INTERNATIONAL JOURNAL ON SMART SENSING AND INTELLIGENT SYSTEMS, VOL. 1, NO. 1, MARCH 2008

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 corrected using the progressive polynomial calibration method, allowing after calculation of various calibration coefficients to systematically correct in real time each taken measurement.

A test bench was realized, and we present experimental results relating to the system applied to two various sensors (a pressure sensor and a strain gauge). The results prove the effectiveness of the proposed auto-calibration method, and shows well how the measuring accuracy can be considerably improved.

2 Auto-calibration system

The calibration of the measurement chain is performed first by carrying out a calibration step, which must be realized in order to correct its current response referring to its original response (figure 1). The measurement chain is subjected to various tests employing N calibration inputs x. These tests are performed in a controlled environment, in order to take into account the effect of the main influence input z (temperature, moisture...). The measurement chain response $F(x)$ related to inputs (x,z) is compared with its reference response $G(x)$ (supposed linear). According to the evaluated difference between these two responses, the correction coefficients a_i are calculated, in order to decrease the calibration error. The measurement accuracy relates to the calibration inputs, the test conditions as well the adopted correction method. Once the measurement system is calibrated, it passes directly to the measurement step.

$$y = H(x,z) = f((Fx), G(x), z, a_i) \qquad (1)$$

The data y represents the output measurement systematically corrected in real time, using measurements of the input x influenced by input z and calibration parameters already obtained previously in the calibration step. The correction results can be examined perfectly by the observation of the error curve $E(x)=H(x,z)-G(x)$ and its evolution. If several aberrant values are detected, or if a considerable distance of the corrected transfer curve compared to the reference curve is observed, a new calibration step will be necessary. It is also possible to perform the measurement chain calibration in a periodic way, according to the application specificity and the hardware which composes it.

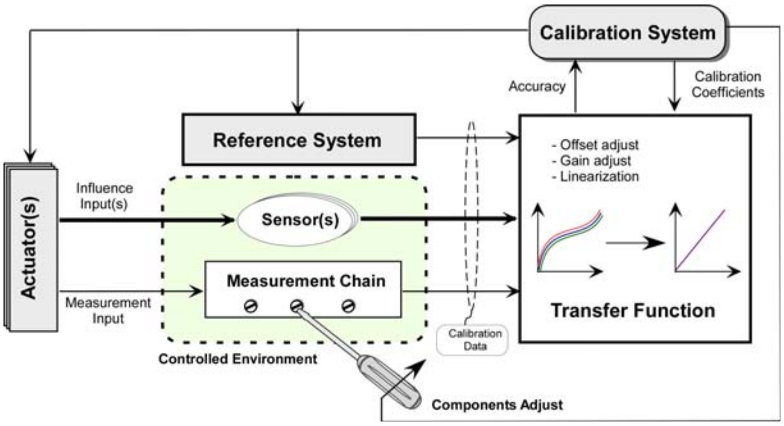


Figure 1 : Reconfigurable measurement chain calibration.

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® [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.

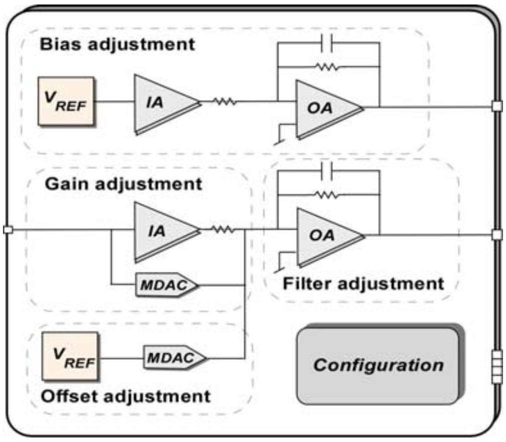
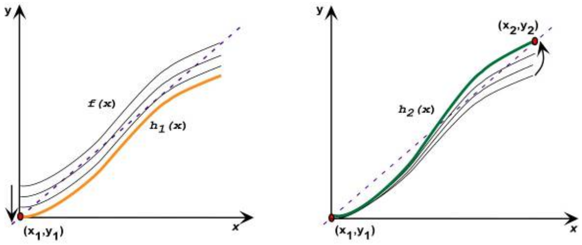


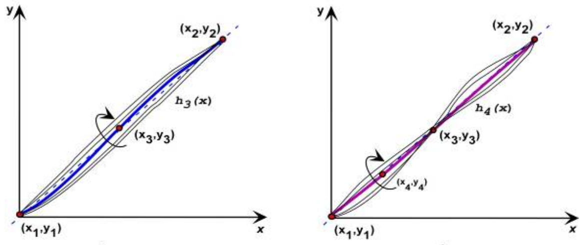
Figure 2 : Measurement chain adjustment.

2.2 Correction of Measurement

The measurement chain curve could present combination of errors (offset error, gain error, linearity error and cross-sensitivity error). To correct these errors, we have adopted the progressive polynomial calibration method, explained graphically in figure 3. The incremental steps of correction explain the way to obtaining the polynomial correction curve, which approaches the desired linear curve. In fact, to each calibration step the corrected transfer curve tends towards the desired transfer curve, hence the label *polynomial progressive calibration***.**



(a) Offset correction (b) Gain correction



(c) 1st linearization (d) 2nd linearization

Figure 3: Polynomial progressive calibration method.

This method consists in using one calibration measurement (x_i,y_i) to calculate a calibration coefficient a_i of the interpolation function *h(x)*. The correction is applied immediately to correct the measurement chain output *f(x)*. Each additional correction step uses another calibration measurement to perform a progressive correction of the measurement curve, the 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)	$h_2(x)=h_1(x)+a_2.(h_1(x)-y_1)$	$a_2=\frac{y_2-h_1(x_2)}{h_1(x_2)-y_1}$
…	…	…
Step N (x_n,y_n)	$h_N(x)=h_{N-1}(x)+a_N.\prod_{i=1}^{N-1}(h_i(x)-y_i)$	$a_N=\frac{y_N-h_{N-1}(x_N)}{\prod_{i=1}^{N-1}\left(h_i(x_N)-y_i\right)}$

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]:

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

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

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.

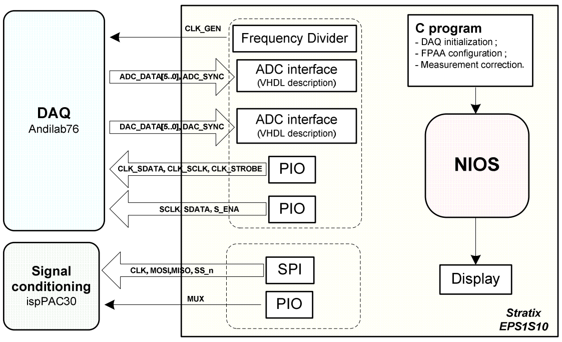


Figure 4 : Diagram of the system

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 embedded solution we propose exploit directly the data using the *Stratix-EP1S10* platform from ALTERA, it is composed of a FPGA which can integrate one or more heart of completely customized microprocessor. This solution is really economic and reliable since only one component is necessary, moreover the joint hardware/software design is allowed and made with less time. In addition, the design descriptions in advanced languages such VHDL and C allow simple modification and adaptation.

The complete functional blocks of the developed embedded system and the various interactions between these blocks are shown in figure 4. The hardware part can be used for simple and fast processing (Timing and AN/NA conversion). The software part managed by the FPGA *NIOS* Processor carry out the developed C program that monitors the measurement chain dynamic reconfiguration, the data acquisition setup, the measurement correction and the results display. With this architecture it is possible to process data with two different speeds.

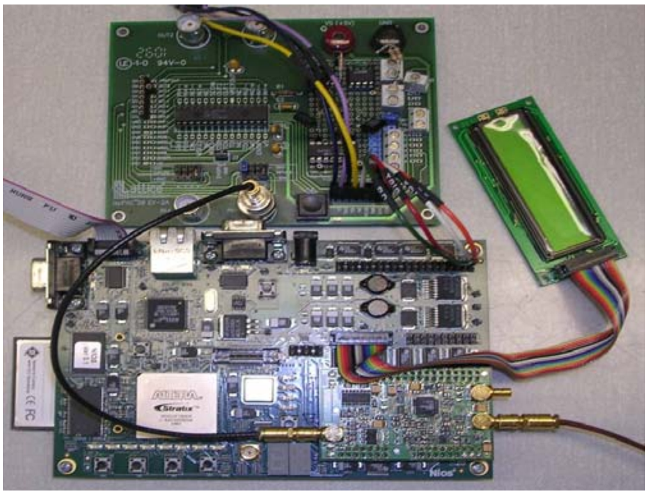


Figure 5 : View of the electronic instrumentation

3.1 Measurement chain configuration

The SPI (*Serial Peripheral Interface*) programming protocol makes possible the analog measurement chain auto-reconfiguration in fast and dynamic way (even during its operation), in order to perform auto-test and auto-adjustment operations. The *NIOS* Processor send via the SPI protocol the wanted configuration bits to the FPAA circuit (*ispPAC30*®) as shown in figure 5.

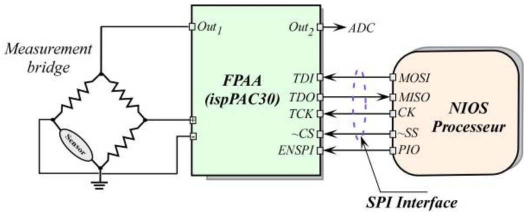


Figure 6 : SPI communication protocol.

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 coeffecients 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 configration 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 steps for 4 curves simulating different sensors responses, used to test the calibration method. For the 4 cases, a combination set of measurement input and cross-sensitivity input were used, to correct various function shapes (polynomial, square, logarithmic and exponential curves). The larges bars in this figure represent the initial linearity error which remains to be corrected after a 2x2 steps correction of offset and gain errors. The figure shows how this linearity error is reduced when the correction order increase respectively to 3x3, 5x3, 5x5 and 7x5 steps.

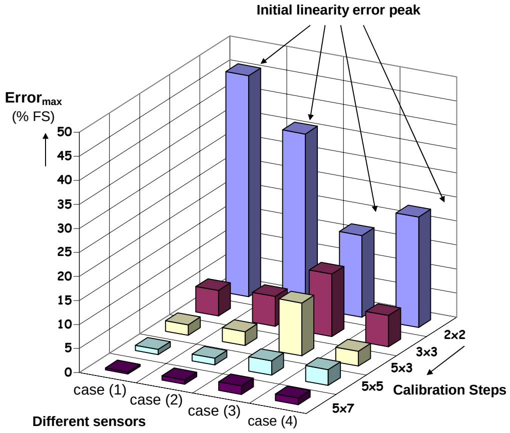


Figure 7 : Linearity error peak evolution according to the correction order for various sensors.

5 Experimental Results

We have realized a test bench to validate our auto-calibrated measurement system. Since the proposed system supports various sensors kinds, we choosed to apply the calibration method to two various different sensors. In the first case, we studied a pressure sensor, and applied the progressive polynomial calibration to correct and linearize its measurement curve. In the second case, we studied a strain gauge and we were mainly interested on correcting the temperature cross-sensitivity.

5.1 Study of a pressure sensor

The piezoresistive pressure sensor we have used in our experiment is Honeywell 26PC, it is subjected to the air pressure of a hose insufflated by a syringe, an output voltage appears according to the mechanical strain applied to this sensor. After amplification and numerical conversion of the sensor signal, we established at the ambient temperature the calibration sensor curve (by comparison to a pressure gauge using 5 calibration measurements). The curve (1) of figure 7 informs us that the sensor calibration response is not perfectly linear but contains error accumulations (offset, gain drift, non-linearity).

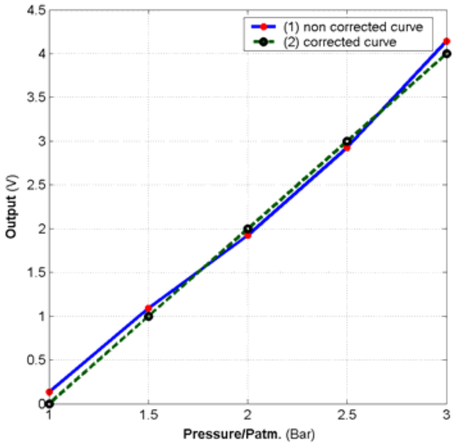


Figure 8 : The pressure sensor calibration curve before and after correction.

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%.

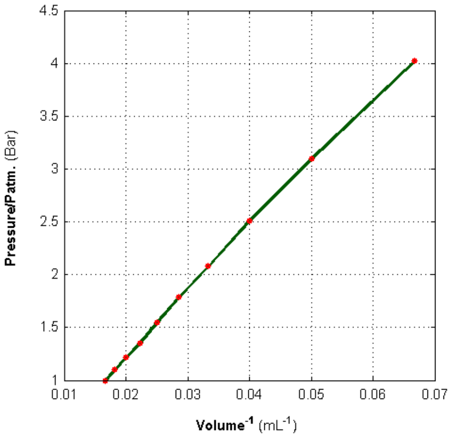


Figure 9 : Pressure vs. volume.

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 pasted [7] (see figure 9):

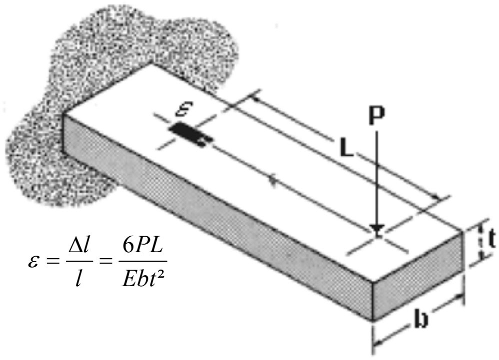


Figure 10 : Strain gauge structure and dimensions

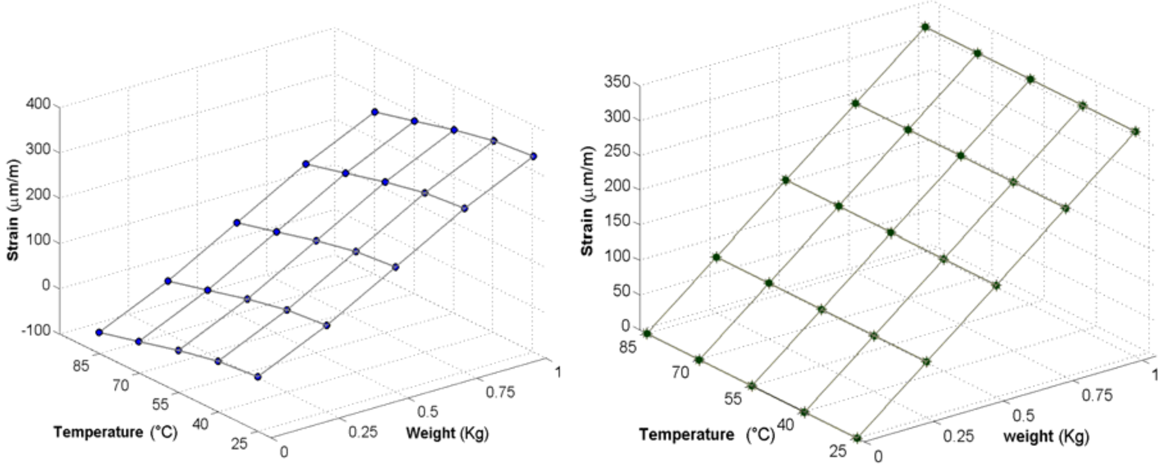
The strain gauge resistance variation *ΔR/R* related to deformation *Δl/l* by the gauge factor *F*, according to the following equation:

$$\frac{\Delta R}{R} = F.\frac{\Delta l}{l} \qquad (4)$$

The temperature is the main cross-sensitivity input of the resistive strain gauges. A solution to compensate the result apparent deformation is using a thermal probe and referring to the gauge correction curve to determine the compensation coefficients [8]. In most of the time, the user can be brought to determine himself the apparent deformation of the gauge due to the temperature influence, without make use of the correction coefficients supplied by manufacturer, because these coefficients were established only for a given gauge associated to certain test structure (since the user implemented measurement system can be different compared to the referred system). However the progressive calibration method presented before is completely able to solve this problem of temperature cross-sensitivity of the measurement.

The strain gauge used in our experiment is ECA-06-250UW. It is pasted on an aluminum blade. This strain gauge is inserted in a Wheatstone bridge, using the bridge output voltage variation it is easier to carry out measurements, in particular with an instrumentation amplifier. The Wheatstone bridge is assembled in ¼ bridge, on balance its four resistances are equal to 350 Ω ± 0.01%.

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°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).

The gauge deformation measurements estimated before require some corrections, especially to eliminate the temperature cross-sensitivity effect. A systematic correction in 2-dimensions (*P,T*) of the measurements provided by the gauge is realized according to the progressive polynomial calibration algorithm. The calibration coefficients are calculated based on a set of 5x5 calibration measurements. We have obtained as proved by figure 11 a linear curve, and we can see that the temperature cross-sensitivity is well compensated in interval [25°C, 85°C]. The estimated average measuring accuracy is 5%.

6 Conclusion

The developed measurement chain is completely reconfigurable to perform auto-test and auto-adjustments operations, thus considerable calibration time and cost decreasing is achieved. The measurement chain is designed around a programmable circuit FPAA, offering a good reliability and a great flexibility. The adopted progressive polynomial calibration method guarantees correction and linearization of different sensors curves, using only low number of calibration data. The easy and economic implementation of the hardware/software processing in a FPGA platform allows a fast measurement chain dynamic reconfiguration (82ms) and a fast calculation of the calibration coefficients (402ms for a 5x5 steps correction). This solution associates an electronic intelligence to a dumb measurement system based on ordinary sensors. The obtained results confirm that the proposed calibration method adapts easily to various sensors kinds and guaranteed an excellent accuracy.

7 References

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