Basics 04 : Board Calibration

This document describes the calibration of the SLab system. Having a properly calibrated system is fundamental to obtain measurements that resemble the real magnitudes.

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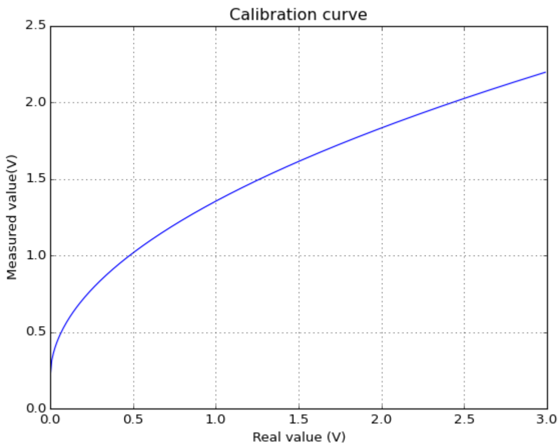
Introduction

In the previous document we have mounted the SLab buffer circuits, connected them to the hardware board and checked that it all works. Now we will try to guarantee that we can get good measurements from the system.

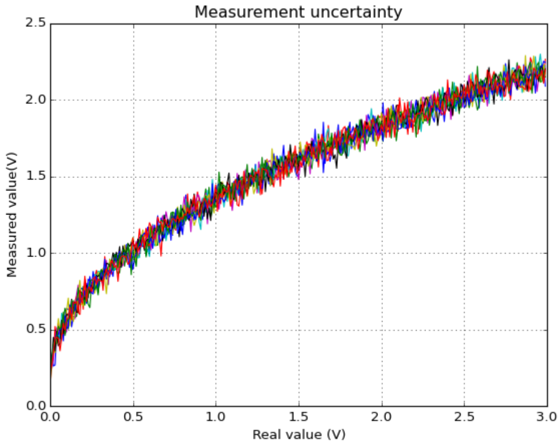
In a measurement system the most important feature is to obtain repetitive measurements. That is, every time we measure the same real magnitude, we should get the same reading. Having a good read value is not as important as having always the same value.

Let's say we have a measurement system that for real voltage values between 0V and 3V gives voltage readings between 0.2Vand 2.2V like in the figure below:

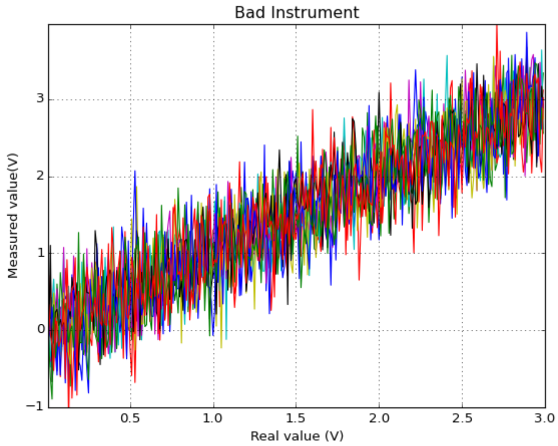


For instance, if the real voltage is 1V, the read value will be 1,35V. That's a big error but it is not a measurement problem. As long as we always get the same input to output relationship, we can always use the curve to deduce the real value from any measured value. That's why it is called a **calibration curve**. Using this curve we can calibrate our readings to reconstruct the real values.

In practice, we never get exactly the same values when we measure the same magnitudes. The following figure shows a more real case where there is some uncertainty to the measurement values. We have superposed different colors for different measurements using the instruments. The uncertainty from one measurement to the next could be due to noise or drifts in the instrument.



The uncertainty is what limits the precision we can get from the instrument as the systematic measurement to real value relationship can always be calibrated.
In general, it is best to have a nonlinear low uncertainty instrument than a linear high uncertainty instrument as uncertainty cannot be calibrated. That way, the following will be a bad instrument because, although it is linear, the response has a lot of random content.



In a laboratory setup we usually deal with systematic errors with calibration and we deal with uncertainty errors with the averaging of several measurements.

In this document we will obtain the calibration curves for the ADCs and DACs so that we correct the systematic errors in the measurements of our circuits.

Ratiometric measurements

In the SLab system we use DACs to set voltages and ADCs to measure voltages. Both ADCs and DACs are ratiometric devices. That means that the input to a DAC and the output of an ADC is given as a unitless ratio to a reference voltage. Although it is not always true, most microcontroller boards use its Vdd voltage as the reference. The SLab system holds the both the value of the supply Vdd voltage and the Vref reference voltage for the ADCs and DACs although they are usually similar.

We can define the ADC and DAC ratios as:

$$ratio = \left.\frac{Voltage}{V_{ref}}\right|_{V_{ref}=V_{dd}} = \frac{Voltage}{V_{dd}}$$

In a n bit DAC, the ratio is set as a DAC_{in} number from 0 to 2^n-1 respect to 2^n. So, the voltage V_{DAC} generated by a DAC is:

$$V_{DAC} = V_{ref} \cdot DAC_{ratio} = V_{ref}\frac{DAC_{in}}{2^n} \qquad 0 \leq \ DAC_{in} \ < 2^n$$

The F303RE board includes two 12 bit DACs. Input on those DACs can be from 0 to 4095, so the maximum output voltage value will be:

$$V_{DAC\ max} = V_{ref}\frac{2^{12}-1}{2^1} = 3{,}3V\frac{4095}{4096} = 3{,}299V$$

In a similar way, in a n bit ADC, the measured voltage V_{ADC} is provided as a ratio against the Vref reference.

$$ADC_{out} = 2^n \cdot ADC_{ratio} = 2^n\frac{V_{ADC}}{V_{ref}} \qquad 0 \leq \ ADC_{out} \ < 2^n$$

Note that the ADC and DAC ratio cannot reach 1. For a 12 bit converter the maximum ratio is:

$$ratio_{max} = \frac{2^{12}-1}{2^{12}} = 0{,}9998$$

In practice it is so close to one that the SLab commands set this maximum value when we request an impossible ratio of 1.0.

SLab calibration explained

Calibration in the SLab system uses three elements:

- Vref voltage (Reference for ADCs and DACs)
- Ratiometric DAC curves $CalDAC_i(x)$
- Ratiometric ADC curves $CalADC_i(x)$

For each ADC number **i**, from 1 to 4, it shall hold:

$$\frac{Mesured\ Voltage}{Vref} = CalADC_i\left(\frac{Real\ Voltage}{Vref}\right)$$

So the calibration curve of the ADCs indicates the ratiometric value we measure on the ADC when we set each possible real ratiometric value at the input of the ADC.

In a similar way, for each DAC number **i**, it shall hold:

$$\frac{Real\ Voltage}{Vref} = CalDAC_i\left(\frac{Set\ Voltage}{Vref}\right)$$

So the calibration curves for the DACs indicates the ratiometric real value set for each intended ratio we set the DAC to generate.

All operations on the DACs and ADCs use the three calibration elements so that we always work with the real values. Slab uses Vref and $CalADC_i(x)$ to obtain real values for measured ADC values and uses Vref and $CalDAC_i(x)$ to set the DAC inputs from the intended real value to set at the DAC outputs.

In order for the calibration system to operate correctly we need to guarantee two conditions:

- That calibration is constant. That is, each time the buffer circuit or the hardware board changes we need to recalibrate. It is also advisable to calibrate from time to time to correct from temporal deviations. Ideally you should calibrate at the start of each measurement session but that is not always practical.

- That calibration curves are monotonous. That is, that you can invert the curves to obtain real voltages from measured voltages in ADCs and set voltages from real voltages in DACs.

As DACs and ADCs are quite linear, SLab system uses calibration curves with only 11 points. Data is linear interpolated between points.

Hardware boards are not guaranteed to contain any reliable voltage reference, so we will need a measurement instrument capable of reading voltages to perform the calibration. A hand held multimeter usually will do. From this point we will call this instrument Voltage Metter (VM).

One way to calibrate a system is to perform a chain of calibrations. First, we calibrate one instrument, and then we use the measurements from that instrument to calibrate other instruments. Each calibrated instrument can be used to calibrate any uncalibrated instrument.

Calibration in our case is performed in three stages. In the first stage we do a rough calibration of DAC 1 against the VM and also obtain the Vref and Vdd values. In the second stage we calibrate de ADCs against the calibrated DAC 1. Finally, in the third stage, we calibrate all the DACs against the calibrated ADCs. That means that DAC 1 is calibrated two times. A rough calibration in stage 1 and a finer calibration in stage 3.
There is an optional fourth stage to check the calibration.

The calibration can be performed by calling the appropriate commands, but to ease the methodology, three Python scripts are provided, one for each calibration stage.

During all the calibration procedure, all ADCs and DACs shall be connected to their buffer circuits.

Absolute calibration of DAC 1

We will first calibrate DAC 1 and we will next calibrate the ADCs. Finally we will recalibrate DAC 1 and calibrate DAC 2.

Any instrument needs to be calibrated against another better calibrated instrument. We will use a VM instrument capable of measuring voltages to calibrate DAC 1. A handheld multimeter will do. If you cannot get your hands on any voltage measuring instrument you can skip this section buy you should note that skipping the DAC 1 calibration will degrade the precision of any measurement you perform in the SLab system.

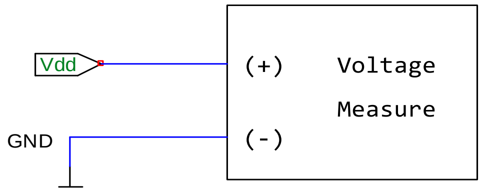
Once the system is calibrated, you don't need the multimeter any more until another calibration is performed.

To perform the DAC 1 calibration, connect the buffered DAC 1 output to the (+) terminal of the voltage metter and connect the ground (GND) terminal to the (-) terminal of the voltage metter. Then, run the script ***Calibrate1.py*** located in the ***SLab/Code*** folder.

The script will write something like:

```
Manual calibration of DAC 1
You will need a voltage measurement instrument (VM)

Put VM between the Vdd terminal and GND
Write down the voltage value and press enter

Voltage value [Volt]:
```

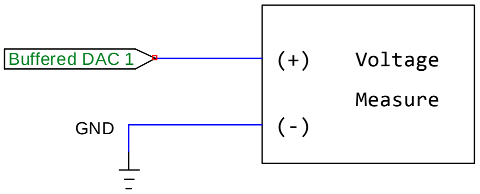
That is, you need to implement the following connections in your board:



After you input this voltage you will receive another request:

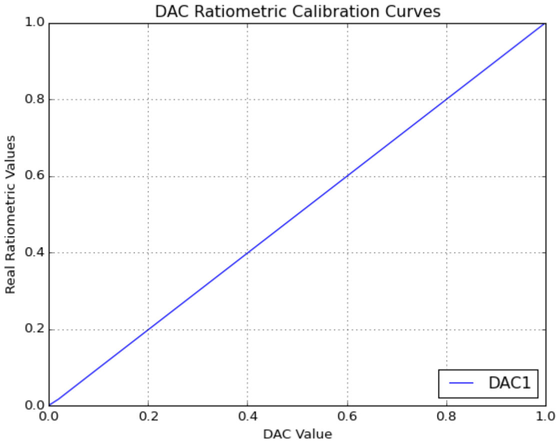
```
Put VM between the buffered DAC 1 output and GND
Write down the voltage value and press enter each time it is asked

Voltage value [Volt]:
```

That is, you need to implement the following connections in your board:



Then, input in the Python script, the voltage read on the instrument each time it is requested.

After you enter the last reading you should get a ratiometric calibration curve $CalDAC_1(x)$ like the one below.



We see that the calibration curve is quite good. That means that DAC 1 practically doesn't require any ratiometric calibration.

See that two files have been generated in the ***SLab/Code*** folder. "Cal_Vdd.dat" contains the reference Vref and the supply Vdd values and "Cal_DAC.dat" contains the DAC 1 ratiometric calibration curve. Next time you connect to the board those files will be loaded so the calibration is persistent in the system.

ADC calibration

The DAC 1 calibration guarantees that when we set DAC 1 to output 1V it really generates 1V output and not 0,8V or 1,2V. In practice it won't be exactly 1V but it will be close enough for our experiments.

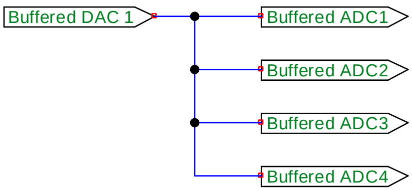
Using DAC 1 as a reference, we can now calibrate all four ADCs.

To perform the ADCs calibration, connect the buffered DAC 1 output to all four buffered ADC inputs. Then, run the script ***Calibrate2.py*** located in the ***SLab/Code*** folder.

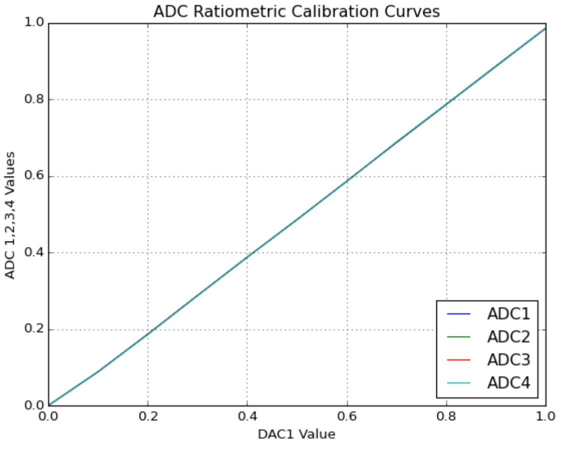
The script will write something like:

```
Connected to Nucleo64-F303RE SLab v1.0
No ADC calibration data found
DAC Calibration data loaded
Vdd loaded from Vdd_Cal.dat as 3.311 V


Calibration of ADCs

Connect the DAC 1 output to all ADC inputs
Use the buffers in all connections

Press [Return] to continue
```

Note that Python explains that the Vdd value and the DAC calibration has been obtained from the files generated in the previous calibration stage.
The script also instructs you to implement the following connections:



After you hit the return key, some measurements will be performed and you will get the ratiometric ADC calibration curves:



Observe that the calibration curves are not perfect; the voltage generated on the DAC for a ratio of 1.0 is not exactly read as a 1.0 ratio on the ADCs. In this particular case it means that ADCs and DACs doesn't have the same reference. Fortunately, the curves are monotonous so we can always correct the ADC errors.

Observe also that a file "Cal_ADC.dat" has been generated. This file holds the above curves so they are persistent in the system.

Dismiss the curve to end this calibration stage.

Final DAC calibrations

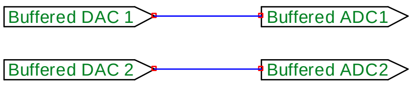
At this points DAC 1 and all four ADCs are calibrated. We only need to calibrate DAC 2, any other DAC if is available in our board. DAC 1, however, has been calibrated with fewer points than the ADCs, so now we will calibrate all DACs including DAC 1. That means that DAC 1 will be calibrated twice.

To perform the DACs calibration, connect each DAC output to the ADC input with the same number. Then, run the script ***Calibrate3.py*** located in the ***SLab/Code*** folder.

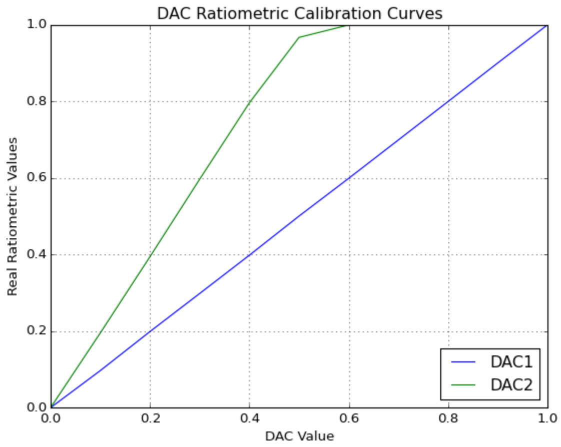
The script will write something like:

```
Connected to Nucleo64-F303RE SLab v1.0
ADC Calibration data loaded
DAC Calibration data loaded
Vdd loaded from Vdd_Cal.dat as 3.311 V


Calibration of DACs

Connect the DAC outputs to ADC inputs with same number
DAC 1 to ADC 1 and DAC2 to ADC2 and son on...

Press [Return] to continue
```

See that Python explains that the Vdd value and both the ADC and DAC calibration has been obtained from the files generated in other calibration stages.
The script also instructs you to implement the following connections:



After you hit the return key, some measurements will be performed and you will get the ratiometric DAC calibration curves:



Note that in the F303RE board the DAC 1 calibration curve is near perfect, as it was in the first stage. DAC 2 calibration curve has a gain of two. This is due to the amplifier configuration set at DAC 2 so that we don't turn-on the user LED present in the board.

At this point the system is fully calibrated.

Calibration test

In order to end the calibration procedure it is an optional but wise idea to check the calibration.

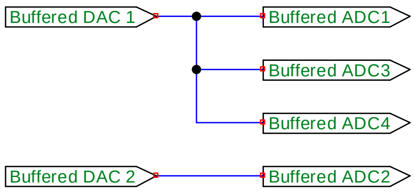
To perform the check, connect each DAC output to the ADC input with the same number. Then, connect the remaining ADC channels to DAC 1 output. Afterwards, run the script ***Calibrate4.py*** located in the ***SLab/Code*** folder.

The script will write something like:

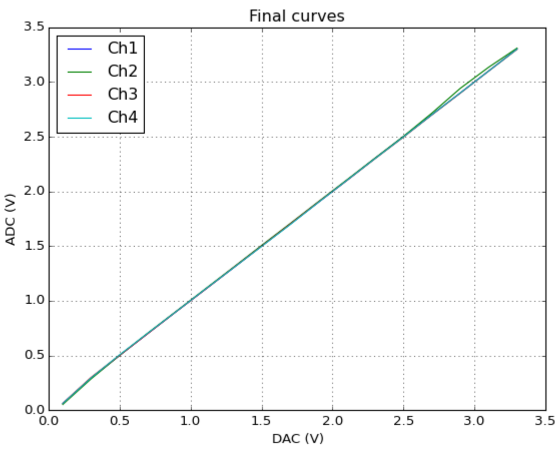
```
Calibration check

Connect the DAC outputs to ADC inputs with same number
DAC 1 to ADC 1 and DAC2 to ADC2 and son on...
Connect the rest of ADCs to DAC 1

Press [Return] to continue
```

See that Python explains that the Vdd value and both the ADC and DAC calibration has been obtained from the files generated in other calibration stages.

The script also instructs you to implement the following connections in the case of the F303RE board that features two DACs:



After you hit the return key, some measurements will be performed and you will get the final calibration check curves:



If the calibration is successful you should get a set of curves that feature the same value in the horizontal and vertical axes. Observe how the gain of the DAC 2 channel has been automatically corrected using its calibration curve.

After drawing the curve and before you dismiss it, the script also sets both DACs to 1.0V. If you want, you can use a multimeter to check their voltage so that you are confident that not only the ratiometric calibration curves are good but also that we use a proper value of the Vdd reference voltage.

The SLab system doesn't pretend to be high precision so a less than 10 mV error can be considered enough.

Recalibration of the SLab system

Calibration is not permanent. It starts to drift as soon as you complete it due to component aging and effects of ambient variables like the temperature. Ideally you should calibrate the board at the start of each work session. In practice you don't need to calibrate as often as our experiments don't demand high precision.

At any time you can check the calibration by running the ***Calibrate4.py*** script. If you observe that any curve is not good you can recalibrate the system.

All SLab experiments assume that you are using a properly calibrated hardware board and that you use buffers for the ADCs and DACs.

That's all for now. It also ends the setup of the system so now you have a complete calibrated measurement environment and you can start working with real circuits.

References

SLab Python References

Those are the reference documents for the SLab Python modules. They describe the commands that can be carried out after importing each module.
They should be available in the **SLab/Doc** folder.

TinyCad

Circuit images on this document have been drawn using the free software TinyCad
https://sourceforge.net/projects/tinycad/

SciPy

All the functions plots have been generated using the Matplotlib SciPy package.
https://www.scipy.org/