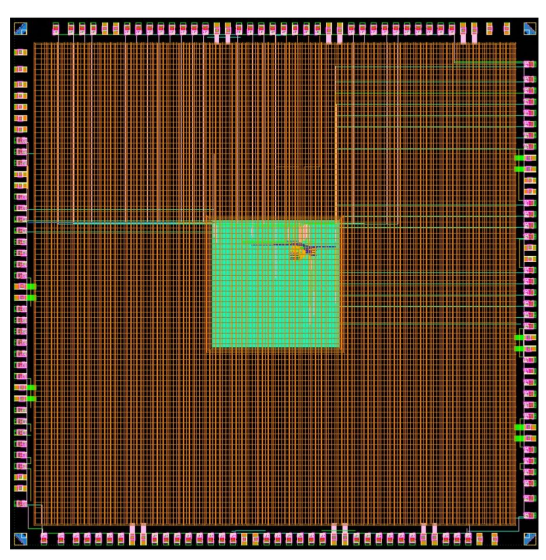


The SCM operates in Calibration Mode and Normal Mode. In Calibration Mode, single and segmented calibration coefficients are computed and stored. In Normal Mode, the appropriate coefficients are applied to sensor data to generate calibrated outputs.

Ⅲ. Adaptive Segmentation Module (ASM)

ASM determines optimal segment boundaries and assigns independent calibration functions to each segment for improved accuracy.

ASIC Design & Fabrication



Tech	Samsung FD-SOI 28nm
Chips Size	4 mm X 4 mm
Supply Voltage	1.0 V
Frequency	100 MHz
Gate count	200K
Critical path delay	1.72ns
Power consumption	85.06 mW

- The proposed calibration processor is fabricated using a 28nm FD-SOI process with a die area of 4 mm × 4 mm.
- The design operates at 100 MHz and achieves a 1.72 ns critical path delay, demonstrating low-latency performance.
- The hardware implementation shows efficient resource usage with 200K gate count and 85.06 mW power consumption.

Conclusion

- This work presents a Smart Meter SoC based on 2D SPPC and its segmented extension.
- Segmented calibration improves accuracy by reducing localized nonlinear errors.
- MATLAB, RTL, and ASIC results validate the effectiveness and hardware feasibility of the proposed architecture.
- The proposed processor is suitable for real-time smart metering and IoT applications.

* This work was supported by Korea Planning & Evaluation Institute of Industrial Technology (KEIT) grant funded by Korea government(MOTIE) (No.RS-2023-KT226455(20026455), Integrated technology development for SoC development and performance evaluation for sensors for braking systems and renewable energy systems)
* The chip fabrication and EDA tool were supported by the IC Design Education Center(IDEC), Korea.