

# Embedded system design and implementation of standard auto-calibrated measurement chain

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## Abstract

This paper presents the design and the implementation of a standard auto-calibration system, to correct measurement chain and ensure its accuracy. The adopted solution consists in designing a reconfigurable instrumentation based on the use of a programmable analog circuit (FPAA), allowing the automation of various test and adjustment operations. The measurement chain transfer curve is periodically corrected using the progressive polynomial calibration method, ensuring systematic correction of each taken measurement. The hardware/software implementation of the system was carried out in an embedded configuration based on a FPGA platform. The obtained results highlight adaptability of the proposed calibration method at various sensors kinds as well as the implementation simplicity, and shows how the measuring accuracy can be considerably improved.

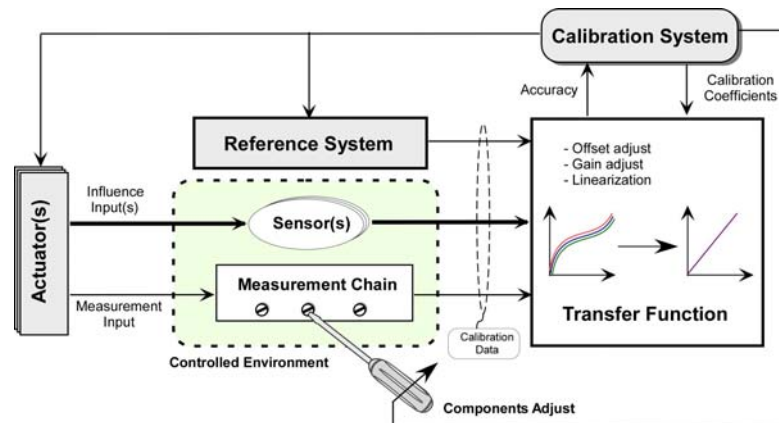
**Keywords:** Calibration, Reconfigurable systems, FPAA/FPGA, Linearization.

## 1 Introduction

The role of measurement instrumentation is mainly confined to analog signal acquisition, digital conversion, and transmission via a simple connection towards an intelligent processing unit. The measurement chain transfer function may vary during the real time process, thus requiring periodically various calibration and adjustment operations. The classic procedure for calibration of sensors implies human interventions, which results in a high exploitation cost and unavailability of measurement during maintenance [1]. The instrumentation and metrology evolve more and more towards the autonomy and the supervision of the acquired information reliability. The optimization of measurement chain performances is then essential for real time system or/and difficult to access systems.

In this paper we define and implement a measurement system with auto-calibration capability, associating a programmable electronic instrumentation and a software calibration method. The main idea is to carry out various auto-test and auto-correction operations, in order to guarantee the necessary measurement accuracy, overcome the inaccessibility problem and reduce the relative cost. The developed measurement chain is based on the use of a programmable analog circuit (FPAA), which is completely reconfigurable and being able to interface various sensors kinds. The measurement chain transfer curve is periodically





**Figure 1 :** Reconfigurable measurement chain calibration.

In case of persistent anomaly in the measurement chain response, the calibration loses its meaning and a maintenance intervention becomes essential.

The measurement errors correction consists in, correcting the systematic error initially and then the residual random error [2] [3]. We combine in this method two complementary techniques allowing each one the correction of various measurement errors kinds. First, a hardware adjustment technique consists in intervening on the measurement chain level, by adjusting the values of its components, in order to find its initial accuracy. For that, it is necessary to choose hardware instrumentation configurable by software. In complement, a polynomial progressive calibration technique allows using a reduced number of calibration data, to calculate calibration coefficients forming the new interpolation function which will represent the corrected measurement function.

## 2.1 Measurement chain adjustment

We have designed our reconfigurable measurement chain based on an FPAA circuit (*Field Programmable Analog Array*) ispPAC30<sup>®</sup> [4], employed like universal signal conditioner, supporting several sensor/transducer kinds. This circuit has a great flexibility by the dynamic capacity of reconfiguration of its amplification gain, interconnections, reference voltages and analog functions.

The programmable reconfiguration of the measurement chain through SPI interface of the FPAA circuit makes easy its auto-calibration. Thus test and correction routines are performed in autonomous way [5]. As shown in figure 2, the adjustment of the measurement chain makes possible the offset error correction, the gain drift compensation, and the cut-off frequencies filtering adjustment. Obviously, this solution allows a significant reduction of the realization and calibration cost of such a measurement chain.



actual correction step does not disturb the previous step. The mathematical formalism of this method is summarized in the following table [6]:

**Table 1:** Functions and coefficients of correction

	Calibration function	Calibration Coefficients
Step 1 ( $x_1, y_1$ )	$h_1(x) = f(x) + a_1$	$a_1 = y_1 - f(x_1)$
Step 2 ( $x_2, y_2$ )	$h_2(x) = h_1(x) + a_2 \cdot (h_1(x) - y_1)$	$a_2 = \frac{y_2 - h_1(x_2)}{h_1(x_2) - y_1}$
...	...	...
Step N ( $x_n, y_n$ )	$h_N(x) = h_{N-1}(x) + a_N \cdot \prod_{i=1}^{N-1} (h_i(x) - y_i)$	$a_N = \frac{y_N - h_{N-1}(x_N)}{\prod_{i=1}^{N-1} (h_i(x_N) - y_i)}$

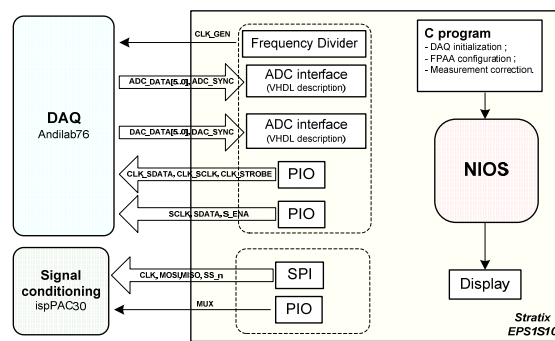
The proposed calibration method can be extended to a 2-dimensions measurement function, if the sensor output is not only sensitive to the main input  $x$ , but also to another influence input  $z$ . In this case the correction functions  $h_{n,m}(x, z)$  and their calibration coefficients  $a_{nm}$  are expressed respectively according to the two following equations [6]:

$$h_{n,m}(x, z) = h_{n,m-1}(x, z) + a_{nm} \cdot \prod_{i=1}^{n-1} \{h_{i,m}(x, z) - y_i\} \cdot \prod_{j=1}^{m-1} (z - z_j) \quad (2)$$

$$a_{nm} = \frac{y_n - h_{n,m-1}(x_n, z_m)}{\prod_{i=1}^{n-1} \{h_{i,m}(x_n, z_m) - y_i\} \cdot \prod_{j=1}^{m-1} (z_m - z_j)} \quad (3)$$

### 3 System implementation

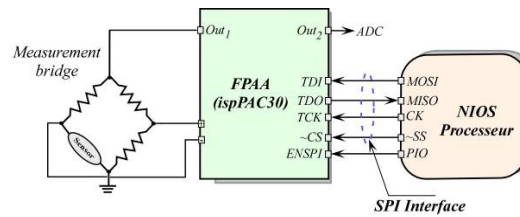
The developed measurement system brings the adequate analog processing to the sensor signal, the acquisition and the correction of the measurement in real time. These various tasks are coordinated and managed by a same intelligent unit.



**Figure 4 :** Diagram of the system

Unlike the solution we have developed before and presented in [4] [5], where acquisition, analysis and processing of measurement are dissociated and ensured by the computer, the





**Figure 6 :** SPI communication protocol.

### 3.2 Data acquisition setup

We have employed the data acquisition board *andilab76* from ANDIMEDES, to digitize the analog measurement signal. The *NIOS* Processor carries out a C program in order to setup the data acquisition board through (PIO) interface. We have also written a software module in VHDL language, to allow detection and demultiplexing of the conversion word (2x6 bits). The management of the timing clock is performed with hardware blocks.

### 3.3 Measurement Correction

Algorithms of the 1-dimension and 2-dimensions calibration method described in §2.2 are software implemented on C program, that calculates the various calibration coefficients relating to the desired correction order. These coefficients are then immediately used to perform the real time measurement to eliminate the various errors types.

## 4 System Performances

The estimates of the resources related to the hardware implementation, as well as the computing times relating to the main software processing are given in table 2 below. These results show that this implementation associates at the same time economic use of the hardware FPGA resources and fast execution time of the various processing.

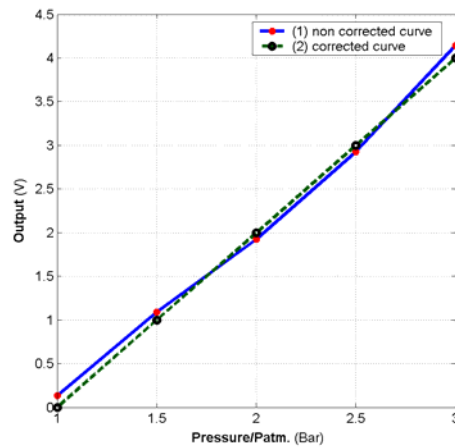
**Table 2 :** Occupied resources and computing time.

FPGA Ressources		Processing times	
Logical Cells	2804/10570 (26%)	Andilab76 board setup	3,07mS
		Calaibration coefficients calculation.	12,11mS (1-dim.)
Pins	145/427 (33%)		403mS (2-dim.)
		Measurement correction	1,94mS (1-dim.)
Memory	62Ko		17,3mS (2-dim.)
		SPI configuration of the Measurement chain	82.06mS

The simulation results obtained by the progressive polynomial calibration method prove that an excellent accuracy could be reached, as well as a considerable decreasing of the cross-sensitivity. The figure 6 gives an outline of the remaining error peak after several correction

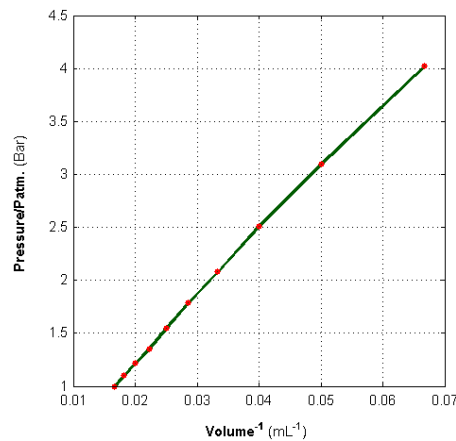






**Figure 8 :** The pressure sensor calibration curve before and after correction.

The progressive polynomial calibration algorithm was used to obtain 5 calibration coefficients composing the sensor correction curve shown in curve (2) of figure 7. From this correction results an average accuracy of 3%.



**Figure 9 :** Pressure vs. volume.

For validate the calibration results, we carried out various measurements of pressure to verify the Boyle-Marriott law. The goal of this experiment is to prove that the product (Pressure x Volume) is constant, at a constant temperature of course. The measurement results collected from various air volumes are represented on figure 8. This curve shows the measured pressure vs. the volume of air in the syringe, we can easily see that the Boyle-Marriott law is confirmed, which proves that our pressure sensor was well calibrated and gives trustable measurements.

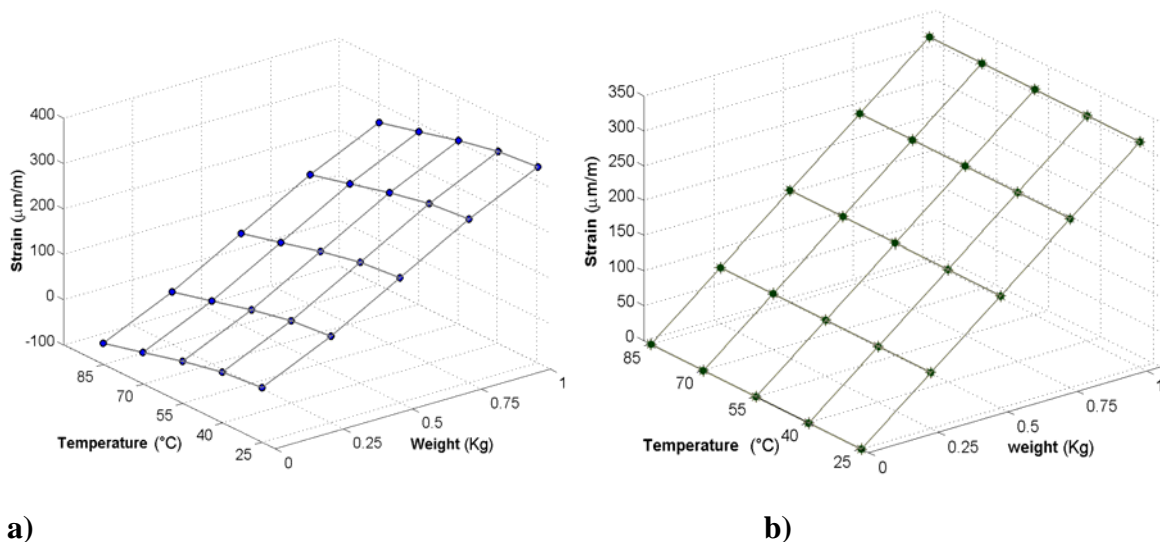
## 5.2 Study of a strain gauge

A strain gauge is a passive sensor translating in electric resistance variation its own deformation. Under ideal conditions, where the gauge undergoes only the mechanical strain, the resistance variation is proportional to the structure deformation at the place where it is





**Figure 11 :** View of the experimental set up used for the calibration



a)

b)

**Figure 12 :** Deformation vs. applied load and temperature (a : before correction) (b: after correction).

In order to determine the strain gauge calibration curve, we submitted it to a series of tests, using various loads (weight of: 250, 500, 750 and 1000g) at various temperatures (25, 40, 55, 70 and  $85^{\circ}\text{C}$ ) ensured by temperature oven. The figure 10 shows the calibration curve, and we notice the presence of combination errors (offset, gain drift, non-linearity and temperature cross-sensitivity). Without correction, this curve can't be useful to accurately find out the exact deformation of the strain gauge only related to the main measurement (load).



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