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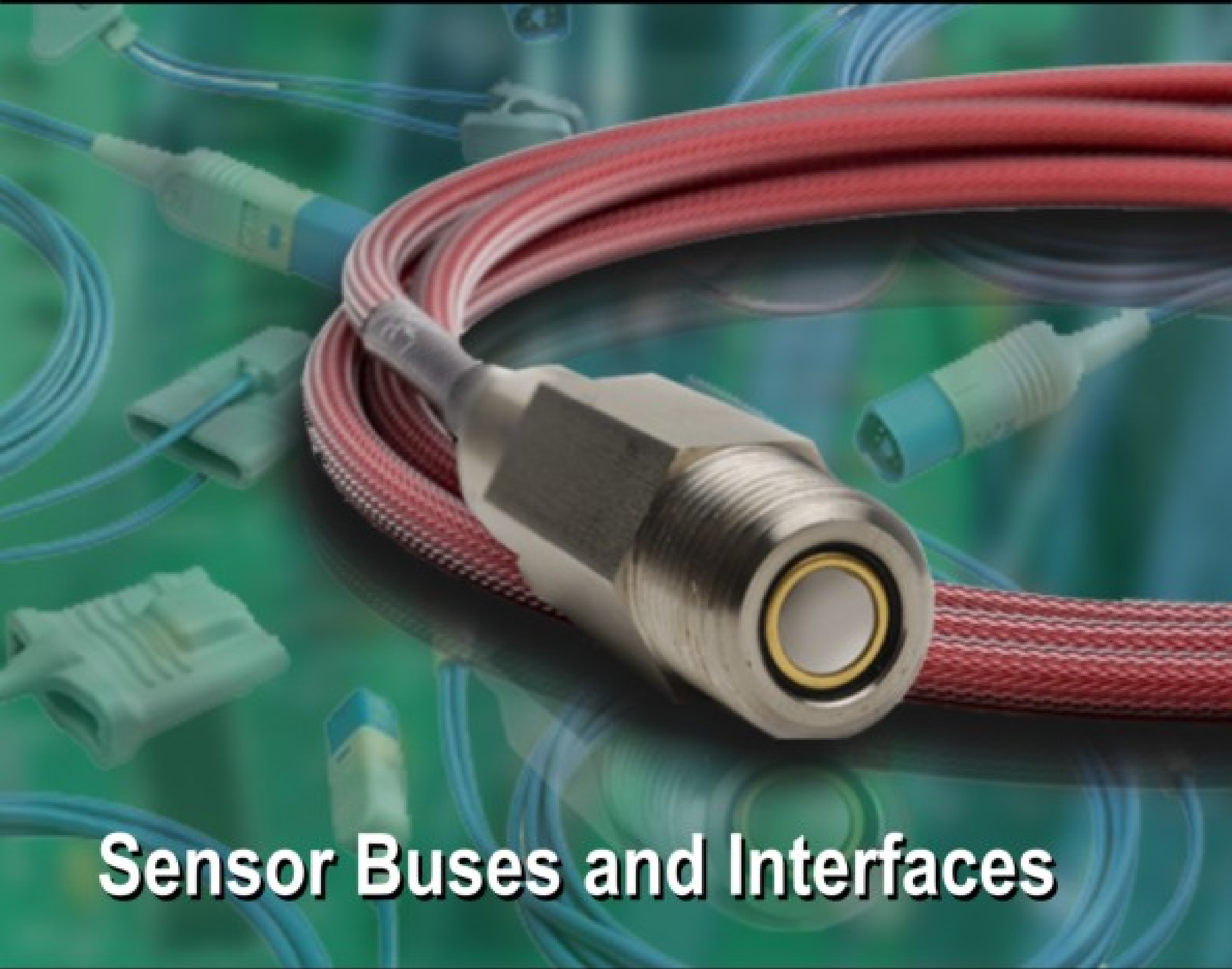

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Online Corrosion and Force Monitoring for Inner Containment Concrete Structures

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Abstract: Corrosion of steel in concrete reduces the service life and durability of concrete structures. It is a worldwide problem, which causes heavy losses to the economy of the country. The durability of concrete structures primarily depends on the condition of the embedded steel in concrete, apart from any deterioration that concrete may undergo. In general potential surveys are carried out on concrete structures to know about the condition of steel. Most of these measurements in the field are carried out manually and the data obtained are analyzed. This offline measurements leads to an error in the data collected, time consuming and involvement of huge man power.

Online corrosion monitoring eliminates such errors in the measurements and improves the accuracy of the data collected from humanly inaccessible regions of a structure. To mitigate corrosion prior to significant degradation and optimize the performance of such concrete structures, various sensors have been used to detect the corrosion and to provide early warning. To assess the condition of the embedded steel, the sensors of the probe are connected to a computer through specialized data acquisition hardware. The computer controls the data acquisition using suitable user friendly software that calculates the corrosion rate at prescribed intervals for continuous monitoring. New types of corrosion sensors and its mechanism in real time measurements are described. Online analysis of data for corrosion and force monitoring is described in this paper. *Copyright © 2008 IFSA.*

Keywords: Corrosion monitoring, Corrosion in concrete, Online corrosion monitoring, Real-time corrosion monitoring, Force monitoring

1. Introduction

ASTM (G15) defines corrosion as "the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties." For steel embedded in concrete, corrosion results in the formation of rust [1]. The most important causes of corrosion initiation of reinforcing steel are the ingress of chloride ions and CO_2 to the steel surface [2]. After initiation of the corrosion process, the corrosion products (iron oxides and hydroxides) are usually deposited in the restricted space in the concrete around the steel. As the steel corrodes, the volume of the rust also increases and at one stage the force induced by the corrosion products may exceed the tensile strength of the concrete and thereby cracking of concrete will occur. These corrosion products would exert enormous stress on the surrounding concrete promoting the deterioration of concrete structures. Methods of investigating metal loss are based on the premise that the corrosion of reinforcement steel is an electrochemical process. For measurement of the corrosion rate of reinforcing steel in concrete, many electrochemical and non-destructive techniques are available for corrosion monitoring of steel in concrete structures. Rebar corrosion on existing structures can be assessed by different methods such as open circuit potential (OCP) measurements, resistivity measurement, linear polarization resistance (LPR) measurement, etc., Different types of data acquisition systems available were analyzed. Online simultaneous measurement system is a reliable, more efficient and less time consuming method. To measure the data automatically, simultaneously in multiple locations and to analyze, this measurement system was developed. Computer is a useful tool for such tasks as data acquisition (slow or fast), on-line experiment supervision and evaluation, modeling and sophisticated data treatment. Before computers became common in laboratories, transient recorders, data loggers, etc. were used. Data acquisition in atmospheric corrosion experiments has evolved from hand taking of data to chart recorder to computer acquisition of data. Large amount of data can be acquired simultaneously from many measurement points on the system for analysis. As a result, tremendous advances in the accuracy and speed of experimental data acquisition have emerged.

2. Experimental

2.1. General Layout of Process

The following steps were applied for online corrosion and force monitoring and shown in Fig. 1.

1. Embedment of sensors in the structure.
2. Connect the sensors of the probe to a computer through specialized data acquisition hardware.
3. Controls the data acquisition using developed software.

2.2. Embeddable Sensors for Corrosion Monitoring

One approach to corrosion monitoring is the use of the component/structure itself for corrosion measurements. However, when this is not practical, separate corrosion probes (sensors) can be installed for corrosion monitoring purposes. The use of sensors usually facilitates the measurement of corrosion damage in a well-controlled manner over a relatively small sensor area [3].

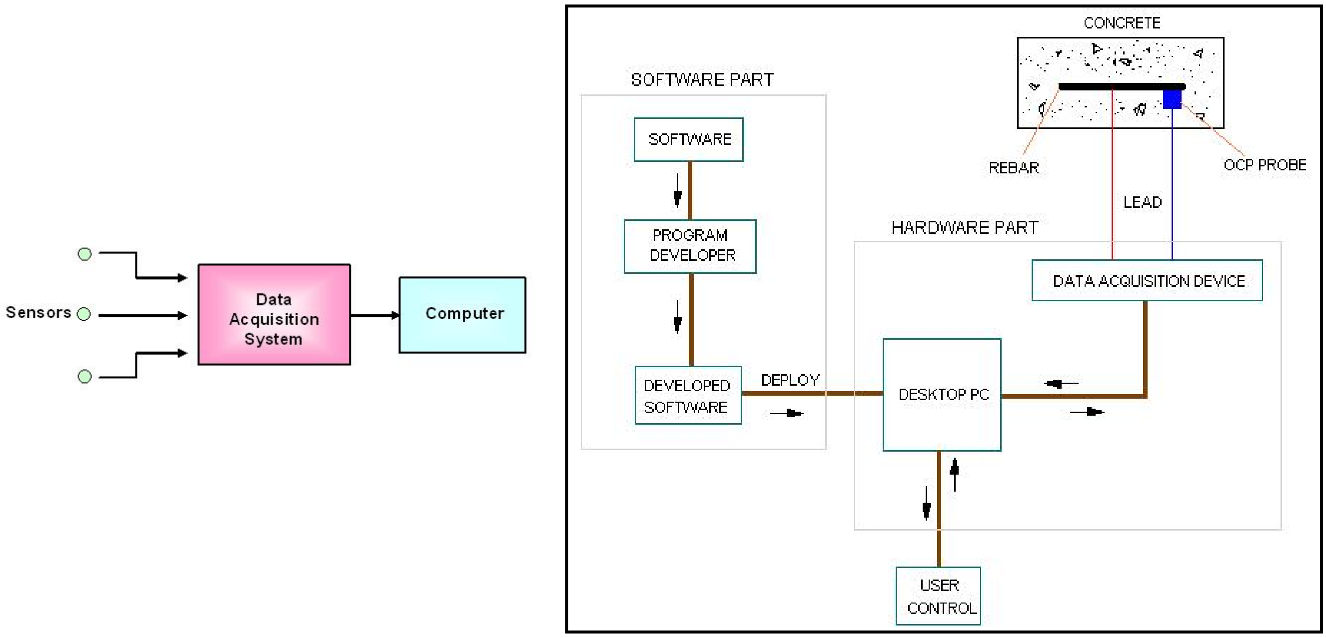


Fig. 1. Steps involved in corrosion and force monitoring.

Advantages of using corrosion probes for monitoring purposes include:

- Corrosion measurements can be performed in a controlled manner, without affecting the actual component/structure.
- Probes usually represent small "samples" that can be periodically removed from the main component/structure and examined in detail.
- The above removal ability can facilitate the correlation of the sensor signal with the nature of corrosion attack on the sensor.
- Probes can be used to evaluate "what if" scenarios. What if we change the material, surface finish, heat treatment, stress level, interrupt the CP system ... etc.
- Highly sensitive corrosion measurements can be performed on sensors to provide early warning of potential problems. Such techniques may not be fundamentally applicable to the actual component/structure.

2.2.1. OCP (Half-cell Potential) Measurements Using Potential Sensor

Fig. 2 shows the installation of potential sensor over the rebar. OCP probe must have a negligible liquid junction potential, monitor through service life, low temperature coefficient, maintenance free, stable, historical potential analysis and high reversibility. Also compact in size and provide signal lead to measure the potential.

Half-cell potential measurements:

This method was first developed in the late 1950's and has since been extensively used, particularly in the USA, for the assessment of concrete bridges. It was adopted in 1977 as an ASTM method C876. The method has also found wide use in Europe, among other countries also in Denmark since beginning of 1980 [4]. The principle involved in this method is appearance of an electrical potential between the reinforcing steel and a standard reference electrode such as saturated calomel electrode (SCE), copper/copper sulfate electrode (CSE), silver/ silver chloride electrode etc., named half-cell. The half-cell consists of a metal rod immersed in a solution of its own ions as shown in Fig. 3.

Fig. 2. Installation of OCP sensor over the rebar.

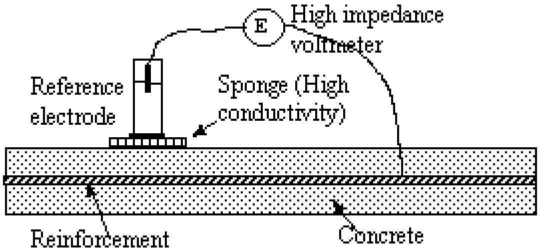


Fig. 3. Principle of the Half-cell method.

The role of the half-cell is to insure constant reference potential. The metal rod is connected with reinforcement steel by a voltmeter, and the ion solution is connected to the pore water via moist porous plug [1]. Measuring method is based on many measurements of potential and correlation of measured potentials with observed corrosion rate at reinforcement. Table 1 presents criterion according to ASTM C-876 and the main application of this method is in situ [5].

Table 1. Criteria for rebar potential measurements.

$Cu/CuSO_4$	Calomel (SCE)	Ag/AgCl	Interpretation
E > -200 mV	E > -126 mV	E > -119 mV	Greater than 90% probability that no corrosion is occurring
-200 Mv < E < -350 mV	-126 mV < E < -276 mV	-119 mV < E < -269 mV	Corrosion activity is uncertain
E< -350 mV	E < -276 mV	E < -269 mV	Greater than 90% probability that no corrosion is occurring

Open circuit potential measurement is a qualitative and useful technique to find out the anodic and cathodic sites in reinforced concrete structures provided the reinforcing bars are exposed to the environments. The open circuit potential method has been widely used because of its simplicity and cost effectiveness.

2.2.2. Linear Polarization Resistance Method Using LPR Probe

- The linear polarization resistance method is an effective and non-destructive way of measuring corrosion rate directly, in real time and it is used to rapidly identify corrosion upsets and initiate remedial action, thereby prolonging plant life reactor and minimizing unscheduled downtime.[6]
- The technique is utilized to maximum effect, when installed as a continuous monitoring system. The major advantage to LPR monitoring is the speed in which it can provide a measurement of the corrosion rate. Changes in the corrosion rate can typically be detected in minutes, providing an almost instantaneous measuring system.[7]
- This technique has been used successfully for over thirty years, in almost all types of water-based, corrosive environments.
- The measurement may be made between two nominally identical electrodes (a two-electrode system) or a conventional three-electrode system as shown in Fig. 4.
- In the polarization resistance method it is possible to estimate whether the reinforcement corrodes in active or passive.

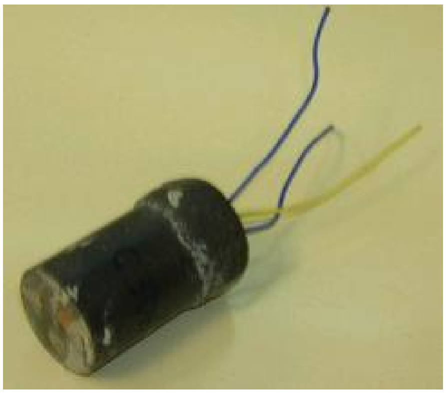


Fig. 4. Schematic of LPR probe.

The polarization resistance, R_P, of the reinforcing steel is defined as the slope of a potential-current density plot at the corrosion potential (E_{corr}) as follows:

$$R_p = [\Delta V / \Delta I]_{Ecorr}$$

Considering the correction of potential drop due to concrete resistance (IR drop correction), R_P is:

$$R_p = [(\Delta V - \Delta I * R_c) / \Delta I]_{Ecorr} ,$$

where ΔV and ΔI are the applied potential and current response, respectively, and R_c is the concrete resistance between the reference electrode and the surface of reinforcing bar, which can be obtained by AC impedance technique. The corrosion current density is calculated from the Stern-Geary equation:

$$I_{corr} = B / R_p \quad \text{and} \quad B = [(b_a * b_c) / 2.303 * (b_a + b_c)] ,$$

where "B" is the so-called "Stern-Geary constant" that can be determined from the ba and bc, which are the Tafel slopes for the anodic and cathodic reactions, respectively. A value of 26 mV and 52 mV is often used in the calculation for the bare steel in the active and passive stages respectively. For simplicity, a value of 26 mV was used to calculate all the corrosion rates in this paper since the corrosion current is inversely proportional to R_P. The criteria [8] for estimating the reinforcing steel corrosion are given in Table 2.

Table 2. Criteria for estimating reinforcement corrosion conditions.

Corrosion Rate ($\mu A\ cm^{-2}$)	Extent of Corrosion
$I_{corr} < 0.1$	P : passive condition
$0.1 < I_{corr} < 0.5$	L : low to moderate corrosion
$0.5 < I_{corr} < 1.0$	M : moderate to high corrosion
$I_{corr} > 1.0$	H : high corrosion

2.2.3. Electrical Resistance Method

Measurement of electrical resistance of the post tensioned cable will give a qualitative indication of the corrosion in prestressing strand. The measured resistance can be analyzed to find the area reduction of the strand using the following relation.

$$R = \rho L/A$$

R : Measured resistance
ρ : Resistivity of the material
L : Length of the cable.
D : The diameter of the strand
N : No. of strand
A : Cross-section area $[N * (\prod D^2 / 4)]$

To measure the resistance on the post tensioning cable all the strands are required to be short circuited externally in both the ends of the cable. The excitation is to be made and the voltage is measured to find the resistance. The schematic of electrical resistance measurements is given in Fig. 5.

2.3. Strain Gauge Measurement for Force Monitoring

2.3.1. Strain Gauge

To design a structure which ensures the necessary strength, it is significant to know the stress borne by each material part. However, at the present scientific level, there is no technology which enables direct measurement and judgment of stress. So, the strain on the surface is measured in order to know the internal stress. Strain gages are the most common sensing element to measure surface strain.

The strain gauge is a versatile sensor. Strain gages are designed to electrically detect "strain," minute mechanical changes occurring in response to applied force. Strain gages enable detection of imperceptible elongations or shrinkages occurring in structures. Measurement of such elongations or shrinkages reveals the stress applied to the structure. Stress is an important factor to confirm the strength and safety of structures. The location at which strain gauges are to be installed is determined by the purpose of measurement, access available and the protection required during and after installation. If stress is required to be measured at a particular point, the gauge can simply be located at that point. It is however not so simple in most measurements. Generally speaking, to get the true picture on stress or the loading pattern, strain has to be monitored in number of points.

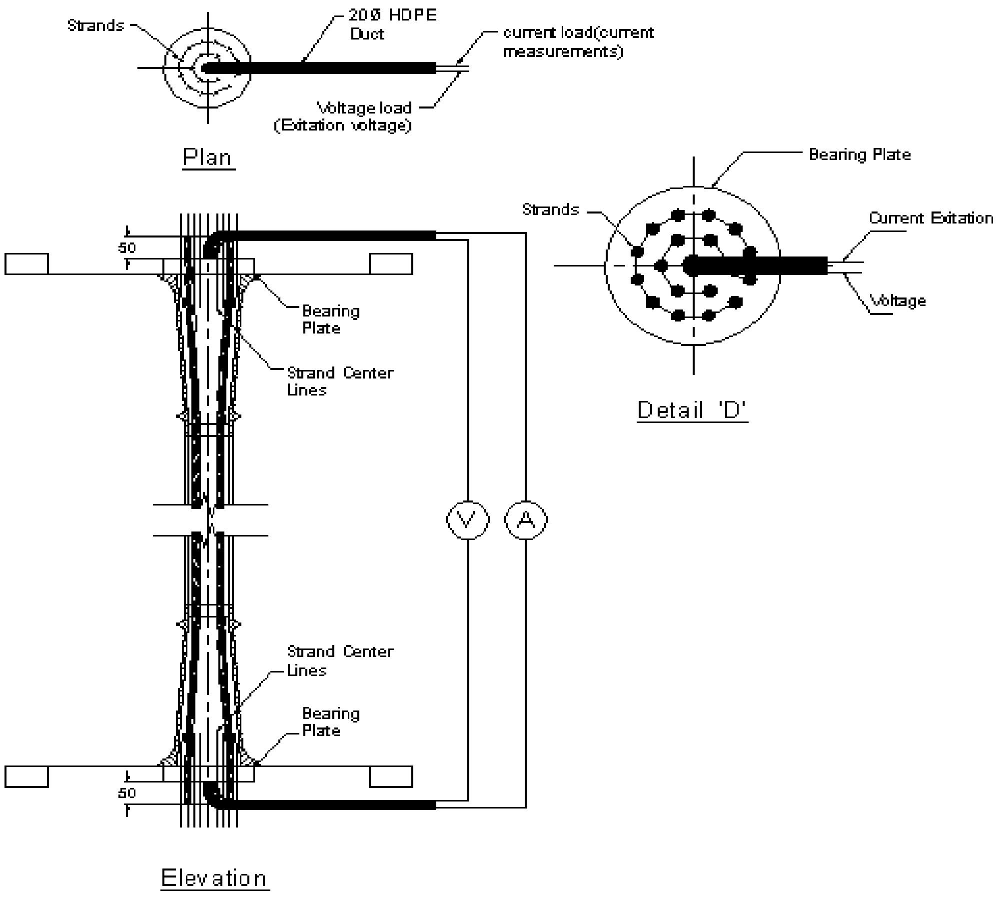


Fig. 5. Schematic installation of electrical resistance measurement.

Measurement of strain at one point would be sufficient if no bending was occurring in the member, for example, near the centre of a long thin member subjected to tensile load. To take care of bending effects and uneven stress, more than one strain gauge is required to mount at each cross section of the structural member. The number of gauges is determined by the nature of application and the accuracy of measurement.

2.3.2. Strain

When a force is applied to a body, the body deforms. In the general case, this deformation is called strain. This write up will be more specific and define the term STRAIN to mean deformation per unit length or fractional change in length and give it the symbolε. This is the strain that we typically measure with a bonded resistance strain gage.

Since practical strain values are so small, they are often expressed in micro strain which is ε x10^{-6} (note this is equivalent to parts per million or ppm) and is expressed by the symbol, $\mu\varepsilon$. As described to this point, strain is fractional change in length and is directly measurable.

Online stress measurement

The loss of prestress is a very serious problem in the stressed prestressing cables. A reasonably good estimate of the magnitude of loss of prestress is necessary from the point of view of design. The losses are due to various factors such as elastic deformation of concrete, relaxation of stress in steel, shrinkage of concrete, creep of concrete, friction and anchorage slip. Some time sudden changes in temperature will also causes loss of prestress, especially in the case of steam curing.

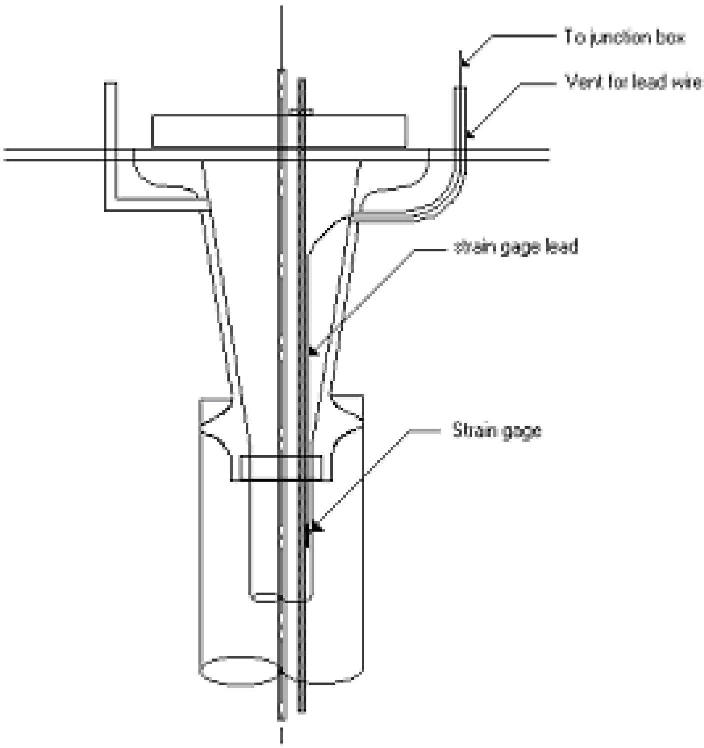


Fig. 6. Schematic for strain gage fixing.

2.4. Hardware

Generally data acquisition device must have a high performance and a very accurate measurement. To acquire the data correctly, we use National Instruments Field point modules. The hardware is more precious and very accurate measurements device. Following are the National Instruments field point modules were used for the online corrosion monitoring system [9].

- FP-2000 (Ethernet Module)
- FP-AI-100 (Filed Point Analog Input Module)
- FP-DO-410 (Field Point Discrete Output Module)
- FP-AO-210 (Filed Point Analog Output Module)

Initially the module was configured using Measurement& Automation Explore (MAX) software.

Table 3. Field Point Modules range and description.

Module Name	Description of Module	Operating Range
FP-2000	Filed Point Network module, 11-30 VDC, 16 MB DRAM,	Speed 10/100 mbps, 100m, -25 ºC to 55 ºC
FP-AI-100	Field Point, Analog Input Module, 8 channel, 12-bit resolution, -40 ºC to 70 ºC	Voltage ±30 VDC, Current ±20 mA
FP-AO-210	Field Point , Analog Output Module, 8 Channel, 12 bit resolution, -40 ºC to 70 ºC	Output Voltage 0 to 10 VDC

FP-2000 module is an interface between PC and the sensors. The power supply is connected to the FP-2000. The positive terminal is connected to the voltage pin and the negative terminal is connected to the common pin in FP-2000. The data were transferred from the Field Point module FP-2000 to computer through RJ-45 cable. Fig. 7 illustrates the signal lead connection with the hardware.

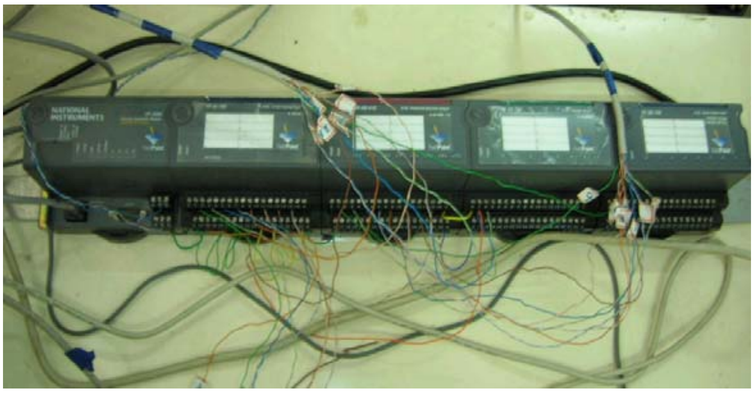


Fig. 7. Signal lead connection with the hardware.

2.4.1. Hardware Configuration

Before activating the hardware system each Field Point Modules must be configured using the software Measurement & Automation Explorer (MAX). It is an interface between the computer and the hardware. Following were involved in the configuration of hardware.

1. Open Measurement & Automation Explorer.
2. Set the IP No, Name for FP-2000 network module.
3. After configure the FP-2000 module select the name and click Find Devices to access the other modules connected with them.
4. After display of connected modules, we can set the needed configuration to each module.
5. Save the configuration.

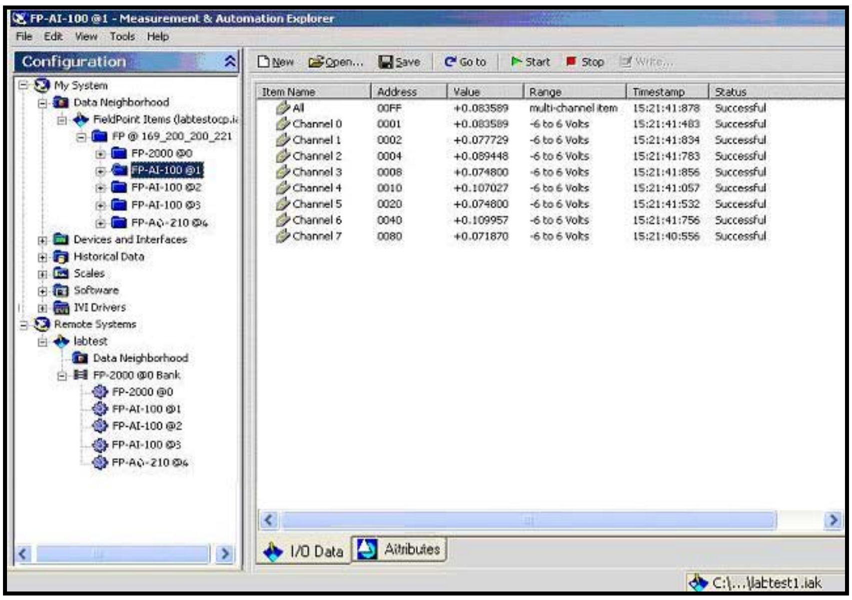


Fig. 8. The configuration window in NI MAX.

2.5. Software for Online Corrosion and Force Monitoring System

The corrosion and force monitoring system for the prestressing steel in the post tensioning cable will be made automatic by online corrosion and force monitoring system. The coding was developed using LabVIEW 8.0 software and the data acquisition was made by National Instruments hardware. The structure will be divided in to different units and the units are connected with Ethernet hubs. The main PC at the control room will control the entire system for the operation.

2.5.1. LabVIEW – An Introduction

- LabVIEW, which is an acronym for Laboratory Virtual Instrument Engineering Workbench and is distributed by National Instruments.
- LabVIEW is written in G or graphical programming language, which is composed of many "nodes" wired together. There is no text based code like C++, Fortran, Basic, etc., but a diagrammatic view of how the data flows through the program.
- Also, unlike the other programming languages, LabVIEW has continuous Auto-compiling, i.e. it tells you when an error has been committed immediately!
- LabVIEW includes libraries for data acquisition, data analysis, data presentation, and data storage.
- LabVIEW programs are called virtual instruments, or VIs, because their appearance and operation imitate physical instruments, such as oscilloscopes and multimeters.

2.5.2. Purpose of LabVIEW

Use Lab VIEW to communicate with hardware such as Data acquisition, vision, and motion control devices and GPIB, PXI, VXI, RS-232, and RS-484 devices.

- Lab VIEW also has built-in features for connecting applications to the web using the Lab VIEW web server and software standards such as TCP/IP network and active X.
- Use LabVIEW, can create text and measurements, data acquisition, instrument control. Data logging, measurements analysis, and report generation applications.
- It can also create stand-alone executables and shared libraries, like DLLs between LabVIEW is a true 32-bit compiler.
- Finally, National Instruments technical support and developer Zone ensure successful development of solutions.

2.5.3. Virtual Instruments

LabVIEW programs are called virtual instruments, or VIs, because their appearance and operation imitate physical instruments, such as oscilloscopes and multimeter. Every VI uses functions that manipulate input from the user interface or other sources and displays that information or moves it to other files or other computers.

LabVIEW is a true 32-bit compiler. It is used for data collection, analysis, presentation and storage. LabVIEW communicates with most instruments through instrument drivers, which are libraries of VIs that control programmable instruments.

A VI contains the following three components:

Front panel	- Serves as the user interface.
Block diagram	- Contains the graphical source code that defines the functionality of the VI.
Icon and connector panel	- Identifies the interface to the VI so that you can use the VI in another A VI within another VI is called a subVI

Front Panel:

- The interactive user interface of a VI is called the front panel, because it simulates the panel of a physical instrument.
- Fig. 9 shows the front panel set-up which contains knobs, push buttons, graphs, and other controls and indicators. You enter data using a mouse and keyboard, and then view the results on the computer screen.

Block Diagram:

- The VI receives instructions from a block diagram, which you construct in G.
- The block diagram is a pictorial solution to a programming problem.
- The block diagram is also the source code for the VI.

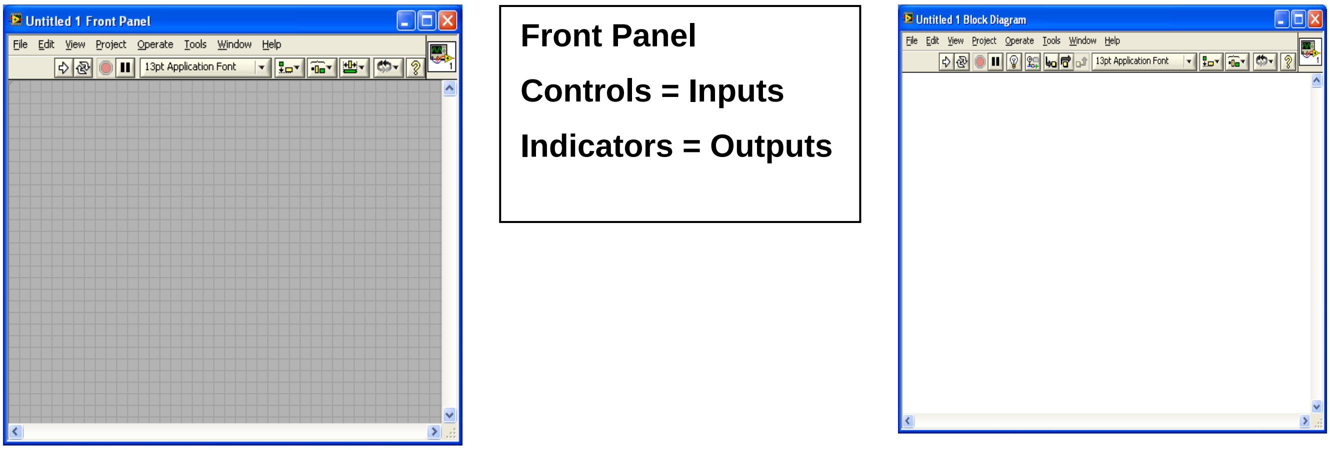


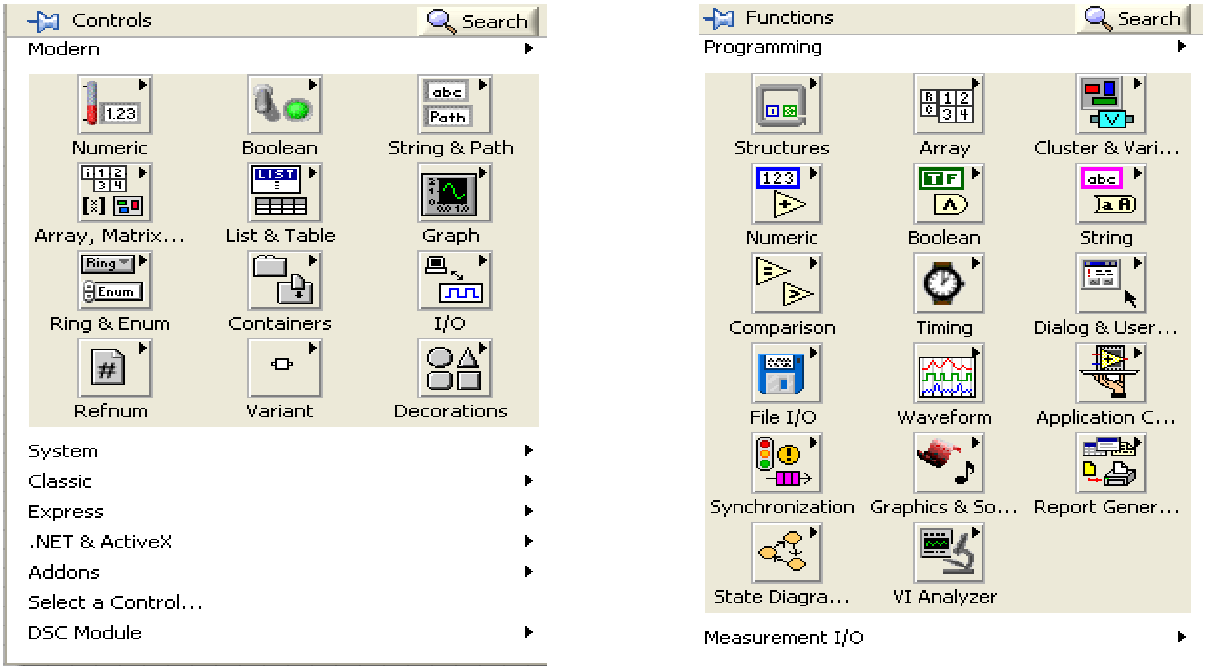
Fig. 9. Front panel setup.

Controls and Functions Palettes: are shown in Fig. 10.

Stand Alone System:

For the online instrumentation purpose a concrete structure is to be divided into different units in which the stand alone system is required to be incorporated.

A standalone system consisting of Ethernet Module and input and control modules. Data Acquisition will be made by input modules and control modules. The data’s were controlled and processed through Ethernet moduleA software coding in LabVIEW program is developed and was used to run the stand alone system. Fig. 11 shows a block diagram of the coding and Fig. 12 shows a front panel of the coding.



(a) (b)

Fig. 10. Control and function palette: (a) Controls Palette (Block Diagram Window), (b) Functions Palette (Front Panel Window).

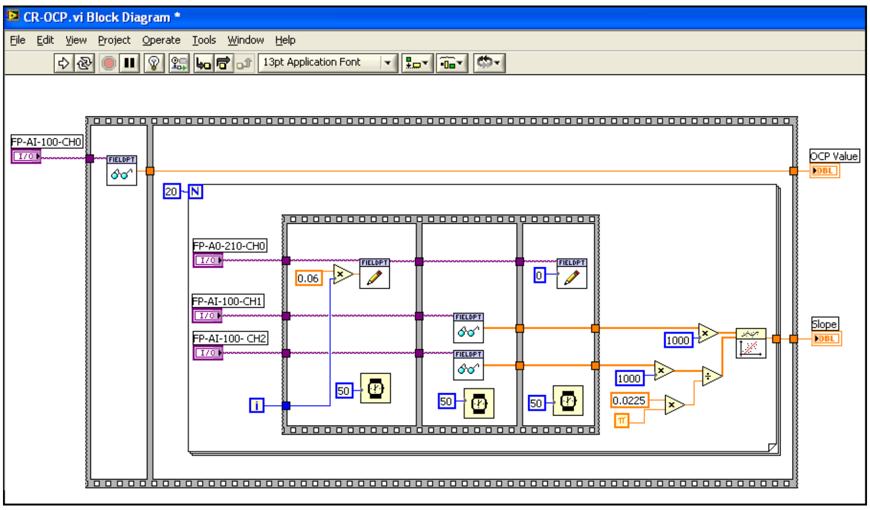


Fig. 11. Sample coding for data acquisition block diagram.

The stand alone system made running in real time mode and the system made executable file using build application. Now the system will run automatically as an independent module. The Ethernet module continuously acquires the data and transfers the data with time interval to the control room PC. In a control room PC all the stand alone systems were controlled by Data logging and Supervisory Control (DSC) software. Separate coding was developed in DSC module. In control room PC following facilities were provided.

i) To view individual Stand Alone System.
ii) To view individual sensors data in engineering units.
iii) Historical view of all the sensors data.
iv) Back-up Facilities.

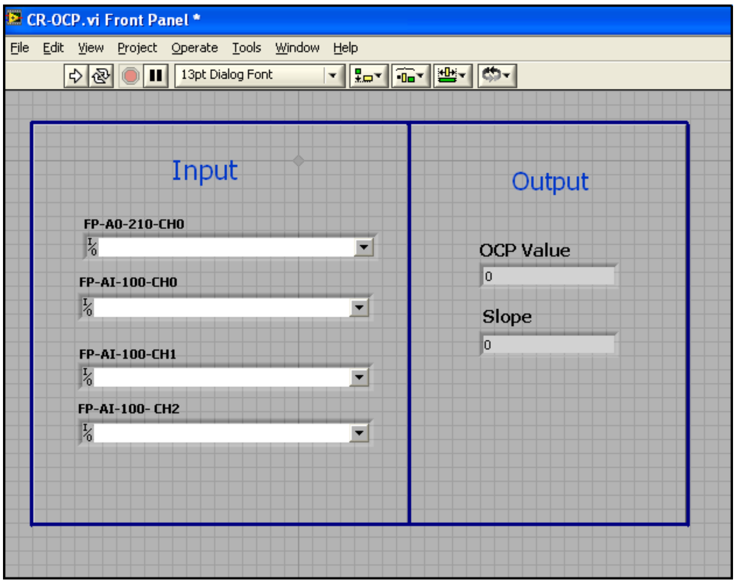


Fig. 12. Sample coding for data acquisition front panel.

Real time data presentation

The data presentation will be made by LabVIEW 8.0 coding and with LabVIEW DSC Module. Following are the steps involved for data presentation.

1. Data from all the sensors are to be retrieved from data acquisition hardware to data logging computer.
2. The data's were reallocated in Host computer.
3. The time limit for data retrieval will be set in coding.
4. The data's were transmitted to shared variable.
5. Formatted data were retrieved from the shared variable in the DSC Module of the host software.
6. The data's were properly tagged and entered in to the Citatel database.
7. The data are to be remodified according to the client's requirement to engineering values.
8. In the Main window, options were made for time interval, data logging time, types of engineering values, Historical trend and Back-up facilities.
9. Different windows were designed to integrate with Main-Host windows.
10. The logged data can also be retrieved from the Citatel database in the excel format.

Fig. 13 shows the front panel of the online corrosion monitoring system for a typical prestressed concrete structure and Fig. 14 shows the historical data review.

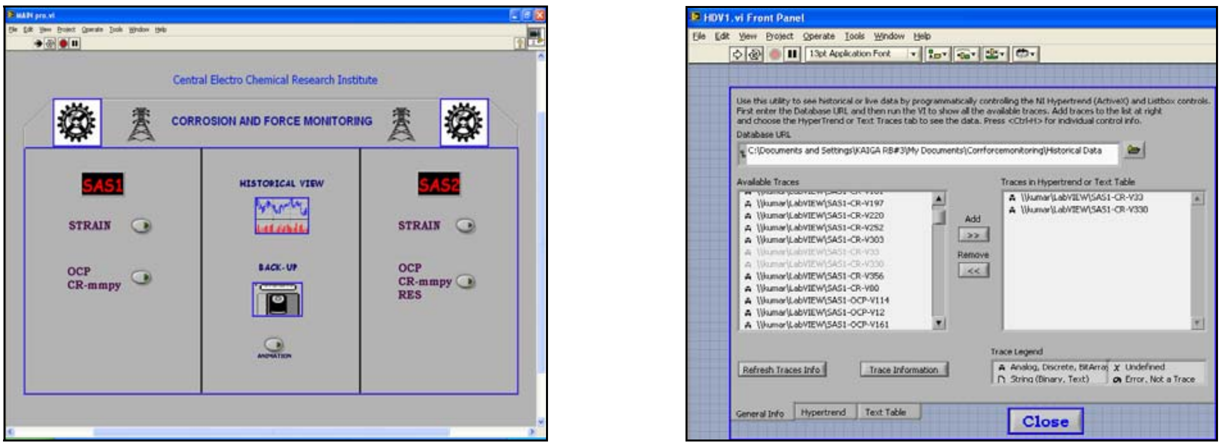


Fig. 13. Corrosion monitoring front panel setup.

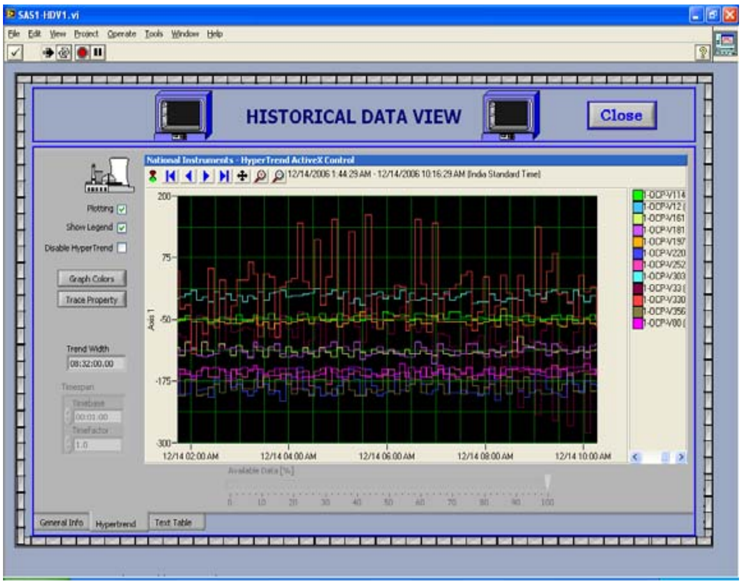


Fig. 14. Historical data view.

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MINALOGIC

Thursday June 26

Image Sensors & Image Processing

Discover the Expertise of Minalogic

Several global leaders in the field of imaging technologies, members of Minalogic (the French competitive cluster for micro- and nano-technologies and embedded software), will present their recent development.

8h45 Introduction : Nicolas Leterrier, Minalogic

9h05 - 10h30

Visible Imagers

> 9h05 : **CMOS Image sensor for Mobile Phone camera : past and trends**
J.-L. Jaffard, STMicroelectronics

> 9h25 : **Imager process evolution and benchmark**
E. Mazaleyrat, STMicroelectronics

> 9h45 : **Adaptative multi-resolution for low power image sensor**
A. Verdant, CEA/LETI-MINATEC

> 10h00 : **TSV technology for image sensors**
J. Michailos, STMicroelectronics

> 10h15 : **Liquid lens for miniature camera application**
B. Berge, VARIOPTIC

10h30 - 11h Break

11h - 12h25

Visible Imagers

> 11h00 : **Design and evaluation of TDI operation of CMOS sensor for industrial imaging applications**
H. Bugnet, e2V

> 11h15 : **New image sensor color filters materials deposited by MOCVD**
S. Guerroudj, LMGP/STMicroelectronics

OLED

> 11h30 : **Active Matrix of Any Shape for Organic Light Emitting Diodes displays (AMAzOLED)**
J. Magarino, Thales LCD et al.

> 11h50 : **Microdisplays for near-to-the-eye applications**
G. Haas, Microoled

Astrophysics

> 12h10 : **Where integrated optics developed for high speed networks meets astronomy : photons from far astrophysical sources mixed at the focus of the world largest telescopes reveal their intimate nature**
J.-P. Berger, LAOG (Laboratoire d'Astrophysique de l'Observatoire de Grenoble)
F. Malbet, LAOG

12h30 - 14h00 Lunch

14h00 - 16h00

Infrared Detectors

> 14h00 : **Uncooled Infrared detectors : state-of-the-art and future trends**
J.-L. Tissot, Ulis

> 14h20 : **Advanced HgCdTe technologies and applications**
P. Tribolet, Sofradir

> 14h40 : **HgCdTe APD focal plane array development at CEA-Leti-Minatec**
J. Rothman, CEA/LETI-MINATEC

> 14h55 : **Scene base correction for thermal IR imaging**
B. Dupont, CEA/LETI-MINATEC

> 15h10 : **3D IR imaging with time of flight techniques**
F. Guellec, CEA-LETI/MINATEC

X-Gamma Imagers

> 15h25 : **Recent development in semi-conductor based X-and gamma-ray imaging**
J.-L. Amans, CEA-LETI-MINATEC

> 15h45 : **New technique for high dynamic range pixel**
A. Peizerat, CEA/LETI-MINATEC

16h00 - 16h30 Break

16h30 - 17h20

Bio-Imaging

> 16h30 : **State-of-the-art and future trends in Optical Molacular Imaging**
P. Rizo, CEA/LETI-MINATEC

> 16h50 : **Innovative neuronal image sensor circuit**
O. Billoint, CEA/LETI-MINATEC

Instrumentation

> 17h05 : **The SWIFTS Micro-spectrograph**
P. Benech, IMEP
E. Le Coarer, LAOG (Laboratoire d'Astrophysique de l'Observatoire de Grenoble)

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 6-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

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