

PROJECT PRIN 2006 – Scientific Coordinator: Prof. MARIO SAVINO

Development of Innovative Methods for Characterizing, Modeling and Correcting the Non-Ideal Behavior of A/D and D/A Conversion Channels, in Order to Contribute Towards Harmonizing and Upgrading International Standards

<i>Units involved in the research</i>	<i>Scientific Responsible</i>	<i>Month-Man</i>
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Abstract- The research program aims at improving the performance of appliances based on Analog-to-Digital and Digital-to-Analog conversion (ranging from measuring instruments to on-chip ADC and DAC). This will be done by developing methods for the accurate measurement and correction of conversion errors (including, when applicable, errors caused by transducers and signal-conditioning blocks). Another aim of the research is to expand the scope of the theory of measurement uncertainty, including conversion errors in dynamic conditions. This will allow the manufacturers to qualify correctly the non-ideality of a conversion channel in the specifications, and the users to use correctly the given figures to compute the uncertainty introduced by the conversion. The research, developed for the parts of competence by the five coordinated Units, aims also at contributing in real terms towards the improvement and the harmonization of the existing standards, which currently present various discrepancy and obvious deficiencies with respect to the state of the art.

I. Principal aims

The conversion of electrical signals from the analog to the digital realm, and vice versa, is the key operation in uncountable electronic appliances and technologies. From measuring instruments to biomedical apparatuses, from radar to cellular phones, almost any modern electronic system requires that some information, in the form of electrical signal, is converted one or more times between the analog and the digital domain.

A final aim of the research can be, consequently, stated as follows:

1. taking a further, and as wide as possible, step forward in improving the performance of A/D and D/A converters.

An intermediate goal, not less important, actually, than the former, is:

2. achieving a better knowledge – from both the mathematical and the technological point of view – of the error mechanisms in A/D and D/A conversion systems.

In this framework we aim at a further result that is very important, for example, for the final users of measuring instruments, and more generally for those who must choose and purchase the components required to realize a specific electronic system:

3. determining the best figures of merit to represent and qualify the performance of A/D and D/A conversion systems.

Besides, a final concrete result of the project, included also for the purpose of an easy “ex-post” evaluation of the performed research work, is the following:

4. submitting the research results to the IEEE and possibly to standardization bodies (IEC, ISO), aiming at their inclusion in technical Standards relevant to A/D and D/A conversion, electronic instrumentation, and measurement uncertainty.

The goals 2 and 3 clarify the “level” at which we want to investigate in order to achieve the aim n. 1 (improving the performance of ADC and DAC). The goals 3 and 4 clarify, instead, that the research project aims at providing useful and usable results for enterprises, designers of electronic appliances, and final users of electronic instruments.

In order to understand the meaning of the goals 2 and 3 one should think, as a useful analogy, of the true technologic “revolution” of the sigma-delta A/D conversion. These devices are built with a very

low quality ADC that, however, yields an extremely “clean” output signal thanks to proper digital signal processing and trade-off between bandwidth and resolution. The spirit and the methods of the present research program, which is focused on the mathematical modeling and the digital correction of conversion errors, are analogous to those which brought, not many years ago, to the development of the sigma-delta conversion technology.

In order to understand the meaning of the goals 3 and 4, on the other hand, it is sufficient to read the technical characteristics of different ADCs or DACs, or different instruments of the same kind, for example oscilloscopes. Different manufacturers (or even the same manufacturer for different products) give different figures of merit and sometimes with obscure meaning, so that it is often impossible an objective comparison of products, or even a definite interpretation of the yielded figures.

Moreover, international trade makes products produced in one country and sold in others, to be developed or redesigned to meet different standards in different countries. Consequently, standard harmonization is needed so that standards of different countries can be substantially the same, providing benefits for manufacturers, in terms of reduced products variations, inventory & cost, product quality and for focusing on new products; for customers giving more choices among cheaper and better products, and for the government, for promoting international trade and cooperation.

The currently available standards, both international (IEC 60748-97, IEC 62008-05) and category (IEEE Std 1057/94, IEEE Std 1241/00) standards don't adopt a unified approach, since they often give different definitions or not completely clear of the same quantities. The troubles arise especially when dealing with non-ideal behaviour in dynamic conditions, for which many problems, both theoretical and practical, are currently open.

The description of the aims of the research would not be complete without reference to error phenomena which, even if not originated by the conversion hardware, are quite common in ADC and DAC based electronic appliances, and can often be analysed and minimized with similar techniques. These phenomena are, essentially, the errors originated by transducers and signal conditioning blocks, and errors caused by electromagnetic compatibility (EMC) issues. Therefore, further aims of the research project are:

5. extending the developed methods of error analysis and correction to transducers and signal conditioning blocks;
6. integrating the developed methodologies with EMC-related techniques and solutions.

II. Phases of the research

The project program is subdivided in two stages of twelve months each. The passage to the second stage will be possible once the first-stage local and global objectives have been achieved.

The first phase of the research program consists mainly in an indispensable experimental verification of the advanced methods of error analysis and correction already proposed in the literature, in order to determine their actual limits and working to generalizations and improvements. Of course, this first phase of the research may already bring to the development of improved methods, or of radically new methods, which are, however, more properly the aim of the second phase of the research. During this first phase the research units also begin the transcription of the research results, in a harmonized and formally correct way, in draft standard documents, to be submitted to the relevant institutions (IEEE TC-10, IEC, etc.).

Then, the research Units aim also to develop, both by means of formal-mathematic methods and by means of numerical simulations, a theory of the uncertainty of measurements associated to the most complex conversion errors. This task is preliminary to the choice of good figure of merits, suited to qualify A/D and D/A conversion channels. The second phase is devoted to the realization and the implementation of the results of the previous one, jointly to a suitable verification of the achieved aims.

III. Expected partial results

In the first phase it is expected, first of all, to obtain a clear list of the good and the bad methods for measuring and removing conversion errors. In other words, analyzing the most advanced existing techniques must bring to a clear-cut choice of those which are likely to become standard, and what modifications are needed to obtain this. Another aim is to increase the theoretical understanding of the effect of conversion errors on measurement uncertainty.

It is perfectly possible, of course, that already in the first phase of the research some completely new method will be fully developed: the primary aim of this phase of the work, however, must be the experimental verifications (also inter-laboratory verifications involving European and U.S.

laboratories), and the identification of the most promising methodologies to develop during the second phase. The results of this work will be expounded in international conferences and published on international scientific journals, as well as organized in draft standard documents on the characterization and optimization of the converters.

The first result expected from phase two is a set of new methodologies for measuring and correcting conversion errors, ready to: be published in international scientific journals; be included in the relevant international Standards (including the IEEE Standards); be adopted by manufacturers of instrumentation and electronic appliances using A/D and D/A conversion.

These methodologies must refer, obviously, to the errors with the most difficult mathematical description, which the state-of-the-art methods (described above) are not yet able to measure with sufficient accuracy. It is expected, in particular, that radically new methodologies will be developed as regards the D/A conversion errors, on which the current knowledge is, currently, noticeably smaller than the one on A/D conversion.

The second expected result is widening the methods described in the *Guide to the Expression of Uncertainty in Measurement* (GUM) to the case of A/D and D/A conversion of dynamic signals. The aim is to inspire into users a better “culture” of the uncertainty, going beyond the simplistic approach, currently too common, of taking into account only the static and deterministic amplitude errors (gain, offset, INL), and ignoring noise, dynamic errors, time-base errors, etc.

In the following, we detail the research activities of each Operative Unit for the Project purposes.

IV. Research activities during the first 18 months of the Project

A. Unit of Bari

The research project has been developed in the following respects:

1. deeper understanding, from the mathematical as well as technological point of view, of the error mechanisms that arise in A/D and D/A conversion systems;
2. improvement of the techniques adopted in characterizing A/D and D/A conversion systems;
3. implementation of an integrated software tool for the control of automated test equipment systems and for the exchange of test data.

All the research results have been validated by means of computer simulations and experiments, and attention has been given to the evaluation of their performances. The results are illustrated in the papers listed in the References section, and can be summarized as follows:

- a) *measurement of timing errors of high speed A/D conversion systems.*[1] A new technique has been proposed for the measurement of the time base distortion (TBD) of analog-memory sampling digitizers. The TBD greatly affects the quality of the acquisition of fast signals, but its systematic nature makes possible and greatly advantageous its measurement and correction. This research has been motivated by the fact that existing techniques for measuring TBD have good performance with equivalent-time sampling digitizers, but they are not able to measure the distortion in real-time analog-memory systems, a technology of widespread use in modern high speed scopes.
- b) *measurement of dynamic nonlinearities of high speed A/D conversion systems.*[2][3][4] The problem of measuring dynamic nonlinearities in the presence of TBD has been addressed. The used technique allows the simultaneous measurement of the distortions produced by the vertical section (ADC nonlinearity) as well as by the horizontal section (time base), and the separation of their effects. This separation is necessary for the correct interpretation and measurement of the dynamical distortions introduced by a wide range of high speed A/D conversion systems. The proposed technique is based on the LS estimation of actual sampling instants and of a multi-sine signal model. The resulting INL can be estimated and expressed in two forms: parametric (relying on Chebyshev polynomials); non parametric (essentially, a table of tuples: input value , input slope, output value).
- c) *static linearity test of ADCs.*[5][6][7][8][9] In this research, a maximum likelihood (ML) estimator has been derived for the problem of measuring the ADC code transition levels. The proposed method is intended to test the linearity of an ADC in the static regime, using only constant test signals, except for a small amount of additive noise. The measurement data are employed in a nearly optimal manner, due to the statistical properties of the ML estimator. These have been thoroughly examined with the aim of giving rules for the design of the test under a given uncertainty constraint. The proposed test is very convenient in terms of instrumentation required, because the test signal generator needn't to have resolution higher than the DUT.

- d) *simultaneous static linearity test of ADCs and DACs in a loop-back scheme.*[10][11] The proposed technique, based on ML estimation, is intended to measure both ADC and DAC nonlinearities without resorting to any external reference instrument, thus it is particularly suitable for effective implementing of a BIST strategy. The research is aimed at improving the performances, in terms of accuracy, of the loop-back test, in which each DAC output level is dithered by a constant amount of noise and acquired many times by the ADC. The formulated theoretical framework is rather general in that it can be applied to several problems: ADC linearity testing using a reference DAC; DAC linearity testing using a reference ADC; contemporaneous ADC and DAC testing; and, finally, transfer of accuracy between ADCs and/or DACs.

Scientific publications of the Unit

- [1] F. Attivissimo, A. Di Nisio, N. Giaquinto, M. Savino, "Measuring Time Base Distortion in Analog-Memory Sampling Digitizers," *IEEE Trans. Instrum. Meas.*, vol. 57, no. 1, pp. 55-62, Jan. 2008.
- [2] F. Attivissimo, A. Di Nisio, N. Giaquinto, "Measuring Dynamic Nonlinearity in High-Speed Digital Scopes," in *Proc. IEEE IMTC 2007, Instrumentation and Measurement Technology Conference*, Warsaw, Poland, May 1-3, 2007.
- [3] F. Attivissimo, A. Di Nisio, N. Giaquinto, "Measuring Dynamic Nonlinearity in High-Speed Digital Scopes," to be published in *IEEE Trans. Instrum. Meas*
- [4] F. Attivissimo, A. Di Nisio, N. Giaquinto, "Misura di Non Linearità Dinamica di Oscilloscopi Digitali ad Alta Velocità," in *Atti del XXIV Congresso GMEE*, Torino, 5-8 settembre 2007.
- [5] G. Cavone, A. Di Nisio, L. Fabbiano, N. Giaquinto, M. Savino, "Improved Static Testing of A/D Converters for DC Measurements," in *Proc. IEEE IMTC 2007, Instrumentation and Measurement Technology Conference*, Warsaw, Poland, May 1-3, 2007.
- [6] G. Cavone, A. Di Nisio, L. Fabbiano, N. Giaquinto, M. Savino, "Improved Static Testing of A/D Converters for DC Measurements," to be published in *IEEE Trans. Instrum. Meas*
- [7] G. Cavone, A. Di Nisio, L. Fabbiano, N. Giaquinto, M. Savino, "Test Statico di Convertitori A/D per Misure DC," in *Atti del XXIV Congresso GMEE*, Torino, 5-8 settembre 2007.
- [8] A. Di Nisio, L. Fabbiano, N. Giaquinto, M. Savino, "Statistical properties of an ML estimator for static ADC testing," in *Proc. of the 12th Workshop on ADC Modelling and Testing*, Iasi, Romania, Sept. 19-21, 2007.
- [9] A. Di Nisio, L. Fabbiano, N. Giaquinto, M. Savino, "Maximum Likelihood Estimation for Linearity Testing of ADCs Stimulated by Known Constant Signals," to be published in *Computer Standards and Interfaces J.*
- [10] G. Cavone, A. Di Nisio, N. Giaquinto, M. Savino, "A Maximum Likelihood Estimator for ADC and DAC Linearity Testing," to be published in *Proc. of 16th IMEKO TC4 Symposium*, Florence, Italy, September 22 - 24, 2008.
- [11] G. Cavone, A. Di Nisio, N. Giaquinto, M. Savino, "Test di linearità simultaneo di convertitori A/D e D/A mediante stima di massima verosimiglianza," in *Atti del XXV Congresso GMEE*, Roma, 7-10 settembre 2008.

B. Unit of Benevento (Sannio University)

The research group of the University of Sannio has developed a method for the reduction of non-linearity (NL) errors of the ADCs, based on the Bayes theorem. The basic idea consists of modeling the ADC as a sequence of an ideal quantizer and a non-linearity block, located in the digital domain, as shown in Fig. 1.

The analog signal to be converted, opportunely oversampled, is given to the ADC. A dithering is also applied to the analog signal before the conversion, with amplitude comparable with the ADC non-linearity and a frequency much greater than that of the signal.

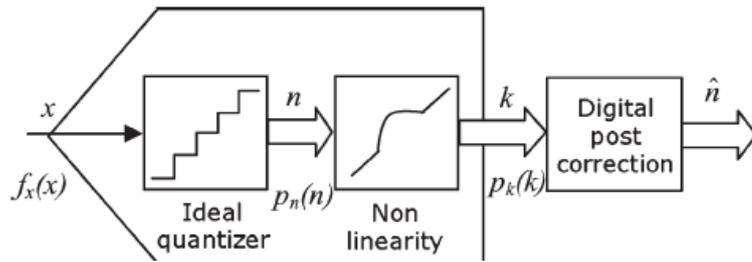


Fig. 1. Block scheme of the method for the reduction of non-linearity errors in ADCs.

The first block of the model is an ideal quantizer, which provides, instantaneously, the quantized sample n , having the probability mass function $p_n(n)$. Such value is then input to the NL block, which, for each transition level of the ADC characteristic, models both the random distribution of the codes around it and the deviation of such level from the ideal position.

Because of the presence of the NL block, the output sample k of the NL block will differ from the ideal one, which is represented by n .

Therefore, the problem of correcting the non-linearity errors of the ADC is faced similarly to the design of a digital receiver that has to recover the codes generated by a data source starting from the observation of the received ones.

This operation is performed by the digital post-correction block. It consists of a digital filter, based on the Bayes theorem. Moreover, a further low-pass filter allows removing the dithering signal. In general, the dithering is used to remove NLs, whose amount is less than the amplitude of the dithering. Then, high-scale NLs require high amplitudes of the dithering signal.

The application of a method which is capable of estimating the original code, starting from the corrupted one allows optimizing the dithering effects also to remove small-scale NLs.

In particular, the method based on the Bayesian model is capable of attenuating the distortions

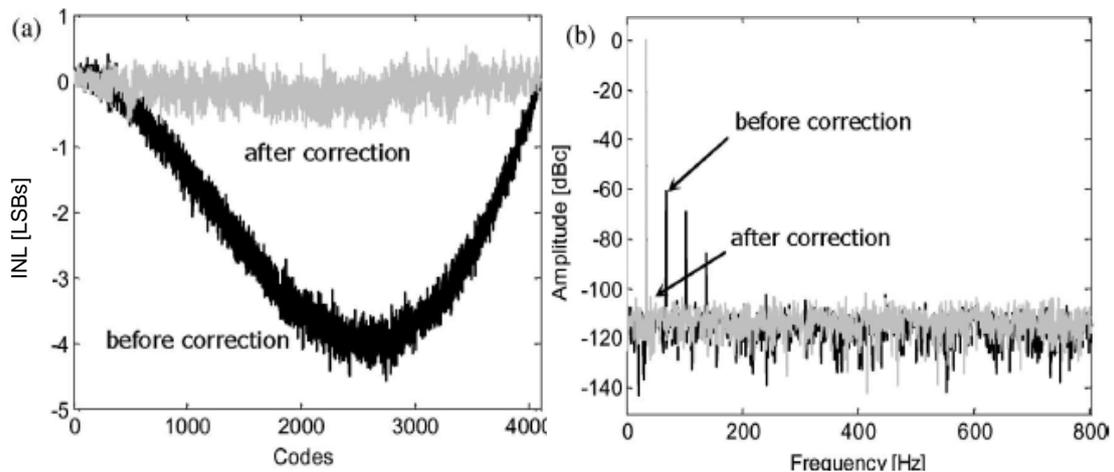


Fig. 2. Simulation results of the NL reduction method on ADC model with a fourth-order non-linearity. (a) The INL of the converter before and after the correction. (b) The spectra of the signal before and after the correction. It can be noted the reduction of the harmonics.

introduced by the ADC. In addition, such reduction is achieved by a reduced-order low-pass filter, that can be implemented with low computational load.

In Fig. 2 some simulation results obtained from the application of the developed method, are presented. In this case a simple model of a 12-bit ADC with a fourth order polynomial non-linearity has been used. It can be noted how the method is capable of drastically reduce the NL. In the same way it can be easily seen the effect of the application of the method on the spectrum of the signal. After the correction, the harmonics of the signal, introduced by the NL, are reduced to values close to the quantization noise level.

The knowledge acquired during the development of the project has been transferred to the students of the "International Measurement Confederation (IMEKO) TC-4 International Summer School on Data

Acquisition Systems”, organized by the research group of the University of Sannio at the Faculty of Engineering of the same University and chaired by Prof. Pasquale Daponte. The school has been held in Benevento since June, 25 up to July 7, 2007.

Scientific publications of the Unit on International journals:

- [12] L. De Vito, H. Lundin, S. Rapuano, "Bayesian Calibration of a Lookup Table for ADC Error Correction", IEEE Transactions on Instrumentation and Measurement, Volume 56, Issue 3, June 2007, pp.873 – 878
- [13] L. De Vito, L. Michaeli, S. Rapuano, "An improved ADC error correction scheme based on a Bayesian approach", IEEE Transactions on Instrumentation and Measurement, vol.57, No.1, gen. 2008, pp.128-133

C. Unit of Bologna

In the last few years the Research Unit at the University of Bologna has developed, implemented and validated an empirical, behavioural approach for the experimental characterization and non-linear modelling of both single A/D-conversion devices and, from a more general standpoint, the overall digital data acquisition channels at the front-end of sampling instrumentation.

The method (namely, the Discrete-Time Convolution Model, DTCM [14-16]) is based on a modification of the classical Volterra series which, beside preserving the theoretical generality and accuracy of the latter when considered in its full expansion, presents very different convergence properties that can be exploited, under mild hypotheses on the memory-time duration of the system [17], for the definition of a single-kernel, non-linear dynamic model with negligible truncation errors. Due to its particular input/output analytical formulation in the time-domain, which consists of the superposition of two non-linear contributions, a purely-algebraic term (the zero-order kernel - i.e., the "DC" response of the ADC) and a purely-dynamic term (associated with the first-order modified kernel), respectively, both cascaded at the input with a linear system, the model is inherently capable of separately describing all the different non-idealities associated with the behaviour of a typical A/D channel, independently of its technology: purely-linear long-memory effects, static (i.e., "memoryless") non-linearities, and purely-dynamic non-linear effects. In particular, the latter increase their relevance as the dynamics of the input signals get higher, and can lead to distortion levels comparable with those associated with the quasi-static response of the channel, which is often the only source of non-linearity taken into account by conventional methods.

At the present, the research activity is being addressed along two strictly correlated topics:

1. optimization of the experimental procedures for the reliable extraction of DTCM parameters, and the use of the latter as figures of merit for the classification of A/D channels in terms of dynamic non-linearities
2. compensation of non-idealities within A/D channels based on numerically-efficient algorithms aimed at the inversion of the DTCM non-linear dynamic input/output relationships.

As far as the first issue is concerned, the main goal is the definition, implementation and validation of modified laboratory set-ups and related numerical techniques for the improved experimental extraction of DTCM parameters, which does not make use of any auxiliary reference channels, as instead adopted in the past. As a result, the DTCM characterization approach will also be applicable to state-of-the-art systems, such as fast sampling rate, wideband digital oscilloscopes, and high vertical resolution A/D boards, for which reliable reference channels are either not available or too expensive. In addition, since the DTCM approach explicitly describes the dynamic non-linearities of the DUT by separating them from all the non-idealities of other nature, in particular the static ones, novel figures of merit and methodologies are being investigated, which are based on the DTCM parameters and allow for both the performance investigation of A/D channels and their comparison in terms of dynamic non-linear effects. This activity is mainly oriented to supplement the performance parameters suggested by the literature and international standards, (i.e., INL, THD, SFDR, IMD, etc.) which usually either fail in taking into account such effects, or make not possible to directly estimate their contribution to the overall perturbation at the output of the channel with respect to linear and static non-linear distortion.

In the framework of the second topic, the possibility of correcting the distortion at the output of the A/D channel by means of the analytical inversion of the DTCM integral laws has been demonstrated [18]. However, the iterative Newton-Raphson numerical techniques which have been employed for the solution of the non-linear system of equations representing the DTCM inversion problem, although very robust in terms of convergence introduce the need for the inversion of a large Jacobian differential matrix at each iteration. This task can be easily performed, but at the cost of considering only off-line

compensation procedures. Instead, the research activity is presently devoted to the investigation on more efficient numerical techniques (*fixed-point* iteration algorithms), which are based on the assumption of an overall mild non-linearity of the system (as in the case of A/D channels), suitable for the *run-time* implementation of the DTCM-based compensation procedures. Since fixed-point techniques allow us to reformulate the non-linear system of equations in an equivalent form, and directly converge to its exact solution without requiring matrix inversions, the overall compensation procedure can be carried out by the standard controlling hardware and software available in most of commercial sampling instrumentation or, for custom acquisition systems, implemented by low-cost DSP-based auxiliary boards.

Scientific publications of the Unit

- [14] F. Filicori, G. Iuculano, D. Mirri, G. Pasini, P.A. Traverso, "A finite-memory discrete-time convolution approach for the nonlinear dynamic modelling of S/H-ADC devices," *Computer Standards & Interfaces*, vol. 25, No. 1, pp. 33-44, Mar. 2003.
- [15] F. Filicori, D. Mirri, G. Pasini, P.A. Traverso, "A Nonlinear Dynamic S/H-ADC Device Model Based on a Modified Volterra Series: Identification Procedure and Commercial CAD Tool Implementation," *IEEE Trans. on Instrumentation and Measurement*, vol. 52, No. 4, Aug. 2003, pp. 1129-1135.
- [16] F. Filicori, G. Iuculano, D. Mirri, G. Pasini, P.A. Traverso, "Experimental validation of a general-purpose non-linear dynamic model for S/H-ADC devices," in: *Proc. IMEKO TC-4 8th International Workshop on ADC Modelling and Testing*, Perugia, Italy, Sep. 2003, pp. 235-238.
- [17] F. Filicori, G. Iuculano, D. Mirri, G. Pasini, P.A. Traverso, "Non-linear dynamic system modelling based on modified Volterra series approaches," *Measurement*, vol. 33, No. 1, pp. 9-21, Jan. 2003.
- [18] F. Filicori, G. Iuculano, D. Mirri, G. Pasini, A. Raffo, P.A. Traverso, "On the use of the Discrete-Time Convolution Model for the compensation of non-idealities within digital acquisition channels," *Measurement*, Vol. 40, pp. 527-536, 2007.

D. Unit of Florence

The activity developed by the research unit of the University of Florence regards the estimation and the analysis of the measurement uncertainty in numerical data acquisition channels. In particular, a detailed study of Bayesian analysis and on the practical use of Jaynes principle of entropy maximization (MAXENT-PME). This is a method of inductive inference which is used when the knowledge at our disposal of statistical distribution of the random variables involved in the model is not enough to define an adequate output quantity.

In practical situations the measurement process represents a controlled learning process in which various aspects on uncertainty analysis are defined as the study proceeds in an up-to-date alternation between conjecture and experiment carried out via experimental design and data analysis. A measurement process is performed if information supplied by it is likely to be considerably more accurate, stable and reliable than the pool of information already available. The substantial amount of information, got with respect to the conditions prior to the result, after the measurement process is performed, is connected to the above mentioned PME. This, as it is known, is a correct method of inductive inference when no sufficient knowledge about the statistical distributions of the involved random variables is available before the measurement process is carried out except for the permitted ranges, the essential model relationships and some constraints, gained in past experience, valuable usually in terms of expectations of given functions or bounds on them.

Many practical cases proposed by the GUM and in its Supplement 1, on the propagation of the distribution using Monte Carlo methods (JCGM – Working Group 1, in the drafting of which several participants of the University of Florence research unit have taken part) have been solved.

In our opinion, two important results regarding the research have been obtained. Referring to publications below, these results can be summarized as:

- in [21], two practical cases of remarkable interest have been analyzed by using the exponential model and the usefulness and efficiency of methods bound to the entropy estimation and to the above mentioned principle with numerical results. In the first case, in particular, two problems concerning the uncertainty evaluation are solved by means of the principle of maximum entropy considering exponential distribution. In particular, the probability density distribution and the main parameters are obtained, characterizing the problem from both the statistical and scientific point of view at the same time.

- in [22], the Bayesian inference methods take into account, with the aim to describe a practical case, a multivariate non-linear measurement model, in which measurand is defined by the ratio of two quantities: at the numerator, the sum of systematic effects and experimental data, at the denominator the measurement standard. Using the Bayesian inference and the principle of maximum entropy, a problem of uncertainty evaluation in the utilization of a digital multimeter has been solved applying the results obtained theoretically. In this case too, the numerical results obtained and above all the complete measurand statistical characterization confirm the validity of the proposed approach.

Recently, the University Florence Research Unit has set itself to two following objectives:

- a contribution to a future review of the IEEE 1241 Standard for terminology and test methods for analog to digital converters. Our attention is directed towards the word error rate estimation and to the Annex A of this standard. The errors associated to the word error rate measurement are analyzed; meanwhile new statistical techniques which can better integrate the IEEE standard have been proposed. In particular, Student and chi-square distributions have been introduced for a more accurate measurement of the word error rate in the case of n successive observations [24]. The aim is to give a contribution for a new draft of the standard;
- as integration of the theoretical aspects cited above, there is a collaboration under way with National Instrument Italy, which has kindly lent us National Instruments 4070 FlexDMM 6 1/2-digit card. This card achieves remarkable throughput rates while maintaining precision and stable measurement accuracy. These DMMs also provide a fully isolated, high voltage digitizer capable of acquiring waveforms at sampling rates up to 1.8 MS/s at all voltage and current values. Using the analysis functions in NI LabVIEW software, we can analyze these waveforms in both time and frequency domains.

Scientific publications of the Unit

- [19] G. Iuculano, L. Nielsen, G. Pellegrini, A. Zanobini, "The Principle of Maximum Entropy Applied in the Evaluation of the Measurement Uncertainty" AMUEM 2006 – International Workshop on Advanced Methods for Uncertainty Estimation in Measurement Sardagna, Trento, Italy, 20-21 April 2006, pp. 14-17.
- [20] A.Falciani, G.Iuculano, A.Zanobini, "Automatic-test equipment for the characterization of aluminum electrolytic capacitors" IEEE Transactions on Instrumentation and Measurement, Volume: 55 Issue: 2, Apr. 2006 pp. 682 –688.
- [21] G. Iuculano, L. Nielsen, G. Pellegrini, A. Zanobini, "The Principle of Maximum Entropy Applied in the Evaluation of the Measurement Uncertainty". IEEE Transactions on Instrumentation and Measurement, Volume 56, Issue 3, June 2007, pp.717 - 722.
- [22] L.Ciani, G.Pellegrini, A.Zanobini, "Quantifying the Measurement Uncertainty Using Bayesian Inference" AMUEM 2007 – International Workshop on Advanced Methods for Uncertainty Estimation in Measurement Sardagna, Trento, Italy, 16-18 July 2007.
- [23] M. Catelani, L. Ciani, G. Iuculano, "Fault Diagnosis on Board for Analog to Digital Converters" IEEE IMTC proceedings, Warsaw – May 2007.
- [24] M. Catelani, L. Ciani, A. Zanobini, "Word Error Rate measurement in Analog-to-Digital Converters: some statistical considerations about IEEE Std 1241-2000 Annex A" to be published in Proc. of 16th IMEKO TC4 Symposium, Florence, Italy, September 22 - 24, 2008.

E. Unit of Palermo

The main target of the Palermo research Unit has been the uncertainty evaluation in the measurements performed by using analog-to digital converters, mostly focussing on those instruments approached as a standard personal computer with a connected data acquisition board (DAQ). With this aim, we proposed and validated two methods [25]: a theoretical method based on an original application of the uncertainties propagation law of the GUM; a numerical method which, by means of an ad hoc developed software tool, estimates the uncertainties using the Monte Carlo approach.

Starting from the acquired experience, in the last two years we have dealt with the uncertainty management, which is the discipline of optimising the uncertainty target and the cost of the measurement. Without a systematic approach to the uncertainty evaluation, the performed measurements could be either not adequate for the target uncertainty or too expensive.

To achieve the objective, we performed the uncertainty estimation by means of the PUMA (Procedure for Uncertainty Management) approach [26]. This iterative method, described in the ISO/TS 14253-2 standard [4], is completely based on the GUM rules but provides a more engineering methodology. In

fact its basic inspiration is completely different: the GUM prescribes that, in the uncertainty evaluation, it is necessary to avoid overestimations, since an overestimation debases the measurement quality; according to the PUMA approach, on the contrary, when it is necessary to know if an already available instrumentation and an already defined measurement environment are appropriate for a stated target uncertainty, the uncertainty overestimate can be tolerated, especially when an accurate uncertainty estimation involves high expenses. The method is based on a sequence of uncertainty over-estimations, starting from the coarser but quicker ones and carrying on with more accurate but more expensive and more time-consuming techniques.

In order to apply the PUMA method to the DAQ-based measurements instruments, we conceived and presented [26] four approaches for the uncertainty assessment. The approaches imply different levels of estimate accuracy, but different amounts of required resources. We applied all the proposed uncertainty estimation approaches on various DSP basic blocks that are typical of a measurement chain. The obtained results [26] have shown that the four methodologies are perfectly adequate for the implementation of the PUMA method and for a correct management of the uncertainty budget.

Another goal of our unit has been the choice, among the large number of parameters proposed by the various standards concerning the ADCs, of the optimal set of merit figures that allows a correct uncertainty evaluation of a generic measurement performed by using an ADC. For this purpose, we analyzed the uncertainties propagation on various DSP basic blocks that are typical of a measurement chain. The study has shown [27] that by using the specifications of offset, gain, total harmonic distortion (THD), total spurious distortion (TSD) and noise floor, it is possible to evaluate the combined uncertainty of whatever measures obtained by means of analog-to-digital conversion. Therefore, in our opinion, the awaited harmonization of all the standards concerning the ADCs should prescribe that at least the aforesaid five figures of merit have to be compulsory included in the data sheets provided by the ADC manufacturers.

Beside the uncertainty estimation, our unit has dealt with the impact of the electromagnetic (EM) disturbances on the DAQ-based measurement instruments. A first series of experiments has been carried out subjecting various configurations of these systems to the standardized disturbances prescribed in the “*Electrical equipment for measurement, control and laboratory use – EMC requirements*”, in order to check if and how their performances are corrupted.

By analyzing the results of the tests, we have been able to assess the immunity degree of a generic DAQ-based instrument when it is subjected to the standardized disturbances prescribed in IEC 61326, deducing that only under the disturbance levels prescribed for industrial location and mainly for not-shielded configurations, the instrument performances reveal perceptible degradations. However, from the obtained data, it is not possible to establish if, considering the real shielding and grounding conditions of the measurement chain, the actual EM environment, where the instrument will actually operate, is able to compromise its metrological characteristics. With the aim to overcome this problem, we defined a procedure [30] which, by means of a simple and fast test, allows the assessment of the actual immunity degree to the EM disturbances that are actually present in the place where the measurement is performed. The procedure has been conceived by having experimentally noticed that the disturbance effect is linearly added to the measurement signal and that, simultaneously applying various EM threats, the effects of these disturbances combine in an approximately linear way. Therefore, for whatever input signal, if it is known, it is possible to quantify the consequences produced by the actual EM conditions. It is clear that the more accurate and less expensive signal to use in order to perform the test is a 0 V DC signal. It is enough, therefore, to close the measurement chain in short circuit and, by means of a time and/or frequency analysis, it is possible to evaluate if, considering the target uncertainty, the real EM disturbances can distort the measurement results. In the cases of steady disturbances and if their effects are not within the bandwidth of interest, it is possible to implement, into the software part of the instruments, algorithms to compensate for the disturbance effects.

In order to validate the proposed approach, we performed various measurements in locations where heavy, but unknown, EM disturbances were present [30]. The performed experiments have shown that the full-shielded configurations of the instruments are practically immune to the electromagnetic interferences. Even the heaviest radiated and conducted disturbances cause a negligible impact if the good practices of shielding are observed.

However a full-shielded configuration of the whole measurement chain is quite expensive, since it is necessary to employ rather costly cables and connector boxes and the measurement shall be carried out by skilled personnel.

We have investigated the chance to use also the not-shielded configurations in a hostile electromagnetic environment, by the implementation of a procedure which allows the compensation of the disturbance

effects. The basic idea is established on a two channels acquisition technique. The measurement signal is sent to the first channel and, simultaneously, to the second channel, but with inverse polarity; the cable paths are arranged in order that the EM emissions induce the same effects on the two channels. Adding and dividing by two, via software, the data acquired by the two channels, the effect of the EM disturbances are significantly reduced. We are performing various tests to validate this technique and the first results are encouraging. Obviously, this technique implies some drawbacks: it is necessary to use two channels to acquire one signal and it is necessary to employ two anti-alias filters.

Scientific publications of the Unit

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