

## **WATER QUALITY SENSORS CALIBRATION SYSTEM BASED ON RECONFIGURABLE FPGA TECHNOLOGY**

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**Abstract:** An implementation of a reconfigurable FPGA (Field-Programmable Gate Array) is proposed for digital control and acquisition tasks associated with a water quality sensor calibration system. The system permits the water quality (WQ) sensor auto-calibration based on FPGA control of different actuators (pumps and electrovalves) and of WQ data sensor acquisition, real time WQ data processing based on real-time controller capabilities and wireless data communication. Elements related with the power consumption of the calibration system are also presented.

**Keywords:** environmental measurement, real-time controller, field-programmable gate array, water quality sensors, calibration

### **1. INTRODUCTION**

Water is essential to human life and to the health of the environment. As a valuable natural resource, it comprises marine, estuarine, freshwater (river and lakes) and groundwater environments, across coastal and inland areas. Water has two dimensions that are closely linked - quantity and quality. Water quality is commonly defined by its physical, chemical, biological and aesthetic (appearance and smell) characteristics.

Human life can be seriously affected by water quality. Not only is drinking water a problem. Water pollution affects rivers, estuaries and a lot of elements that are an important part of human life resources. Some animals, especially fish and shellfish, can retain large quantities of pollutants that are very dangerous to humans. Thus, not only laboratory analysis of water quality are required but field on-line monitoring of water quality, in distributed networks, must be implemented to measure and, if possible, control water parameters.

In order to perform the water quality monitoring, different measuring systems including WQ sensors associated with the physical, chemical or biological characteristics were designed and implemented [1][2]. Environmental sensors require frequently calibrations, which imply the development of field calibration units. Several results were obtained by the authors in this area [3]

expressed by a WQ sensor calibrator prototype for one or multiple WQ measurement channels including a set of centrifugal pumps and electrovalves controlled by an RS232 multifunction I/O board and a Field Point real-time controller.

The present article presents a novel solution on water quality sensor calibration characterized by a small number of pumps and electrovalves and low power consumption, embedded digital control of the main calibration actions and analog-to-digital conversion control based on FPGA as part of a reconfigurable embedded NI cRIO-9103 system. The FPGA unit is able to communicate with a real-time controller (cRIO-9002) with 64 MB storage capability that reliably and deterministically executes the LabVIEW real-time software component of the calibration system. The main components of the real-time software are: sensor data processing, data logging and Wi-Fi data communication.

### **2. WQ SENSOR CALIBRATION SYSTEM**

To perform in-situ WQ sensors' calibration and WQ parameter measurement a virtual reconfigurable system based on FPGA and a real-time controller was designed and implemented (Fig.1).

#### **2.1 Sensors and actuators**

An important part of the implemented WQ sensor calibration system is a set of pumps and electrovalves that permit to perform different tasks such as the realization of the calibration and test solution using a mixing procedure, vessels cleaning, used solution storage, and continuous injection of the water under test.

As shown in Fig.1, two mixing peristaltic pumps (Watson Marlow 102R, S-pump and W-pump) are used to obtain the sensor testing or calibration solution by mixing the concentrated solution on the turbidity and conductivity sensor calibration case (e.g. formazine calibration solution 4000 NTU, KCl conductivity calibration solution 10 mS/cm) with de-ionized water. In order to inject the proper solution, several 3 ways electrovalves (Burkert 6014) are actuated. In Table 1 the on/off state of the pumps and electrovalves is presented according with the test and calibration of the considered sensing channel.

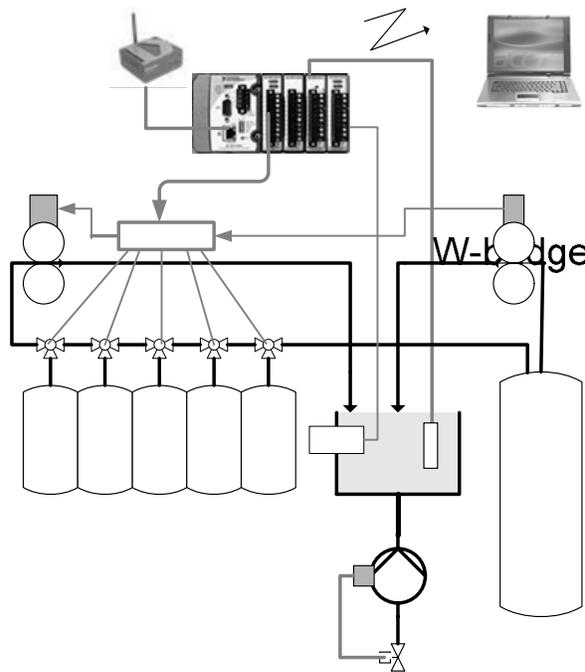


Fig. 1. The WQ sensor calibration system block diagram: C-SS, TU-SS, pH1-SS, pH2-SS, pH3-SS – conductivity, turbidity and pH standard solution vessels, DW-deionized water vessel, S-pump – testing solution peristaltic pump, W-pump - peristaltic pump for deionized water, M-mixer centrifugal pump, EVM - output electrovalve, EV-C conductivity electrovalve, EV-TU turbidity electrovalve, EV-pH1, EV-pH2, EV-pH3 – pH electrovalves, level-S- level detector, P- sensor under test), M – mixing pump , REL C – relay switching scheme , T – testing vessel

Table 1. WQ calibration system pump and electrovalves operation states

	Calibration/Test procedure			
	C sensor multiple points calibration	TU sensor multiple point calibration	pH one point sensor calibration	Tubes Cleaning
S-pump	on	on	on	on
W-pump	on	on	off	off
EV-C	off	on	on	on
EV-TU	off	off	on	on
EV-pH1	off	off	off	on
EV-pH2	off	off	off	on
EV-pH3	off	off	off	on

The appropriate control of the pumps and electrovalves permits multiple or single point calibration of the sensing channel. At the same time, different cleaning procedures such as tubes or testing cuvette cleaning are implemented controlling the pumps and electrovalves. Thus, in the testing cuvette cleaning case, the M-pump (Jabsco 42510) is actuated while EV-M is off. After the cleaning time, the EV-M is switched on and the cleaning solution is put away.

Referring to the pumps and electrovalves digital signal controls (24V – on state), they are provided by the DO0-DO5 digital output channels of cRIO-9472 digital output module and excite a set of 24V relays (REL C) that power on and off the actuators.

The WQ sensors for pH, conductivity and turbidity measurements (Global water WQ201 WQ301 and WQ770) are characterized by 4-20mA analogue outputs while the level sensor (Honeywell optical sensor) outputs 0V when the liquid level is higher than an imposed value and 5V otherwise. The voltage information delivered by the water quality sensors set that includes a temperature sensor WQ101 is read using the 4 channels,  $\pm 10VDC$ , 16-bit simultaneous analogue input module (CompactRIO cRIO-9215), taking into account the type of information obtained from the level sensor, the DIO digital input channel of 8-channel digital input module (CompactRIO cRIO-9423) is used.

### 2.2. FPGA core and real-time controller

The heart of the WQ calibrator is a reconfigurable I/O (RIO) core that is connected to the CompactRIO real-time controller through a local PCI bus interface. The RIO FPGA core (cRIO-9103) [4] used in the present application, which has an individual connection with the above mentioned I/O modules (analogue input, digital input, digital output), provides to the system the ability of an easy implementation of the calibration or measurement procedures. Thus, if additional elements are introduced in the system (new electrovalves associated with new calibration solutions), the FPGA core will be reconfigured based on LabVIEW FPGA programming assuring the system functionality upgrade. Several characteristics of the FPGA used core are: number of logic slices 14336, available embedded RAM 196kB, maximum power consumption 3W. The RIO core can perform local integer-based signal processing. However, to extract the WQ information, floating point-based signal processing is required and is implemented in the CompactRIO real time controller. The real-time controller will retrieve data from the controls (e.g. DO0-DO5) and indicators on the front-panel of the RIO FPGA application through the FPGA read/write function of the real-time controller embedded software.

Referring to the real-time controller (NI cRIO-9002), it has a real-time processor for intelligent stand-alone operation, low power consumption (7W max), 10/100BaseT Ethernet port with built-in LabVIEW remote panel Web server and FTP sharing server. Using the real-time capabilities, the digital codes obtained from the analogue-to-digital conversion module are converted into floating-point values and processed according with the calibration, testing and measuring requirements. The embedded software component is developed in LabVIEW real-time (ETS).

### 2.3. WQ wireless network

To provide flexibility and considering in-situ calibration and measurement requirements, a water quality wireless network was designed and implemented. Considering the NI cRIO-9002 Ethernet compatibility, a 2.4GHz Ethernet

Laptop PC with Wi-Fi

cRIO system

REL C

W-pump

pH2-SS, pH3-SS levels

DW

wireless bridge (DWL-810+) is connected to include the cRIO real-time controller as a part of the WQ wireless network infrastructure that includes an advanced processing and cRIO programming unit expressed by a laptop PC. Additional tasks, such as WQ sensor calibration and measurement data publishing are included in the system.

### 3. SYSTEM SOFTWARE

The calibration system software includes different components associated with the FPGA core I/O, with the real-time controller and with the advanced control and processing unit expressed by the laptop PC.

#### 3.1 FPGA core software

The FPGA core software was developed using LabVIEW for FPGA Module. The software is mainly related to the WQ sensor voltage acquisition control, pumps and electrovalves digital control and level sensor digital signal acquisition (Fig. 2).

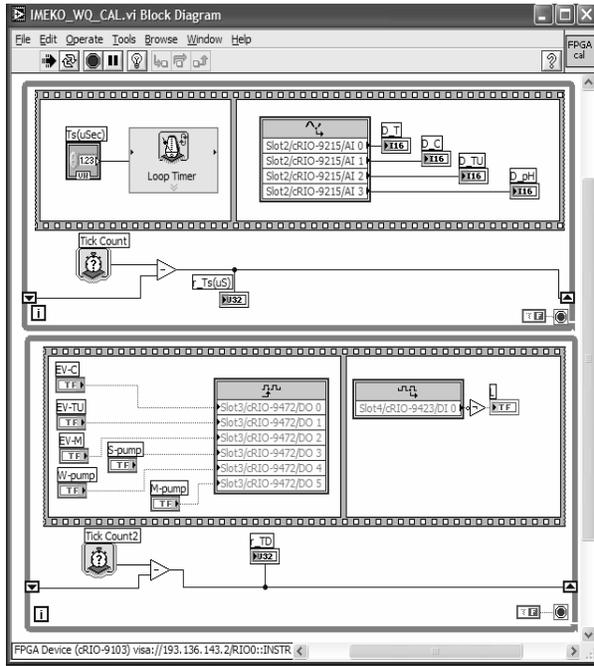


Fig. 2. The LabVIEW FPGA software block diagram associated with WQ sensor voltage acquisition control, level sensor digital signal acquisition, and digital output signal control

In Fig. 2 are shown the digital indicators (D\_T, D\_C, D\_TU and D\_pH) that correspond to the digital codes obtained after analogue-to-digital conversion of the WQ sensing channels, EV-C, EV-TU, EV-M, S-pump, W-pump and M-pump correspond to the on/off control of the electrovalves and pumps for a restricted number of calibrated sensors (conductivity and turbidity), while at the end the L boolean indicator shows the level sensor on/off state. Taking into account the parallel processing capability of the FPGA core, the acquisition of the analogue signals and digital control and acquisition is implemented in two different while loops.

#### 3.2 Real-time controller software

The real time controller software (RTCS) is characterized by higher complexity and permits: (1) to communicate with the FPGA software component using “open FPGA VI reference”, (2) to perform the conversion of voltage digital codes (e. g. D\_T=3543) to WQ floating-point values (e.g. T=17.5°C), (3) to perform data logging and data processing associated with sensor calibration curves, and (4) to transmit the data over the WQ Wi-Fi network between the real-time controller and the laptop PC.

One of the important parts of RTCS is the calibration/testing sequence. The real-time controller software components communicate with FPGA software block using VISA (RIO0::INSTR). The main steps of the procedure are presented in Table 2.

Table 2. WQ sensor calibration/testing procedure

step no.	action	comments
1	W-pump=on	Inject cleaning water in the calibration vessel and checks the L sensor output value
2	W-pump=on EV-M=off, M=on	Stop W-pump when L is on (imposed level is reached) and start cleaning forcing the water on the vessel wall
3	EV-M=on M=on	Put out the cleaning water
4	W-pump/ $t_{mix1}$ =on S-pump/ $t_{mix2}$ =on EV-C=on (TU calibration case)	Prepare the calibration/test solution mixing the concentrated solution (e.g. formazine 4000NTU) with the dilution solution (de-ionized water): the S-pump is actuated during $t_{mix2}$ period and W-pump during the $t_{mix}$ period.
5.	M=on EV-M=off	Solution homogenizing
6.	W-Pump, S-pump, M-pump, EVs=off	WQ measuring during a specified $t_{calib}$ period (e.g. $t_{calib}$ =60s with 1S/s acquisition rate). Calculation of statistical parameters as variance and standard deviation
7	M=on, EV=on	Put away the used solution and prepare the new cleaning step

As it was above mentioned, different calibration solutions are obtained mixing de-ionized water with a standard solution previously prepared and stored in vessels (e.g. turbidity, TU-SS). One example: using 50ml of 4000 NTU formazine standard solution [5] from TU-SS vessel injected in the calibration vessel by the S-pump and 200ml of de-ionized water injected by W-pump, an 800 NTU standard solution is obtained. This is achieved by activating S-pump (DO3=on) and EV-C (DO0=on) during  $\Delta t_{mix1}$ =8.6s while W-pump (DO4=on) is activated during  $\Delta t_{mix2}$ =34.5s. The obtained formazine solution precipitates easily and thus it is stirred thoroughly before the calibration using a feedback tube when M is switching on and EV-M is switched off.

If in the conductivity sensor calibration/testing case, the calibration solution is obtained in the same mode mixing a concentrated KCl solution (e.g.  $C_{CS}=12.8\text{mS/cm}$ ) with de-ionized water ( $0.2\mu\text{S/cm}$ ). In the pH case, the calibration solution previously prepared is extracted from the calibration vessels pH1-SS, pH2-SS or pH3-SS according to the chosen pH calibration point.

#### 4. RESULTS AND DISCUSSION

Using the above mentioned WQ sensor calibration system and the associated software components, several tests were carried out. For conductivity and turbidity sensors the calibration curves were obtained for 2, 3 and 5 synthesized calibration solutions. In the particular case of the five-point calibration of the WQ301 sensor, the obtained calibration curve is depicted in Fig. 3. The calibration solutions were obtained mixing the concentrated test solution  $C_S$  ( $12.856\text{mS/cm}$  that corresponds to  $7.456\text{g}$  KCl for  $1\text{L}$  of solution) with de-ionizer water. Thus and for example, the  $1408\text{ }\mu\text{S/cm}$  calibration value is obtained mixing  $20\text{mL}$  of  $C_S$  with  $380\text{mL}$  of de-ionized water. The pumps and electrovalves are actuated during  $3.4\text{s}$  (S-pump) and  $65.4\text{s}$  (W-pump).

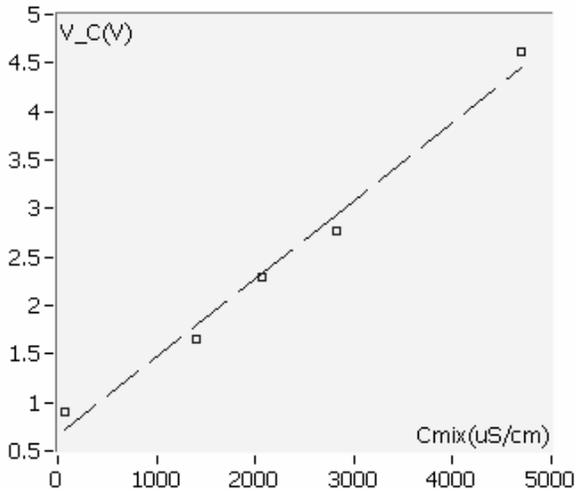


Fig. 3. The conductivity calibration curve for WQ301 sensor at  $25^\circ\text{C}$

Referring to the WQ770 (TU sensor), different tests were also performed and some of the results are presented in Fig.4. As mentioned before, the appropriate calibration solutions associated with  $0\text{-}50\text{NTU}$  and  $0\text{-}100\text{NTU}$  WQ770 measurement ranges are obtained diluting a high turbidity formazine solution ( $4000\text{NTU}$ ) in de-ionized water.

Considering the in-situ field operation requirements of the water monitoring system, it must have an adequate autonomy, which means that power consumption is a very important issue. The system is powered by  $12$  and  $24\text{VDC}$  batteries and tests were conducted to obtain the evolution of current and power during the calibration session, especially for the calibration procedure steps that are intensively power consuming.

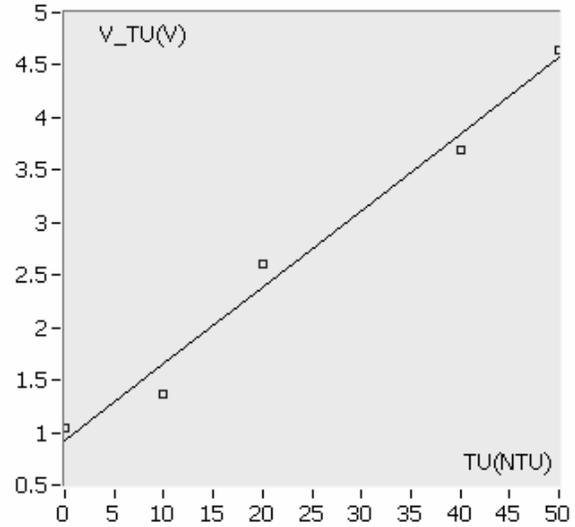


Fig. 4. The WQ770 turbidity sensor calibration curve for a set of 5 calibration formazine solutions

The calibration session involves a set of cycles (according to the number of calibration points) that include the cleaning, calibration solution injection, mixing and measurement actions that are expressed in Table 2. Figure 5 shows the values of power for different actions of the WQ sensor calibration procedure.

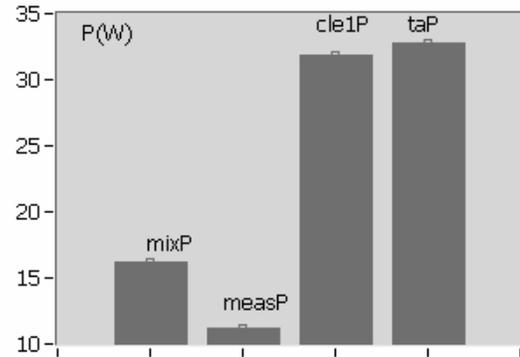


Fig. 5. Power values for different calibration procedure actions (mixP – power associated with the preparation of a calibration solution, measP – power for the measurement, cle1P power for cleaning, taP- power to put away of the used or cleaning solutions)

Another important feature of the present system is its utilization both for calibration and water quality measurement with fault detection and diagnosis capabilities. Thus the pollution and fault detection events are detected by a comparison procedure described in [6] that uses the historical values of the WQ parameters and the current acquired values. The WQ parameter variation is calculated and if this value is greater than an imposed threshold a one point calibration/testing task is executed to allow the discrimination between fault and pollution events. If the current measured value  $WQ_M$  (e.g. conductivity value) differs from an imposed test solution  $WQ_C$  (prepared by mixing the concentrated solution with de-ionised water) by a value  $\Delta WQ$  greater than an imposed tolerance,  $\delta WQ$ , a fault event is signalled on the tested measuring channel.

## 5. CONCLUSION

The real time controller connected to the FPGA core through a PCI bus implements a water quality sensor calibration system with reduced power consumption due to the utilization of low power electrovalves and peristaltic pumps. Data communication in a water quality monitoring network uses the Ethernet connectivity of the used real time controller.

FPGA based implementation permits different tasks (actions) associated with the calibration system to be performed in parallel mode, which means short processing times.

The FPGA core added to a real time controller permits the implementation of advanced processing techniques and data communication tasks not possible with conventional processing devices.

The sensor test/calibration system is a good solution for water quality sensor field calibration procedures allowing, at the same time, the detection of anomalous functioning through a one point calibration test.

The Wi-Fi communication capability is an asset of the system because it allows remote control flexibility.

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