A Large Measurable Range Capacitance-to-Digital Converter for Smart Humidity Sensors

Term Paper

AV491 - Advanced Sensors and Interface Electronics

Saurabh Kumar
SC22B146
Indian Institute of Space Science and Technology
Department of Avionics

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Chapter 1

Introduction

Capacitive sensors are widely used for sensing humidity, proximity, and many MEMS applications due to their high sensitivity and low power consumption. A capacitance-to-digital converter (CDC) interfaces capacitive sensors to digital systems by converting capacitance changes directly into digital codes. The paper describes a CDC with a *large measurable range* (0–388 pF), specifically intended for smart humidity sensors where the sensor capacitance can vary significantly. This report provides a comprehensive analysis of the paper and presents possible improvements and suggestions for further work.

Chapter 2

Background

2.1 Capacitive Sensing Principles

A parallel-plate capacitance is given by

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d}$$

where ε_r is the relative permittivity, A is the electrode area, and d the separation. In humidity sensors, ε_r changes with water vapor content causing C to change.

2.2 CDC Architectures (Brief Survey)

Common CDC methods include:

- **Charge-based CDCs:** Inject/discharge charge, measure time or voltage.
- **Capacitance-to-time converters:** Use RC or switched-capacitor oscillators.
- **Sigma-Delta CDCs:** Use an incremental $\Sigma\Delta$ modulator for high resolution and noise shaping.
- **VCO-based CDCs:** Translate capacitance into oscillator frequency.

Wei uses a CIFF incremental sigma-delta architecture to achieve a large dynamic range and high resolution.

Chapter 3

Motivation

The motivation for selecting this particular paper arises from both the course objectives and the technical relevance of capacitance-to-digital conversion in modern sensor systems. In the field of advanced sensor interfacing, capacitance-based sensors are widely used due to their simplicity, low power consumption, and compatibility with integrated circuit technologies. However, one of the main challenges is the accurate and robust conversion of a wide range of capacitance values into precise digital information, especially when the sensing element exhibits large variations, as in the case of humidity sensors.

This work aligns strongly with topics such as capacitive sensing, sigma–delta based digitization, low-power analog front-end design, and sensor-to-electronics interfacing methodologies. The paper demonstrates a complete signal chain - from the capacitive transducer to its digital output - which makes it an excellent case study to understand practical CDC architectures.

In addition, the motivation for selecting this paper is driven by the fact that real-world humidity sensors often experience large capacitance swings (tens to hundreds of picofarads). Many traditional CDC designs address only small-signal capacitance variations, making them unsuitable for such applications. The ability to measure capacitances up to nearly 400 pF while still achieving high resolution and low power consumption is technically impressive and relevant for embedded and IoT humidity sensing platforms.

Furthermore, the paper provides clear insight into how an incremental sigma–delta modulator (specifically a CIFF architecture) can be adapted to achieve both high resolution and a large measurable range. This blend of analog design, mixed-signal signal processing, and sensor interfacing motivated me to study the paper in detail as part of this course project.

Finally, humidity sensing is a critical requirement in applications such as environmental monitoring, indoor air quality assessment, industrial process control, and smart agriculture. The integration of a practical humidity sensor (HS1101) with the proposed CDC demonstrates real-world applicability, reinforcing the value of analyzing this paper for a deeper understanding of sensor system.

Chapter 4

Methodology

4.1 Approach

The CDC is built using a third-order CIFF (Cascade of Integrators with Feed-Forward) incremental sigma-delta modulator tailored for capacitive input. A programmable front-end and calibration scheme enable the large input range.

4.2 Block Diagram

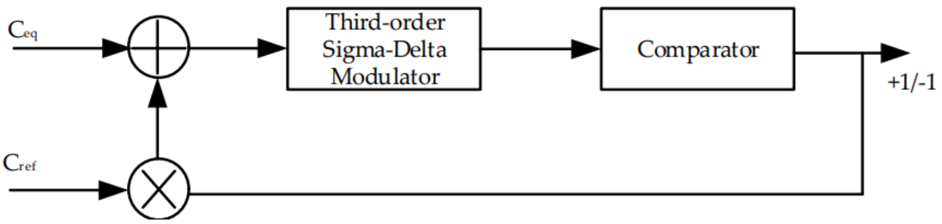


Figure 4.1: Charge balanced operation of the CDC

4.3 Techniques

- **CIFF incremental $\Sigma\Delta$:** Integrators shape quantization noise and allow oversampling for high resolution.
- **Range extension:** Use quantized front-end switching and programmable capacitors to map large input capacitances into the modulator input range.
- **Calibration:** Digital calibration logic corrects offsets and nonlinearity; integration with a microcontroller is shown.
- **Implementation:** Designed in 0.18 μm CMOS; measurements carried out with integrated test chip and the HS1101 humidity sensor.

Chapter 5

Circuit and Sensor Structure

5.1 CDC Internal Circuits

5.1.1 Integrator and Switch Network

The integrator stages are implemented with switched-capacitor integrators (SC integrators), using sampling switches and accurate capacitors to realize precise charge transfer.

5.1.2 Quantizer and DAC

A 1-bit quantizer (comparator) followed by a feedback DAC implements the $\Sigma\Delta$ loop. The CIFF structure places feedforward coefficients to control modulator dynamics.

5.1.3 Front-End Multiplexing and Range Selection

Programmable capacitor arrays and switching networks allow the CDC to handle inputs from near 0 pF up to hundreds of pF. Range selection is managed digitally.

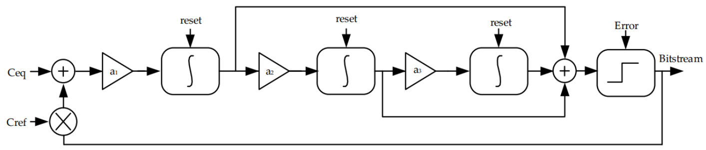


Figure 5.1: Third-order cascade of integrators with a feed-forward (CIFF) modulator

5.2 Sensor and System Integration

- **Humidity sensor (HS1101):** A capacitive humidity element with nominal capacitance range when exposed to humidity changes.
- **System:** Sensor connected to CDC input; digital output processed by MCU to compute relative humidity (RH) using calibration tables/polynomial fits.

Chapter 6

Main Results Reported

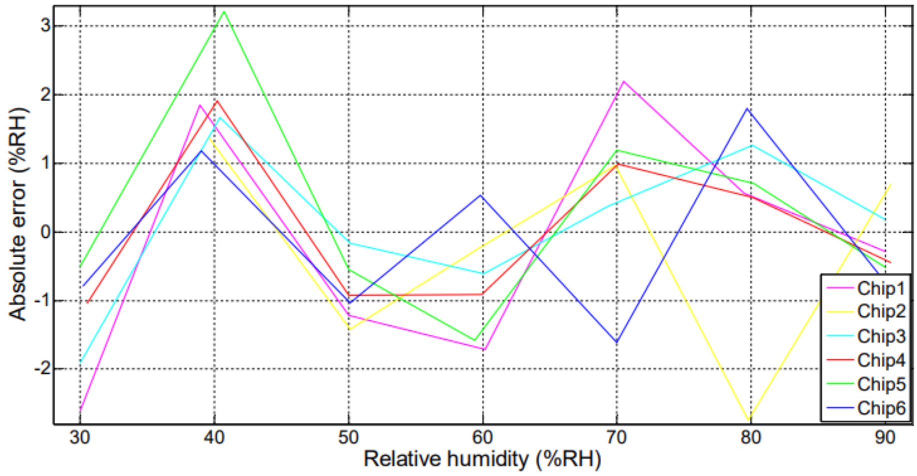
6.1 Key Performance Metrics

Table 6.1 summarizes the primary reported metrics.

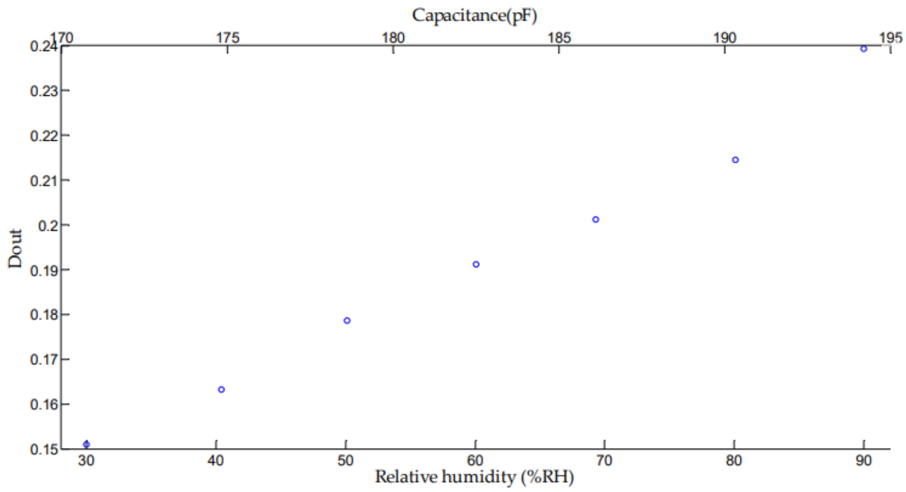
Table 6.1: Selected performance results from the paper

Parameter	Value	Notes
Input measurable range	$0 - 388\,\text{pF}$	Large dynamic range
Resolution (effective)	13 bits	Reported digital resolution
Conversion time	$0.8\,\text{ms}$	Per sample
Supply voltage	$1.8\,\text{V}$	CMOS $0.18\,\mu\text{m}$ design
Power consumption	$\approx 169.7\,\mu\text{A}$	Low-power operation
Humidity resolution (system)	$\approx 0.7\%$ RH	Using HS1101 sensor

6.2 Measurement Results



(a) Measured relative humidity error at 25 °C



(b) Measured Dout

Figure 6.1: Measurement plots

6.3 Discussion of Results

- The CDC achieves a rare combination of *large measurable input range* and *high resolution*, making it suitable for humidity sensors with large capacitance swings.
- Conversion latency (0.8 ms) is sufficient for many environmental sensing applications; power budget is compatible with battery-powered sensor nodes.
- System-level tests with HS1101 show the CDC can be used in a practical humidity measurement system with sub-percent RH resolution.

Chapter 7

Analysis

7.1 Strengths

- **Large input range:** The main contribution - a CDC that handles up to $\sim$388 pF - is highly practical.
- **Low-power operation:** Reasonable current consumption for embedded applications.
- **Good system demonstration:** Evaluation with a commercial humidity sensor proves applicability.

7.2 Limitations

- **Temperature sensitivity:** Capacitive humidity sensors often require temperature compensation; the paper includes calibration but on-chip temperature compensation could be improved.
- **Linearity/Nonlinearity:** For very large capacitance changes, linearization errors can increase; digital correction is used but could be extended.
- **Parasitic and stray capacitance:** Long leads or PCB parasitics may reduce measurement accuracy — the paper addresses this in part but further shielding/guarding suggestions could help.

7.3 Suggestions for Improvement

1. **Differential Sensing Front-End:** Use a differential CDC input (two matched electrodes) to suppress common-mode parasitics and temperature-induced drifts.

2. **On-Chip Temperature Sensor & Compensation:** Integrate a small temperature sensor and real-time digital compensation curve or look-up table to reduce RH measurement drift.
3. **Adaptive Gain/Auto-Range:** Implement an automatic range control which adjusts front-end division/scale depending on sensed input to maximize effective resolution.
4. **Calibration Automation:** Provide an on-chip calibration routine (self-test) that can be triggered in the field to re-calibrate offsets and linearization tables.
5. **Lower Technology Node Porting:** Port the design to a more advanced CMOS technology (e.g., 65 nm or 40 nm if feasible) to reduce area and power and permit additional on-chip digital processing.
6. **Guarding and Shielding Techniques:** Design PCB and package with driven guard traces on the input to minimize stray capacitance influence.

Chapter 8

Conclusion

This report analyzed the CDC proposed by Wei and found it to be a strong, practical design for enabling smart humidity sensors with large capacitance variation. The combination of a CIFF incremental sigma-delta architecture, programmable front-end, and system calibration yields a converter suitable for low-power environmental sensors. The suggestions above (differential front-end, on-chip temperature compensation, auto-range, etc.) would further strengthen the CDC for field deployment and increase measurement robustness.