Data Acquisition Systems for Operational Modal Analysis

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ABSTRACT: Operational Modal Analysis is today performed on a wide range of structures, under various operating conditions, in different test environments and often under extreme time and cost constraints. As a result, numerous requirements have to be taken into consideration when designing an optimal data acquisition system for Operational Modal Analysis.

This includes the ability to make very accurate measurements in a fast, safe and easy manner regardless of whether the system is to be used in the field, in a lab, or in a centralised or distributed setup. In addition, modularity, scalability and Plug & Play are functionality expected from a modern data acquisition system. Many of these requirements are, however, very divergent. Consequently data acquisition systems for operational modal analysis have up until now either been optimised for dedicated use or been the result of a compromise.

This paper describes the new LAN-XI concept combining several different technologies including Precision Time Protocol (PTP), Power over Ethernet (PoE), Dyn-X, REq-X and TEDS. With the introduction of the LAN-XI concept, a hitherto unseen combination of requirements can be fulfilled in the same data acquisition system thereby significantly increasing the versatility of the system and at the same time reducing the amount of measurement equipment and accessories needed.

1 INTRODUCTION

Chapter 2 describes some of the many requirements to an ideal data acquisition system for Operational Modal Analysis (OMA). Most data acquisition systems, however, only fulfil a very limited number of these requirements and consequently make OMA measurements complicated, time-consuming, costly, less accurate or in worst cases even impossible.

In Chapter 3 the philosophy behind the LAN-XI concept is explained. It is shown how the combined use of several different technologies ranging from powering the data acquisition system, over sample synchronisation techniques to correcting the measured data in real-time makes it possible to design a data acquisition system meeting the most demanding requirements for OMA measurements. The conclusion is presented in Chapter 4.

2 REQUIREMENTS TO A DATA ACQUISION SYSTEM FOR OMA MEASUREMENTS

Planning, setting up and performing OMA measurements can be very different from one test to another. A number of factors have to be taken into account including the nature of the test object, the test environment and the operating conditions. In addition, high quality data must be obtained in the shortest possible time with the lowest possible cost.

2.1 Nature of test object

From being a novel technique mainly done on large civil engineering structures, OMA is today performed on a large variety of civil engineering as well as mechanical structures ranging from the smallest components to the largest structures. Measurements range from a few channels to hundreds of channels and a versatile data acquisition system must therefore be scalable, modular and easily reconfigurable. The same data acquisition system capable of doing a large multi-channel measurement using up to several rack systems one day, should be easily dividable into multiple systems the next day for doing many smaller measurements at different locations without compromising performance, ease-of-use or cost.

In general, it is advantageous to place the data acquisition system as close as possible to the test object to shorten the length of the transducer cables. Apart from significant cost savings on expensive high-quality transducer cables and the lower risk of setup and measurement mistakes due to reduced cable “infrastructure”, short cables minimise the potential risk of adding noise to the measurement data.

For large test objects, this requires that small front-ends – or individual modules - can be freely distributed around – or inside - the test object and the measurements can be made 100% sample synchronously between all measurement channels. Many traditional systems are, however, neither distributable nor capable of ensuring sample synchronisation between front-ends. Newer systems have offered various cable-based synchronisation techniques between the individual front-ends, but all with the disadvantage of requiring extra cabling.

2.2 Test environment

Historically most OMA measurements were performed as in-situ field measurements, e.g. for civil engineering structures like buildings, towers, bridges and off-shore structures. Many OMA measurements are still performed in-situ including in-operation measurements on mechanical structures like aircraft, vehicles, ships, trains and rotating machinery in general. However, many civil engineering structures are also measured as scaled models in labs and especially many mechanical structures are measured in labs and test cells.

Field measurements are often performed in harsh environments placing high demands on the robustness of the data acquisition system. In addition, the data acquisition system must be light weight, small and truly portable, have low power consumption, have the option of battery operation and the possibility of distributing the front-ends.

For fixed lab or test cell setups, a centralised data acquisition system with one or more rack systems has traditionally been used. Long transducer cables have been required with the significant disadvantages previously mentioned. In both test environments the use of distributed front-ends could significantly reduced the required cabling. Fig. 1 shows a traditional test cell setup using long transducer cables between connector panels in the various test cells and the operator room.

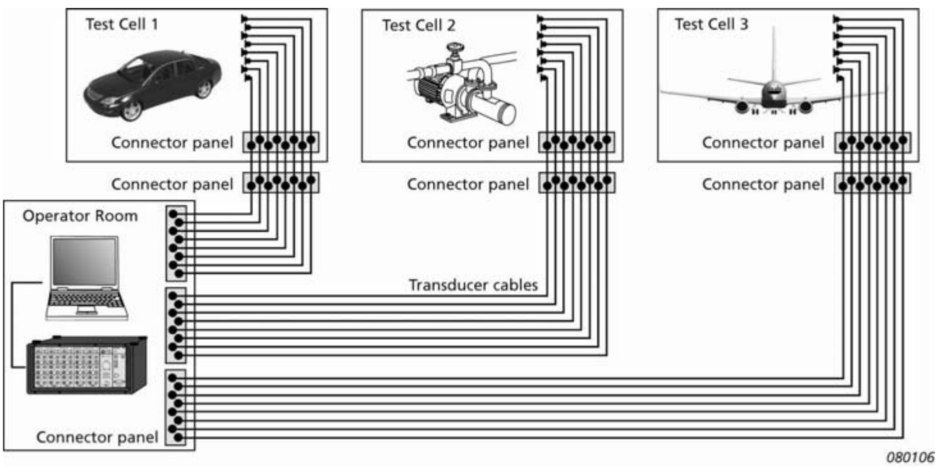

Figure 1: Traditional test cell setup requiring extensive cabling.

2.3 Operating conditions and data quality

OMA is based on only measuring the output responses of a structure and using the ambient and natural operating forces as unmeasured input. The input forces are therefore typically both unknown and uncontrollable and the response levels can typically not be predicted.

Traditionally this has been tried compensated for by performing numerous trial runs and auto-ranging procedures to set the input attenuators in the most optimal way. However, this is both a very time-consuming and error prone procedure. Consequently, to get the measurements right the first time, a high dynamic range throughout the complete measurement is required to avoid erroneous results from overload and underrange situations. Especially when harmonic components are present a high dynamic range is frequently required to measure the low-level stochastic noise from where the modal parameters can be extracted.

Another characteristic of many OMA measurements is the high content of low frequency modes due to the large size of many structures (bridges, buildings, aircraft, ships etc.). The data acquisition system including transducers must be able to measure down to DC.

2.4 Time and cost constraints

OMA measurements are often subject to extreme time and cost constraints and can often not be re-done. Planning, setting up and performing the measurements in a fast, safe and easy manner is therefore of outmost importance.

Ease-of-use can be significantly improved using true Plug & Play functionality throughout the complete measurement chain. Ideally it should be possible just to attach the transducers to the data acquisition system, connect the data acquisition system to the PC, open the data acquisition software and then just press the “Start” button and get the results right the first time.

As a result of the extreme time constraints there is, however, an impending risk of setup and measurement mistakes. Intelligent user feedback from the data acquisition system is consequently mandatory to quickly and easily detect and correct these potential errors. The information should preferably come from each front-end, module and channel in terms of identification, calibration, conditioning and measurement status.

2.5 Beyond OMA measurements

A key requirement to most data acquisition systems is versatility. A versatile data acquisition system must support different types of sound & vibration measurements. This includes other types of structural dynamics measurements like ODS analysis, hammer or shaker(s) modal testing, but also other types of vibration measurements as well as vibro-acoustics and acoustics measurements. This gives a range of new requirements to the data acquisition system including powerful generator functionalities and silent operation mode, which, however, will not be discussed in this paper.

3 THE PHILOSOPHY AND TECHNOLOGIES BEHIND LAN-XI

The LAN-XI concept has been developed from the philosophy “Less is More” to ensure very accurate sound & vibration measurements in a fast, safe and easy manner at the lowest possible cost. By using a very modular and highly reconfigurable architecture, a minimum of data acquisition hardware, accessories and cables are required and the same data acquisition system can quickly be configured for field, lab or test cell use based on a centralised or distributed setup.

Core technologies behind the LAN-XI concept are Precision Time Protocol (PTP), Power over Ethernet (PoE), Dyn-X and REq-X technologies and support of Transducer Electronic Data Sheets (TEDS).

3.1 Precision Time Protocol (PTP)

With LAN-XI a new technique is introduced to ensure sample-synchronous measurements over the same LAN connection used for transferring measurement data. This simplifies the data acquisition system's cabling and makes it possible to perform sample-synchronous measurements over long distances, eliminating the effect of delays over the cables and switches.

The technique is based on the Precision Time Protocol (PTP) described in the IEEE 1588 standard (2002) of which an updated version was approved in March 2008, see IEEE 1588 (2008). PTP enables precise synchronisation of PTP devices on a network, e.g. Ethernet. Synchronisation with sub microsecond accuracy can be achieved using hardware generated time stamps. PTP synchronisation thus provides a whole new set of possibilities for combining data acquisition systems located in different places, closer to the actual measurement point and with long distances between. Only a LAN connection is required.

By measuring the delays between the individual PTP devices, the individual clocks on the network can be set to exactly the same time. This is done using a hierarchy of a Master and one or more Slave clocks. The Master clock is the most accurate clock present on the network and if a PTP device with a more accurate clock is added to the network, the Master clock will pass the role as Master to the better clock and become a Slave.

The basic principle of PTP synchronisation is shown in Fig. 2 and explained below.

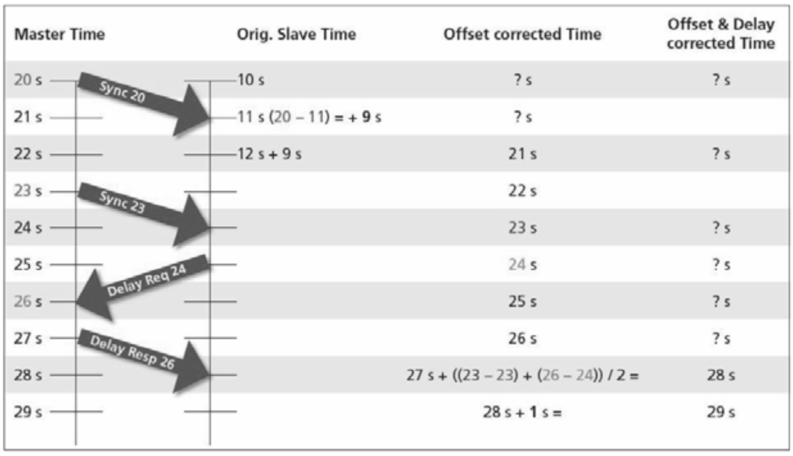

Figure 2: Basic principle of PTP synchronisation.

The Master clock continuously sends out time stamped synchronisation messages to the Slaves. When the Slave clocks receive the synchronisation messages they are time stamped as well. The difference between the time stamp of the Master and the Slave is equal to the network propagation delay plus the offset between the Master and the Slave clock. The Slave now adjusts its clock, thereby reducing the difference between the two clocks to the network propagation delay. All time stamping is implemented in the hardware of the PTP devices to avoid the variable delays that would be caused by software time stamping.

The PTP synchronisation technique assumes that the propagation is the same from the Master to a Slave as from a Slave to the Master. Using this assumption, the Slave sends a time stamped Delay Request to the Master that promptly returns a Delay Response stamped with the time at which it received the request. The difference between these two time stamps is the network propagation delay and the Slaves can thus adjust their clocks to match the Master clock.

This simplified description does not take oscillator errors into account. A simple servo implementation handles that. On top of the PTP synchronisation, the LAN-XI concept also corrects the unavoidable phase drifts of the Slave clocks by continuously measuring and counter-adjusting the Slave clocks.

The PTP is independent of the network topology and it is self-adjusting to actual system setup in terms of selecting the most accurate clock and adapting to the actual delay in the network. This makes it very easy to set up a data acquisition system using PTP to synchronise multiple front-ends. As all synchronisation is done by the PTP devices on the network, a data acquisition system with PTP complying front-ends can operate on a standard network.

Switches used in standard LAN do not include any special features to support PTP, but special PTP switches are available from manufacturers of network backbone devices. However, the typical phase deviation measured at 25.6 kHz in a network using a standard 1 Gigabit LAN switch is less than 1 degree, see Fig. 3.

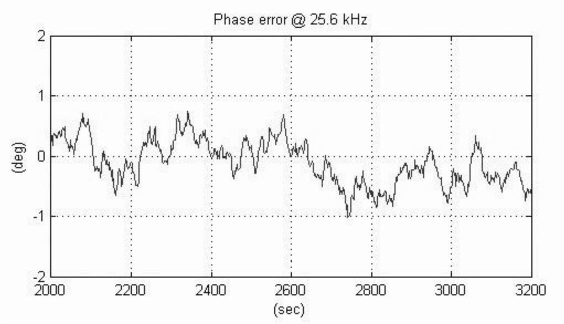

Figure 3: Typical phase deviation using a standard 1Gigabit LAN switch.

The ‘channel x bandwidth’ performance is practically unlimited using LAN-XI. With 1 Gigabit LAN data backbone in each LAN-XI front-end measurements from 2 to more than 1000 channels can easily be measured with the same system.

3.2 Power over Ethernet (PoE)

Power over Ethernet (PoE) is a technology that allows power to be transmitted along with measurement data and sample synchronisation (PTP) on a LAN cable in an Ethernet network. The technology is specified in the IEEE 802.3af standard (2003) and updated in the IEEE 802.3 standard (2005). Devices called Power Sourcing Equipment (PSE) are used to supply the required power. A PSE can either be an in-line power injector or a LAN switch/hub. A device powered by a PSE is called a Powered Device (PD). Standard LAN cables can be used, but for providing power over long distances CAT-6 LAN cables are required. An example of communication between a PSE and a PD is shown in Fig. 4.

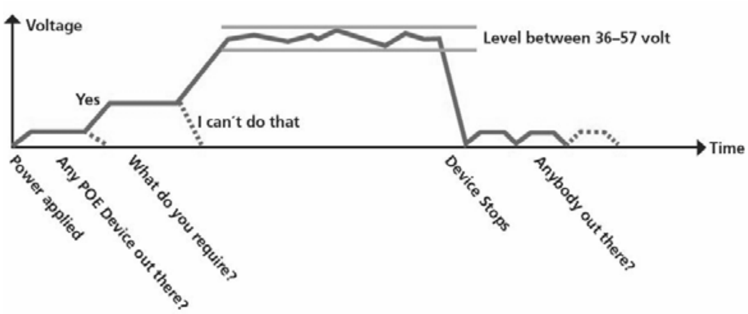

Figure 4: Example of PoE communication between a power source and a powered device.

When the PSE is turned on it starts a detection cycle in order to find out if any PD needs power. A PD that needs power will indicate this by placing a “signature resistance” (19 – 26.5 kΩ) and “signature capacitance” (150 nF) between the powering pairs. This is recognized by the PSE and power is turned on. The PSE injects between 36 V and 57 V (usually 48 V) into the cable and must be able to provide up to 15.4 W with max. 400 mA. In order to prevent overloading as well as powering open lines, the PSE will turn off the power if the resistance becomes less than 15 kΩ or greater than 33 kΩ or the capacitance becomes greater than 10 μF.

The IEEE 802.3 standard specifies a set of different power classes used for PoE, see Table 1.

Table 1: Power classes for PoE.

Power Class	Usage	Input Power Level [W]
0	Default	0.44 – 12.95
1	Optional	0.44 – 3.84
2	Optional	3.84 – 6.49
3	Optional	6.49 – 12.95
4	Reserved for future use	-

The PD can indicate the required power to the PSE. The communication is done in a manner similar to that described for turning on the power. If the PD requires more power than the PSE is able to supply, the power to the line is disabled and the detection cycle restarted.

With a maximum cable length of 100 m, the available power for the PD will drop from 15.4 W to 12.95 W when accounting for cable loss.

3.3 PTP and PoE – One-cable operation

The combined used of PTP and PoE in the LAN-XI data acquisition system has made it possible to drastically reduce the amount of cabling in distributed front-end set ups by significantly reducing the length of the transducer cables and using the same LAN cable for data transfer, sample synchronisation and power supply, see Fig. 5 (compare with Fig. 1) and Fig. 6. The benefits are obvious and include reduced noise and cable cost, faster setup and easier maintenance, less risk of setup and measurement errors, inexpensive LAN switches can replace expensive Patch Panels and no need for additional power outlets.

To support the concepts of distributed front-ends and field use, the LAN-XI modules are cast in magnesium for maximum stability and light weight and battery operation is supported.

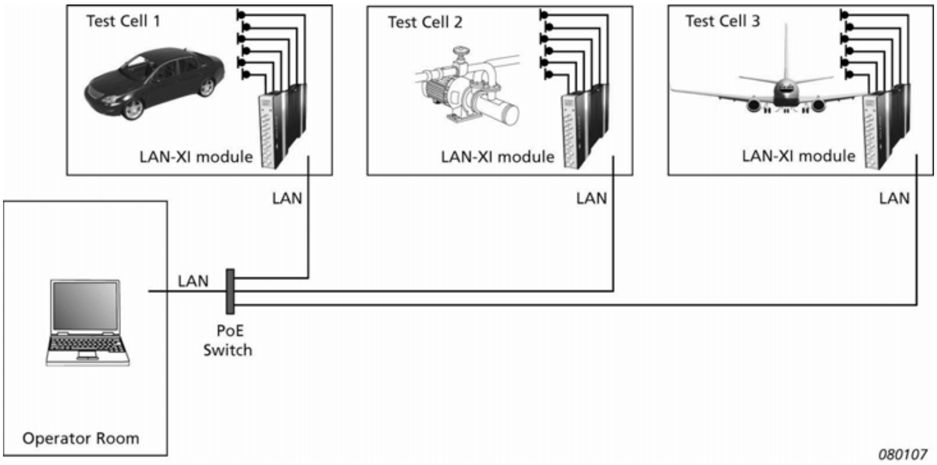

Figure 5: Using LAN-XI, cabling between test cells and operator room is drastically reduced.

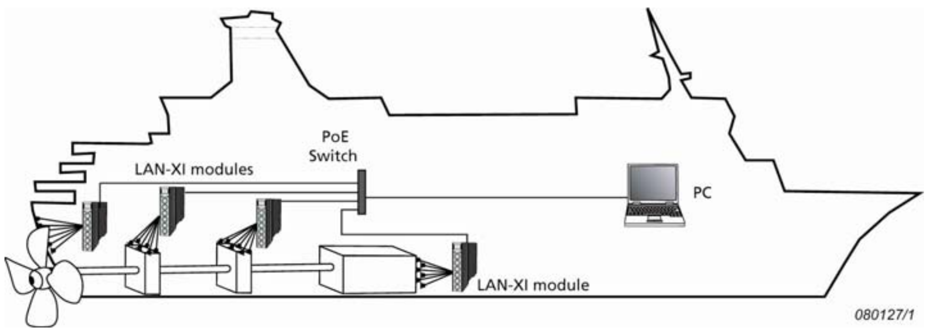

Figure 6: Using LAN-XI, cabling can be drastically reduced for measurements on large structures.

3.4 Dyn-X technology

With the introduction of the Dyn-X (Dynamics eXtreme) technology, data acquisition systems for the first time fully match or outperform the dynamic performance of high-quality transducers as explained in Jacobsen et al. (2006). A Dyn-X input channel with a single input range has a useful analysis range of 160 dB narrowband and more than 125 dB broadband, see Fig. 7.

The Dyn-X technology utilises a special analog input design to provide a very high dynamic range of the analog circuit, pre-conditioning the transducer signal before feeding it to the ADC. A Dyn-X input channel has no input attenuators, but two input ranges: $10V_{peak}$ and $31.6V_{peak}$.

The digitising is performed synchronously in two specially selected, high-quality, 24-bit delta-sigma ADCs, and both data streams are fed to the DSP environment where dedicated algorithms in real-time merge the signals while obtaining an extremely high accuracy match in gain, offset and phase, see Fig. 8.

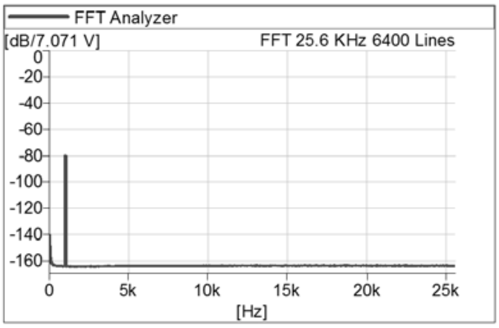

Figure 7: 160 dB analysis in one range. FFT analysis of a 1 kHz signal 80 dB below full scale (7 V_{rms}). Noise and all spurious components measure 160 dB below full scale input.

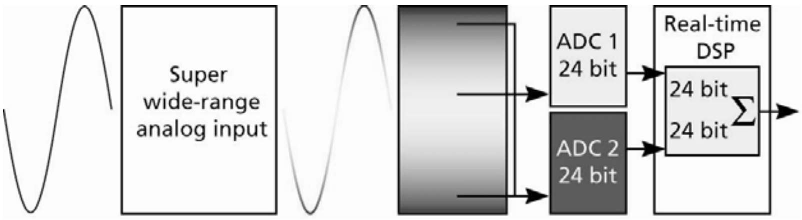

Figure 8: A simplified block diagram of the Dyn-X technology.

With no setting of input ranges, and with no need to be concerned about overloads, under-range measurements and the accuracy of the measurements done, the ease and safety of measuring are drastically increased using Dyn-X technology. And with no need for trial runs to ensure correct input ranges for the various input channels, the certainty of getting the measurements right the first time is also significantly increased.

3.5 REq-X technology

Transducer Response Equalisation eXtreme (REq-X) is a recent technique that flattens and stretches the frequency response of accelerometers, microphones and couplers in real-time, see Gade et al. (2008). This extends the useful frequency range of the transducers, improves the accuracy of the measurements and expands the use of existing transducers. For a correctly mounted accelerometer REq-X will increase the usable frequency range from 1/3 of the accelerometer's resonance frequency to 1/2 - an increase of 50%. Consequently, an accelerometer optimised for low frequency measurements can now be used for more general purpose tasks.

The REq-X technique corrects the time signal of a transducer by the inverse of its calibrated frequency response as shown in Fig. 9. Both amplitude and phase are corrected.

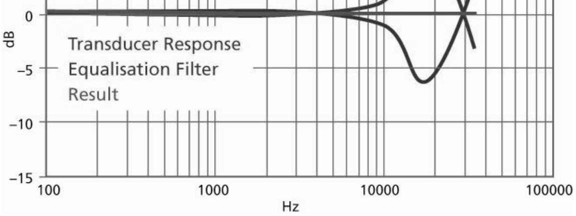

Figure 9: Basic principle of REq-X. Upper curve shows transducer response before equalisation.

3.6 *Transducer Electronic Data Sheet (TEDS)*

Transducers with Transducer Electronic Data Sheet (TEDS) contain information about their sensitivity, serial number, manufacturer, calibration date etc. When a transducer with TEDS is connected to an input module supporting TEDS, it is automatically detected and its data read into the hardware and analyzer setups. TEDS is specified in the IEEE 1451.4 standard (2004).

3.7 *Plug & Play functionality*

To ease setting the LAN-XI data acquisition system up, each module has its own built-in network interface that can be configured to use dynamic or static IP addressing. Using dynamic IP addressing (default), the modules automatically receive their IP addresses from a DCHP server on the network. If modules are connected directly to a PC, the modules will use “link-local” (“auto-IP”) and addresses in the 169.254.xxx.xxx range are selected. A Windows® XP/Windows Vista® PC will do the same and the PC and modules can now communicate.

The dynamic IP addressing together with the Dyn-X, REq-X and TEDS technologies ensure true Plug & Play functionality. You basically just attach the TEDS transducers to the LAN-XI modules, connect the modules/front-ends to the PC, open the data acquisition software and then press the “Start” button and get the results right the first time. If, however, errors occur due to setup or measurement mistakes, the LAN-XI data acquisition system includes intelligent user feedback from each front-end, module and channel in terms of identification, calibration, conditioning and measurement status to quickly and easily detect and correct these potential errors.

4 CONCLUSION

Designing a modern data acquisition system for OMA measurements is not a trivial matter as numerous often divergent requirements have to be taken into consideration. Thus many data acquisition systems are either optimised for dedicated use or are the result of a compromise.

It has been shown with the description of the LAN-XI concept for data acquisition systems how a hitherto unseen combination of requirements can be fulfilled in the same system by combining a number of different technologies like PTP, PoE, Dyn-X, REq-X and TEDS. The same data acquisition system can now be configured from 2 to more than 1000 channels and be used in a centralised or distributed setup either in the field or in a lab environment without compromising data quality, performance or ease-of-use.

The LAN-XI concept significantly reduces the amount of measurement equipment, cabling and other accessories needed thereby requiring less investment in hardware, less setup and maintenance time and lower risk of potential setup and measurement errors.

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