EMBEDDED FPGA SOLUTION FOR WATER QUALITY MONITORING SYSTEM
Calibration and Measurement

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Keywords: Reconfigurable measuring system, calibration control, real-time processing.

Abstract: This paper presents a field operating water quality monitoring system based on real time controller and FPGA module. The system features functioning includes in-situ automatic cleaning and calibration of stand alone sensors such as turbidity, pH or conductivity, on-line measurement of water quality parameters using the calibrated sensors. In order to perform the above mentioned calibration and measurement tasks the system uses a set of centrifugal pumps and electrovalves and associated embedded control materialized by the LabVIEW programmed FPGA module. The voltages associated with water quality measurement channels are acquired using a four channels analog input module that work also under FPGA control. The data processing tasks are distributed between the FPGA module and the real-time controller included in the system. A practical approach concerning the sensor model implementation capabilities using the real-time controller (NI cRIO-9002) or FPGA (NI cRIO-9003) is also included. In order to provide the wireless remote control of the system an Ethernet – wireless bridge (IEEE802.11g) and client-server TCP software developed in LabVIEW were included in the system. A PDA based remote control solution was also implemented to evaluate system performance.

1 INTRODUCTION

Real time monitoring and water quality assessment of surface waters represents nowadays an important challenge associated with water quality assurance and requires measuring systems with multiple measuring nodes with calibration facilities.

The systems architectures generally includes different measuring nodes, installed at different points of the monitored area, that includes sensors able to output information related with the quantities elected to characterize water quality and the hardware required to power the sensors and to process their outputs. Data collected at the different nodes is preferably transmitted to a central land-based station where it is further processed to yield the desired information. The nodes must then also include hardware for data transmission and usually some kind of processing unit (e.g. microcontroller) able not only to format data for transmission but also to transform sensors' output voltages into values of the measured quantities. In previous papers, the authors have presented solutions of distributed measuring systems for water quality monitoring and assessment (Postolache, 2002, Postolache 2003, Girao, 2003, Postolache, 2005).

The quantities commonly used in the assessment of water quality are: temperature, pH, conductivity, turbidity, dissolved oxygen, and heavy metals concentration. With the exception of temperature, the performance of the sensors for these quantities is highly dependent on periodic cleaning and calibration.

Considering the calibration and measurement requirements associated with water quality measurement nodes the present work propose a novel architecture based on a reconfigurable control and acquisition system (NI CompactRIO). The system permits accurate timing and the control of several pumps and electrovalves associated with water quality sensor (e.g. conductivity) test or calibration for different standard solutions. Data acquisition, data processing and data communication are additional capabilities of the presented system. Considering the field operation conditions and the Wi-Fi compatibility of the presented system a mobile solution based on a PDA is developed in

Postolache O., Dias Pereira M. and Girão P. (2006).
EMBEDDED FPGA SOLUTION FOR WATER QUALITY MONITORING SYSTEM - Calibration and Measurement.
In *Proceedings of the Third International Conference on Informatics in Control, Automation and Robotics*, pages 154-160
DOI: 10.5220/0001221301540160

order to perform tasks such as water quality data reading, start/stop calibration or measuring, fault or pollution events checking, calibration or measuring control, fault or pollution events detection and diagnosis.

2 SYSTEM HARDWARE

The water quality field measurement system includes as the main parts: a set of water quality measurement channels (temperature, pH, conductivity and turbidity) connected to high accuracy analog input module plug in NI cRIO-9103 FPGA reconfigurable chassis that communicate through the PC bus with NI CompactRIO 9002 real time controller (National Instruments, 2005). Additional digital output modules assure the control of the system pumps and electrovalves, devices that are actuated when the system works in calibration or measuring mode. In order to distribute the data and to receive the control commands an Ethernet to wireless bridge is connected to the cRIO Ethernet port. Data access, calibration and measurement commands can be sent using a PDA Pocket PC (HP iPaq 2700) included in the water quality wireless network (Figure 1).

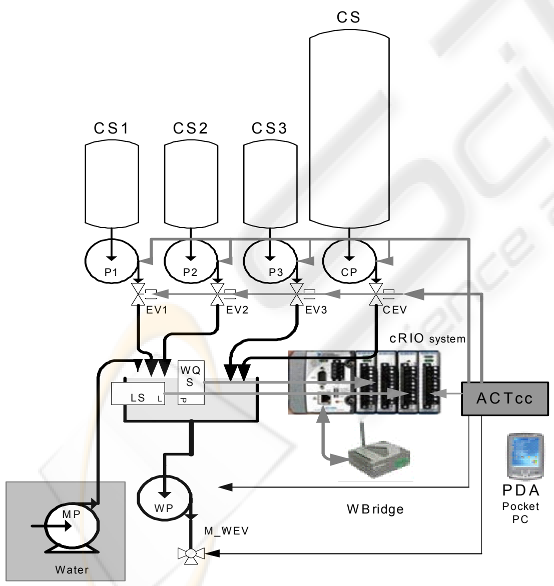

Figure 1: CRIO based embedded system for water quality measuring and WQ sensor calibration tasks

Figure 1 shows the block diagram of the field operating WQ monitoring system hardware that includes the main sensing, control and processing blocks associated with WQ parameters measurement and the calibration of corresponding sensors such as turbidity, conductivity and pH. Thus the control is based on the FPGA reconfigurable I/O hardware (NI cRIO 9103) which control the system actuators (pumps and electro-valves) through a NI- cRIO 9472 digital output block, acquires the level information (on/off) of the liquid (standard calibration solution, water under test) in the test cuvette using the optical level sensor connected to one of the digital input of the NI cRIO 9423 module. In the calibration or measurement mode the system acquires the voltage from the WQ measurement channels using four analog input of the NI cRIO 9215 module.

In Figure 1 the following notations were used: CSi – calibration solution vessels l, P_1, P_2, P_3, P_4 - calibration pumps, LS-level sensor, WQ-S water quality sensor under calibration, CP-cleaning pump, WP –waste pump, ACTcc- actuator conditioning circuit block, EVi-calibration electrovalves, CEV-cleaning electrovalve and M_WEV-measurement and waste electro-valve. The FPGA module communicates using the PCI bus with a NI cRIO-9002 real-time embedded controller characterized by 32 MB DRAM memory and 64 MB of non-volatile flash storage. The real-time controller permits to implement advanced processing algorithms (fault detection, data forecasting, data fusion), WQ file storage and wireless communication using an Ethernet to wireless bridge (D-LINK DWL 810) connected to the Ethernet port.

Considering the communication capabilities the designed WQ calibration and measurement unit can be considered as a smart node of WQ monitoring distributed network that can deliver and receive the data from different devices such as laptop, desktop PC or a PDA included in the network. In the present application special attention was dedicated to the utilization of the PDA to read current values of the measurement data delivered by the WQ measurement system based on cRIO 9002.

As it was presented in Figure.1 the WQ sensor calibration is performed using a set of standard calibration solution (e.g. OAKTON pH 4.01, 7 and 10 standard buffer solutions for pH) stored in the CS_i calibration vessels and injected in the testing cuvette using a set of pumps (pumps - Jabsco Pumps 42510-000, 12 VDC, 1.5A, 7.5 l/min) and electrovalves (Bergamo 0-15 bar, 12 VDC, ¼”) that work under control of embedded FPGA calibration program. Additional pumps included in the system are: the CP pump that is used to pass the cleaning solution from the cleaning vessel to the test cuvette, the WP pump is used to empty the test cuvette either to the waste vessel (calibration phase) or to water under test (measurement session), and the MP (measuring pump) that is a submersible pump (1 submersible 12 VDC, 2.5A, 49 l/min Johnson pump) and used to assure the circulation of the water between the monitored area (river, estuary) and the test cuvette.

3 SYSTEM SOFTWARE

The system software includes two parts, one related with
the smart calibration and measurement system based on cRIO real-time controller and FPGA reconfigurable module and another represented by the software of the PDA Pocket PC.
The FPGA reconfigurable module software was developed using LabVIEW for FPGA toolset and is associated with the pump and electrovalves control through digital output lines, the level on/off sensor reading, the acquisition of the water quality sensors voltage values when the system works in the measurement mode and the sensor under test voltage acquisition when the system works in calibration mode. Using the FPGA onboard memory and the memory read/write functions the FPGA embedded algorithms for digital-code voltage to water quality parameter (e.g. temperature) is carried out.
Taking into account the limitation of the FPGA related the numerical values calculation (only integers operation) the main part of processing of the acquired data is developed on the real-time controller level using the LabVIEW real-time. Thus a multichannel voltage-to-WQ conversion block was implemented. Taking into account temperature variation influence on the measurement channel accuracy, the temperature compensation based on IEEE1451.2 correction engine algorithm was also implemented.
Data logging software block was implemented on the cRIO controller in order to store the information about measured water samples.
Regarding data distribution in the water quality network that includes the PDA and other PCs (laptop or desktop PC) the cRIO real-time controller includes a TCP server-multiple client component. Implementing client software on the PDA level using (LabVIEW for PDA) the PDA operator can obtain the current values of the Water Quality parameters and the calibration coefficients of the water quality measurement channels. Calibration and measurement start-up actions or measurement channel tests when anomalous functioning is reported (fault events) can be ordered using the PDA software component.

3.1 Embedded FPGA Software

The embedded FPGA software is developed using the LabVIEW FPGA toolset and is associated with: electro-valves and centrifugal pumps control, WQ sensor calibration, water quality measurement, fault or pollution event detection multi-channel analog-input and digital input control, digital filtering of the acquired samples from the WQ measuring channels associated with NI cRIO-9215 module.
For the particular case of WQ sensor calibration the flowchart of the calibration session is presented in Figure 2.
Referring the measuring mode an additional submersible pump is used to bring the water under test into the test cuvette and the voltages obtained on the sensor channels are acquired. The water under test level on the testing cuvettte is imposed constant thus a simple on/off control of the WP and M_VEW is implemented on the system while the level information is obtained from the LS sensor.
When the system works in the measuring mode and a strong variation of WQ parameter from one of the measuring channel is detected (using the derivative information) the pollution event detection mode is start-up. In order to make an accurate discrimination between the pollution and measuring channel anomalous functioning a "one point test procedure" is designed and implemented.
The action associated with this procedure is similar to the calibration of the considered measuring channel for one standard solution.
A comparison between the current acquired voltage $U_{WQ}^{CS}(t)$ from the tested channel and reference voltage value $U_{WQ}^{CS}(t_{ref})$ considered for the same calibration solution (CS) is carried out.
The fault detection is expressed by the following relation:

$$\left|U_{WQ}(t)-U_{WQ}(t_{ref})\right| \leq \xi_{WQ\,fault} \qquad (1)$$

Thus if the difference between the considered values is greater than an imposed limit $\xi_{WQ\,fault}$ (5% of $U_{WQ}^{CS}(t_{ref})$ in the present case) the anomalous functioning message is delivered in the WQ monitoring network. In opposite case the pollution event signal is generated.
In order to increase the SNR (signal to noise ratio) the acquired samples from the WQ measuring channels are filtered using a FPGA embedded

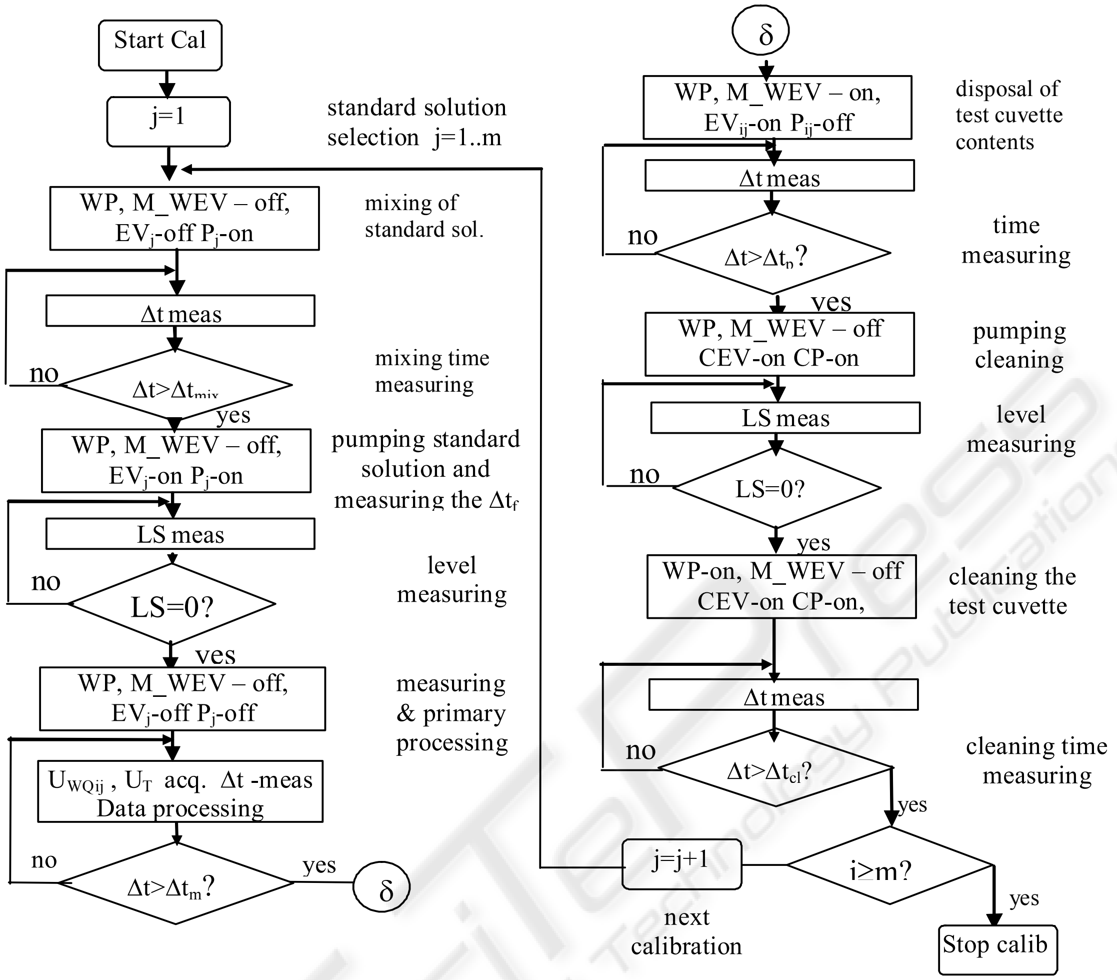

Figure 2: Calibration flowchart: U_{WQ}j-voltage associated with the sensor under calibration for the calibration point j, U_T-voltage associated with the temperature measuring channel, m – number of calibration points, Δt – time interval associated with the filling and disposal of the test cuvette contents, LS – level sensor.

moving average digital filter algorithm. that is implemented for each analog input channel of NI cRIO-9215 module (Figure 3)

$$y(iT) = \frac{1}{M} \cdot \sum_{j=0}^{M-1} x(iT + jT) \qquad (2)$$

The effectiveness of the implemented filter is controlled by selecting the appropriate number of samples M for the averaged group. For the present case a M=4 “smoothing factor” was used. Other filter technique was also implemented in order to achieve a shorter measurement time and less noise sensitivity:

$$y(iT) = F \cdot x(iT) + (1 - F) \cdot y((i-1)T) \qquad (3)$$

where F represents the filtering coefficient varying between [0,1].

The acquired and smoothed voltages during the t_m period are sent through PCI communication to the cRIO-9002 controller where a LabVIEW Real-Time developed software performs data processing, data storage and data communication tasks.

3.2 Real-time Controller Software

The software component associated with the cRIO real time controller includes the GUI of the system, the data processing, the data storage and data communication blocks.

Referring to the data processing block it provides the digital-code to voltage conversion:

$$V_{WQ} = WQ\_code \cdot \frac{FS}{2^n}, \quad FS = 10V \qquad (4)$$

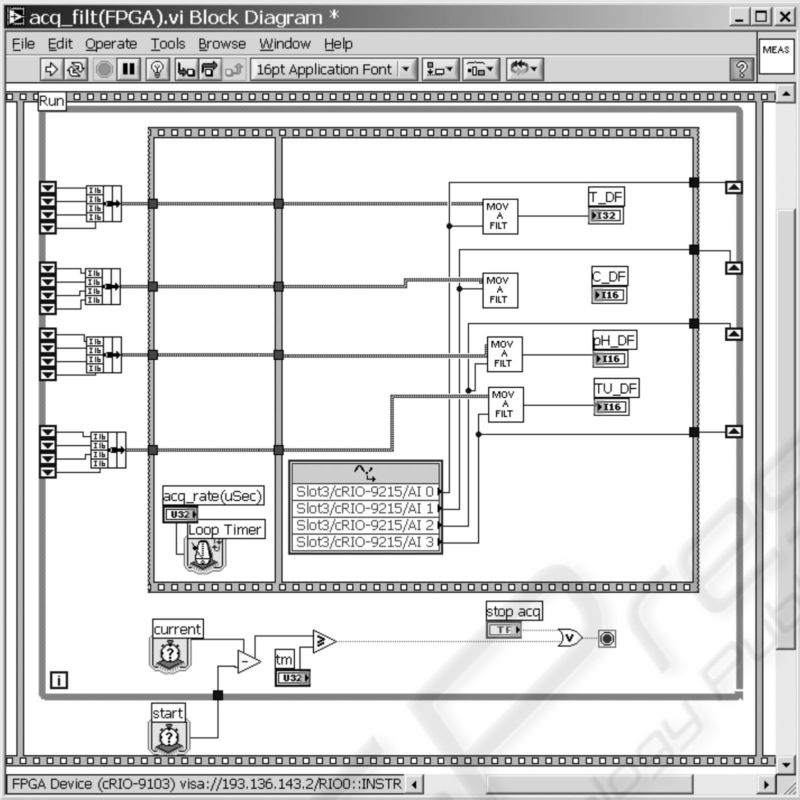

Figure 3: The LabVIEW sequence of FPGA based WQ channel acquisition software including the acquisition rate control(acq_rate(uS)), the acquisition time period and the moving average filtering block for average factor M=5.

and voltage to WQ parameter value conversion that uses the IEEE1451.2 for Smart Transducers (correction engine) standard (Eidson,1998) given by:

$$WQ=\sum_{i=0}^{D(1)}\sum_{j=0}^{D(2)}\cdots\sum_{p=0}^{D(n)}C_{i,j,\ldots p}\cdot[X_1-H_1]^i[X_2-H_2]^j\ldots[X_n-H_n]^p \quad (5)$$

where X_n represent the input variable expressed by acquired voltages from the sensor measurement channel (U_T, U_{pH}, U_{σ},, U_{TU}) in the present case, H_n the offsets of the input variables, D(k) the degree of the input X_k, and $C_{i,j,..p}$ the POL_m coefficients. The $C_{i,j,\ p}$ coefficients are obtained using the multiple regression method [11] associated with the latest calibration of the measurement channel. Thus on the particular case of considered water quality sensors: temperature, pH, conductivity and turbidity sensors, the multivariate relations are used to extract the following quantities:

$$\begin{aligned} pH&=C_0^{pH}+C_{01}^{pH}U_{pH}+C_{10}^{pH}U_T+C_{11}^{pH}U_{pH}U_T\\ \sigma&=C_0^{\sigma}+C_{01}^{\sigma}U_{\sigma}+C_{10}^{\sigma}U_T+C_{11}^{\sigma}U_{\sigma}U_T\\ TU&=C_0^{TU}+C_{01}^{TU}U_{TU}\\ T&=C_0^{T}+C_{01}^{T}U_T; \end{aligned} \quad (6)$$

where U_{pH}, U_{σ}, U_{TU}, U_T represents the primary variable associated with pH, σ, TU, T quantities. At the same time U_T represents the perturbing effect variable for pH and conductivity (σ) calculation. The calibration solution for the particular case of conductivity, assumes the following conductivity values σ={80 uS/cm, 447uS/cm, 1413 uS/cm and 2070 uS/cm} and the temperature variation was included in the [5;30]°C interval.

Referring the implemented software it permits to perform the WQ data logging during the measurement mode. For example the operator can specify a fixed data logging rate (DTR=**WQ**/15min) where the **WQ** represents the water quality vector.

The data file can be accessed through the cRIO-9002 ftp server capabilities from other PCs of the water quality wireless network. At the same the current values of the WQ can be shared with a PDA pocket PC using the TCP client-server architecture implemented in LabVIEW.

3.3 PDA Software

The mobile software component of the water quality calibration and measuring system were developed in order to permit an easy access of the WQ measured data and send commands associated with measuring and calibration procedures. The software that implements the TCP/IP communication between the PDA and cRIO real time controller was developed using the LabVIEW PDA for PocketPC toolkit (National Instruments, 2006). Based on the TCP client components the operator can check the normal functioning of the field water quality measurement system by a direct access of the data acquired from one of the measuring channels. The Figure.4 present the PDA user interface associated with WQ parameters values.

Figure 4: PDA interface for data visualization and remote calibration control.

In the figure can be observed the current values measured by the field node based on the cRIO system during a measurement cycle. Changing the WQ data to Calib CTRL tab the user can verify the date of the latest calibration and also can start-up a new calibration. Additional functionalities related with the fault detection and diagnosis are also included.

4 RESULTS AND DISCUSSIONS

In order to underline the proposed solution capabilities, in terms of the water quality measurement, auto-calibration, data processing and data communication capabilities, different testing procedure were carried out.

4.1 Calibration and Measurement

Using the above mentioned calibration and measurement system and the associated software components several laboratorial and field tests were carried out. In Figure 5 and Figure 6 present several calibration curves associated with conductivity and turbidity measurement channel calibration.

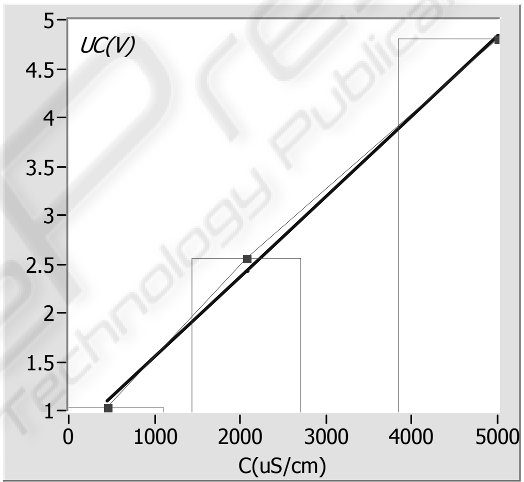

Figure 5 Conductivity calibration curve.

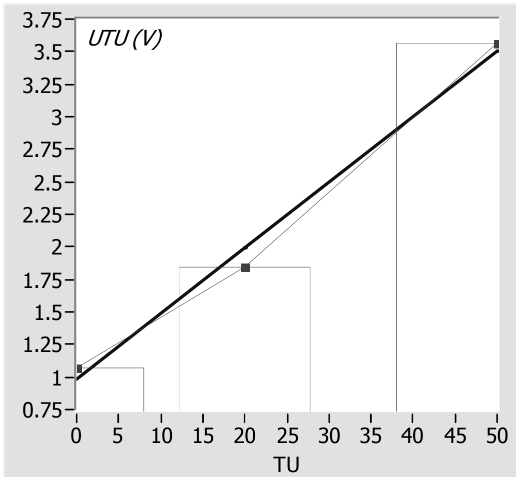

Figure 6: Turbidity calibration curve.

Referring to the above mentioned figure it can be underlined that the turbidity curve non-linearity is about ε_{TU}= 4% that justify the implementation of voltage-to-turbidity conversion algorithm based on piecewise linear approximation of sensor channel inverse model.

4.2 Power Consumption Tests

Considering the measurement requirements the field operation water monitoring system must have an autonomy, power consumption is a very important issue. The system is powered by a 12 VDC battery and tests were conducted to obtain the evolution of current and power consumption during both calibration and measurement sessions.

The calibration session includes a maximum 3 cycles (1 cycle flowchart being presented in Fig.2) according to the number of calibration points. Figure 6 shows the current and power evolution during the calibration of one point for the TU sensor. The total time (Δt_i sum) is 178 s, for an average current of 1.67 A and an average power consumption of 20.19 W.In the measurement phase, which takes about 200 s, the current consumption is 1.25 A.

5 CONCLUSIONS

The hardware and software proposed solution makes not only viable stand-alone smart sensing nodes for distributed water quality monitoring and assessment but also increases the accuracy of the measured quantities and assures equipment autonomy and life time, reducing, in particular, maintenance costs. The reconfigurable system based on FPGA assures accurate timings and voltage acquisition that guarantees accurate results on measuring or calibration procedures. The system interface with the operator is strongly improved by using the mobile component expressed by a PDA and the corresponding software is included in the system. This feature is especially important when the WQ measuring node is installed in inaccessible points.

Another important feature of the proposed system, now presented, are the fault detection and diagnosis capabilities at WQ node level and the advantage of mobile component implementation in order to receive signalling messages associated with anomalous functioning, of one or multiple measurement channels, pollution events that occurred in the monitored area.

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