Gain and Offset Calibration of the Analog Signal Conditioning (OPAMP) Peripheral

Introduction

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The Analog Signal Conditioning (OPAMP) peripheral can be configured as a programmable gain amplifier (PGA) using an internal resistor ladder to select a gain value. Because the resistors in the internal resistor ladder have some tolerances and may vary as a function of temperature or other parameters, the actual gain may be slightly different from the selected gain value. In some applications, it may be beneficial to precisely determine the gain and input offset of the PGA. This document explains how to calibrate the gain and offset of the PGA using the microcontroller's (MCU’s) internal digital-to-analog converter (DAC) and analog-to-digital converter (ADC). The DAC is used to control the voltage at the input of the PGA, while the ADC is used to measure the voltage at both the input and output of the PGA. The values measured by the ADC can be used to calculate the gain and input offset of the PGA. No external components are required.

Features

- Gain and Offset Calibration Performed Using the MCU’s Internal DAC and ADC
- Zero External Components Required

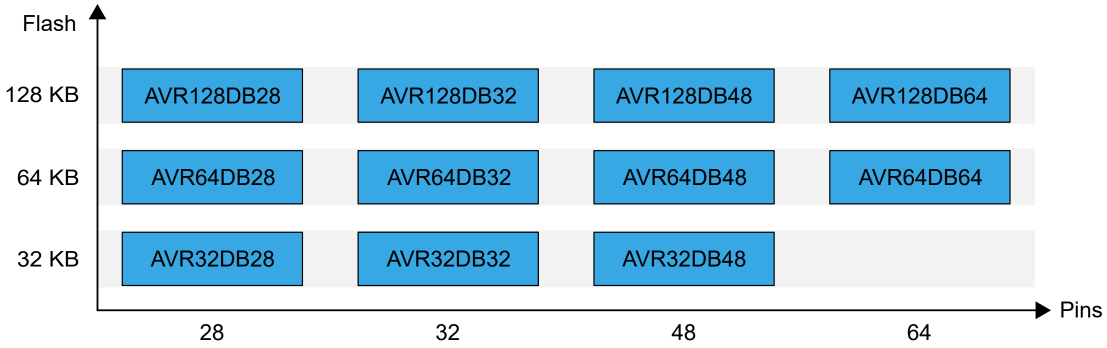
Table of Contents

1. Relevant Devices

This section lists the relevant devices for this document. The following figures show the different family devices, laying out pin count variants and memory sizes:

- Vertical migration upwards is possible without code modification, as these devices are pin-compatible and provide the same or more features
- Horizontal migration to the left reduces the pin count and, therefore, the available features
- Devices with different Flash memory sizes typically also have different SRAM and EEPROM

Figure 1-1. AVR® DB Family Overview

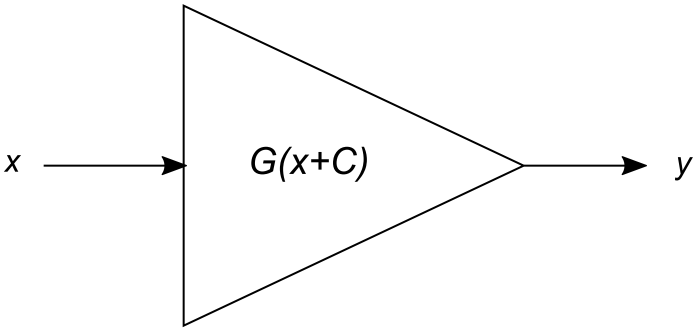


Flash	28	32	48	64
128 KB	AVR128DB28	AVR128DB32	AVR128DB48	AVR128DB64
64 KB	AVR64DB28	AVR64DB32	AVR64DB48	AVR64DB64
32 KB	AVR32DB28	AVR32DB32	AVR32DB48	

2. Calibration Theory

An ideal programmable gain amplifier (PGA) amplifies an input voltage by a precise programmed gain value, *G*. If the PGA is ideal, the voltage measured at the output can be divided by *G* to determine the input voltage. However, many PGA implementations have two imperfections that must be considered in an application. First, there is an input offset voltage that is effectively added to the input signal before amplification. Second, the actual gain may be slightly different from the programmed value due to analog component tolerances, etc.

Figure 2-1. PGA with Gain and Offset Equations



$$y_a = G(x_a+C)$$

$$y_b = G(x_b+C)$$

$$G = (y_b-y_a)/(x_b-x_a)$$

$$C = (y_a/G)-x_a$$

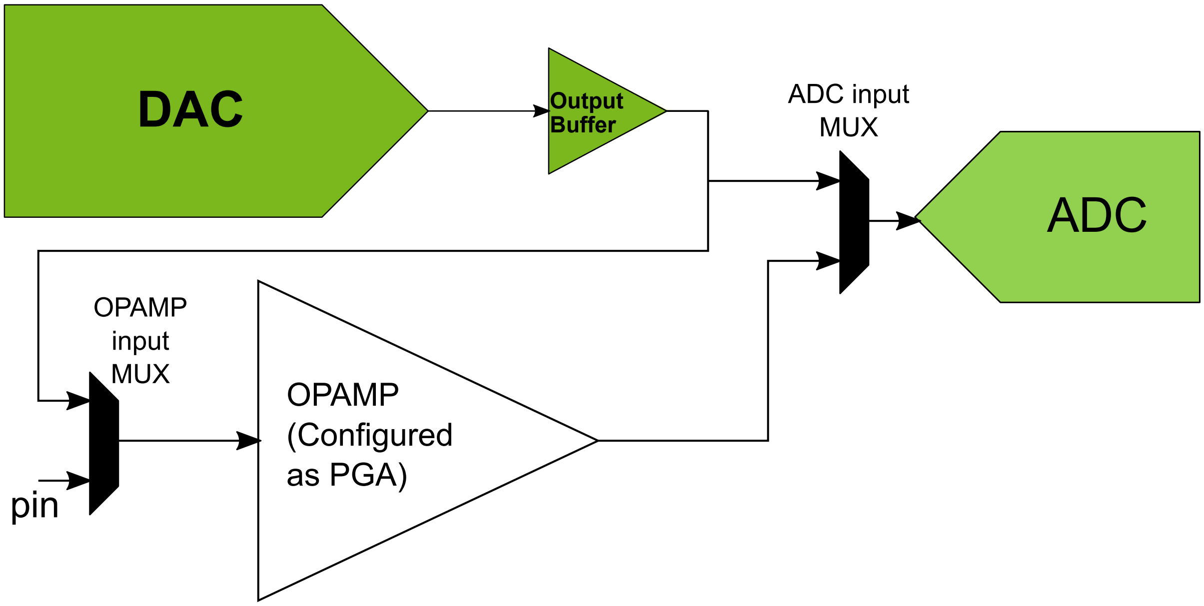
The figure above depicts a high-level representation of a PGA with gain and offset equations included. For an input signal x, an offset value of C is added, and then the sum $(x+C)$ is multiplied by the gain value G to obtain the output signal y. The fundamental idea behind gain and offset calibration is to input two different values, x_a and x_b, so as to obtain two different output values, y_a and y_b. If x_a, x_b, y_a, and y_b are all determined accurately via measurement, the first two equations can be solved for G and C, allowing the gain and input offset to be calculated.

As a realistic example, consider a PGA that has been programmed to have a nominal gain of 16. First, a voltage of 60 mV is input, and the output voltage is measured as 986 mV, so x_a is 60 mV, and y_a is 986 mV. Next, a voltage of 120 mV is input, and the output voltage is measured as 1940 mV, so x_b is 120 mV, and y_b is 1940 mV. Inserting these four values into the equations for G and C leads to a result of 15.9 for the gain G and 2.0 mV for the input offset C.

3. Calibration Implementation on MCU

Because the microcontroller (MCU) contains both a digital-to-analog converter (DAC) and an analog-to-digital converter (ADC), as well as analog multiplexers that allow flexible interconnections, it is possible to perform gain and offset calibration of the programmable gain amplifier (PGA) using no external components.

Figure 3-1. Block Diagram of DAC, OPAMP, and ADC Interconnections Used for Calibration



The figure above shows the DAC, OPAMP, and ADC interconnections that are used for calibration. The buffered DAC output feeds into the ADC input multiplexer and the OPAMP input multiplexer. The OPAMP input multiplexer can select between the buffered DAC output or a pin of the device. The ADC input multiplexer can select between either the DAC output or the OPAMP output.

After the OPAMP, DAC, and ADC have all been initialized and enabled, the following steps are used to implement a gain and offset calibration procedure:

1. Configure the OPAMP input MUX to select the DAC output.
2. Write a first value (x_a) to the DAC.
3. Configure the ADC input MUX to select the DAC output.
4. Allow time for the DAC output and ADC input to settle.
5. Start an ADC conversion.
6. Wait for the ADC conversion to complete.
7. Save the ADC result as x_a.
8. Configure the ADC input MUX to select the OPAMP output.
9. Allow time for the ADC input to settle.
10. Start an ADC conversion.
11. Wait for the ADC conversion to complete.
12. Save the ADC result as y_a.
13. Write a second value (x_b) to the DAC.
14. Configure the ADC input MUX to select the DAC output.
15. Allow time for the DAC output and ADC input to settle.
16. Start an ADC conversion.
17. Wait for the ADC conversion to complete.
18. Save the result of the ADC conversion as x_b.
19. Configure the ADC input MUX to select the OPAMP output.

20. Allow time for the ADC input to settle.
21. Start an ADC conversion.
22. Wait for the ADC conversion to complete.
23. Save the result of the ADC conversion as y_b.
24. Steps 2 through 23 may be repeated many times, and the ADC results averaged to obtain more accurate values for x_a, y_a, x_b, and y_b.
25. Compute the calibrated gain value as $G = (y_b - y_a)/(x_b - x_a)$.
26. Compute the calibrated input offset value as $C = (y_a/G) - x_a$.
27. Calibration is complete, and the OPAMP (configured as PGA) is ready to be used by the application. Configure the OPAMP input MUX to select the device pin.

The calibrated gain and input offset values should be used by the application code for any calculations that involve gain and/or offset.

The code below implements the gain and offset calibration procedure outlined above:

```
#define F_CPU 4000000UL // 4 MHz is default CPU and peripheral frequency

#include <avr/io.h>
#include <util/delay.h>

// The VREF (Voltage Reference) peripheral will be set up to generate a
// reference voltage of 2.5 V
#define VREF_REFSEL_CONTROL VREF_REFSEL_2V500_gc
#define VREF_MV 2500.0 // Floating-point value of reference voltage in mV

// The DAC (Digital-to-Analog Converter) has 10-bit resolution and 2^10 = 1024
// possible input values
// DAC outputs of approximately 60 mV and 120 mV will be used to perform a
// two-point gain and offset measurement/calibration of the op amp gain stage
// Here is the calculation of the two DAC data values needed to generate these
// output voltages:
// (60 mV / 2500 mV) * 1024 = 25
// (120 mV / 2500 mV) * 1024 = 49
#define DAC_DATA_A 25
#define DAC_DATA_B 49

// The AVR-DB ADC (Analog-to-Digital Converter) has 12-bit resolution and
// 2^12 = 4096 possible output values
// Determine the number of mV equivalent to one LSB change in the ADC output:
#define MV_PER_ADC_LSB (VREF_MV/4096)

// Number of measurements to average
#define N_AVERAGE 100

void measure(uint16_t dac_data, uint8_t muxpos_dacout, uint8_t muxpos_opout,
                int16_t *dac_meas, int16_t *opout_meas){

    //Given a DAC setting, this function measures the op amp input and output values

    DAC0.DATA = dac_data << DAC_DATA0_bp; // Write a new value to the DAC
    ADC0.MUXPOS = muxpos_dacout; // Configure the ADC input mux to select the DAC output
    _delay_ms(1); // Allow time for the DAC output and ADC input to settle

    ADC0.COMMAND = ADC_STCONV_bm; // Start an ADC conversion
    while(ADC0.COMMAND & ADC_STCONV_bm); // Wait for the ADC conversion to complete
    *dac_meas = ADC0.RES; // Save the ADC result as a measurement of the DAC output value

    ADC0.MUXPOS = muxpos_opout; // Configure the ADC input mux to select the OPAMP output
    _delay_ms(1); // Allow time for the ADC input to settle

    ADC0.COMMAND = ADC_STCONV_bm; // Start an ADC conversion
    while(ADC0.COMMAND & ADC_STCONV_bm); // Wait for the ADC conversion to complete
    *opout_meas = ADC0.RES; // Save ADC result as a measurement of the OPAMP output

    return;
}

volatile float meas_gain = 0; // Measured gain
volatile float meas_offset = 0; // Measured input offset in ADC units
volatile float meas_offset_mv = 0; // Measured input offset in mV
```

```
int main(void)
{
    uint8_t n;
    int16_t xa, ya, xb, yb;
    int32_t accum_xa, accum_ya, accum_xb, accum_yb;
    float avg_xa, avg_ya, avg_xb, avg_yb;

    // Disable digital inputs on OP0 input and output pins
    PORTD.PIN1CTRL = PORT_ISC_INPUT_DISABLE_gc;
    PORTD.PIN2CTRL = PORT_ISC_INPUT_DISABLE_gc;
    PORTD.PIN3CTRL = PORT_ISC_INPUT_DISABLE_gc;

    // Disable digital input on DAC output pin
    PORTD.PIN6CTRL = PORT_ISC_INPUT_DISABLE_gc;

    // Set up the timebase of the OPAMP peripheral
    OPAMP.TIMEBASE = 3; // Number of CLK_PER cycles that equal one us, minus one (4-1=3)

    //Configure OP0 as non-inverting gain of 16 with DAC as input
    OPAMP.OP0INMUX = OPAMP_OP0INMUX_MUXPOS_DAC_gc | OPAMP_OP0INMUX_MUXNEG_WIP_gc;
    OPAMP.OP0RESMUX = OPAMP_OP0RESMUX_MUXBOT_GND_gc | OPAMP_OP0RESMUX_MUXWIP_WIP7_gc |
OPAMP_OP0RESMUX_MUXTOP_OUT_gc;
    // Configure OP0 Control A
    OPAMP.OP0CTRLA = OPAMP_RUNSTBY_bm |  OPAMP_OP0CTRLA_OUTMODE_NORMAL_gc | OPAMP_ALWAYSON_bm;

    // Enable the OPAMP peripheral
    OPAMP.CTRLA = OPAMP_ENABLE_bm;

    // Set up VREF peripheral to generate the same reference for both ADC and DAC
    VREF.ADC0REF = VREF_ALWAYSON_bm | VREF_REFSEL_CONTROL;
    VREF.DAC0REF = VREF_ALWAYSON_bm | VREF_REFSEL_CONTROL;

    // Set up DAC peripheral by enabling it and its output pin
    DAC0.CTRLA = DAC_OUTEN_bm | DAC_ENABLE_bm;

    // Set up ADC peripheral
    ADC0.CTRLC = ADC_PRESC_DIV4_gc; // Set up ADC prescaler to DIV4
                                    // so CLK_ADC = 4 MHz / 4 = 1 MHz
    ADC0.CTRLA = ADC_ENABLE_bm; // Enable ADC in single-ended mode

    accum_xa = 0; accum_ya = 0; accum_xb = 0; accum_yb = 0; //Reset accumulators
    for (n = 0; n < N_AVERAGE; n++){
        measure(DAC_DATA_A, ADC_MUXPOS_AIN6_gc, ADC_MUXPOS_AIN2_gc, &xa, &ya);
        //                  DACOUT              OP0OUT
        measure(DAC_DATA_B, ADC_MUXPOS_AIN6_gc, ADC_MUXPOS_AIN2_gc, &xb, &yb);
        //                  DACOUT              OP0OUT
        accum_xa += xa; accum_ya += ya; accum_xb += xb; accum_yb += yb; //Add to accumulators
    }
    avg_xa = ((float) accum_xa)/((float) N_AVERAGE);
    avg_ya = ((float) accum_ya)/((float) N_AVERAGE);
    avg_xb = ((float) accum_xb)/((float) N_AVERAGE);
    avg_yb = ((float) accum_yb)/((float) N_AVERAGE);

    meas_gain = (avg_yb - avg_ya)/(avg_xb - avg_xa); // Measured gain
    meas_offset = (avg_ya/meas_gain) - avg_xa; // Measured input offset in ADC units
    meas_offset_mv = meas_offset * MV_PER_ADC_LSB; // Measured input offset in mV

    // Calibration is complete and the OPAMP is ready to be used by the application,
    // so configure the OPAMP input mux to select the input pin.
    OPAMP.OP0INMUX = OPAMP_OP0INMUX_MUXPOS_INP_gc | OPAMP_OP0INMUX_MUXNEG_WIP_gc;

    while(1){
        // Place application here
    }

}
```

View Code Example on GitHub
Click to browse repository

4. Revision History

Doc. Rev.	Date	Comments
A	09/2020	Initial document release

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