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TWO ALGORITHMS FOR THE AUTO-ESTIMATION OF THE UNCERTAINTY IN THE VIRTUAL INSTRUMENTATION

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Abstract – In our recent papers we have dealt with the assessment of the uncertainties associated with the virtual instrument measurements, proposing two completely different methods. The first one is based on an original application of the "uncertainty propagation law" of the ISO "Guide to the expression of uncertainty in measurement". The second one is a numerical approach, based on the Monte Carlo simulation. In this paper we show how the proposed approaches can be implemented in the virtual instruments in order to make the instrument itself able to auto-estimate the measurement uncertainties.

Keywords: Digital Signal Processing, Measurement Uncertainty, Virtual Instrument.

1. INTRODUCTION

The measurements based on virtual instruments (VI) are becoming more and more common in each sector of the measurement field. In fact these instruments, based on analog-to-digital conversion of acquired signals and their successive digital processing, offer undeniable advantages if compared with the traditional instrumentation.

However, given that these instruments are usually designed, assembled and programmed by the users themselves, the difficulties in a correct evaluation of the uncertainties have limited their spread on the industrial environment. In fact, for a correct employment in a quality management system, it is essential to characterize all the employed measurement instruments and to estimate the uncertainties associated with the measurement results [1].

A straightforward method to assess the uncertainties could be the use of a "black-box" approach, that is to subject the tested instruments to reference signals, and to check how the measurement results vary.

But this approach shows some restrictions: it is expensive, since it requires high-priced instrumentation to generate the reference signals; its validity cannot be extended to other signals different from the reference ones; it is not applicable during the design stage, given that the instrument has to be already realized; it doesn't allow a complete uncertainties analysis, since the error sources which have a systematic behaviour cannot be pointed out in a single instrument test.

Therefore it is necessary to look for an alternative way to carry out the task, trying to find out if it is possible to assess the measurement uncertainties directly starting from the characteristics of each components of a VI. Unfortunately in the standards there is no a systematic approach useful to give an answer to the question, so in the last years some Authors have dealt with this topic, proposing different solutions [2,3]. We proposed two methods as well, trying to follow, as far as possible, the procedures described in the well know ISO – "Guide to the Expression of Uncertainty in Measurement" (GUM) [4].

According to the GUM, for a correct uncertainty evaluation, a key point is the quantification of the standard uncertainties associated with each error source and the study of how these uncertainties compose in each acquired sample.

Another critical point is the analysis of the propagation of the uncertainties of each acquired sample, during the digital signal processing. In order to analyse this aspect, we proposed a theoretical method [5] based on an original application of the "uncertainties propagation law" of the GUM. But often the function describing the measurement algorithm is not an analytical and derivable function, so this procedure is not applicable. To avoid this obstacle, we proposed a software tool [6] that simulates the measurement process and the introduction of the sources of error. By means of this tool, it is possible to evaluate the combined standard uncertainties associated with the measurement results, using the Monte Carlo approach.

In those papers, the proposed methods have been utilized both during the design stage of the instruments, to examine the behaviour of the hardware and software blocks of the instruments regard to the uncertainty viewpoint, and also to characterize an already realized instrument, when it is subjected to known input signals.

In this paper we show how both methods can be applied to really acquired signals and therefore can be implemented in the software part of the virtual instruments in order to make them able to auto-estimate the measurement uncertainties associated with each measurement results.

In the following we illustrate the two methods for the estimation of the combined standard uncertainties (chapter 2). In chapter 3, in order to validate the proposed uncertainty evaluation procedures, we apply both of them to various basic DSP blocks, typical of a measurement chain, comparing the so obtained results with the ones obtained by means of experimental tests. In chapter 4, we describe how to use the proposed approaches, to implement in the real VIs, algorithms for the auto-evaluation of the measurement results. The conclusions are presented in chapter 5.

2. THE UNCERTAINTY EVALUATION

According to the GUM, the first step for a correct evaluation of the uncertainties is the identification of each error source in each hardware block of the VIs and the assessment of the related standard uncertainties.

Without any lose of generality we do not consider the errors generated by transducers and conditioning accessories. Even if these errors are often predominant compared to the errors generated in the A/D conversion, the transducers and conditioning accessories variety is so wide, that it is necessary to analyse separately each particular situation. On the contrary, it is possible to carry out a general treatment in the case of the A/D conversion process and of the digital signal processing. In any case the proposed methods can be extended to each particular transducer and/or conditioning accessory, by identifying all the error sources, evaluating the associated standard uncertainties and analysing how these uncertainties affect the uncertainty of each acquired sample.

With respect to the A/D conversion process, the main error sources are [7]: offset and its temperature drift, gain and its temperature drift, long term stability and temperature drift of the possible onboard calibration reference, integral non-linearity (INL), noise, cross-talk, settling time, timing jitter, quantization and differential non-linearity (DNL).

The quantification of the uncertainties associated with these error sources, can be carried out by means of statistical methods with a Type A evaluation according to the GUM, (but in order to estimate the uncertainties associated with all the sources we should test a statistically sufficient number of instruments of the same kind), or it is also possible to turn to manufacturers' specifications (Type B evaluation). Of course the second way is less expensive and less time consuming, since it does not require any kind of test from the user. However evaluating the standard uncertainties starting from the manufacturers' specifications is not a very effortless task, since each manufacturer furnishes the specifications in an arbitrary way, sometimes inventing some new parameter. In any case it is necessary to formulate some arbitrary hypothesis on the kind of the distributions.

After the quantification of the uncertainties associated with each error source, the next step to carry out is the study of how these uncertainties compose in each acquired sample, and the analysis of the propagation of the uncertainties of each acquired sample, during the digital signal processing.

With the aim to investigate this aspect, we proposed a theoretical method [5] based on an original application of the "uncertainties propagation law" of the GUM, which permits to overcome the hard task of the exact evaluation of the correlation coefficients. All the error sources are divided in three classes, with supposed correlation coefficients exactly equal to 0 or 1. By means of this classification, the combined standard uncertainties associated with the measurement results, can be easily calculated mixing three simplified versions of the uncertainties propagation law.

However, not always this approach can be applied, since not always the function describing the measurement algorithm is an analytical and derivable function. Moreover the uncertainty propagation law is valid only under certain conditions: linearity of the function describing the measurement algorithm and applicability of the Central Limit Theorem.

To avoid this obstacle, we proposed a software tool [6] that simulates the measurement process and the introduction of the error sources. By means of this tool, it is possible to evaluate the combined standard uncertainties associated with the measurement results, using the Monte Carlo approach.

The software tool takes into account all the uncertainty sources and simulates a set of M measurements performed on the same signal and using different instruments of the same type. An input signal simulator generates N samples as if they were obtained from an ideal sampling process of the signal. The core of the tool is a FOR loop executed M times. The N samples vector, inside the loop, is modified in order to simulate the errors generated during the A/D conversion process. The so modified N samples are sent to the software block of the instrument, which calculates the measurement result. The M measures are collected outside the loop and the standard deviation of the measurements results, that is the combined standard uncertainty, is calculated.

It is important to underscore that the Monte Carlo approach is GUM compliant, since the GUM itself prescribes (in Clause G.1.5) that "other analytical or numerical methods" can be used when the conditions for the application of the uncertainties propagation law are not satisfied.

The main advantage of the Monte Carlo simulation is that it intrinsically takes into account every possible correlation among each quantity. Another benefit is that unlike the theoretical approach, which requires a normal probability distribution function (pdf) of the measurement result, it is applicable regardless the kind of pdf. Moreover, the Monte Carlo approach supplies other statistical information, beside the means and the standard deviation: it is possible to obtain the pdf itself, and in this way it is possible to calculate the exact coverage intervals corresponding to a specified probability.

3. VALIDATION OF THE METHODS

It is obvious that we have to validate the effectiveness of the described approaches, before considering them as reliable. In fact, the theoretical method is based on a series of approximations of which we have to prove the plausibility; the numerical approach is strictly depending on how the A/D conversion process and the introduction of the errors are simulated.

Therefore, with the aim of verifying the proposed methods, we applied both of them on various DSP basic blocks, which are typical of a measurement chain, and compared the obtained results with the ones obtained from experimental tests.

For example, in the following we report the results of some tests carried out on a realized instrument.

It is constituted of a IV order lowpass filter, the National Instruments™ AT-MIO-16E10 data acquisition board (16 single-ended or 8 differential channels, successive approximation 12 bit A/D converter, 100 kS/s max sampling rate, ± 10 V maximum input signal range) and a PC with an INTEL™ 866 MHz processor; LabView™ 6.0 is the programming language used to drive the acquisition board, to process the acquired samples and to realize the user interface.

The considered test signals (generated, for the experimental tests, by the National Instruments™ PCI-MIO-16XE10 board with a 16 bit D/A converter) are:

- 9 V peak value, 2 kHz sinusoidal waveform;
- 9 V peak value, 100 Hz rectangular waveform;
- 9 V peak value, 5 Hz triangular waveform.

The implemented algorithms are:

- mean value calculation;
- RMS value calculation;
- lowpass FIR filter;
- lowpass IIR filter;
- DFT;
- THD.

The measurands are respectively the mean value, the RMS value, the peak value of the filtered signals, the amplitude of the fundamental frequency and the THD value. For all signals and all algorithms, the used sampling rate was 10 kS/s and 2000 samples were acquired.

To apply both the theoretical and the numerical method, the first steps to perform are the identification of the error sources and the evaluation of the related standard uncertainties. We carried out a type B evaluation of the uncertainties from the manufacturer specifications, assuming rectangular distributions and operating within ± 1 K of the data acquisition board self-calibration temperature, within ± 10 K of factory calibration temperature, after one year of the factory calibration and with the gain set to 0.5.

Under these operational conditions, we get the values of table I, where the error sources, the manufacturer specifications, the classes (used for the theoretical method) and the standard uncertainty values are reported.

To apply the theoretical method we have to carry out the root sum square of the uncertainties of each class [5], obtaining three values of uncertainty for each acquired sample:

$$u_I = 640\mu\text{V} \quad u_{rII} = 290 \text{ ppm} \quad u_{III} = 3555\ \mu\text{V}.$$

By applying the uncertainty propagation law for each class, we get the combined standard uncertainties u_{cI}, u_{cII} and u_{cIII}, for the three classes. At last, carrying out the root sum square of these values we get the combined standard uncertainty of the measurement result. The obtained values are reported in tables II, III and IV.

On the same instrument, on the same signals and on the same algorithms we applied the numerical method: the values of table I are inserted as inputs of the software tool, which calculates the uncertainty values (reported in tables II, III and IV) from a set of 10000 simulated measurements.

In tables II, III and IV we report also the results of the experimental tests, obtained, also in this case, from a set of 10000 measurements. The experimental obtained uncertainties are (as prescribed in the GUM) the root sum square of the uncertainty actually measured and of the uncertainties due to offset, gain, temperature drift and integral non-linearity because the last ones, having a systematic behaviour, cannot be pointed out as uncertainty in a single instrument test.

TABLE I
NATIONAL INSTRUMENTS AT-MIO-16E10 SPECIFICATIONS

Uncertainty source	Manufacturer specification	Class	Standard uncertainty
pregain offset	± 2 µV	I	1.2 µV
post gain offset	± 1000 µV	I	577 µV
pregain offset temperature coefficient	± 15 µV/°C	I	8.7 µV
postgain offset temperature coefficient	± 480 µV/°C	I	277 µV
gain	0,05 %	II	289 ppm
gain temperature coefficient	± 20 ppm/°C	II	12 ppm
temperature coefficients of the onboard calibration reference	± 5 ppm/°C	II	2.9 ppm
long term stability of the onboard calibration reference	± 15 ppm/√(1000 h)	II	25 ppm
INL	± 1 LSB	III	2819 µV
DNL	± 0.5 LSB	III	1410 µV
quantization	± 0.5 LSB	III	1410 µV
noise	0.07 LSB rms	III	342 µV
settling time for full scale step	± 0.1 LSB in 100 µs	III	282 µV
time jitter	± 5 ps	III	140 µV
cross talk	- 80 dB	III	707 µV

TABLE II
COMBINED STANDARD UNCERTAINTIES FOR THE SINUSOIDAL WAVEFORM

Algorithm	Expected value	Theoretical uncertainty	Numerical uncertainty	Experimental uncertainty
Mean	0.000 V	645 µV	647 µV	512 µV
RMS	6.364 V	1847 µV	1859 µV	1532 µV
FIR filter	6.143 V	2895 µV	3001 µV	2365 µV
IIR filter	5.811 V	2088 µV	2096 µV	1688 µV
DFT	9.000 V	2611 µV	2620 µV	2043 µV
THD %	0.000	$1374 \cdot 10^{-6}$	$1394 \cdot 10^{-6}$	$1012 \cdot 10^{-6}$

TABLE III
COMBINED STANDARD UNCERTAINTIES FOR THE RECTANGULAR WAVEFORM

Algorithm	Expected value	Theoretical uncertainty	Numerical uncertainty	Experimental uncertainty
Mean	0.000 V	645 µV	646 µV	501 µV
RMS	6.364 V	2611 µV	2644 µV	2144 µV
FIR filter	6.143 V	3388 µV	3407 µV	3011 µV
IIR filter	5.811 V	3172 µV	3199 µV	2899 µV
DFT	9.000 V	3324 µV	3339 µV	2947 µV
THD %	0.000	$1876 \cdot 10^{-6}$	$1884 \cdot 10^{-6}$	$1617 \cdot 10^{-6}$

TABLE IV
COMBINED STANDARD UNCERTAINTIES FOR THE TRIANGULAR WAVEFORM

Algorithm	Expected value	Theoretical uncertainty	Numerical uncertainty	Experimental uncertainty
Mean	0.000 V	645 µV	647 µV	494 µV
RMS	5.198 V	1510 µV	1522 µV	1177 µV
FIR filter	7.047 V	2416 µV	2444 µV	1966 µV
IIR filter	6.883 V	2071 µV	2079 µV	1671 µV
DFT	7.298 V	2118 µV	2121 µV	1876 µV
THD %	12.107	$2629 \cdot 10^{-6}$	$2642 \cdot 10^{-6}$	$2128 \cdot 10^{-6}$

The uncertainty values obtained by applying the numerical method are slightly but systematically greater of the ones obtained by using the theoretical approach. However the differences were always lower that 1%, therefore practically the two methods led to the same results.

The other significant conclusion is that the experimental results are lower than the ones obtained by using the proposed techniques, also without considering the uncertainties introduced in the signal generation process and in anti-alias filtering.

The difference between these results is an index of how much the error sources of the particular utilised data acquisition board are far from the limits declared in the specifications. In other words, the greater is this difference the more lucky we were buying that particular board.

We carried out other experimental tests using other hardware configurations, other algorithms and other signals. In all cases we get the same kind of results. Therefore, these results validate the considered approaches and the values of the various uncertainty sources of the utilized data acquisition board, declared in the manufacturer specifications.

4. UNCERTAINTIES AUTO-EVALUATION

Until now we applied the proposed approaches just to simulated signals. So the methods can be used in the phase of the instrument design, to set up the hardware and software blocks, or for the characterization of already realized instruments, when they are subjected to known input signals.

But, it's obvious that the uncertainties are strictly depending on the shape of the signals that, however, are not a priori known. We could apply the methods to the acquired signal, but this one is different from the original signal, since already corrupted by the A/D conversion process.

But, as prescribed by the Guide, the uncertainties have to be calculated starting from the measured values, not from the true values, that, anyway, are not known. This is true just if the errors are small enough with respect to the amplitude of the signals. It is possible to demonstrate it by means of a mathematical analysis, but it will be easier to show the results obtained applying the method to digitally simulated signals and to really acquired signals.

For instance, in tables V, VI and VII, applying the Monte Carlo method and using the same signals and the same measurement algorithms of chapter III, we report the actually measured values, the uncertainty values calculated from the digitally simulated signals (already reported in tables II, III and IV of chapter III) and the uncertainty values calculated from the really acquired signals.

TABLE V
COMBINED STANDARD UNCERTAINTIES FOR THE SINUSOIDAL WAVEFORM

Algorithm	Measured value	Uncertainties with digitally simulated signals	Uncertainties with really acquired signals
Mean	-0.001 V	647 µV	642 µV
RMS	6.362 V	1859 µV	1864 µV
FIR filter	6.146 V	3001 µV	3007 µV
IIR filter	5.809 V	2096 µV	2101 µV
DFT	8.998 V	2620 µV	2627 µV
THD %	0.001	$1394 \cdot 10^{-6}$	$1387 \cdot 10^{-6}$

TABLE VI
COMBINED STANDARD UNCERTAINTIES FOR THE RECTANGULAR WAVEFORM

Algorithm	Measured value	Uncertainties with digitally simulated signals	Uncertainties with really acquired signals
Mean	0.000 V	646 µV	652 µV
RMS	9.003 V	2644 µV	2639 µV
FIR filter	11.120 V	3407 µV	3421 µV
IIR filter	10.775 V	3199 µV	3192 µV
DFT	11.460 V	3339 µV	3339 µV
THD %	45.689	$1884 \cdot 10^{-6}$	$1876 \cdot 10^{-6}$

TABLE VII
COMBINED STANDARD UNCERTAINTIES FOR THE TRIANGULAR WAVEFORM

Algorithm	Measured value	Uncertainties with digitally simulated signals	Uncertainties with really acquired signals
Mean	0.000 V	647 µV	641 µV
RMS	5.200 V	1522 µV	1522 µV
FIR filter	7.044 V	2444 µV	2429 µV
IIR filter	6.884V	2079 µV	2068 µV
DFT	7.298 V	2121 µV	2131 µV
THD %	12.109	$2642 \cdot 10^{-6}$	$2648 \cdot 10^{-6}$

The uncertainties values are practically coincident, whereas the measured values are slightly different from the expected values, but in a consistent way with the related uncertainty values. Applying the theoretical method we get the same results and the same conclusions.

These results show that the proposed approaches can be used for the auto-evaluation of the uncertainties, in compliance with the GUM rules.

As for the theoretical method, it is enough to include in the software block of the VI, the algorithms implementing the proposed simplified version of the uncertainty propagation law. Inserting the standard uncertainties of each error source, as input data, and classifying each source in one of the proposed classes, the instrument itself becomes able to evaluate the uncertainties for the actual signal that is analysing.

Of course, in this case a greater calculus power is required to the digital signal processor. This could become a problem for the "real time" applications, if the processing time is a critical point. In all analysed cases, the time required for the uncertainty evaluation is greater than the time required for the measurement estimate.

When the theoretical method is not applicable, it is possible to turn to the numerical approach. However, the implementation of the software tool for the uncertainties auto-evaluation, requires a much greater calculus power, since for each performed measurement, the instrument has to perform a series of simulation on each acquired signals.

In case the time requirements should be preponderant, in order to reduce the uncertainties computation time, it is always possible to turn to more sophisticated statistical techniques, such as the variance reduction procedures.

As underlined in chapter 1, the proposed methods can be extended to the errors generated by transducers and signal conditioning accessories. As for the theoretical method, after the identification of the error sources, which arise during the quantities transduction and the signals conditioning, and after the evaluation of the related standard uncertainties, it will be enough to divide those sources in the three proposed classes.

As for the numerical method, the software tool has to be modified in order to simulate, beside the data acquisition, the whole measurement process. Our next target is developing other software tools for the simulation of the behaviour of the most used transducers and signal conditioning accessories, as current and voltage transformers, filters and thermocouples.

5. CONCLUSION

In this paper we proposed two different methods for the uncertainty estimation of the VI measurements. The first one is based on an original application of the "uncertainty propagation law" of the ISO "Guide to the expression of uncertainty in measurement". The second one is a numerical approach, based on the Monte Carlo simulation.

Both of them can be implemented in the virtual instruments in order to make the instrument itself able to auto-estimate the measurement uncertainties.

The theoretical method shows many advantages: it is applicable even if the software block of the instrument is not already realized; there is no need to develop or to buy other software; it does not require a great calculus power. Unfortunately the method is not always applicable given that not always, the conditions for the application of the uncertainties propagation law are satisfied.

On the contrary the Monte Carlo approach is always applicable, but it requires a very great calculus power, which limits its usability.

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