

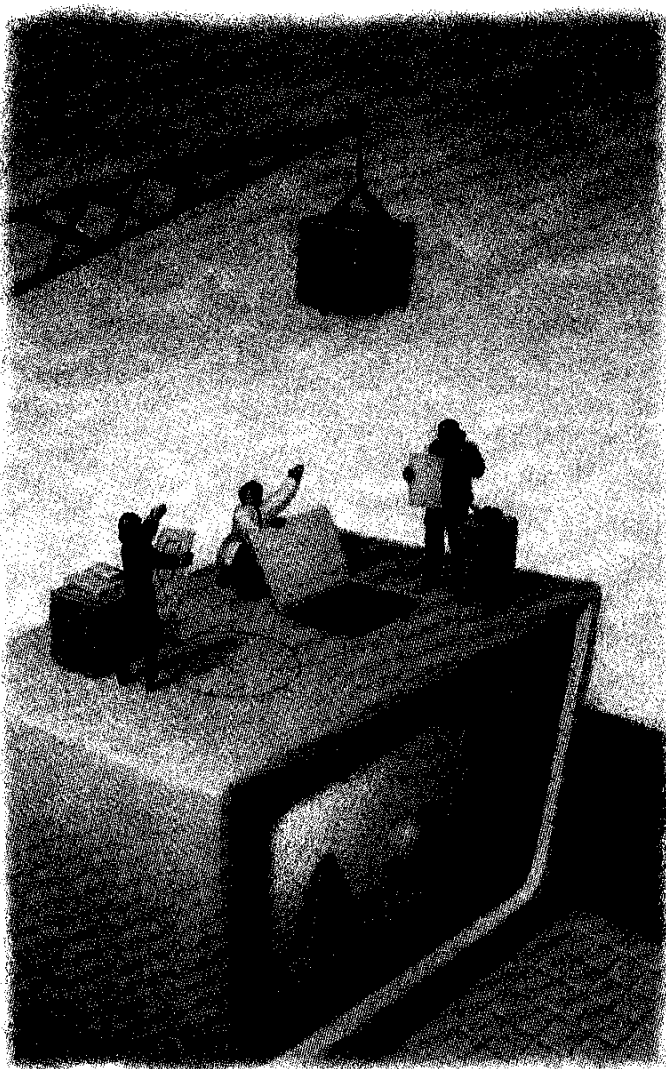
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Programmable Instruments, Virtual Instruments, and Distributed Measurement Systems:

What Is Really Useful, Innovative and Technically Sound?

The development and use of programmable measurement systems have been widely explored both in the academy and industry, with interesting and effective results (e.g., [1], [2]). The availability of advanced computing architectures with high performances at reasonably low cost (e.g., a personal computer with acquisition and DSP boards) to implement the measurement algorithms on a programmable architecture makes this approach attractive and cost effective in many application areas. In particular, the possibility of modifying the measurement procedure simply by changing the algorithm executed by the computer-based architecture without replacing the hardware components makes the experimental activity easier, especially when the measurement procedure is not completely assessed. Besides, reusability, flexibility, and generality of the programmable measurement components reduce acquisition and operating costs.

Virtual measurement systems have been introduced to simplify the design, implementation, and use of programmable measurement systems by adopting a visual interface (e.g., [1], [3], [4]). Visual programming allows for a straightforward implementation of the measuring algorithm, even to people who are not expert in computer programming. The algorithm is, in fact, created by graphically selecting and interconnecting the functional blocks available in the system-development library, similar to the ladder diagrams well known to people working in industrial control. Graphical interfaces resembling the real instruments



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make the use and comprehension of the virtual instruments more immediate for individuals accustomed to working with conventional instrumentation.

Networking has also been introduced successfully in measurement to interconnect different instruments and data processing sites into a distributed measuring system (e.g., [1], [5]-[7]). Multi-computer processing systems are effective in creating complex measurement systems by overcoming the limitations of a single computer concerned with the overall computing power or the number of signals to be acquired and processed. Locally distributed processing systems based on local area networks can be adopted to deal with monitoring and control applications in large machinery and plants. This is particularly attractive when many signals must be processed or the acquisition points are too far for a cost-effective EMI-free interconnection between the processing system and the remote sensors. Geographically distributed processing systems interconnected by wide area networks are suited to implement measurement applications over long distances through telemetry and distributed processing.

All the above technologies can be considered technically sound and effective only if their characteristics and limitations are well understood from the theoretical point of view as well as in practice. Unfortunately, many problems and misunderstandings still occur both in academia and industry. Complexity, novelty, and rapid evolution of these technologies often make it difficult to stay really up-to-date with sufficiently wide and in-depth knowledge, as well as practical experience. In addition, the apparent simplicity of these techniques often makes one assume that they are quick and easy to comprehend and apply. Finally, many researchers and practitioners who adopt these solutions are not really experienced in measuring problems and issues because they come from other technological, scientific, and industrial areas. Thus, they are misled by the techniques' apparent simplicity.

Moreover, industry and laboratories need automated measurement systems with high flexibility, adaptability, and programmability to automate the measurement procedures in complex and distributed applications. In this kind of application, quality issues cannot be neglected! They often become mandatory, according to industrial operating procedures and standards, especially when industry and laboratories have certified operating quality (e.g., ISO 9000 for production processes, services, and products). Quality means that the metrological characteristics of accuracy, precision, and sensitivity must be ensured, as well as the quality of the measurement processes [4].

This article is, therefore, directed to discuss the fundamental characteristics of measurement systems based on digital processing, with specific focus on virtual instruments and distributed measurement systems. Its goal is to point out the characteristics and the features related to the above-mentioned issues, so as to achieve a better

understanding of the effective usability of these technologies, avoid problems due to their superficial application, and promote the best use of these advanced, powerful methods. Finally, we will consider the problem of the traceability of the measurement results coming from the instrumentation based on digital signal processing.

DSP-Based Instruments

The introduction of DSP techniques in modern instrumentation represents a fundamental step in the development of the measurement science, since it led to a significant growth and improvement of the instruments' performance.

The block diagram of a typical DSP-based instrument is shown in Fig. 1. It is the basic structure of this kind of instrument. Four fundamental blocks can be identified:

- » The Analog-Signal Conditioning Unit: this block adapts the input signal dynamic to that of the subsequent A/D conversion unit and removes possible aliasing effects by low-pass filtering the input signal.
- » The A/D Conversion Unit: this block converts the input signals into a digital representation, with the resolution and sampling rate required by the correct execution of the measurement algorithm.
- » Storage Memory.
- » The DSP Unit: this block performs the measurement algorithm by the specified time slot.

With this architecture, any measurement process can be viewed as one that extracts the desired information from the input signals by means of possibly complex DSP techniques.

This approach changes the traditional measurement philosophy, which associates a single, dedicated measurement device to each measurement process. In DSP-based measurement systems, a measurement process is associated with a dedicated algorithm that is implemented on the same general-purpose computing system of Fig. 1. By changing the algorithm, the same computing system performs new measuring processes.

The main features of DSP-based instruments are:

- » The capability of combining information coming from many different field transducers as well as data fusion.
- » The capability of implementing complex measurement algorithms.
- » The capability of working under strict environmental conditions and correcting the measurement results according to the actual working conditions.
- » The capability of networking.
- » The capability of self-calibration and self-monitoring in order to guarantee that the system is operating in the op-

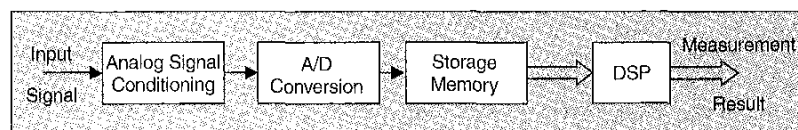


Fig. 1. The block diagram of a DSP-based measurement system.

timal condition to obtain the desired measurement uncertainty and characteristics.

These features make the DSP-based measurement systems quite attractive not only for research, but also for many industrial applications. For example, due to their high integration capability, DSP-based measurement systems are highly suitable for automatic test equipment. The capability of implementing different functions on the same hardware architecture and the ability of post-processing the measurement results allow self-estimation of uncertainty, under real operating conditions. This is important to certify the operating quality in manufacturing systems.

The availability of low-cost ADCs and personal computers led to a wide, cost-effective diffusion of DSP-based instruments in industrial applications and embedded systems for monitoring and control.

The core metrological characteristics of the DSP-based measurement systems are determined by the characteristics of both the A/D conversion unit (as far as accuracy, resolution and sampling rate are concerned) and the DSP unit (as far as the overall bandwidth and accuracy are concerned).

The measurement algorithm also plays a fundamental role in designing DSP-based instruments. Its development requires a deep knowledge of the digital-signal-processing theory applied to measurement [2] to avoid the typical measurement errors due to aliasing and leakage. On the other hand, the algorithm implementation requires a good knowledge of software-development techniques. This makes the specification, design, and implementation of high-quality DSP-based measurement systems very difficult. In fact, people involved in the measurement field have the theoretical knowledge about the measurement science, but unfortunately, often have limited skills in software techniques. Conversely, people involved in software development often have rather poor skills in DSP-based measurement techniques. In the past, this fact confined the development of DSP-based measurement systems only to scientific laboratories.

In addition, the man-machine interface of the very first DSP-based instruments was based on a keyboard-screen interface with string-based commands. This was totally different from the knobs, buttons, needles, and scope display-based interfaces that people working in the measurement field were accustomed to. As a consequence, this often creates problems for inexperienced users because they have to learn interaction and operation techniques as well as constraints (often computer-oriented) that are different from the ones to which they are accustomed. Training costs and time for system operating personnel, therefore, are greatly increased by the adoption of computer-based systems. On the other hand, frustration may occur due to the difficulties that are intrinsic in computer systems for people who are not expert either in computer science

or engineering. These disadvantages prevented a wide diffusion of the first generation of DSP-based instruments into the industrial end-user market.

Virtual Instruments

To simplify the solution of the problems pointed out in the previous section, the concept of the virtual instrument was introduced in the literature as well as in the market at the beginning of the 1990s, and is now widely used by practitioners. This idea is the natural evolution of the computer-based measurement systems and follows the enhancements of the computer hardware as well as the new programming techniques that can be applied thanks to such powerful hardware.

Innovation comprises the deployment of the computer architecture not only to perform the software programs implementing the measurement procedures, but other user-oriented functions,

as well. The main goal is, in fact, to provide a user-friendly support to implement and execute the measurement algorithm and the management of the hardware measurement resources.

As in conventional computer-based measurement and control systems, the use of the computer allows for confining the hardware components dedicated to the measurement application to the data acquisition/actuation subsystem responsible for sampling the field signals, as well as for generating the possible field actuation signals. All operations of the measurement procedure

are performed in software. This ensures high flexibility in the system without requiring hardware changes as long as it guarantees that the field signals are acquired and the field-actuating signals are generated, with the required accuracy and sampling rate and within the required cycle time. This confinement leads to simplify and standardize the input/output interface boards for acquisition and actuation and, consequently, to reduce the overall cost of system ownership (e.g., acquisition, maintenance, training, and software development).

The second aspect dealt with by the virtual instruments is the psychological impact on the users, which directly affects the distribution of these measurement systems. As emphasized in the previous section, computer-based systems, even if effective and efficient from the measurement point of view, may appear very different from the conventional instruments and measurement workbenches as far as the human user interface is concerned. The availability of computational power unused by the real-time measurement procedure in modern computer architectures (especially in the low-cost systems based on personal computers) allows for adopting graphic interfaces to overcome these problems. The appearance of real instruments and measurement workbenches is thus mimicked in the virtual systems so that they resemble the interfaces of their real counterparts.

To achieve the above goals, the graphic features of modern computers (in particular, personal computers) have been ex-

The name "virtual instruments" derives, in fact, from the realistic aspect and operation with respect to the real instruments, even if they are internally made in a different way.

ploited. Graphic interfaces have been developed based on windowing and iconic interactions to issue commands and observe the operation of the measurement systems as well as the related applications.

The advanced graphic features of most of the modern personal computers allow for implementing a realistic user interface of the computer-based instruments and workbenches, very similar to the real ones. The name "virtual instruments" derives, in fact, from the realistic aspect and operation with respect to the real instruments, even if they are internally made in a different way.

The front panel presented on the computer screen comprises the graphic representation (icons) of conventional controls (e.g., buttons, selectors, potentiometers) and indicators (e.g., oscillograms, scope-like display, lights, pointer indicators, digital indicators), that are familiar to users in measurement areas. An example of a dedicated application is shown in Fig. 2. Graphic flexibility also allows for easy merging of the front panels of several instruments with field actuators to create a comprehensive workbench of virtual devices with all the components of the envisioned application. This simplifies even more the user interaction with the monitoring and control system since it concentrates all relevant devices in one single inter-related view by discarding the information and the parts of the devices that are not of direct and immediate interest. Conversely, in real workbenches, the user must face all of the instruments' and actuators' parts, making it more difficult both the identification of relevant items and their visual observation.

The user can operate on the icons as on the corresponding real devices; in particular, controls are operated by using the pointing device available in the personal computer (e.g., the mouse) instead of moving them directly with the user's fingers. The presentation and user's observation of the measured quantities either on pointer indicators or other visual devices may be less accurate than a numeric view. However, the visual overview of the pointer and the whole scale helps the user to understand immediately the relative position of the measured quantity in the scale of values and, thus, the reasonableness of the observed value. This, in turn, immediately triggers the operator's actions by deploying automatic reactions induced by training in his memory. In fact, it is often easier to associate actions to patterns in observed images than to read a value and mentally compare it to critical ranges to deduce the opportunity of action.

Graphic programming techniques have also been imported from computer science to simplify the definition of the measurement procedures by means of object-oriented data-driven techniques.

By using these techniques it is possible to describe the measurement procedure without any need for a conventional procedural programming language. In the programming language, the sequences of operations on data must be given with a detailed view of the computing architecture typical of computer scientists and engineers. In visual programming, data and operations are represented by icons. The measurement procedure is obtained by drawing a procedural diagram

or graph that defines data dependencies and operations to be performed. Nodes of the graph are high-level operations typical of the numeric processing in measurement, as well as operations for visual data presentation and management of the acquisition boards. Icons that are associated to functional blocks, visually represent nodes. Nodes have input and output connections that allow receiving and delivering operands and results, respectively. Input nodes connect the graph to the external sources of data (the input boards), while output nodes connect data to the output boards to the field. Directed paths represent the data dependencies among operations. To simplify the design process, huge libraries of functional blocks are now available for the widely used development environments for virtual instruments and workbenches, including data processing operation as well as board management. In addition, to deal with complex measurement procedures, hierarchical definition of the graph is usually adopted to structure the definition at different abstraction levels. A node may, therefore, be either a library function or a subgraph. An example is shown in Fig. 3.

A graphic editor allows for creating the measurement procedure graph. Editing functions include: selection of functional blocks from the library, connection functions, placement and routing, drag and drop, cut and paste, hierarchical expansion, and filing actions. Customization of the operation parameters is possible according to the characteristics associated with the envisioned icon. Data flow is defined by properly connecting the instances of the functional blocks. The graphic interface is then associated to the measurement procedure so that inputs and outputs are associated to the corresponding presentation operation blocks.

The measurement procedure graph coincides with the conventional block diagram that every measurement designer is accustomed to drawing to describe the overall measurement procedure, as well as all details specifying the characteristics of the desired data processing. This is independent from the techniques adopted to implement the procedure itself. Therefore, the visual programming allows the measurement procedure designer to focus on the measurement problems and issues instead of wasting efforts in computer programming

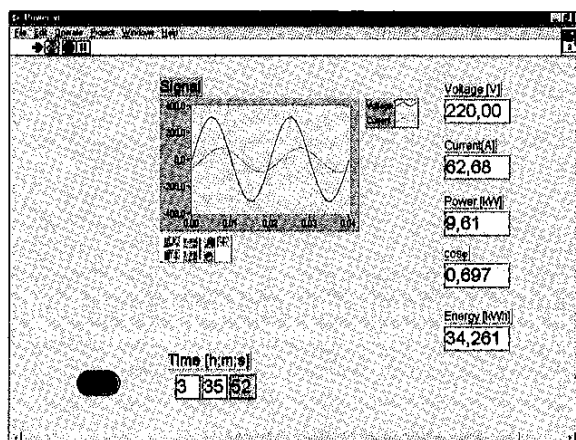


Fig. 2. The front panel of a dedicated virtual instrument.

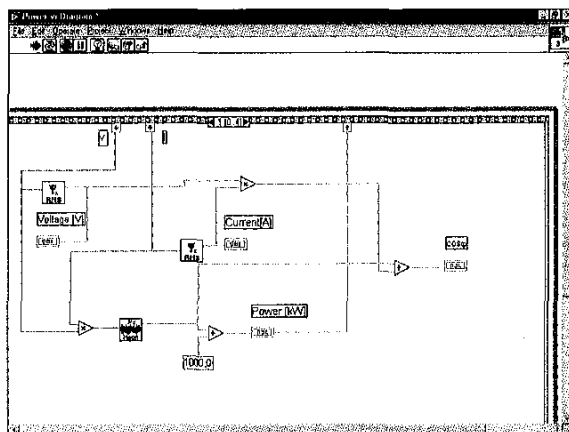


Fig. 3. The block diagram of the instrument presented in Fig. 2.

details. Visual interaction for programming is based on items that are well known to the measurement designer (i.e., the block diagrams and the block interconnection through terminals, as in real workbenches), and is centered on relationships among them that mimic the ones among the measurement procedure quantities. As a result, visual programming for virtual instruments and workbenches can be essentially viewed as writing the block diagram of the measurement procedure by means of a computer program (i.e., the editor) instead of writing it on paper. A very short training session on the use of the editing and development system is, therefore, required for measurement experts to become familiar with a development system for virtual instruments and workbenches. The required background knowledge is limited to the measurement science and technology that is mandatory to define (on paper) the block diagram of the measurement procedure and to define the information needed to draw such a scheme in the virtual instrument development system.

The block diagram of the measurement procedure is then translated into the computer-executable code by suitable automatic translation programs available in the virtual system development environment. Translation is, therefore, another task moved from the designer's shoulders to the computer. The compiler generates the executable code from the visual source code of the measurement procedure and the function library, and stores it in an executable file for subsequent use. The interpreter performs translation and immediate execution of the functional blocks without storing them in a file. This is useful during system development to test interactively the procedure behavior without the need of completing the system definition, generating the executable code, and leaving the development environment to run the executable code itself.

Very recently, the need for further reduction of the development time as well as for quality enhancement and standardization suggested the sharing and massive reuse of the functional blocks and the measurement procedures developed and tested by experts. In this direction, some companies in the measurement and application areas started joint studies and development of interchangeable virtual instruments, i.e.,

measurement subsystems having standard connections and user interfaces. These components will be connected together easily and directly at their terminals to build complex measurement systems by mimicking the construction of real workbenches obtained by connecting the physical terminals of physical instruments.

In summary, virtual systems are simply computer-based measurement systems having a graphic interface that makes them more programmable and usable by people who are measurement experts and practitioners, but not computer experts. This is both positive and negative from the measurement science and application points of view. It is positive because advanced measurement systems can be built and maintained at lower costs and developed faster, especially by exploiting component reuse. It is negative because people who are not expert in measurement can easily build measurement systems without a good knowledge about the main issues of the measurement science (e.g., accuracy, precision, real-time operation, traceability). This may lead to misunderstanding and misuse of the measurement system results. In addition, ease of development and testing often makes people hungry to reach the solution faster, but they end up thinking less about the measurement procedure, its correctness, its completeness, its theoretical feasibility, its operating constraints, its limits, its efficiency, and its adherence to the application needs.

Networked and Distributed Measurement Systems

In the literature and in practice, many examples have been presented concerning the use of networking to extend the measurement and the computational ability of computer-based systems and virtual environments.

The first limitation in designing complex systems is given by the number of different signals to be sampled. When the measurement procedure needs to operate on many different signals, the computer-based architecture may not be able to host enough signal-acquisition boards. The use of networked instruments and acquisition subsystems allows for expanding the acquisition capability of the processing unit. Industrial standards (e.g., GPIB, fastbus) were proposed a long time ago and are widely used in the industry, especially when complex processes and systems need to be monitored and controlled in real time. The locality of the interconnections and dedicated interconnection interfaces and procedures ensures the lack of delays in communications as well as the consistency of the field view obtained by samples. The presence of a single processing unit makes the creation of consistent and coherent images of the sampled signal simple. As a consequence, networked instrumentation and acquisition subsystems are suited for real-time monitoring and control of systems.

A second restriction is the operating area covered by a single processing unit. Sensors and acquisition subsystems cannot be located too far from the signal source, according to the specification of the signal quality allowed by the acquisition boards. If signals must be acquired from distant sensors, networking of acquisition subsystems and instruments can be

useful to overcome the signal degradation induced by environmental noise on the direct connections between sensors and the acquisition boards installed in the processing unit. In fact, the communication protocols adopted in the digital interconnections, possibly on optic fibers, are more immune to the environmental noise and EMI. This approach allows for real-time monitoring and control of large and complex systems and plants so that sensing and control applications can be distributed over a larger area in the factory. The covered area is, however, bound by the maximum distance allowed by the interconnection cables.

The third limitation in complex processing that extracts the desired information from the data acquired by the field, is the computational complexity of the measurement programs. The higher the complexity, the more powerful and expensive the computing architecture must be in order to guarantee real-time operation according to the application needs.

Often, dedicated DSP boards must be installed to speed up the host processor. When processing becomes too demanding, a single computer may not be sufficient or may have an excessive cost. Partitioning the computational burden over independent processing units interconnected by a local computer network can be an effective solution to create a distributed measurement system—if suitable synchronization and cooperation are provided to guarantee parallel operation and consistency of the collected data.

The locality of the interconnections makes communications practically instantaneous. If the network is dedicated to interconnect only the processing units for the measurement procedure, the resulting traffic, even on commercial and inexpensive networks (e.g., Ethernet links at 10 Mbps), is usually so low that no delay is introduced by network contention. In addition, if the time at which samples were taken must be certified, time stamping can be effectively implemented because computer clocks can be synchronized easily and quite precisely. On the other hand, if higher throughput is necessary, high-speed connections (e.g., FDDI or other dedicated fiber optic links) can be installed at reasonable costs. The certainty of the time at which samples are taken and the low response time make feasible the use of locally networked processing units for monitoring systems as well as for real-time control of systems and plants. In fact, data practically appear to have been sampled simultaneously by a single computer.

A further restriction concerns the monitoring and control of very large plants, e.g., chemical and oil plants. Complexity and distribution of these systems make impossible the use of a single processing unit—several units must be networked and distributed in the plant by creating a distributed measurement system to monitor and control each part in a coordinated way. Also, in this case, the use of a dedicated computer network to connect the processing units is usually sufficient to minimize the communication delays and the interference, as well as to

ensure a reasonable processor clock synchronization. In this case, the computer network has the size of a typical campus network. Consequently, consistency of the overall view of the field from the sampled signals is provided for processes having slow dynamics, with respect to the global update time constrained by network delays. A better approach for fast dynamics consists of partitioning the plant into processing cells and controlling each cell with a dedicated processing unit. Networking the processing units and possibly sharing signals in the plant to co-ordinate operation of the processing units can be achieved without broadcasting all the signals of the plants. In this case, the individual processing unit is responsible for controlling, possibly in strict real time, a plant's cell, while interconnection among computers ensures overall coordination at a higher abstraction, but slower level.

The present trend in interconnected measurement systems

is to extend the area covered by the interconnected systems in a geographical scale. However, this sets a further limit to the use of such systems. As in the case of large and complex plants, a structured networked measurement and control system can be adopted by scaling its use to the geographical area. The geographical process to be monitored and controlled is partitioned into cells that can be dealt with by a single processing unit or a group of locally connected units. Then, the geographical

distributed units are connected by a geographical computer network into a distributed measurement system. In this case, communication delays usually cannot be neglected. This is even more relevant if the traffic in the computer network is not negligible due to the number of computers connected and the amount of communications, especially if a public computer network is used to realize the interconnections among the measuring processing units. Consequently, local monitoring and control become mandatory to guarantee correct real-time operation, while geographical interconnections can be used for global observation and monitoring, but without any actual control in strict real time. In global monitoring, the user must be aware of the possible inconsistency of the observed data coming from the different distributed processing units. No further data processing and fusion should, therefore, be performed on samples coming from different units, except the processing done in the cells themselves. These data might not be correctly synchronized, leading to possible errors in the derived quantities if the applied processing procedure assumes (as usual) that all data have been acquired at the same time. As far as control is concerned, the global network can be centrally used only for some very-slow dynamics of geographical systems or to coordinate the control operation of each control unit by working at a higher abstraction level. Operating on inconsistent images of the field may lead to errors in the control procedure, and to control instability. These effects may become very evident and dangerous when the system dynamics are fast.

A better approach for fast dynamics consists of partitioning the plant into processing cells and controlling each cell with a dedicated processing unit.

Introduction of virtual instruments (e.g., [5]) in distributed measurement systems is an obvious evolution of the above networked measurement systems. Distribution over the network of the measurement components is obtained by designing each component individually and by providing it with suitable interfaces to exchange data through the network with the other components; then, each component is allocated on a different computer in the network. Suitable icons and system components are often provided to support easy design of the distributed virtual instruments, in particular to make the details of the computer interconnection protocols transparent to the user, as well as the measurement component communications. Distributed virtual measurement systems suffer from the same problems outlined above for the different classes of networked systems, which are somehow given by the simplicity of creating such systems. This seems an intrinsic contradiction. However, simplicity makes it possible to design and use virtual systems even for people with limited knowledge in measurement as well as in networking. While these people are expert in their application areas, they are often not totally aware of consistency and synchronization issues related to the complex system observation for monitoring and control. In addition, they may be unaccustomed to considering the needs related to control, real-time operation, accuracy, precision, sensor fusion, characterization, and calibration for correct measurement and applications. Consequently, they often adopt virtual distributed measurement systems without fully considering their limitations, operating constraints, and application influences. This may be critical and even result in erroneous measurement and control, especially when real-time operation is very strict due to the fast system dynamics, with respect to the network communications and synchronization.

In all types of networked and distributed measurement systems discussed above, real-time operation and constraints are critical issues to be considered during system design to ensure the correct system operation. If the system to be measured or controlled is connected to the computer directly through suitable acquisition boards, real-time operation of the measurement system is possible. Some researchers and companies claim that real-time operation in networked and virtual instruments and environments with remote sensing is always feasi-

ble and correct under any operating and environmental condition, including geographical computer networks. This is correct only under some restrictive conditions, as shown in Fig. 4. Sampling of all quantities used by the measurement workbench are not guaranteed to be obtained exactly at the same time when acquired by different systems that cannot share the same sampling clock. Data analysis for monitoring and control must, therefore, consider explicitly the time at which samples were taken. Traditional control algorithms need a consistent picture of the inputs, sampled contemporaneously. Practically, analysis and control are still correct even if sampling is not performed contemporaneously on all input signals, but in a time period short enough to allow for considering the input values invariant within this period. This occurs when system dynamics are slow enough, with respect to the period. Conversely, when input signals vary by a quantity larger than the system resolution within the sampling delay period, the above approximation is not correct, and remote sensing should not be used for monitoring or control. In control, improper use of remote sensing may lead to system instability and safety problems. Fig. 4 shows that signal S1 can be indifferently sampled at time T1 or T2 because it does not change in this interval. The same does not apply for signals S2 and S3. Therefore, one sample of S3 taken at time T2 cannot be considered contemporary to one sample of S2 taken at time T2. Large measurement errors due to this sampling delay may occur, even if the signals S2 and S3 are locally sampled in the correct way.

Conclusions

The trend in modern DSP-based instrumentation increasingly integrates of the measurement systems into more complex monitoring and control systems, distributed over different—possibly geographically distant—locations.

Virtual instruments, as well as networked and distributed measurement systems, are the natural evolution of the first DSP-based systems. Their main feature consists of the exploiting of the ever-increasing computational power of the modern DSP processors to simplify the development of the measurement algorithms, the man-machine interface, and the system interconnection.

From this point of view, innovation provided by such systems seems to be coming more from the computer science field rather than measurement science. However, many issues typical of the latter field are involved in the correct design and operation of these systems. All problems related to the DSP theory must be carefully considered to avoid all those great measurement errors (e.g., aliasing and leakage) that may easily occur in these intrinsically nonlinear measurement systems.

As long as the influence of the computing side becomes more and more significant, new problems must be addressed. For example, networking instruments on a geographical scale requires accurate consideration of the lack of synchronization between the interconnected acquisition systems, to avoid measurement errors, whose consequences may be dangerous.

The trend toward increasing complexity of instruments shows to an increasing difficulty in the correctness of use, from

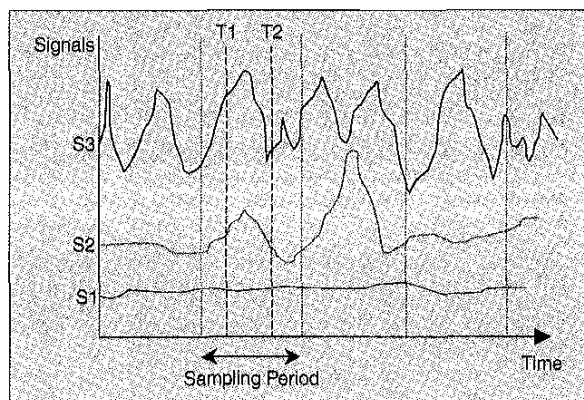


Fig. 4. Sampled signals with different dynamics. The influence of sampling time on the sampled value.

the metrological point of view. This problem is somehow made even worse by graphic interfaces and programming languages that make their practical configuration and use very easy. Many relevant theoretical aspects and measurement issues remain hidden to inexperienced practitioners and technicians who cannot be fully aware of the consequences of their choice.

In many application cases, the solution of complex problems is not easily expressed in terms of an algorithm, while it can be effectively and efficiently described by examples. Soft-computing technologies (namely, neural networks, fuzzy logic, and expert systems) have been shown to be a viable approach [8]. After configuration (i.e., selection of the model parameters), these computing paradigms become algorithms to describe the exact and deterministic sequences of operations that must be performed on inputs to generate the desired outputs. In the near future, therefore, DSP-based instruments, as well as virtual instruments, will evolve to include soft-computing blocks as standard building blocks. This will lead to further problems in the metrological characterization of these new instruments.

In addition, the more complex measurement algorithms play a relevant and critical role both from the theoretical point of view and in many application areas. This results in further problems concerning the uncertainty, i.e., the measurement quality. What is the influence of data processing on the measurement uncertainty? How does the uncertainty affecting each signal sample propagate through the measurement algorithm? How can the final measurement uncertainty be estimated?

The present and the future challenges of researchers and educators in the field of instrumentation and measurement are two-fold. From one side, fundamentals of the digital signal processing theory and related metrological issues must be disseminated as widely as possible at any technical educational level. On the other side, the evolution of these measurement systems must be pushed toward self-evaluating systems that are able to warn the users about the presence of possible error conditions [2] and to self-estimate the measurement uncertainty.

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