DESIGN AND DEVELOPMENT OF IN SITU FPGA-BASED WATER QUALITY MONITORING KIT

BY

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ABSTRACT

In 2017, about 144 million people collected water from untreated water bodies, such as lakes, streams, and rivers. One of the major causes of death is consuming contaminated or polluted water. Measuring and monitoring water quality are usually done using two methods. The conventional method occurs by taking samples of water and then transferring them to the laboratory. The second method is real-time water quality by integrating the Internet of Things (IoT). This method is preferable as it only requires smart sensors and processors to monitor the water quality. Among the widely used processors are the Arduino and Raspberry Pi. However, these two processors have a limitation, including a limited number of hard-coded input/output pins, unlike the Field Programmable Gate Array (FPGA) processor, which has many input/output pins not hard-coded to allow different interfacing of multiple sensors. Based on the literature, an FPGA platform provides more flexibility and reconfigurability features when compared with the Arduino and Raspberry Pi. This research mainly focuses on designing a reconfigurable multi-core Smart Water Quality System (SWQS) measuring the pH, Total Dissolved Solids (TDS), and turbidity parameters. The hardware design was developed based on the system-on-chip (SoC) design methodology on an FPGA to parallelize the SWQS functionality. A Liquid-Crystal Display (LCD) display has been incorporated into the Raspberry Pi to show real-time data. The Platform Designer on Quartus II has been used to instantiate four cores to integrate all functions into one processor. The Eclipse tool on Quartus II, on the other hand, was used to program the sensors using embedded C language. The proposed design has been implemented on DE10 Nano FPGA-SoC consuming 9% of logic resources and 57% of internal memory. To verify the proposed system functionality, the sensors were tested on different liquids. To test the pH level, the pH sensor was tested on pure water, lemon juice, and milk to show the acidity and alkalinity. The pH sensor showed 7, less nearly 2, and less than 8 for pure water, lemon juice, and milk, respectively. The TDS sensor successfully detected the salt added to the water, and the TDS values increased to approximately 1800 ppm. Finally, the turbidity sensor revealed the dust inserted in the solution. The more dust in the liquid, the more TDS value there was recorded. Additionally, results showed that the processing time of all the sensors using FPGA is approximately 300 ms for ten readings; on the other hand, the processing time of using other processors, such as Arduino, took 2 s for ten readings. This is because FPGA is functioning at 100 MHz, while Arduino’s frequency is not more than 24 MHz. All real-time sensor readings were shown on a Linux Terminal. In conclusion, the proposed FPGA-based system can be utilized as a heterogeneous multi-core system for many applications, including the SWQS.

ملخص البحث

اكثر من مائة واربع واربعون مليون انسان ياخذون احتياجاتهم من المياه من مصادر غير معالجة مثل الانهار والبحيرات .في بعض الدول النامية ,معظم المصانع تقوم برمي الفضلات في المياه وهذا يجعل المياه بالقرب من المصانع اكثر تلوثا لأنها تحمل مواد كيميائيه بالأضافه الى المواد الثقيلة .هذه المواد تؤثر بشكل سلبي على البيئة وعلى الكائنات الحية التي تعيش في المياه لان المواد الثقيلة تنشر الفايروسات والبكتيريا .في هذه الايام يتم قياس جودة المياه بطريقتين هما اما الطريقة التقليدية وهي عبارة عن اخذ عينات من المياه ونقلها الى المختبر ومن ثم قياس جودتها ,ولكن هذه الطريقة تحتاج الى وقت وتكلفه اكثر .بالاضافة الى ذلك , حالة المياه من الممكن ان تتغير خلال عملية النقل .اما الطريقة الثانية فهي قياس جودة المياه بأستخدام الحساسات الذكية مع المعالجات ونقل البيانات بطرق مختلفة .هذه الطريقة مفضلة بشكل اكبر من الطريقة التقليدية لانها فقط تحتاج الى الحساسات الذكية بالاضافة الى المعالج لقياس جودة المياه في كل وقت . هذه الطريقة ستساعد المستخدم على اتخاذ القرار بسرعة في الحالات المفاجأة .لهذا فأن هذا المشروع يركز بشكل اساسي على استخدام حساسات لقياس الأس الهيدروجيني والعكورة بالأضافة الى كمية المواد الذائبة .بعد ذلك تقوم مصفوفة البوابات المنطقية القابلة للبرمجة بمعالجة البيانات وارسالها لأجل عرضها على الشاشة .هذا المشروع سيقلل من تعقيد الأجهزة الأخرى المستخدمة في قياس جودة المياه .وسوف تقوم بأستخدام الأجهزة مع البرمجة لتقليل الوقت المستخدم في تطوير جهاز متحسس المياه الذكي .اخيرا وليس اخرا ,جهاز الراسبري باي سيستخدم فقط لعرض البيانات على الشاشة المترابطة به .سيقوم معالج الراسبري باي بأستلام البيانات عن طريق تطبيق مبرمج بداخله ومن ثم عرضها على الشاشة .الجهاز المصمم قد تم اختباره على سوائل مختلفة مثل المياه النقية ,عصير الليمون ,الحليب لقياس الأس الهيدروجيني .

اما نسبة العكورة فقد تم استخدام المياه النقيه بالاضافه الى مياه مع القليل من الرواسب ومياه مع الكثير من الرواسب. اخيرا فقد تم استخدام المياه النقية ومياه تحتوي على الملح لقياس المواد المذابة في الماء. عن طريق هذا المشروع يمكن استخدام البيانات عن طريق ربطها ببرامج اتخاذ القرار, تحليل البيانات وغيرها من البرامج.

APPROVAL PAGE

I certify that I have supervised and read this study and that, in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science Engineering.

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DECLARATION

I hereby declare that this dissertation is the result of my investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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Signature…………………………………. Date 2022/12/05

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

1.1 OVERVIEW

Water quality is an important factor that needs to be considered as it is directly related to people's lives. Therefore, this research focuses on designing a Smart Water Quality System (SWQS) Field Programmable Gate Array (FPGA)-based to eliminate the problems and drawbacks of previous works. This chapter illustrates the work by giving a brief background and defining the research problem. The chapter then presents the research motivation. Finally, it emphasizes the research scope.

Section 1.3 defines the research problem statement. Then, in Sections 1.4 and 1.5, the research objectives and research scope are presented, respectively. In addition, an outline of the main structure of the thesis is briefly reported in Section 1.6. Finally, Section 1.7 summarizes Chapter 1.

1.2 RESEARCH BACKGROUND

One of the major causes of death is consuming contaminated or polluted water. According to the World Health Organization (WHO), in 2017, 2.2 billion people were drinking water without any safety management services, and 144 million collected water from untreated water bodies, such as lakes, streams, and rivers ("2.1 Billion People Lack Safe Drinking Water at Home, More than Twice as Many Lack Safe Sanitation," 2017). To reduce the death rate due to contaminated and polluted water, measuring water quality, especially for consumption, becomes important. Water quality indicators can mean differently. It shows the suitability of any water body used for different uses, such as drinking, cooking, and cleaning. Water usage has different chemical, biological, and physical acceptance levels. For instance, drinking water has specified water quality parameters, such as pH levels ranging from 6.5 to 8.5. As many parameters need to be measured, thus, several sensors must be employed for the water quality test. To this date, the water safety management services that utilize a system that support large computational loads need a huge amount of power, not portable, and big devices, making it impossible to be commercialized.

Hence, it is pertinent to establish a new smart system considering the latest technological advancement that can carry out the huge computational load at lower power but with high performance. Therefore, this research proposes a water quality system that utilizes the FPGA platform and the Adcanced RISC Machine (ARM) processor.

1.2.1 Field Programmable Gate Array (FPGA)

FPGA is a reconfigurable computing device with several programmable units that could solve any computational issues (Giesemann, Paya-Vaya, Blume, Limmer, & Ritter, 2014). This device is an integrated circuit made of semiconductor material, and the main feature of FPGA is the device's electrical functionality can be reconfigured even by the customer. As a result, these powerful devices can be customized to accelerate key workloads and enable design engineers to adapt to emerging standards or changing requirements.

Figure 1.1 illustrates the common design flow for an FPGA platform, beginning with hardware design specifications. The hardware design specifications consist of the needed hardware design's functionality, memory size, the number of input/output ports, speed, and finally, how the data transfers. The next step is the architecture design, in which the hardware design can be further split into system and sub-system modules, i.e., the micro-architecture level design (Gerstlauer et al., 2009).

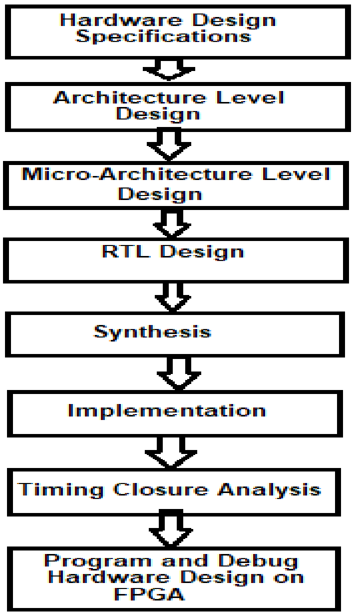

Figure 1.1 Hardware Design Flow of FPGA (Intel, 2020)

Once the architecture and the micro-architecture level of the needed hardware design are completed, the Register Transfer Level (RTL) will begin. At this level, Hardware Description Language (HDL) will be used to translate the system and sub-system blocks into a Hardware netlist ("AN 311: Standard Cell ASIC to FPGA Design Methodology and Guidelines," 2009). Synthesis and implementation processes will begin when the digital module design is done. These two steps will translate the HDL design into a physical netlist prepared for timing analysis. Timing analysis is the process of ensuring the hardware design is working from a time perspective. In other words, it will check whether the design is the speed requirements of the system or not (Gerstlauer et al., 2009). In the end, the hardware design will be executed on an FPGA board.

1.2.2 Heterogeneous System Architecture (HSA)

A Heterogeneous System Architecture (HSA) is a computer platform that functions with associated software that makes different kinds of processors with different architectures work in shared memory efficiently and cooperatively from a single source program (Kyriazis, 2012). Integrating multiple computing elements at low frequencies leads to high performance with low power consumption; architectural heterogeneity improves platform flexibility (Burgio et al., 2016). This heterogeneous platform, such as FPGA-System-on-Chip (SoC), improves the performance of embedded using hardware containing more than one type of processor. This approach has shown improved performance, particularly in artificial intelligence (AI), in which computationally demanding models must be trained and executed.

SWQS utilizes different sensors to measure water parameters such as pH, turbidity, and Total Dissolved Solids (TDS) and then processes the data on FPGA-SoC. The proposed design methodology reduces the complexity of the FPGA-SoC heterogeneous platform by adding a middleware layer for software developers to interact with the FPGA system in the form of an application program interface. Therefore, heterogeneous architecture is the best choice for complex systems with multiple input and output ports to enhance the overall system performance.

1.3 PROBLEM STATEMENT

Currently, in Malaysia, water quality monitoring is done by traditional methods, consisting of taking samples from the area under test and then driving them back to a laboratory to analyze them. The analysis usually is for detecting chemicals and microbial that cause the water’s pollution. This method is not only time-consuming but requires significant human interaction. As a result, important data may be lost because of the manual collection process. In addition, the water quality analysis is not done within a short time, so determining a real-time water condition is not plausible. This traditional method is only good if the samples are taken and analyzed simultaneously (Geetha & Gouthami, 2016). Moreover, the water might get contaminated, making it very difficult and costly to recover (Billah, Yusof, Kadir, Ali, & Ahmad, 2019). Moreover, the technicians cannot take samples from all locations, which may lead to inaccurate data (Lezzar, Benmerzoug, & Kitouni, 2020). Besides the issues arising from the manual sample collection, the chemical materials used in water quality testing are usually toxic and very expensive (Khatri, Gupta, & Gupta, 2020).

Even though the research on water quality monitoring systems have been applied many times, the current system is still expensive, has short-distance data transmission, and is not easy to use (Geetha & Gouthami, 2016). Most current SWQS is costly (Pasika & Gandla, 2020), and there should be a big effort by researchers to reduce the cost to make the system more affordable for everyone. Performance is also an important issue that needs to be considered. SWQS must have high performance and accuracy to reduce errors that might cause poor health conditions and death for the people who consumed the water if the measurements are incorrect.

While FPGA has high processing power, developing an FPGA can be complex and requires more effort than configuring the same design on the Central Processing Unit (CPU) (Besta, Stanojevic, Licht, Ben-Nun, & Hoefler, 2019). In addition, it provides less specialized components (i.e., floating point) operations. It is for this reason that FPGA remains to be a prototype platform for embedded systems. That said, the use of heterogeneous platforms mesh with FPGA has recently gained popularity for design applications that need performance and programmability offered via a processor and flexibility and configurability accomplished using the FPGA fabric (Zhong, Niar, Prakash, & Mitra, 2016). The SoC heterogeneous platforms improve the performance of embedded systems using a hardware design that contains more than one processor.

In addition, when comparing FPGA with other processors such as Arduino and Raspberry Pi, in terms of configurability and implementation, FPGA is reconfigurable based on the user’s requirements. However, Arduino and Raspberry Pi are configured and implemented during manufacturing. Additionally, FPGA can process the data in parallel to overcome the latency issue when many inputs are used. On the other hand, there is no way to perform pipelines using processors such as Arduino and Raspberry Pi. In addition, the processing rate of the SWQ data using an FPGA processor is high as its frequency reaches 1 GHz. However, the frequency is slightly lower in other processors, for instance, 16 MHz and 400 MHz for Arduino and Raspberry Pi, respectively. Last but not least, the pins of FPGA are 40 pins that are not hardcoded as their interface can be modified based on the sensor’s data exchange protocol, unlike the pins of Arduino and Raspberry Pi, which are hardcoded during the manufacturing process. Moreover, FPGA-SoC is a heterogeneous platform that can work with shared memory for more cooperativity and efficiency. In addition, a heterogeneous platform such as FPGA-SoC improves the performance of embedded using more than one processor.

For these reasons, the main objective of this project is to design SWQS using an FPGA-SoC platform to monitor different water parameters, namely; pH, TDS, and turbidity parameters, rather than relying on the conventional way of measuring water quality parameters.

1.4 RESEARCH OBJECTIVES

The main objectives of the project are as below:

i. To design a reconfigurable hardware-based Smart Water Quality System (SWQS) via using a Field Programmable Gate Array-System-on-Chip (FPGA-SoC) heterogeneous platform.
ii. To implement a real-time prototype for the proposed Smart Water Quality System (SWQS).
iii. To evaluate the proposed Smart Water Quality System (SWQS) based on pH, Total Dissolved Solids (TDS), and turbidity parameters.

1.5 RESEARCH SCOPE

The scope of this research mainly concentrates only on the hardware design of SWQS by utilizing the heterogeneous platform of FPGA-SoC to process signals obtained from water quality sensors. The system design integrates FPGA with the SoC to create a customizable heterogeneous platform that segments the system functionality into tasks. The proposed design in this study will utilize two development kits, the DE10 Nano FPGA-SoC development kit from Intel and the Raspberry Pi development board. The utilized boards will not impact the proposed system design since the design flow is the same for any FPGA development board. The system has two SoC sub-systems: an external one (Raspberry Pi) and an internal one (ARM SoC). The external sub-system will provide the system with all the required augments to ease prototype implementation, like LCD, mouse, and keyboard. The internal SoC will be part of the SWQS as the main system processor.

In addition, testing the proposed system will only be based on three water quality parameters to verify and validate the functionality and reliability of the proposed FPGA-SoC platforms. The utilized sensors in this design will be the pH, TDS, and turbidity sensors. These sensors were used as a proof-of-concept to validate the system's functionality. However, other sensors related to SWQS can be adapted to any future system based on the user's requirements.

1.6 DISSERTATION LAYOUT

This dissertation is composed of five chapters; a brief introduction and overview of the research are provided in Chapter 1. In Chapter 2, an in-depth investigation was conducted about the previous studies in the SWQS development field. Chapter 3 elaborates on the proposed system, and the design steps needed to develop an SWQS hardware design based on a heterogeneous platform are presented as well as presenting the flow of software to program the system. Furthermore, the proposed system test results and the collected data, were discussed in Chapter 4. Finally, in Chapter 5, the summary of the research findings, contribution, claims, and comparative analysis was reported.

1.7 SUMMARY

This chapter presented a detailed overview of the research topic, known as SWQS. First, the problem statement of this study was illustrated. Then, the research objectives are presented in this chapter. Furthermore, the scope was explained. Finally, the thesis layout and the relation between each chapter were discussed.

CHAPTER TWO

LITERATURE REVIEW

2.1 OVERVIEW

This chapter describes the academic literature correlated with Smart Water Quality System (SWQS) hardware implementation. The main objective of this chapter is to find out and elaborate on the latest research achievements in the field of SWQS design and development. In addition, this chapter highlighted the drawbacks and problems encountered by researchers in their designs, as well as obstacles in providing suitable SWQS solutions.

In Section 2.2, a brief overview of water quality approaches is presented. Then, Section 2.3 explains some sensors that measure water quality parameters such as pH, temperature, turbidity, electrical conductivity (EC), and dissolved oxygen (DO). In Section 2.4, previous studies have been presented based on the controller or the processor. They have been used to collect data on water quality parameters and summarize the related studies' motivations and drawbacks. Section 2.5, on the other hand, shows the proposed SWQS FGPA-based followed by Section 2.6. It presents general information about FPGA in terms of architecture, such as memory, speed, interfaces, etc., and software tools, such as Quartus, Platform Designer, etc. Finally, Section 2.7 summarizes this chapter.

2.2 DIFFERENT WATER QUALITY APPROACHES

There are two ways of measuring water quality. The first is the traditional method involving samples from the river, lake, or any water source, while the second uses sensors to measure water quality. In the following subsections, both conventional and Internet of Things (IoT) methods will be discussed in detail.

2.2.1 Conventional Approach

The traditional way of measuring water quality parameters, such as the water pH, turbidity, DO, and EC, starts with several samples for testing. Note that sampling selects a small portion of the water to be handled and transported to the laboratory (Ngom, Diallo, Gueye, & Marilleau, 2019). After transporting the samples to the laboratory, specific materials or solutions must be added to measure a specific parameter. For example, to measure the level of phosphorus, one of the crucial water parameters, samples must be transferred to the lab as soon as possible to minimize any external effects that might change the measurement of the total phosphorus. Potassium persulfate should be mixed with the water sample before heating it for 30 minutes. After the heating process, the mixture must be cooled to room temperature. Before measuring the total phosphorus, sodium hydroxide is added and mixed with the sample gently. The last step is to measure the total phosphorus using a spectrophotometer device 7 minutes after mixing. Sometimes, the process can take more than five working days (Li, Jaafar, & Ramli, 2018).

Besides the elaborated identification process, the sampling process is not easy as the samples must be taken from the specified location and involve a highly complex process. Additionally, water samples should be transferred to the laboratory and tested as soon as possible to avoid water pollution. Moreover, this method is time-consuming and costly, requiring equipment cleaning, measuring procedures, and recording. Finally, due to human interaction, many errors might occur during the process, and that will affect the accuracy of the reading.

To conclude, this method is inefficient, and more research should be conducted to develop alternative methods to avoid the challenges mentioned above. Figure 2.1 shows an example of measuring water quality using the traditional method.