ProCal: A Low-Cost and Programmable Calibration Tool for IoT Devices

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Introduction
Introduction

Accurate Sensor Data Conversion for IoT Applications

- **ADC (Analog-to-Digital-Converter)** convert sensor’s analog information to digital data
- Digital data can be directly sent to cloud or processed by agent

- **Accuracy of data conversion** is essential for mission-critical IoT applications
Introduction

Accuracy of Data Conversion

• Factors impacting data precision of conversion
  • Quantization error
  • Differential non-linearity (DNL)
  • Integral non-linearity (INL)
  • Temperature variation
  • Process technology
  • Resistance of circuit
  • Device characteristic
Introduction

Common ADC Error Correction Approaches

Error Correction Process

• **Trimming**
  - Performed *during* the post-silicon production phase
  - Measure and correct device parameter **under a controlled condition**

• **Calibration**
  - Perform *after* device manufacturing
  - Used to compensate errors influenced by environmental conditions
    - **Self calibration**
      - Perform measurement-correction process within *device itself*
    - **External calibration**
      - Perform measurement-correlation process with *entire system*

![](trimming_poweron_calibration_runtime_external.png)

- **Trimming** ~40% Error
- **Power on Calibration** ~ 25% Error
- **Run time Calibration** ~ 3% Error
- **External Calibration** ~1% Error
Introduction

Existing External Calibration Solution

Approaches to generate variable loads for calibration

• **Resistors**
  - **Pros**: Provide an accurate and stable load
  - **Cons**: Time consuming, non-scalable

• **Potentiometer**
  - **Pros**: Resistance can be programmable
  - **Cons**: Less accurate load and limited operating condition

• **Power analyzer**
  - **Pros**: Provides stable and accurate load
  - **Cons**: Costs $14,000 for a solution

• We need a low-cost, accurate and scalable calibration solution for building reliable IoT systems
Problem Statement

We need a solution to

- Minimize the calibration error
- Offer programmability
- Provide scalability
- Offer a large dynamic range
- Lower the cost
Design Overview
Design Overview

Design Challenges Consideration

• **Time synchronization**
  ▪ Provide a time synchronization mechanism between the target device and a high-precision measurement equipment (e.g., DMM)
  ▪ Output frequency flexibility

• **High accuracy and dynamic range**
  ▪ Provide a high dynamic output range to support various types of IoT devices
  ▪ Provide information to ensure calibration during output stability instances

• **Volume calibration steps**
  ▪ A well characterized profile can improve ADC data distortion
  ▪ High resolution for both current and voltage

• **Portability and low cost**
  ▪ Low cost
  ▪ Easy integration with commercial MCUs
Design Overview

ProCal Prototype

Figure presents the block diagram of ProCal. Figure shows a ProCal board. We implement MCU function by developing a Python configuration code running on a Raspberry Pi board. MCU connects to RCU through a SPI bus and GPIO pins. MCU controls the RCU to perform the desired changes. MCU also provides a trigger signal through GPIO to trigger target device and DMM to start and stop sampling simultaneously.

RCU contains one AD digital potentiometer and four ADG digital switches. AD regulators differerent resistance values that can be digitally programmed by the configuration code through SPI. These different resistances provide full calibration coverage, from a low sleeping current to a high active current of IoT device, as we proved in Section. We connect a resistor with AD in serial as the overcurrent protection. The salient features of AD are its short setup time and MHz SPI speed. These features enable ProCal to provide stable output current and voltage within µs period.

The variable resistor network is a circuit connecting resistors and a digital potentiometer, in parallel. ADG contains four terminals, where each terminal connects to a resistor. MCU sends logic signals to ADG terminals through GPIO. When the terminal receives a logic signal, the resistor controlled by the terminal is connected to the variable resistor network, which increases the total current flow. If the terminal receives a logic signal, the resistor is disconnected from the variable resistor network, which reduces the total current flow. There are four ADGs used in the RCU: one is connected to four high-precision (%) resistors and the other three are connected to four high-precision (%) resistors. These high-precision resistors connected to ADG are part of the variable resistor network, which can provide mA and mA changes in current. It is worth noting that the effect of ADG on current draw is minimal as it only shows a resistance when operating.
Design Overview

System Architecture

• Basic Idea
  ▪ Overcome the current limitation of digital potentiometers and extend the range of output current
  ▪ Choose programmable components

• Basic Structure
  ▪ A digital potentiometer AD5200 connects to resistors in parallel
  ▪ Resistor control unit consists of four digital switches
  ▪ Resistor control unit can change total resistance value of the variable resistor network
  ▪ A control program configures the total resistance and output frequency through SPI and GPIO

• ProCal supports current calibration and voltage calibration
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**System Architecture**

**Design Overview**

![Diagram of ProCal](image)

**Microcontroller Unit (MCU)**

**GPIO**

**Variable Resistor Network**

- AD5200
- R (250Ω)X4
- R (50Ω)X4
- R (50Ω)X4
- R (50Ω)X4

**Resistor Control Unit**

- ADG1612
- ADG1612
- ADG1612
- ADG1612

**Power Source** (up to 5.5V)

**Output Selection** (Current or Voltage)

**DMM**

**Target**

**Current Flow Circuit**

**Control Circuit**

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ProCal's hardware consists of four main units: (i) microcontroller unit (MCU), (ii) resistance control unit (RCU), (iii) variable resistor network, and (iv) output selection jumpers. MCU is used to control RCU, synchronize the operation of the target device and DMM, and record settling time of each output value generated by ProCal. RCU is responsible for controlling the variable resistor network. The output selection jumpers on the board enable the user to select current or voltage output for calibration.

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**Fig. 1** Block diagram of ProCal. MCU provides synchronized trigger signals to the resistor control unit, target ADC, and DMM. AD is a digital potentiometer, and ADG is the digital switch connected to the resistor network.

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The next challenge is to ensure that when we compare two sampled values, those belong to the same interval when the output was stable. Therefore, ProCal should also provide mechanisms to synchronize the readings of ADC and DMM. To overcome these challenges, ProCal stores voltage or current settling time information after applying each configuration that results in current or voltage change. For example, assume that the minimum sampling rate of ADC and target device is \( r_{\text{min}} \). We first ensure that \( T > \frac{1}{r_{\text{min}}} \), where \( T \) is the period of changing the output. ProCal provides this feature to support the sampling rate of various ADCs. Second, assuming that a new output value is configured at time \( t_i \), to correlate the values collected by DMM and target IoT device, we find in their readings the values that are closest to time \( t_i + T \). This synchronization approach ensures that the two values belong to the same output value.
Design Overview

Software Architecture

• **ProCal’s control software**
  - This program controls the digital potentiometer and digital switches
  - User provides target current and voltage range to calibrate
  - User provides output change period $t$
    - ProCal records settling time stamp $\frac{1}{2} t$, ensures the readings of the target IoT device and measurement equipment are correlated with a stable value
    - Thereby, a precise time synchronization is not necessary
Design Overview

Software Architecture

ProCal Current Program

Start

Trigger start signal to begin measurement

\[ I(t) = 0.476 \text{ mA} \]

\( I(t) < I_{\text{max}} \)

Program AD5200 / ADG1612 to increase current \( I(t) \)

Delay time \( t \)

Write time stamp \( t/2 \) and \( I(t) \) into file

Stop

ProCal Voltage Program

Start

Trigger start signal to begin measurement

\[ V(t) = 5 \text{ V} \]

\( V(t) > V_{\text{min}} \)

Program AD5200 / ADG1612 to decrease voltage \( V(t) \)

Delay time \( t \)

Write time stamp \( t/2 \) and \( V(t) \) into file

Stop
Evaluation
Evaluation

ProCal Scalability and Minimum Resolution

• Scalability

\[ I_{\text{ProCal}}(t) = I_{\text{potmax}}(t) + \sum_{j=1}^{n} I_j(t) \quad \forall n \in \mathbb{Z}^+ \]

\[ V_{\text{ProCal}}(t) = I_{\text{ProCal}}(t) \times R_c \]

• Current Minimum Resolution

\[ R(x) = \frac{x}{2^n} \times R_{\text{max}} + R_w \quad 0 \leq x \leq 2^n \]

\[ I_{\text{res}}(t) = \frac{R(x) - R(x - 1)}{R(x) \times R(x - 1)} \times V_{\text{in}}(t) \quad 0 \leq x \leq 2^n \]

• \( R_{\text{max}} \) is digital potentiometer’s maximum resistance

• Digital potentiometer is \( n \) bits

• \( R_w \) is the wiper resistance
Evaluation

Output Evaluation of Dynamic Range

- Use a high-accuracy DMM (Keithley 7510) to validate ProCal’s performance
- Change current and voltage every 5 microseconds
- ProCal maximum dynamic range is 1000:1
- Minimum resolution for current and voltage are 1.82μA and is 0.01μV, respectively
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Case Studies
Case Studies

Test Conditions

ProCal calibration with common COTS ADCs

- Ground truth measurement obtained by Keithley DMM7510
- Target ADC and DMM measure ProCal’s output simultaneously
- Use ProCal’s time synchronization mechanism to correlate ADC and DMM measurements
- Generate a calibration function $f(D)$ to calibrate ADC
Case Studies

Test Conditions

• **Current calibration**
  - INA219 (12 bits ADC)
  - MCP3208 (12 bits ADC)
  - Measure current through a 0.1Ω shunt resistor
  - Use LM4040 to provide a precise 0.1% reference voltage (Vref = 4.096V)

• **Voltage calibration**
  - ATMega2560 (10 bits ADC)
  - MCP3208 (12 bits ADC)
  - Parallel-connect ADC and DMM to measure voltage
  - Use LM4040 to provide a precise 0.1% reference voltage (Vref = 4.096V)
## Case Studies

### Current Calibration

| ADC      | Measurement Type | % Error (Before) | % Error (After) |
|----------|------------------|-----------------|----------------|
| INA219   | Current          | 0.42%           | 0.02%          |
| MCP3208  | Current          | 2.58%           | 0.01%          |
Case Studies
Voltage Calibration

| ADC          | Measurement Type | % Error (Before) | % Error (After) |
|--------------|------------------|------------------|-----------------|
| MCP3208      | Voltage          | 5.29%            | 0.01%           |
| ATMega2560   | Voltage          | 0.20%            | 0.01%           |
Conclusion
Conclusion

• Calibration is an important step towards building reliable IoT systems
• ProCal provides programmable and scalable output, which can adjust calibration range for various types of IoT devices
• ProCal provides a time synchronization mechanism to match ADC and DMM traces
• ProCal is a portable and low-cost solution
• Our evaluations demonstrate that ProCal provides a large dynamic range, fulfilling the IoT market needs
• Our case studies show that ProCal can reduce measurement error significantly
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