

TRACEABILITY ISSUES IN DISTRIBUTED MEASURING SYSTEMS

Alessio Carullo, Franco Ferraris, Marco Parvis

Dipartimento di Elettronica – Politecnico di Torino, corso Duca degli Abruzzi, 24 – 10129 Torino, Italy
e-mail: carullo/ferraris/parvis@polito.it

Abstract: This paper deals with the traceability-assurance problems that are faced when a distributed measuring system is employed. These problems are highlighted for different distributed-system architecture, then a set of guidelines is provided in order to correctly manage such systems from a metrological point of view. The proposed solution is based on a network-assisted calibration procedure, which requires suitable travelling standards that are sent to the nodes of a distributed system under calibration and are remotely controlled through the Internet. Two prototypes of travelling standard are also described that have been designed in order to implement the proposed calibration procedure. The first prototype can be used for the calibration of system, which require tight temporal coherence, while the second one is able to calibrate measuring nodes that monitor the chemical pollution.

Keywords: Measurement, quality assurance, large-scale systems.

1. INTRODUCTION

In the last decades, measuring-system architectures have been deeply changing, due to the availability of digital instruments and telecommunication networks. In the past, an important milestone in the measurement field was the development of communication buses devoted to the instrumentation, such as the IEEE-488, which gave the possibility to arrange automatic test-bench, in which different digital instruments share a communication bus and are controlled through a Personal Computer (PC). Nowadays, the instrument-communication bus can be extended in order to cover very large areas, thanks to the availability of both wired and wireless networks. Different automatic test-benches, as well as smart transducers [1] and instruments that embed a network card, can be interconnected through this extended bus, thus arranging a distributed measuring system, which can either be based on a centralized or a grid architecture. The former refers to a system that is managed by means of a central PC, which remotely configures the different sub-systems, acquires from them the corresponding measurements and, after some form of processing, makes the final results available to the users. In the latter architecture, each measuring node has management capabilities and co-operates with the other nodes on a peer-to-peer basis.

This evolution has enormously increased the usefulness of measuring systems: thanks to the capillarity of the Internet, a distributed measuring system allows the measurement of several quantities distributed over a large area to be obtained at a reasonable cost. Typical applications are the monitoring of the environmental pollution and of the power quality. On the other hand, the traceability assurance is a very difficult task, because the obtained measurements are the combination of hardware and software processes that take place over a wide-distributed environment. Other problems arise due to the data exchange over the network, such as net latency and lack of synchronization among units [2-3]. These issues are tackled in the next sections, by providing a set of guidelines that allows a distributed measuring system to be correctly managed from a metrological point of view.

2. TRACEABILITY IN A DISTRIBUTED MEASURING SYSTEM

Traceability, which is a fundamental aspect of any measurement that has to be compared with other measurements or with acceptance limits, is defined as [4] *the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties.*

The traceability assurance, which for a stand-alone instrument is obtained by periodically calibrating the instrument against devices that are directly or indirectly related to the primary standards, becomes a difficult task for automatic test-benches, and a tricky problems for distributed measuring systems. Both these kind of systems provide results that typically depend on:

- the measurements that different instruments carry out;
- the software processes such measurements are subjected to.

In addition, distributed measuring systems present further traceability-related problems, since instruments are usually spread over a large area and their number could be very high. This situation makes the common calibration approach unsustainable, since it is required that instruments are moved to a laboratory, with high cost for calibration and transportation. Furthermore, during the calibration, the

different nodes are unavailable, thus making the distributed measuring system not completely operative. Other problems arise from the verification of software programs that are involved in the measuring process, since the software process could be either split between the central and the peripheral PCs or, in the case of a grid architecture, distributed over the different nodes. For this reason, it is more convenient to verify the whole “software chain” than verify each program independently from each others: a good solution seems to be a whole calibration procedure, which allows both hardware and software sections of the system to be verified.

Other problems could make the traceability assurance a difficult task, which depend on the performed measuring task as described below.

2.1. Measuring tasks performed by a distributed measuring system

The simplest task a distributed measuring system can perform consists in collecting the results that each node provides. In this case, the central PC acquires the measurement results from each node and makes them available to the users: each node performs independent measurements. An example is a system that monitors the environmental pollution over a geographical area, whose main goal consists in comparing the results of each node with alarm thresholds. The traceability assurance does not present particular problems, since each node can be calibrated independently of the others.

The situation becomes more difficult if the central PC provides results that are obtained by processing the measurements the different nodes provide: the central PC is no longer a data collector, but is a part of the measuring chain. A typical application consists in monitoring the power quality. In this case, each node processes the acquired data and estimates electrical quantities, such as power and energy, and quality indices; such quantities are sent to the central PC, where the harmonic power flow is estimated and harmonic sources are localized [5-6]. Such estimation often requires a strict synchronization among the different nodes, which is usually obtained by employing the Global Positioning System (GPS) [5,7]. The traceability assurance is definitely a not trivial operation: the distributed measuring system has to be considered as a large instrument, whose inputs are located at the different nodes, while the outputs are available at the central PC. Such an instrument has to be calibrated by contemporaneously stimulate the different nodes with synchronized signals, in order to evaluate the robustness of the whole system with respect to lack-of-synchronization.

The most difficult situation is encountered when each node of a distributed system performs a measuring task by processing local measurement and data obtained by other nodes, according to the grid paradigm. In this case, the presence of a central PC is not mandatory, even though it can be present for managing or storing purposes. The system is therefore made up of interconnected nodes with networking and processing capabilities. A possible application is the localization of harmonic sources in the mains, which each node can perform by processing the own

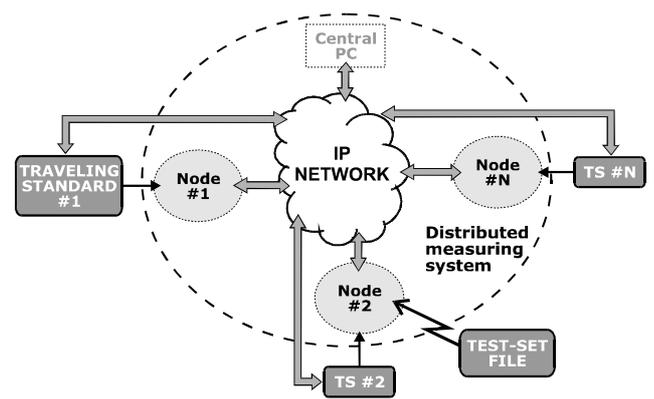


Fig. 1. Remotely-controlled calibration technique for a distributed measuring system.

results and those of the adjacent nodes. Such a grid architecture makes the traceability assurance a very complicate problem, since the system is a multi-inputs multi-outputs distributed instrument, whose calibration requires to verify each node while stimulating the other nodes with known inputs.

In the next section, a remotely-controlled calibration technique is proposed with the aim to tackle the mentioned problems.

3. REMOTELY-CONTROLLED CALIBRATION TECHNIQUE

The proposed technique requires the availability of remotely-controlled travelling standards, which can be commercially-available equipment, such as multifunction calibrators and signal generators, or specifically-designed devices [8]. The travelling standards, which have to be equipped with a network interface, are sent to the different nodes and are remotely controlled through the Internet.

If the distributed system implements the second kind of measuring task, the calibration can be remotely exercised by the central PC, which manages the travelling standards, in order to apply known stimuli at the node inputs, configures the involved nodes and acquires the corresponding measurements, as shown in the figure 1. The obtained results are compared with the expected ones in order to state the “conformity” or “non-conformity” of the whole system. If the system performs measuring tasks that require synchronization among the different nodes, synchronized stimuli have to be employed during the calibration phase.

The calibration of a distributed system that performs the third kind of measuring task, i.e. those based on a grid architecture, can be viewed as the set of calibrations of the different nodes. The remotely controlled technique allows a set of travelling standards to be employed in order to stimulate different nodes, one of which is the node under calibration. Since a central PC that manages the calibration procedure is not always present in such systems, it seems convenient to configure the employed travelling standards as a grid architecture: the calibration of a grid system is therefore performed by means of a grid of standards, as shown in the figure 2. This means that each standard has to be able to communicate with the other standards and to

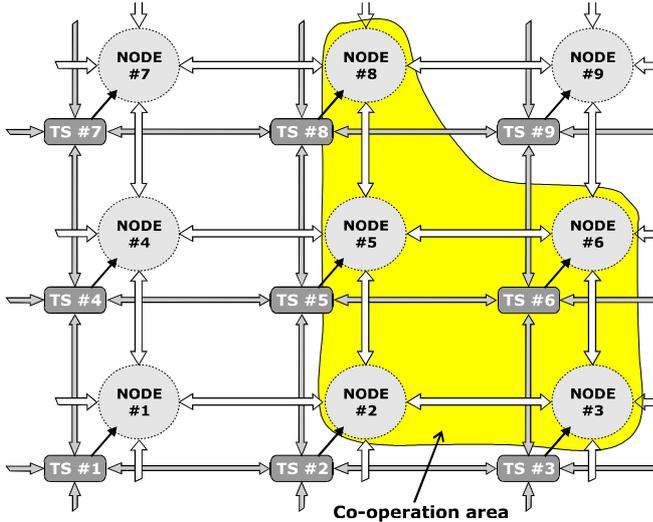


Fig. 2. Remotely-controlled calibration technique for a distributed measuring system based on a grid architecture.

manage the calibration procedure: one of the standards will be configured as the calibration manager, whose main tasks consist in controlling the other standards and processing the calibration results.

The number of nodes of a grid measuring system can be very high, thus requiring a great number of travelling standards. However, from a measurement point of view, only the adjacent nodes typically affect the results a node provides. For this reason, it is convenient to define a co-operation area, which includes all the nodes that mutually affect each others. In the figure 2, as an example, is highlighted the co-operation area for the nodes 2, 3, 5, 6 and 8. The calibration of a node of such a co-operation area therefore requires five travelling standards.

3.1. Calibration test-set

A measuring system is usually calibrated in a group of test points, which is hereafter referred to as test-set. The test-set has to be suitably chosen in order to be representative of the operative conditions of the system, thus making effective the calibration. Such a choice involves several aspects, such as range and nature of the measured quantities, operating principle and configuration of the instruments, and, in the case of a distributed system, the system architecture and the operative conditions at the different nodes. Another important aspect to be considered is the possible multi-input nature of the processing algorithms that are implemented at each node and at the central PC: this situation could lead to a test-set with a very high size, thus making unsustainable the proposed procedure.

For this reason, a modified version of the proposed technique is proposed, which is performed in two subsequent steps. During the first step, complex algorithms are validated, by feeding the nodes where such algorithms are implemented with a great amount of data, by employing a test-set file (see figure 1). The corresponding results are processed at the central PC or at the PC configured as the calibration manager of a grid measuring system. Such step

therefore validates the software section of the system that follows the measuring devices.

During the second step, the inputs of the distributed system are stimulated by means of the travelling standards, which provide a reduced test-set. In this situation, the measurements acquired at the central PC allow the verification of the measuring devices to be performed, since the results the central PC receives follow a path that includes the already validated software section.

4. TRAVELLING-STANDARD PROTOTYPES

In this section, two prototypes of travelling standards are briefly described that have been conceived to implement the proposed remotely-controlled calibration technique.

4.1. GPS-synchronised travelling standard

A travelling standard has been developed by the authors and is now under characterisation that is suitable for the calibration of measuring systems used for the monitoring of the mains power quality in a three-phase system. The calibration of such systems requires one to stimulate the different nodes of the measuring system by employing synchronised signals, therefore the developed travelling standard is designed be synchronised with the other standards employed in the calibration. Fig. 3 shows a block scheme of the proposed device, whose main parts are an embedded Single Board Computer (SBC), a GPS module, and two boards that provide the stimuli to be applied to the measuring node.

The SBC (model EX9529) embeds a LAN 100/10M interface, which provides networking capabilities, and a low-power 300 MHz CPU, which gives the full potentiality of a personal computer: this makes the standard suitable for the calibration of a distributed measuring system based on a central PC, as well as for the calibration of a system based on a grid architecture, since it can be configured as the calibration manager. The SBC is equipped with a 32 MByte Disk-On-Chip and is operated in a Linux environment.

The GPS module (Tyco Electronics model A1029) offers the synchronization capability and is connected to the SBC through an RS-232C serial port. The received GPS-sentences are processed by the SBC in order to extract the Universal Time Coordinated (UTC), which is employed to synchronise different travelling standards by starting the signal generation at a defined time. However, the large time skew due to the transmission delay of the serial port would not allow a good synchronisation to be obtained. For this reason, the signal generation is started simultaneously with the edge of the 1 Pulse Per Second (1 PPS) signal provided by the GPS module: the 1 PPS and the UTC information allows different travelling standards to be synchronized within less than 1 μ s.

A micro-controller (μ C) based board and an analogue board implement an arbitrary-signal generator. The μ C-based board interacts with the SBC through a PC/104 bus (see Fig. 3) and embeds two micro-controllers (Microchip PIC-16F877) and a RAM. The first micro-controller implements a Direct Digital Synthesis (DDS) technique, thus providing a local clock at the frequency f_{ck} that is locked to the GPS clock. The micro-controller

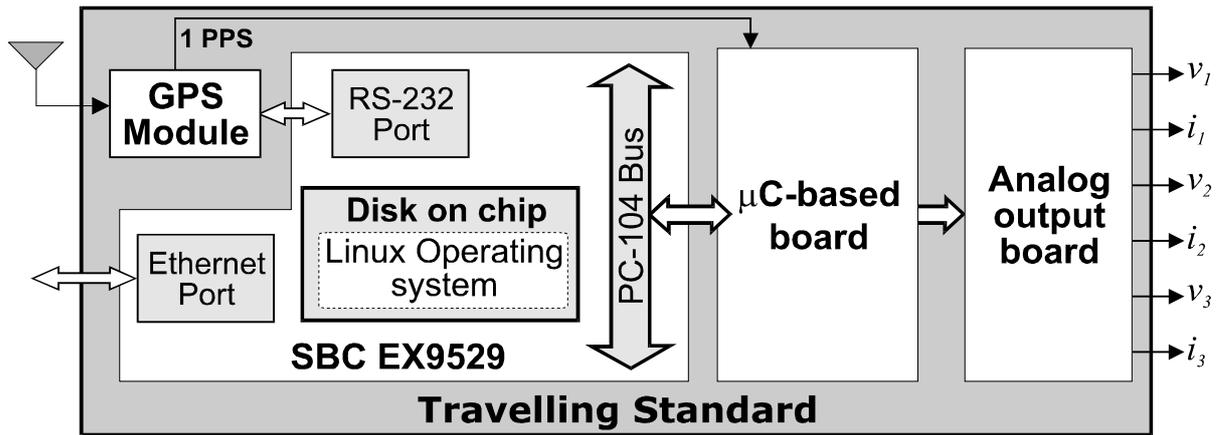


Fig. 3. Basic architecture of the GPS-synchronised travelling standard.

measures the frequency of the local clock by means of its internal counter, which employs the 1 PPS impulse as the gate signal: the control word of the DDS generator is therefore adjusted in order to obtain f_{ck} periods per second.

The samples of the signals that have to be generated, which are computed by means of a specific program that runs on the SBC, are written into the RAM through the second micro-controller, which manages the communication with the SBC through the PC/104 bus. During the generation phase, such a micro-controller suitably addresses the RAM in order to provide the signal samples to the analogue output board. Such a board has been designed to provide six independent channels: three of these channels provide voltage signals, while the other ones provide current signals. Each channel employs low-offset and low-drift components and is based on a 16-bit Digital-to-Analogue Converter (Maxim model MAX542A) and an external voltage reference (Maxim model MAX6325). The DACs are serially fed by the samples that are stored into the RAM. The voltage channels are made up of two operational amplifiers (Analog Devices model OP177), which filter and amplify the DAC output, and an output stage that provide voltage signals in the range of -400 V to $+400\text{ V}$. The current channels employ the same operational amplifier as a filter and a high-current operational amplifier in order to provide current signals in the range of -10 A to $+10\text{ A}$.

The prototype is able to provide voltage and current signals with arbitrary waveforms, fundamental frequency of 50 Hz and harmonic components up to 2.5 kHz , i.e. up to the 50^{th} harmonic.

A preliminary characterisation of the developed prototype can be found in [9], where the synchronisation capability has been experimentally estimated in terms of time skew of the signals generated by means of two different travelling standards. Different measurement series acquired in 3D-fix condition for the GPS-modules have shown a maximum deviation of the time skew of about 200 ns , thus confirming the possibility to synchronise different travelling standards within $1\text{ }\mu\text{s}$.

4.2. Gas calibrator

Another travelling standard has been designed that is able to generate known concentrations of gas, thus allowing the calibration of distributed measuring systems that monitor the chemical pollution to be performed. The block scheme of the prototype is shown in Fig. 4, where three main blocks are highlighted: a control unit, a gas cylinder, and a calibration cell.

The calibration cell, which is made up of a cylindrical central body and two removable circular stoppers, is the chamber where known gas concentrations are generated. One stopper, which is referred as the reference head, is equipped with standard sensors of gas concentration, whose measurements represent the reference values for the sensors under calibration. The other stopper, which is referred to as the test head, embeds the sensors under calibration.

The control unit is based on the same single board computer employed for the GPS-synchronised calibrator that offers networking and processing capabilities. The reference measurements of gas concentration are estimated from the standard-sensor output signals, which are conditioned and acquired by means of a micro-controller board and then transferred to the single board computer.

A gas cylinder is connected to the calibration cell through an electromechanical valve, which is controlled by the control unit: this way approximately known volumes of gas mixture can be inserted into the cell, so that different concentrations can be generated. The reference values of the generated concentrations are provided by means of the gas standard-sensors.

In the prototype the authors have developed, the reference head embeds two thick-film metal-oxide semiconductor devices (Figaro models TGS2106 e TGS2442), which measure the concentration of carbon monoxide (CO) and nitrogen dioxide (NO_2). The basic principle of these devices is the resistance change due to the concentration change of the target gas that is chemically adsorbed and desorbed on the sensor surface. The resistance outputs of the two sensors also depend on temperature and relative humidity, therefore the reference head also embeds a temperature sensor (National Semiconductor model

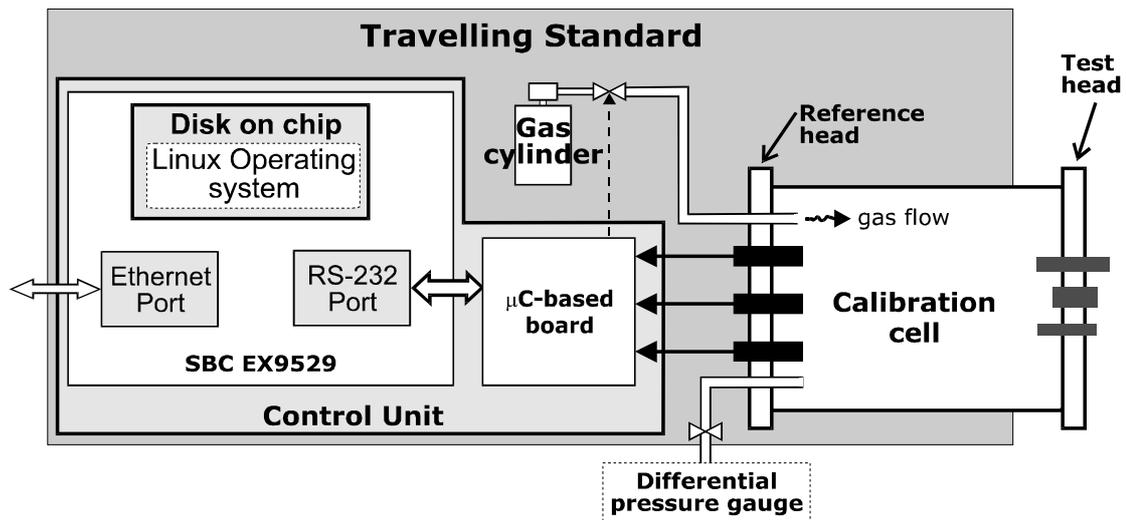


Fig. 4. Block scheme of the gas calibrator.

LM35) and a relative humidity sensor (Humirel model HM1500), thus allowing the effects of these quantities on the gas sensors to be compensated. The reference head is also equipped with two gas quick connectors: one connector is employed to insert the gas mixture into the cell, while the other one allows a pressure gauge to be connected during the calibration of the standard sensors, as explained later. Fig. 5 shows the prototype of calibration cell, which has been made in plexiglass.

The micro-controller board is an application-specific measuring system, which is connected to the SBC through an RS-232C port and performs both the measurements of gas concentration inside the calibration cell and the control of the gas flow. These functions are achieved by means of a micro-controller (Microchip model C18F2620) and its embedded devices. Fig. 6 shows a photograph of the micro-controller board that includes a few voltage regulators, which are necessary to provide the power for heating the gas sensors. The CO sensor requires also specific heating pulses and measurement sequences, which are obtained thanks to the micro-controller timers. The output of all the sensors are first amplified and then acquired by the analogue-to-digital converter of the micro-controller.

The metrological characteristics of the employed gas sensors, such as output sensitivity with respect to the gas concentration and effects of the influence quantities, are stated by the manufacturer as large intervals, thus highlighting a poor reproducibility among different devices. As an example, the resistance output of the NO₂ sensor in clean air is stated as the range (5±50) kΩ. For this reason, a preliminary calibration of such devices is mandatory, which is performed without removing them from the reference head. The calibration cell is sealed by means of a stopper and a gas mixture with known concentration is inserted into the cell: since the gas mixture is inserted into a system at a constant volume, it is possible to express the generated gas concentration as a function of the gas pressure inside the cell, which is measured by means of a differential pressure gauge connected to the second gas quick connector. The details of such a procedure, as well as the estimation of the calibration uncertainty, can be found in [10].

Preliminary experimental results are available that refer to the calibration of the NO₂ sensor of the reference head. In the measuring range of 0 ppm to 7 ppm of NO₂ concentration, a sensitivity of 4.3 kΩ (ppm)⁻¹ has been estimated for the sensor output-resistance. Also the effects of temperature and humidity have been estimated in the ranges (10±30) °C and (20±70) %RH respectively, obtaining a sensitivity of -0.1 kΩ (°C)⁻¹ with respect to the temperature and a sensitivity of -0.15 kΩ (%RH)⁻¹ with respect to the relative humidity. Such results show that the gas concentration can be estimated with a standard uncertainty of 0.1 ppm provided that the sensor resistance is measured with a standard uncertainty of 0.1 kΩ and temperature and humidity are estimated with standard uncertainties of 1 °C and 2 %RH respectively. Unfortunately, the main uncertainty contribution is related to the sensor repeatability, that gives a contribution of about 0.3 ppm. For this reason, the authors are testing other sensors, with the aim to obtain better repeatability, as well as better reproducibility.

5. CONCLUSIONS

The increasing diffusion of distributed measuring systems has made more difficult the traceability assurance. Besides the problem that is faced in the estimation of network-related effects on the measurement uncertainty, the calibration of such systems could become a tedious and very expensive activity if performed in the common way. For this reason, an innovative approach has been proposed in this paper for the calibration of a distributed measuring system, with the aim to make such an activity both economically and technically sustainable.

The main advantages the proposed procedure offers are:

- possibility to calibrate multi-inputs multi-outputs distributed measuring systems;
- minimization of the out-of-service time of a distributed system;
- low management cost, since its implementation does not require the presence of skilled technicians at the different nodes;



Fig. 4. A photograph of the calibration cell.

- possibility to store the calibration results in a centralized database and automatically process them in order to dynamically manage the calibration interval of the whole system, thanks to the available history.

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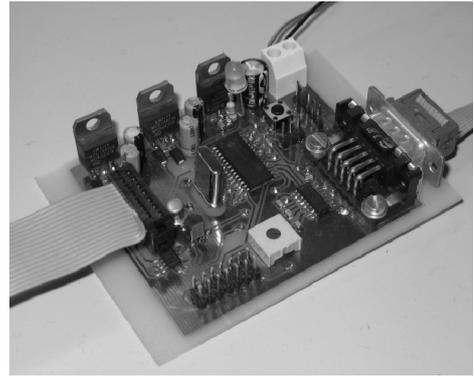


Fig. 5. The micro-controller board of the gas calibrator.

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