Embedded Systems Application and Network in Water Utility Systems

Martin C. Peter
Computer Engineering Department
Faculty of Engineering
Nile University of Nigeria
Abuja, Nigeria
211222002@nileuniversity.edu.ng

Sadiq Thomas
Computer Engineering Department
Faculty of Engineering
Nile university of Nigeria
Abuja, Nigeria
sadiqthomas@nileuniversity.edu.ng

James Agajo
Computer Engineering Department
Faculty of Engineering
FUT Minna
Niger, Nigeria
james.agajo@futminna.edu.ng

2022 IEEE Nigeria 4th International Conference on Disruptive Technologies for Sustainable Development (NIGERCON) | 978-1-6654-7978-3/22/$31.00 ©2022 IEEE | DOI: 10.1109/NIGERCON54645.2022.9803143

***Abstract*—Utility systems form part of everyday life. We use them directly or indirectly as we carry on with daily activities. These systems can simply be our home appliances such as washing machine, Microwave oven and so on. Utility supplies such as electricity, pipe-borne water and cooking gas also have significant influence in our daily lives. The quest to build and manage highly efficient utility systems fueled the development and evolution of control technologies, from classical interwork of mechanical and analog electronics to digital electronic control with programmability. Such functionalities have facilitated utility device automation, versatility and reliability. Today, these digital control capabilities are built into computer-based subsystems referred to as embedded systems (ES). Depending on stringency of requirements in the area of application, a wide range of embedded systems are used to drive operation of utility systems. Some are run by simply miniaturized microcomputers running specific operating systems while others are based on microcontrollers running firmware programs incorporated as part of a larger machine or device. This paper aims to leverage insights from previous research works on ES to proffer cost-effective solution to the problem of pipeline leakages in water supply infrastructure.**

Keywords— Embedded, Utility, Automation, Appliance, Efficiency, Systems, Control, Network

I. INTRODUCTION

Since the advent of micro-computing and systems miniaturization through very large scale integration (VLSI) and Ultra large scale integration (ULSI), the quest and race towards building smart systems had been in an upward trajectory. This has seen the use of microprocessor-based system drivers being on the increase. Utility appliances for home, institutional and industrial application have been revolutionized by incorporation of programmability which further broadened their capabilities and range of use. All these were made possible by the incorporation of microprocessor-based sub-systems, often referred as deeply embedded systems [1]
Embedded systems are built from simple to more sophisticated architecture and configuration depending on area of application and requirement profile. A simple microcontroller with input and output port units can be programmed and used to drive the functionality of a utility appliance. Such simple applications are often implemented using Arduino or Raspberry pi. Other advanced application often do require the use of embedded systems build with multiple processors and running an embedded operating systems such as real-time operating systems (RTOS) , mostly used in real-time systems.

In the world today, embedded systems application has approached its maturation as it now drives the journey of internet of things (IOT) where such devices do not only operate within their local networks but are able to communicate on a wider scope and range over the internet. This maturation invariably put some pressure on internet resource regulation, in specific terms, IP addressing which has led to speedy adoption of the IPv6. In complement, this has rippled to Network communication technologies evolution and the birth of 5th generation mobile communication technology 5G to cater for bandwidth-hungry communication services. These together have form the base platform driving internet of things (IOT), where the “Thing” referred here are essentially Embedded Systems (ES).

II. PHILOSOPHY AND QUEST FOR ES-BASED CONTROL

At the core of embedded systems value proposition is operation efficiency, performance and ease of use. In diverse areas of use of electrically-powered systems and network of systems, the target is usually as aforementioned. This subject dovetails into the area of control engineering where classically the Proportional (P), Integral (I) and Derivative (D) concept of control has been implemented in systems used in industrial automation. This control scheme works well for system with linear operational requirements but has significant limitations in applications with non-linear requirements [2]. Such limitation is often augmented with incorporation of some low level logic such as fuzzy logic. However this control structure and mechanism does not give full automation as some degree of manual intervention may be required at certain points of system operation. This is the reason legacy control systems are vastly replaced by smarter ones which are programmable and with possibility of intelligence, thus greatly minimizing if not eliminating the need for manual interventions. Most safety and mission critical applications across wide range of industries are smart systems based embedded technologies.

III. RELATED WORK

Many scholars have researched this subject based on different areas of application. As this research is focused on control of liquid flow using a network of embedded systems, insights were drawn from research areas involving the flow control of different types of liquids and model used to achieve targeted control aims. One clear insight is that researchers often chose specific attributes or characteristics of liquids based on fluid mechanics to achieve its flow control. Flow control devices integrated with embedded systems could be programmed to control its sensors and actuators, hence controlling liquid flow rate passing through such devices. This is widely applicable in smart valves deployed in oil and gas industries as well as metropolitan water supply infrastructure. Below are some work that has been done been done in this area by some authors and scholars, ranging from stand-alone to networked applications of embedded systems.

On water flow rate determination and control using software-designed fuzzy logic, Prathyusha [3] designed and tested a fuzzy logic-based water pump controller using Arduino interfaced with a personal computer. The goal of his design was to establish controllability of amount of water pumped through a point using flow rate parameter by means of which a written software algorithm is able to control the source of water supply – the pumping machine. Work from other scholars were also researched in order to gain additional insight into parameters and techniques for automating fluid control. These insights are useful guide into the intended research area targeted in this paper.

Patil and Bharkad [2] demonstrated the use of temperature and weight of liquid as parameters for controlling flow rate. This was specifically for high-temperature liquid substance flow in industrial applications which in this case was a smelting and casting industrial process control. The researcher in this case leveraged findings and postulations from other flow process control researchers such as Moon and lee [4] who proposed the use of hybrid algorithm of fuzzy and PI mechanisms to control temperature of molten glass in glass manufacturing industry. The data presented provided empirical outlook and inferential results for the design, prototyping and experimentation of flow control of liquid under different conditions.

Generally, in the science of fluid mechanics, there are a good number of static and kinetic properties of liquid that describe its mechanical state in real time. These can be weight, temperature, pressure, volume, density, speed or velocity in the case rate of flow. These amongst other properties can be leveraged to control the dynamics of liquid transfer processes especially in industrial applications using embedded systems and associated program and programming technologies. Different algorithms are often employed depending on complexity of system or required control mechanism. These range from classical PI and PID to Fuzzy logic, neural network and more advanced techniques used in PLC and DCS industrial process control.

IV. RESEARCH OBJECTIVE AND USE CASE

The production and supply of portable water in urban and rural areas face numerous challenges which limited efficiency, utilization, system robustness and overall commercial viability and sustenance. This challenge is more pronounced in less developed and developing cities as need for portable water being on the increase is hardly efficiently and sustainably met. The Nigerian Federal ministry of water resources (FMWR) in collaboration with UNICEF and National Bureau of statistics (NBS) published a survey report in 2019 detailing these limitations and its socio-economic impact on the populace. The report estimated from survey data across the federation showed that only 35% of installed capacity of public water supply is accessible for utilization, only 8% is metered, and national per capita water supply to end users stands at 9 liters per person per day as against 16 liters per person per day standard benchmark. Also the sector records an average investment loss of 25% per annum [5]. All these stemming from challenges in the implementation, operation and maintenance of installed water supply infrastructure. At the root of the challenge is system automation or lack of it. Hence there are limited or no effective way to monitor and control production and delivery of water supply from production plant to end-users. In developing and under-developed countries most especially, water production and delivery plants operate based on low-end technologies with limited or no automation, data gathering and analysis for performance improvement as well as production planning and scaling. This leaves end-users mostly with limited or low supply of clean portable water due to production and maintenance deficiencies including wastages during delivery owing to infrastructure damages and incapacities.

This research project is aimed at developing a cost-optimized and effective control mechanism for portable water supply delivery infrastructure, ensuring significant reduction or elimination of water wastages and contamination from damaged pipelines through automated detection and control of water flow along the pipelines. The technology adopted for this use case is low-cost embedded systems integration and networking of same along water supply pipelines.

V. SYSTEM DESCRIPTION AND METHODOLOGY

In various literatures reviewed, authors focused on models and designs of stand-alone embedded systems which were programmed to control the flow of liquid based on applicable control methods and appropriated use cases. ES being stand-alone means unsynchronized or uncoordinated management of interconnected pipelines spread over a vast geographic area. This is the gap in legacy research reviewed which this research seeks to address, while leveraging appropriate methodologies used in stand-alone implementations within an integrated Network-based implementation. The ES devices in this case are installed on water pipelines as inline valve controllers.

Sood et al [6] in his work on irrigation water flow control enumerated a number of methods of liquid flow control based on different sensing mechanisms. These methods of sensing and measuring flow rate and their order of accuracy are listed in figures 1 and 2 below.

.

Principle	Types
Differential pressure	Orifice Plate type of meter, Rota Meter, Flow Nozzle, Pitot type Tube, Elbow Tap, Venturi Tube
Positive Displacement	Oval Gear type, Nutating Disc type, Rotary Vane type, Reciprocating Piston
Velocity	Turbine type, Vortex Shedding Electro-magnetic, Ultrasonic Doppler type, Ultrasonic Transit Time type.
Mass	Coriolis , Thermal
Open channel	Weir, Flume

Figure 1: Flow meter types based on different principles [5]

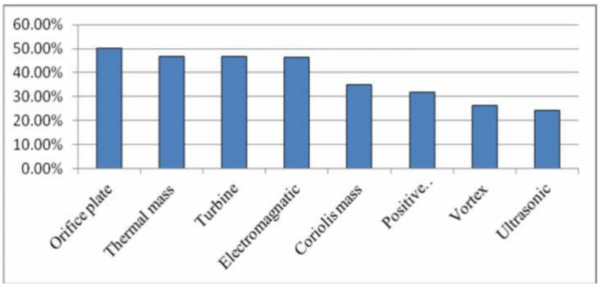


Figure 2: Flow meter types and accuracy index [5]

In this research project, orifice plate method is adopted as the sensing mechanism owing to the nature of use case in focus and degree of accuracy required in measuring liquid flow for efficient control. Actuation is based on electro-mechanical valve sub-system. Each pipeline active junction or node comprises of the ES unit, the orifice plate meter and an electro-mechanical valve, all being incorporated together either as retrofit or manufactured into an integrated unit referred to as the Junction Control Unit or JCU.

In low-cost deployment, simple Arduino-based ES unit programmed in low-level language can be used in the JCU, however the bit of challenge will be in the integration of radiofrequency component for inter-ES wireless communication. For enterprise-grade deployments, embedded system units equipped with enterprise-grade real-time operating system will be a much suitable solution. This removes the challenge associated with wireless networking of the ES devices as such operating systems are mostly built for constrained device environments and features suitable network stack that facilitate efficient operation [7], [8],[9],[10]. Typical software architecture of such OS is shown in figure 3.

The network stack feature is a variant of a traditional TCP/IP suite as shown in figure 4.

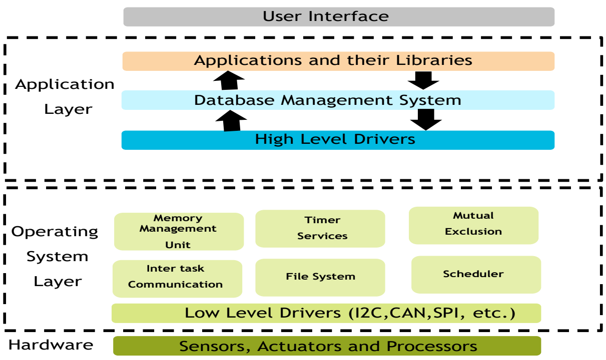


Figure 3: RTOS-based software architecture for ES [9]

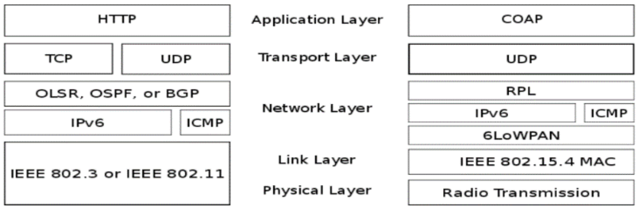


Figure 4: Traditional TCP/IP network stack versus constrained network stack for ES [10]

The junction valves of pipelines heading from supply point(s) to user end points are monitored and controlled through the ES network. The target is for these ES devices to communicate status of water flow in pipes adjoining to the junction valves on which they are installed. It is envisioned that the entire network footprint for a metropolitan areas could be up to a few hundreds of kilometers, and depending on span length between pipe junction valves, several hundreds of ES devices may be required for a full-scale project implementation. A best-fitting and cost-optimized ES device solution equipped with the right RTOS is a key for efficient internetworking between the ES devices [11], [12], [13]. For constrained implementations, RTOS may feature bus-based Network communication protocols such as I2C or CAN as demonstrated by Rajasekhar and Sastry [14].

VI. IMPLEMENTATION AND OPERATIONALISATION

The focus in this project design is use of low-cost materials with innovative design and mechanisms to provide viable solution to the identified problem. Main components of the project design are:

- Junction control unit (JCU)
- Junction Control gateway (JCG)
- Central Office Monitoring Platform (COMP)

A. Junction Control Unit

This component is essentially a junction control valve fitted with ES-based automatic control. This is the main driver of the JCU. Each JCU is electronically ‘self-aware’ and would communicate with adjacent neighboring JCUs in the event of sensing any leakage from an ingress pipeline. This messaging is cascaded forward to JCUs ahead by multicasts until it reaches a Junction control gateway (JCG) which relays such alarm message to the central office monitoring platform (COMP), triggering a corrective maintenance action.

The JCU is primarily driven by an ES equipped with RTOS that keeps it in sleep mode perpetually except at the occurrence of an event whereby it wakes up executes alarm messaging in timed intervals and goes back to sleep mode. The sleep mode mechanism is aimed at sustaining a long battery power life as the device runs on battery power that is targeted to last for a minimum of 2 years before replacement.

JCUs are to be typically spaced within the range of the radio transceiver built into the ES. This can be anywhere between 50 to 100 meters spans. Figure 5 and 6 shows the schematic of a JCU and implementation structure.

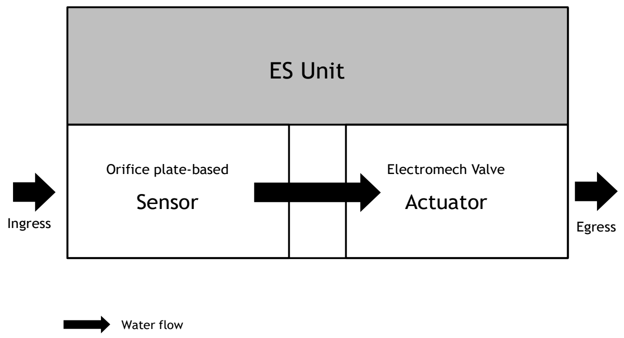


Figure 5: Schematics of a Junction Control Unit (JCU)

Figure 6: Schematics of a Pipeline segment equipped with JCU

B. *Junction Control Gateway*

The JCG is a JCU with additional capability of relaying alarm messages to central office via a public network such as the internet. JCGs should be situated in locations where public network service is available for data connection via 4G/LTE or an appropriate metro Wi-Fi service. As this node communicates via a public network for cost-efficient messaging, the downside of this approach will be cyber security, and being that the device is constrained in terms computing capacity its design economics will be negated by use of high-end computing system, especially the operating system. Light-weight RTOS are still the best-fitting OS for low-cost implementation and operation.
To circumvent the cybersecurity challenge, end-to-end virtual private network connection is recommended between the central office(s) and JCGs installed across the metropolis.

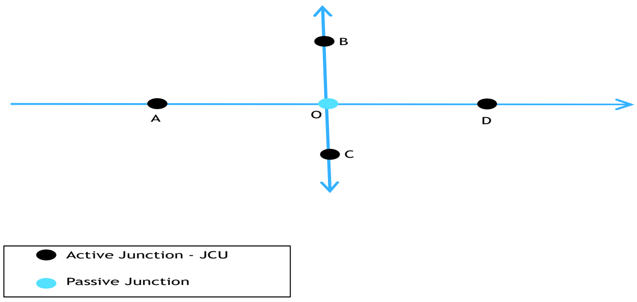
C. *Central Office Monitoring Platform*

The COMP functions like a supervisory control and data acquisition (SCADA) system. It is situated in the water supply company premise or could be hosted in cloud. The platform is essentially an application with built-in features for collecting and analyzing alarms triggered from field JCUs. The COMP app could have geospatial mapping capability with which technical personnel could identify troubled locations from where alarms emanated.

JCU, JCG and COMP units could be manufactured by different original equipment manufacturers (OEM) with varieties of feature-set, sophistications and capabilities for proactive supervision and maintenance interventions on water supply network of pipelines of various scales. The overarching goal is cost-effectiveness and operational robustness.

VII. SYSTEMS OPERATION MECHANISM

Typical operation of the junction control system is explained below using an example of a four-way junction equipped with four active ES nodes A, B, C and D, and a central passive junction O. Junction O being the distribution point into pipeline segments B , C and D as water flows from west to east direction via pipeline segment A. These are shown in figures 7,8 and 9 below.



. **Figure 7: Line diagram of a 4-way Pipeline junction flow**

Location		Segment			
		A	B	C	D
OA	X	S			
OB	X	S			
OC	X	S			
OD	X	S			
A	X	S			
B	X		S		
				S	
C	X				
D	X				S

X : Line fault
S: Valve shut

Figure 8: Tabular matrix of a 4-way junction flow control

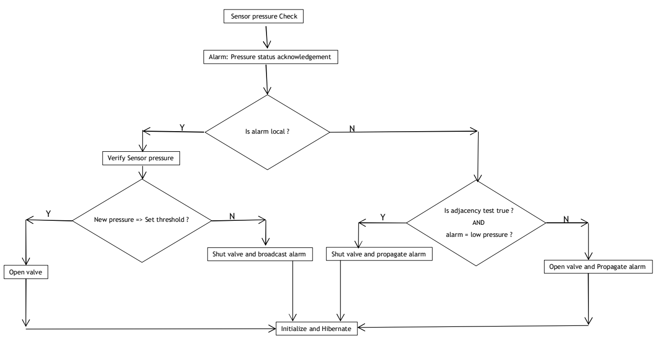


Figure 9: Operation mechanism of a JCU

Figure 9 is a flow chart explaining JCU operation mechanism. In the event of a fault, which in this case is pipeline leakage, a fault alarm is triggered. Fault alarm can be local if triggered by loss of pressure at the ingress sensor of the JCU, or external if a broadcast or propagated alarm message is received by the JCU.
For local fault alarms, verification of ingress pressure is done to trigger the next action which can be a shut or open of the egress valve depending on sensed pressure compared to valve pressure threshold set. Threshold setting is done by calibration of the JCU.

For an external alarm, which is received from a distant broadcast, the JCU performs a threshold pressure check locally and an adjacency test. Adjacency Test is a check of distance of the broadcast-recipient JCU from the original alarm message source JCU, and compared with a pre-set adjacency benchmark value.

The term adjacency refers to a 50 to 100 meters hop between two JCUs within the same neighborhood or cluster. After pressure and adjacency check, the JCU performs a logical AND operation that triggers next action based on truth value of the AND operation. This results in a shut or open actuation of the egress value in the JCU.
At the end of an actuation, the JCU initializes and goes into hibernation mode to conserve energy and battery life.

VIII. CONCLUSION AND FUTURE WORK

Insights gained from the work of different researchers in related use cases of embedded systems particularly in the control of fluid flow has been leveraged in developing the research interest of this paper.
A more advanced automation and network models such as the incorporation of Artificial Intelligence in the valve-controlling ES devices and or gateway ES device could be explored such as explored by Bichu et al [9]. Integration into IOT for a wider communication network may be explored in furtherance of this research . This may require the use of higher grade of ES equipped with more robust operating system such as RIOT OS to enable efficient performance in such constrained environment as the IOT. Such advanced mechanisms and networking can expand the capabilities and service efficiency of metropolitan water supply services through data collection, storage, analytics and share of information with other service providers across different geographies, market and industry. Christian Legare of Micruim Incorporated [15] posited that we are fast approaching the era where data or information generated from products will have stronger value than the product and systems generating them.

In general, this paper harnessed a number of research work that formed useful inputs for solution design of pipeline junction control system and network. It is strongly believed that this concept though presented in its simplest form will form a baseline for designing a functionally smart and cost-optimized automated network of water supply infrastructure across metropolitan areas, particularly in areas vulnerable to pipeline damage. The primary goal being to increase system efficiency, automate infrastructure supervision for agile intervention , proactive and corrective systems maintenance, and in overall to have operational cost-efficiency, seamless management, maintainability, reliability and service or market information analytics. These factors will positively impact the socio-economy of both the service providers and users.

ACKNOWLEDGMENT

With utmost gratitude I would like to acknowledge the contributions of my colleagues and instructors in putting together this paper. Their support was immensely helpful by the way of professional advice and supervision.

REFERENCES

[1] Micrium Incorporated. Internet of things:Embedded Devices. (Jan 20,2015).Accessed: Dec. 22, 2021. [online video].Available: https://www.youtube.com/watch?v=hMPqowfFruo.

[2] N. Patil, S. Bharkad " International Journal of Engineering Research & Technology (IJERT) ISSN: 2278-0181, Vol. 5 Issue 08" in *Embedded based Flow Control for Industrial Furnace Automation*, August 2016.[online].Available:http//.www.ijert.org.

[3] G. Prathyusha "International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering ISSN 2320 – 3765, Vol. 6, Issue 6" in *Embedded Based Flow Control Using Fuzzy*. June 2017. [Online].Available: https://www.ijareeie.com/upload/2017/june/135_%20Embedded.pdf

[4] U. Moon and K.Y. Lee "Hybrid algorithm with fuzzy system and conventional PI control for the temperature control of TV glass furnace" in *IEEE Control System Technology*, Nov 2003.[Online].Available: https://www.researchgate.net/publication/3332471_Hybrid_Algorithm_with_Fuzzy_System_and_Conventional_PI_Control_of_TV_Glass_Furnace

[5] Federal Ministry of Water Resources (FMWR), Government of Nigeria, National Bureau of Statistics (NBS) and UNICEF 2020 "Water, Sanitation and Hygiene: National Outcome Routine Mapping (WASH NORM) 2019": A Report of Findings.FCT Abuja Nigeria

[6] R. Sood et al "International Journal of Computer Science, Engineering and Applications (IJCSEA) Vol.3, No.3".in *Design and Development of Automatic Water Flow Meter*. June ,2013.[Online].Available: http://airccse.org/journal/ijcsea/papers/3313ijcsea06.pdf

[7] IntervalZero. *The Role of an RTOS in an Embedded System* .2018 [Online]. Available: https://www.intervalzero.com/the-role-of-an-rtos-in-an-embedded-system

[8] C. Gregerson. *How To Choose The Best RTOS for IoT Devices, Nabto.* 2020 [Online]. Available: https://www.nabto.com/how-to-choose-best-rtos-for-iot

[9] Bichu et al . *RTOS-based Software architecture for Intelligent Unmanned Systems*.2020.[Online]. Available: https://www.semanticscholar.org/paper/RTOS-Based-Software-Architecture-for-Intelligent-Bichu-Kaingade/768232a9ced45706dc055d4a2ddd02baede63f79

[10] O. Hahm et al. *An OS for the IOT- Goals, Challenges and Solution*. July, 2014. [Online].Available : https://www.researchgate.net/publication/262492183_OS_for_the_IoT_Goals_Challenges_and_Solutions.

[11] Micrium Incorporated. Devices and local Networks.(Jan 20, 2015). Accessed: Dec. 21, 2021. [online video].Available: https://www.youtube.com/watch?v=SDJVFr4VUHA .

[12] A. Milinkovic et al." INFOTEH-JAHORINA, vol.14, pp 504 – 506," in *Choosing the right RTOS for IoT platform* , 2015 [online] Available:https://www.researchgate.net/publication/289253076_choosing_the_right_RTOS_for_IOT_platform.

[13] Media, O. S. *How to pick an RTOS. Embedded Computing Design.* (n.d). [online]Available: https://www.embeddedcomputing.com/technology/software-and-os/how-to-pick-an-rtos.

[14] J. Rajasekhar, JKR. Sastry "Journal of Engineering Science and Technology Vol. 15, No. 2 (2020) 858 – 881" in *Building composite embedded systems-based Networks through Hybridisation and Bridging IIC AND CAN.* 2020. [Online].Available: https://jestec.taylors.edu.my/Vol%2015%20issue%202%20April%202020/15_2_9.pdf

[15] Micrium Incorporated. Internet of things: The cloud. (Jan 20,2015).Accessed: Dec 21, 2021.[online video].Available: https://www.youtube.com/watch?v=l7wQrSBszNc