A Low-Cost System for Real Time Monitoring and Assessment of Potable Water Quality at Consumer Sites

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Abstract— **This paper presents the design and development of a low cost system for real time monitoring of drinking water quality at consumer sites. The system consists of several in-pipe electrochemical and optical sensors and emphasis is given on low cost, lightweight implementation and reliable long time operation. Such implementation is suitable for large deployments enabling a sensor network approach for providing spatiotemporally rich data to water consumers, water companies and authorities. Extensive literature and market research is performed to identify low cost, on-line sensors that can reliably monitor several parameters which can be used to infer the water quality. Based on selected parameters a sensor array is developed along with several microsystems for analog signal conditioning, processing, logging, and remote presentation of data. Finally, an algorithm for fusing on-line multi sensor measurements is developed to assess the water contamination risk.**

I. Introduction

Clean drinking water is a critical resource, important for the health and well-being of all humans. Several experimental studies [1], [2] indicate the need for continuous on-line water quality monitoring with efficient spatio-temporal resolution and demonstrate that the conventional reagent-based water quality methods fail to satisfy this requirement due to higher labor and operational cost. US Environmental Protection Agency has carried out an extensive experimental evaluation [3] of water quality sensors to assess their performance on several contaminations. The main conclusion was that many of the chemical and biological contaminants used have an effect on many water parameters monitored including Turbidity (TU), Oxidation Reduction Potential (ORP), Electrical Conductivity (EC) and pH. Thus, it is feasible to monitor and infer the water quality by detecting changes in such parameters.

A limited number of on-line, reagent-free water monitoring systems exist (e.g. Hach HST GuardianBlue [4], JMAR BioSentry [5]), but these systems are bulky (sensors are installed in flow cells located in cabinets) and remain cost prohibitive for large scale deployments (cost tens of thousands of dollars per unit). It is worth mentioning that cost is mostly attributed not to sensing probes but to instrumentation-automation controllers (analyzers) and panels. Such systems can take frequent samples of the water quality at a very limited number of locations. However, substantial proportion of contamination problems is attributable to problems within distribution systems and due to the limited spatio-temporal sampling, it is impossible for the water companies and consumers to know the quality of potable water delivered to consumer households.

Given the size of the water distribution networks (pipe length) and the number of households served, we consider important that the spatio-temporal sampling is significantly increased, thus it is necessary to collect water quality samples at significantly more locations (if possible at all consumer sites). Therefore, the main challenge is to develop reliable and low-cost sensing systems for accurate and continuous in-pipe water quality monitoring. The system developed is intended to be used as a part (node) of a low cost water sensor network to provide water quality information to consumers, water companies and authorities. The spatio-temporal data provided by such network can support complex decisions concerning the quality of drinking water, including the detection of the location/source of hazardous agents and pathogens, raising awareness, and encouraging better water-handling and management.

Therefore, the contribution of this paper is twofold. First, it proposes the need for a shift in the current monitoring paradigm and propose the idea of monitoring the quality of water delivered to consumers, using low cost, low performance and tiny sensors. We argue that this approach can achieve more reliable quality monitoring due to the large spatially distributed deployment and the possibility of correlating the quality measurements from various consumers. Second, it presents the first step towards this goal which is the design and development of a low cost system that can be used at the premises of every consumer. The embedded systems developed can also be used in a consumer-oriented manner to continuously monitor qualitative water parameters and fuse multi-parametric sensor response in order to assess the water consumption risk at consumer level, locally and independently from other consumer measurements.

The remaining of this paper is organized as follows. Section II presents the methodology and justification for the selection of water quality parameters to be monitored. Section III presents the experimental implementation of the hardware and software modules and validates the performance of the developed system. Finally the paper ends with the conclusion.

II. Methods

Drinking water quality standards are determined according to World Health Organization [6] guidelines for drinking-water quality as well as other pertinent organizations (i.e. EU [7], USEPA [8]). These organizations set the standards for drinking water quality parameters and indicate which microbiological, chemical and indicator parameters must be monitored and tested regularly in order to protect the health of the consumers and to make sure the water is wholesome and clean.

The selection of the physicochemical parameters to be monitored was based on extensive scientific literature review [3], [9], [10], [11], [12], [13] on the relation between certain physicochemical parameters and chemical or biological contaminations that present in water. Table I enumerates the suggested parameters to be monitored from high to low correlation significance when interpreting water contaminations (assess hazard). Table I also presents the measurement cost (for purchase and maintenance) associated with these parameters based on recent review [14] of measurement and instrumentation methods, compensation and calibration procedures and probe lifetime concerning these parameters. Thus, the parameters selected to monitored are the following: 1) Turbidity, 2) Oxidation Reduction Potential (instead of Free Chlorine), 3) Temperature 4) pH, and 5) Electrical Conductivity. It is noted that Free Chlorine concentration can be estimated as a function of the ORP, pH and temperature measurements. Nitrates, though considered as an important parameter for human health is not selected because measurement methods are subjected to failures (Ion-Selective Electrodes) or are cost prohibitive (UV Spectrophotometric Method). Finally, dissolved oxygen is not selected due to several compensations and frequent membrane replacement needed for accurate measurements.

	Parameter	Units	Quality Range	Meas. Cost
1	Turbidity	NTU	0 – 5	Medium
2	Free Residual Chlorine	mg/L	0.2 – 2	High
3	ORP	mV	650 – 800	Low
4	Nitrates	mg/L	<10	High
5	Temperature	^{o}C	–	Low
6	pH	pH	6.5 – 8.5	Low
7	Electrical Conductivity	μS/cm	500 – 1000	Low
8	Dissolved Oxygen	mg/L	–	Medium

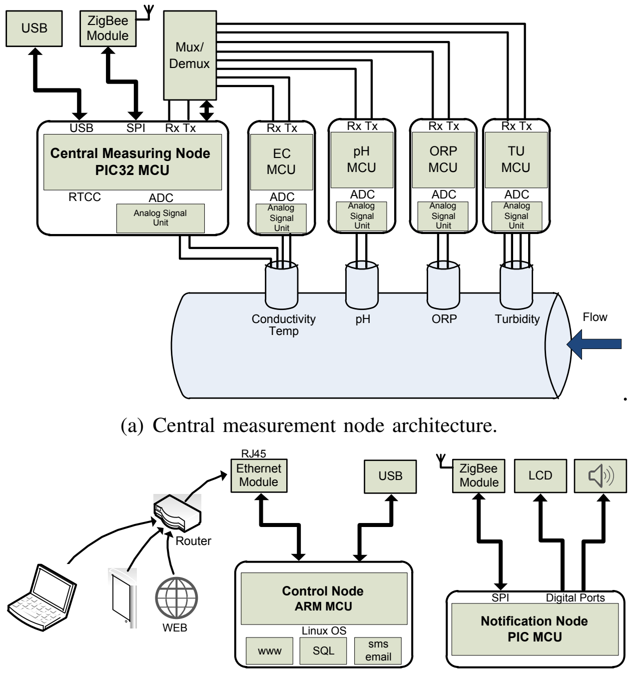
TABLE I

Suggested Parameters to be Monitored. Quality range is suggested by WHO [6] guidelines and EU standards [7].

In line water sensors illustrate the need for efficient and periodic probe cleaning to maintain reliable measurements. Cleaning mechanisms constitute an important cost parameter which can consume as high as 50% of the operational budgets. Conventionally, ultrasonic, brush, water-jet, or chemical type of automatic cleaners [15] are used to remove coatings from the sensor probes. Recently, several alternative cost effective methods have been proposed that can either actively remove fouling (e.g. electrolysis) or passively prevent fouling. Flat measuring surface probe method [16] is the most cost effective, passive self-cleaning method and is based on the mechanical package and design of the probe. When the electrode's flat measuring surface is exposed to turbulent flow, the resulting scrubbing action provides a self-cleaning effect in most applications under medium range flows. The flat sensing surface virtually eliminates deposits that can foul the electrode and significantly reduces necessary maintenance. This simple, but effective method has no moving parts, requires no power and also prolongs electrode life and eliminates breakage.

III. Results

A modular but holistic approach is adopted for the design and development of the system. Modularity enables the simultaneous sampling of all parameters and the decomposition of several operations like calibration, upgrades and repair or replacement of faulty parts. Holisticity focuses on the interdependence of all parts (interfaces and communication protocols) to pursue the objectives of low cost and assessment of drinking water quality.



(a) Central measurement node architecture.

(b) Control node architecture.

(c) Notification node architecture.

Fig. 1. System architecture.

The overall system architecture under discussion in presented in Fig. 1 and is comprised of following three subsystems: a central measurement node (PIC32 MCU based board)

Parameter	Measurement principle	Units	Range	Resolution	Accuracy	Quality Range
Turbidity	Optical/infrared backscattering	NTU	0 – 100	0.1	±0.5	0 – 5
ORP	Galvanic cell, platinum electrode	mV	-2000 – 2000	2	±10	600 – 800
pH	Galvanic cell, glass electrode	pH	0 – 14	0.05	±0.1	6.5 – 8.5
Conductivity	Conductive cell	μS/cm	100 – 20000	10	5%	500 – 1000
Temperature	NTC resistance	^{o}C	-5 – 70	0.1	±0.5	–

TABLE II

SPECIFICATIONS AND ACCOMPLISHED PERFORMANCE FOR EACH MONITORED PARAMETER.

that collects water quality measurements from sensors, implements the algorithm to assess water quality and transmits data to other nodes, an optional control node (ARM/Linux webserver based platform) that stores measurement data received from the central measurement node in a local database and provides gateway to the internet, visualize data (charts), and sends email/sms alerts and finally a tiny notification node(s) (PIC MCU based board) that receives information from the central measurement node through an interconnected ZigBee RF transceiver and provides local near-tap notifications to the user (water consumer) via several interfaced peripherals (LED, LCD, Buzzer). A photo of the central measurement,

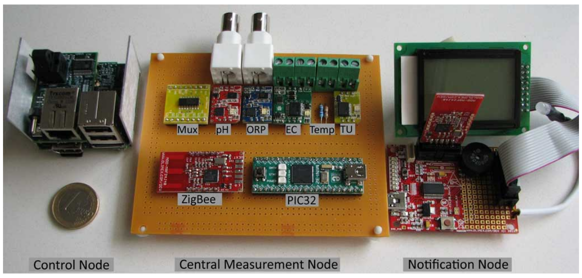
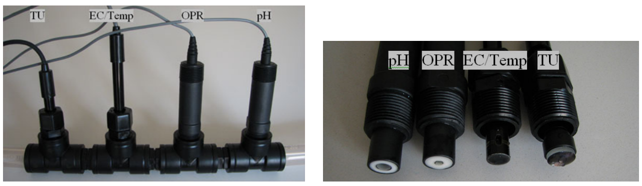


Fig. 2. Photos of system's nodes.

control and notification node is presented in Fig. 2 while Fig.3 presents the multi-parameter sensor array comprised of the Turbidity(TU), ORP, pH, Electrical Conductivity(EC) and Temperature probes mounted in a plastic pipe. The complete system photo is shown in Fig 4. Turbidity sensor is constructed



(a) In-pipe multi-parameter sensor array. (b) Probes with flat sensing surfaces.

Fig. 3. Sensor photos. TU, ORP, pH have flat sensing surfaces for cost effective self-cleaning.

from scratch based on our previous work [17] whether the other sensor probes obtained from SensoreX Corp®. Electrical Conductivity sensor embeds an NTC thermistor which is used for temperature sensing and temperature compensation of conductivity and pH measurements. Turbidity, ORP, pH sensors have flat measuring surfaces for cost effective self-cleaning. Considerable attention is given to the analog signal conditioning circuits, calibration and compensation procedures to reduce noise and attain high resolution and accuracy.

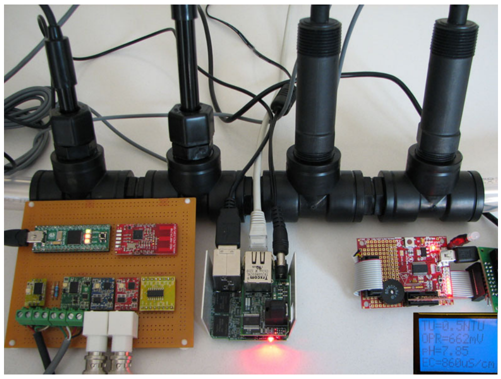
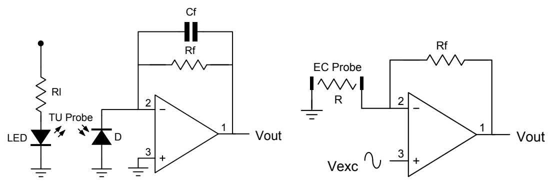
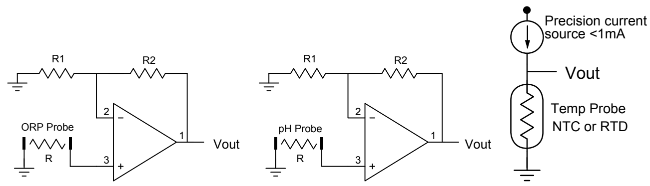


Fig. 4. Complete System Photo.



(a) Turbidity preamplifier (b) Conductivity preamplifier



(c) ORP preamplifier (d) pH preamplifier (e) Temperature

Fig. 5. The first stage of analog signal conditioning circuitry for each parameter

A dedicated PIC based microsystem is developed for each parameter to accomplish this task. The first stage of analog signal conditioning circuitry for each parameter is presented in Fig. 5 while Table II shows the results regarding laboratory evaluation (using standard buffer solutions and reference instruments) of each parameter along with the quality range suggested by WHO guidelines and EU standards. The components for the complete system prototype cost approximately €500 which is at least an order of magnitude less expensive than commercially available multi-parameter instruments.

The software platform developed for the control node is illustrated in Fig. 6. This platform enables real time measurement charts of monitored parameters, real time assessment of water quality and sensor calibration instructions through a Graphical User Interface (GUI). It also logs sensor data in a local database and posts data to web using Pachube open source web platform.

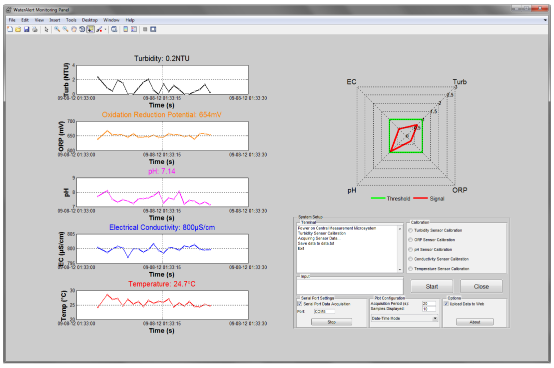


Fig. 6. Software Platform.

Finally, an algorithm for fusing on-line multi-sensor measurements to assess the water contamination risk is developed. This algorithm enables the system to act as an "early warning system" for possible potable water quality deterioration at homes. A flowchart of the risk assessment algorithm is illustrated in Fig. 7. The algorithm is implemented as follows: For every measured parameter i baseline data is estimated (mean μ_i and standard deviation σ_i) over a moving time window. Then, for each new parameter measurement S_i, the normalized sensor output $N_i = \frac{S_i - \mu_i}{\sigma_i}$ is estimated to filter baseline fluctuations. If normalized sensor outputs exhibit sudden and significant changes from baseline data (given some predefined thresholds τ_i, currently under investigation) a trigger is activated and the water consumption risk is estimated as a function of the euclidian distance $\|\mathbf{N} - \boldsymbol{\tau}\|$. The signature of all normalized sensor outputs can be further processed to minimize false alarms and identify possible contaminations, given that a contamination library is available/developed.

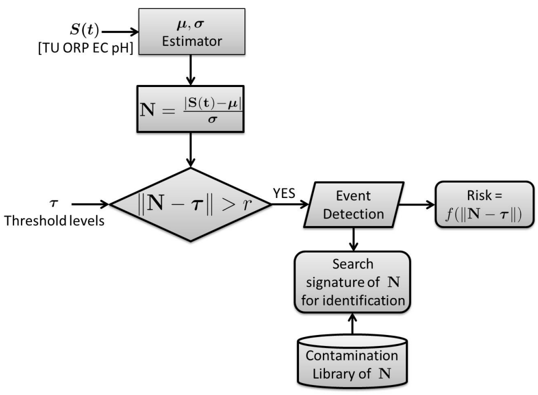


Fig. 7. Risk Assessment Algorithm.

IV. Conclusion

In this paper, the design and development of a low cost system for real time monitoring of drinking water quality at consumer sites is presented. The proposed system consist of several in-pipe water quality sensors with flat measuring probes and unlike commercially available on-line analyzers, it is low cost, lightweight and capable of processing, logging, and remote presentation of data. Such implementation is suitable for large deployments enabling a sensor network approach for providing spatiotemporally rich data to water consumers, water companies and authorities.

In the future, we plan to investigate the performance of the fusion algorithm on intentional contamination events (biological, chemical, etc) and install the system in several locations of the water distribution network to collect spatiotemporally rich water quality data and characterize system/sensors response in real field deployments.

Acknowledgment

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