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The Failure Protection of Wireless-Based IIoT Technology for Fluid Level Control Systems

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Abstract

A novel protection mechanism was proposed for failure of a wireless-based IIoT system to control water level. Control via wireless communication can be executed safely using designed protection. A secondary path as a mesh network was automatically enabled to occur if the main MQTT network protocol failed. System backups were no longer required, with increased reliability of the wireless control network and low risk of failure. Performance control via the developed IIoT was demonstrated. Ability of the protection system to combat network failure was confirmed experimentally.

Keywords: IIoT, Failure protection, Mesh network, MQTT protocol

Introduction

Nowadays, automatic control is a crucial part of industrial processes such as oil and gas, petrochemical plants and food and beverage [1-3]. These plants operate automatically to make final products with specifications and quality according to design aspects. Several process parameters must be controlled and automated. Fluid storage in tanks, transport of fluids interacting between processes and consumption rate all influence plant operations. These phenomena are optimised under the set points of the process. Fluid level control has to be maintained to deal with these tasks [4]. The fluid level control system consists of a measuring device, controller and actuator. Firstly, the level sensor, switch or transmitter works as a measuring device to obtain data of fluid levels. Then, this data is sent to the controller to compare with the desired set points and optimise the controlling command. The type of controller depends on the required application such as a microcontroller [5] or a programmable logic controller (PLC) [6]. The controlling command activates the actuator as a control valve or pump to adjust the process to converge to the desired set point. Generally, control systems rely on physical connections (wires and cables) that interconnect all the components within the control loop. In a few applications, fluid level control equipment is installed in areas with limited access to cable wires for maintenance, while sometimes the long distance between each device in the control loop increases the cost of wiring cable. Hence, technology related to reducing the need for cable wiring has been extensively studied.

The internet of Things (IoT) [7] is a system of interrelated computing devices, mechanical and digital machines provided with unique identifiers (UIDs). Information data can be transferred over a network without the interaction of human-to-human or human-to-computer. This technology enables the opportunity for smart activity, automated operation, and so on in several sectors, such as Agrological [8,9], medical system [10,11], education [12,13], transportation [14] or even in for smart home [15]. Explicitly, the IoT is a crucial part of the industry recently, namely, the industrial internet of things (IIoT) [16,17]. This technology interconnects instruments, control system, and other devices networked together with computers for industrial applications such as manufacturing, process control and energy management. It utilizes various technologies and communication platforms.

Wireless technology based on the industrial internet of things (IIoT) is a hot issue for industry 4.0 and plays an important role in several sectors [18]. Recent advancements in reliability have encouraged wireless data communication and supervisory control. Wireless technology has recently become highly feasible and is now considered in process control systems of large-scale industrial applications [19]. Benefits of wireless implementation consist of (1) cost saving of wire cables, (2) promotion of uncomplicated control loop installations and (3) simplification of maintenance. In the industrial process, wireless sensors and control-actuator networks are an effective smart infrastructure for process control and factory automation [20,21]. This technology has been mainly installed as plant sensors and actuators. However, if the communication network among each component in the control loop fails, this can affect fluid level control and impact fluid overflow, lack of fluid supply or drastic deviations in fluid levels. This situation also influences other interacting processes resulting in plant shutdown. Therefore, when applying wireless technology to a fluid level control system, a redundant path or backup network is an important requirement. Castello *et al.* [22] proposed a wireless redundant process for the PMU of electrical substations. A wireless link was used for transferring information as a backup network of the protection system. It was active when a communication faulted on the cabled connection. This research represented the ability of the wireless system on the redundant task.

Naman *et al.* [23] presented the idea of wireless control feedback loop to control the water level in a water tank. Simbeye *et al.* [24] designed and presented a wireless sensor network monitoring and control system for aquaculture.

Illes *et al.* [25] designed and implemented a water level control system based on a PLC system and wireless sensors without network failure protection, while Lu *et al.* [26] designed and implemented a wireless water level control system. Performance of the wireless network was compared with a conventional wire network. However, redundant networks were not studied by these studies. Extensive study of wireless technology, including redundant networks on fluid level control applications is still lacking and investigation of wireless network switching between the main path and a backup network has not yet been published.

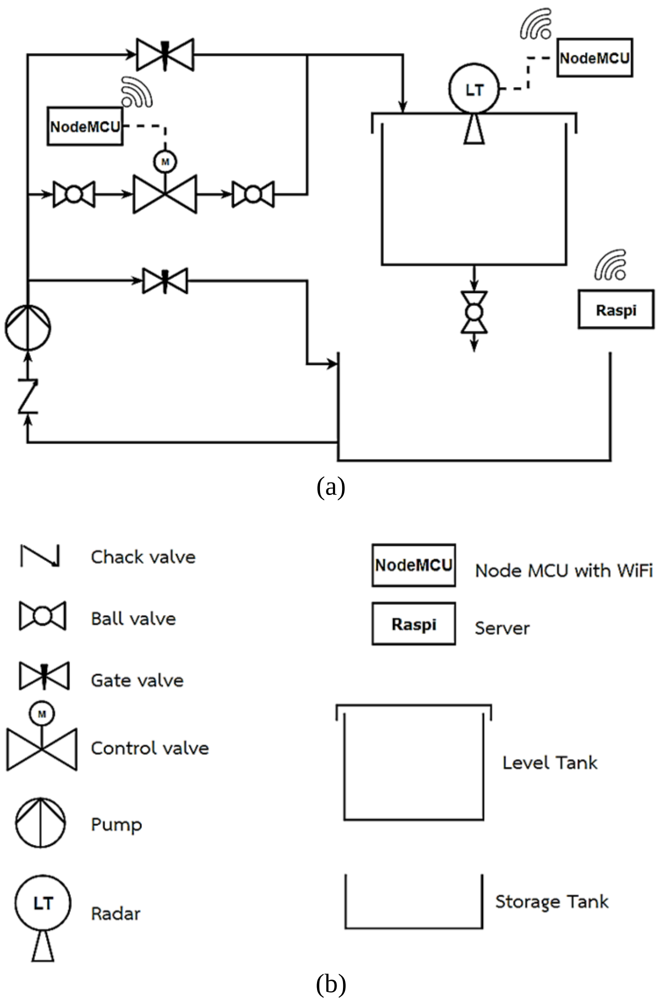
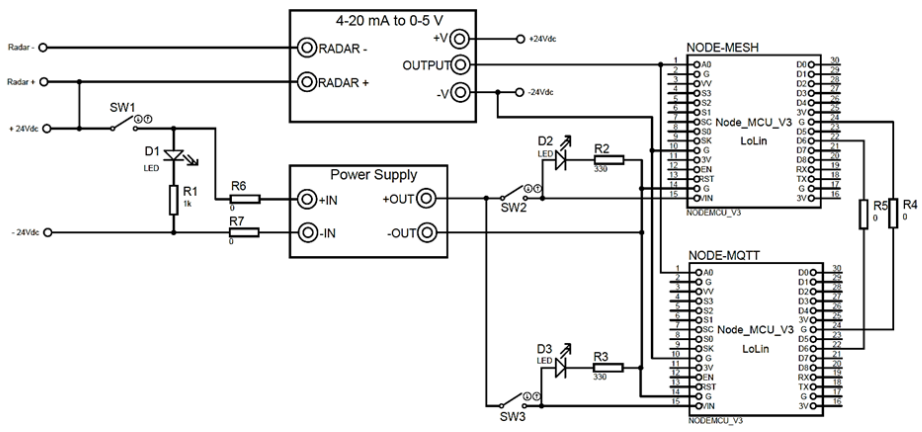


Figure 1 (a) Model of IoT control plant and (b) Device symbols.

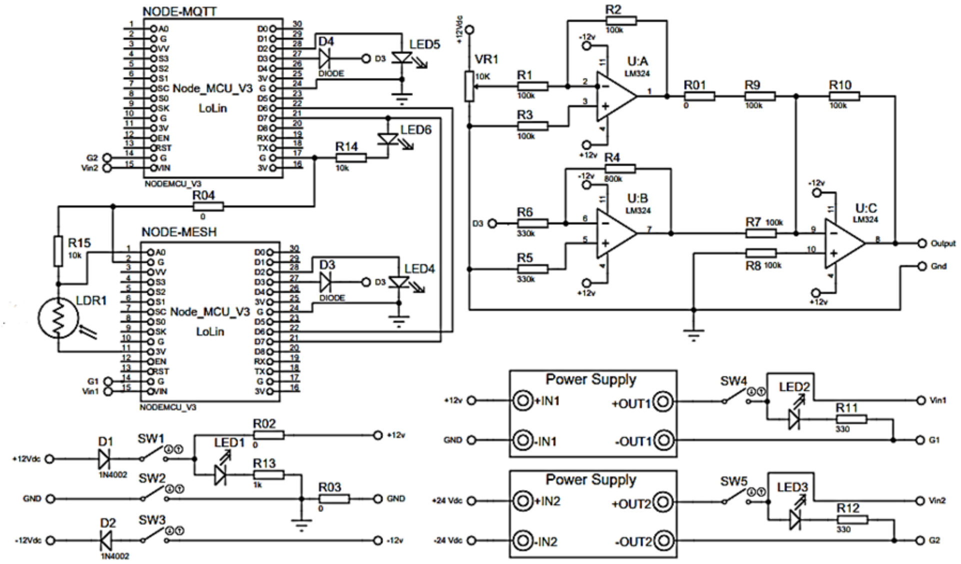
This paper presents the concept of a novel safety system for use in IIoT based wireless technology. The system is free from any controllers in the wireless network; a controlled variable (CV) measured on the sensor is transmitted via the server and a manipulated variable (MV) processed on the server is sent to the actuator. This proposed control system via wireless communication can be operated on 2 safety protection layers to make it more reliable. Network hierarchy of the proposed system consists of a main network that is set to communicate on Message Queuing Telemetry Transport (MQTT) protocol, a secondary network as the local mesh network for backups and as a redundancy for continuing the level process when broken wireless modules occur. Reliability and stability of the system via wireless technology with 2 safety layers are demonstrated experimentally.

Research methodology

The proposed method presents direct communication of field instruments without controllers. **Figure 1** represents the piping and instrumentation diagram (P&ID) of an IIoT pilot plant of water level control. The control process consists of a radar level sensor, the linear control valve, which a motor-operated valve (MOV) employed, and IoT devices (NodeMCU and Raspberry Pi). Node MCUs used for IoT development are ESP32, enabling analogue input and output on their own ports. The level sensor was located on the top of the water tank and interfaced with 2 NodeMCUs in which the primary node is performed to broadcast a process variable (PV) message to the server. The control valve controlled the flow into the water tank. The valve was connected to 2 NodeMCUs. In normal operation, the valve receives a manipulated variable (MV) message from the primary node connecting with the server. If the main network is failure, the redundancy node is utilized to communicate with the redundancy node of the radar level via the backup path (mesh network). The control valve receives the MV via this network. The proportional-integral (PI) control action programmed on the server was applied as a control strategy. Two ball valves placed in the front and back of the control valve were used for maintenance. Another ball valve installed under the water tank aims to alert disturbance to the pilot level plant. Two parallel gate valves were suitable for installation in bypass piping. The flow rate was operated by a pump and circulated back to a storage tank. The radar level transmitter provides 4 - 20 mA of output, and then the current signal is converted to 0 - 3.3 V to support analogue input ports of NodeMCUs. A level sensor node circuit broadcasting PV messages to the server (**Figure 2(a)**) is made up of 2 NodeMCUs (NODE-MQTT and NODE-MESH), a current to voltage converter module, and a power supply. PV messages are directly proportional to 0 - 100 % of the water level going up or down inside the water tank. Similarly, a control valve node is pictured in **Figure 2(b)** also contains 2 NodeMCUs that receive MV messages from the server and a signal conditioning circuit for converting 0 - 3.3 V to 2 - 10 V that drives the linear control valve in accordance with PI action and 2 power supplies. Integration of the IIoT requires implementation of wireless sensors and linear control valves on a single loop via a message queuing telemetry transport (MQTT) protocol or mesh network. For the proposed wireless system, wires from the linear control valve to the server and the water level sensor to the server are eliminated. The algorithm is divided into 2 paths for redundancy backups as shown in **Figure 3**.



(a)



(b)

Figure 2 (a) Measurement node circuit and (b) Control valve node circuit.

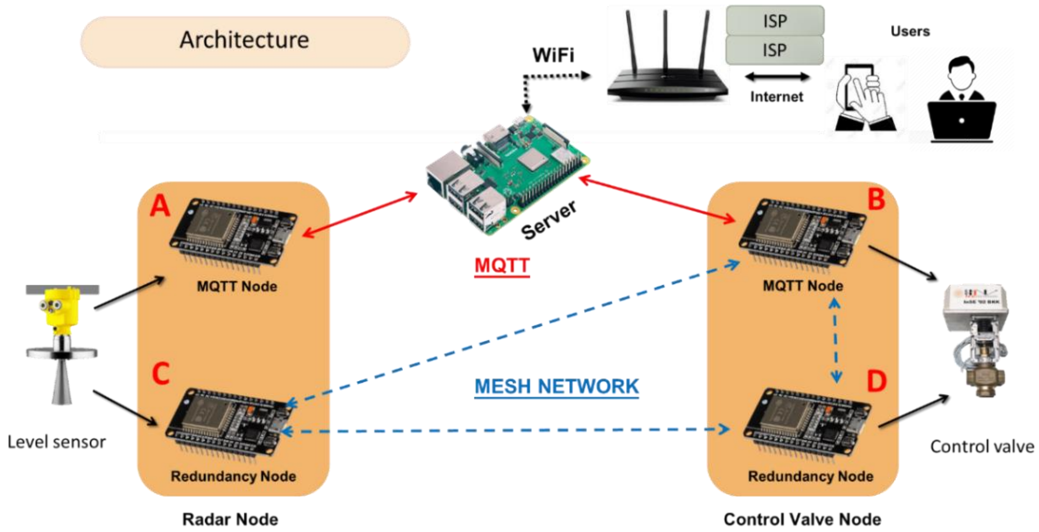


Figure 3 Flowchart of communication algorithms for both measurement and control nodes.

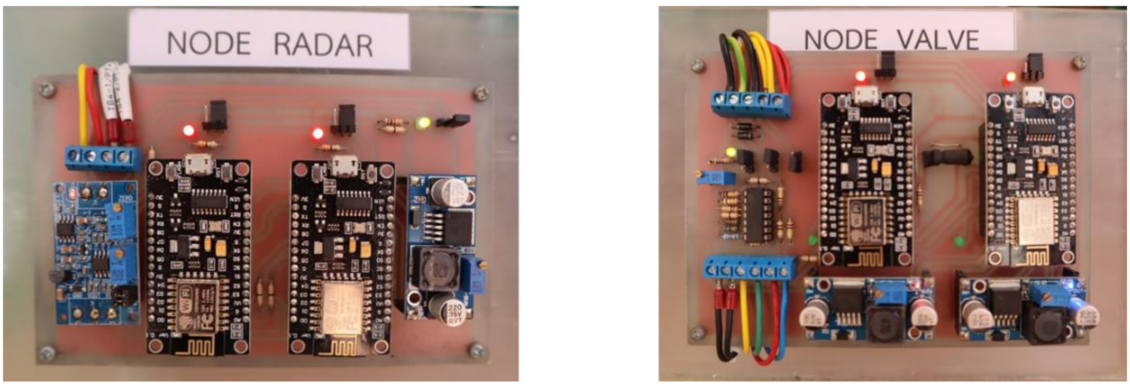


Figure 4 Prototype wireless nodes, (a) radar level transmitter, (b) control valve.

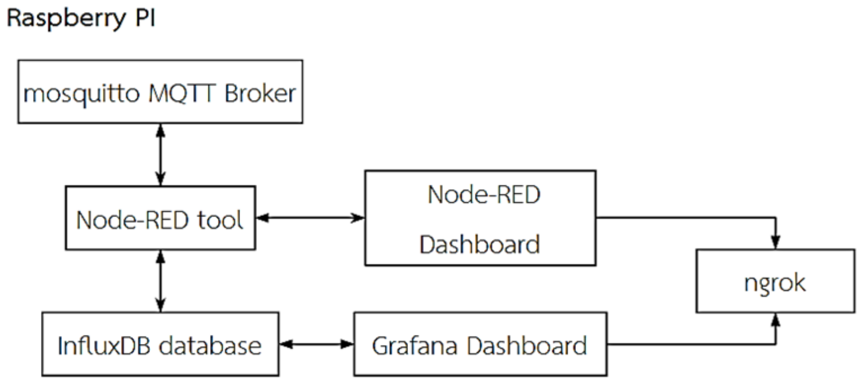


Figure 5 Software functional diagram of the Raspberry Pi.

The solid line represents wired communication while the dotted line represents wireless media communication. A brief definition of devices is as follows:

- Raspberry Pi creates a local network, receives and sends data messages to NodeMCUs over the Local Wireless Network (LWN). It is performed on only MQTT protocol.
- NodeMCUs are responsible for wirelessly transferring data messages of the radar sensor and the linear valve to the server.
- The router is responsible for finding, receiving and sending data packets between the local network and the internet service provider and enabling the local network to connect to the internet.
- The internet Service Provider (ISP) provides internet services that connect data sent through router devices such as Dial, DSL and wireless modems or connecting to high-speed internet.
- Personal computers and laptops have main functions of remoting the pilot level processes over the internet through a router that communicates with the ISP.
- Tablets and smartphones are responsible for remote control over the internet anywhere via 3G/4G or routers that communicate with the ISP.
- Mosquitto acts as a broker hub for NodeMCU over MQTT Protocol. It is used to send and receive topics such as water level (PV), desired water level (SP), parameters of control equations (KP, KI) and percentage of control valve movement (MV).
- InfluxDB is a software used to create a database for the server, designed to store all process values including PV, SP, KP, KI and MV.

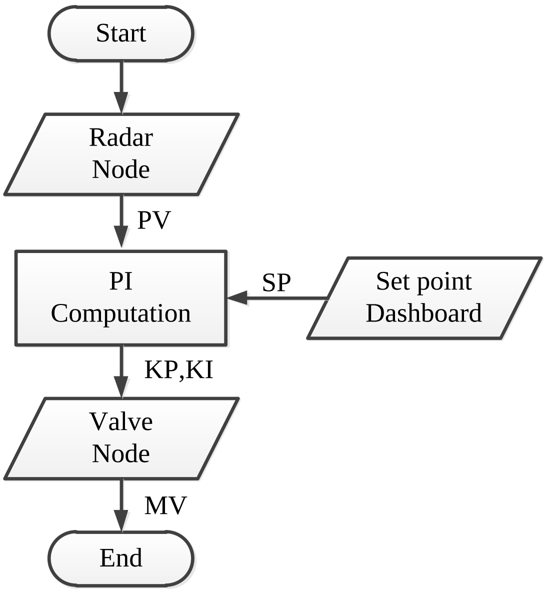


Figure 6 Workflow of server.

- Node-RED makes the server easier to compile and manage a task schedule to integrate all software in a flow format without writing structure text. The user can access the server through the URL via the browser at the localhost port: 1880 as the port where Node-RED is installed.
- Grafana is used as the presentation of information in the database including SP, KP, KI, PV, MV parameters. It also has a dashboard that displays real-time data. Recorded data can be retrieved from the system.
- ngrok makes the Grafana Dashboard and the Node-RED work together on the LWN to the internet so that users can access it from other devices.

A node prototype of both sensor and actuator was experimentally used to evaluate the new design and enhance stability as shown in **Figure 4**. Server architecture was designed to collect and distribute data within the LWN and operated all day all night. Therefore, the Raspberry Pi with low power consumption, small size and also full communication channels including both LAN and Wi-Fi was selected as the server. LWN communication involves 2 networks as main and secondary communications based on MQTT protocol and mesh networks respectively. The server contains programs with the following software as described in **Figure 5**. The flowchart in **Figure 6** shows server operations that receive and send messages from the measurement node and to the control valve node respectively. The dashboard server design consists of a gauge display and the trend is shown in **Figure 7**.

• No. 1 shows gauges of the required water level (SP), the water level (PV), the percentage of control valve movement (MV) and the error value.
• No. 2 indicates the number of the desired water level (SP), the water level (PV), the percentage of control valve movement (MV) and the error value.
• No. 3 shows the trend of the desired water level (SP), the water level (PV), the percentage of control valve movement (MV) and the error value.
• No. 4 shows the KP and KI values.

The MQTT main protocol is a very simple, lightweight package designed for use with low bandwidth, high latency and unreliable networks. The MQTT protocol aims to minimize network bandwidth and equipment resource requirements, to adopt a main node-server architecture and to perform message transmission based on topic subscription and message publishing. The measurement node acts as a publisher of messages, then the server receives messages from that node by subscribing to the topics of interest. On the other hand, the server acts as a publisher and the control valve node subscribes to topics that the server broadcasts. The PI algorithm programmed on the server and NodeMCUs implements and processes MV messages at every sampling time T to the final control element. The computed controller output from the PI algorithm is influenced by the controller tuning parameters and the controller error $e(t)$. Integral action enables PI controllers to eliminate offset, a major weakness of a P-only controller. Thus, PI controllers provide a balance of complexity and capability that makes them by far the most widely used algorithm in level process control applications [27]. Different vendors cast essentially the same algorithm in different forms. This paper explores the variously described dependent, ideal and continuous position form as:

$$CO = CO_{bias} + K_C e(t) + \frac{K_C}{T_i}\int e(t)dt \tag{1}$$

Where:
CO = server output signal (wireless out)
CO_{bias} = bias or null value
$e(t)$ = current controller error, defined as SP-PV
SP = set point
PV = measured process variable (the wireless in)
K_C = controller gain, a tuning parameter
T_i = reset time, a tuning parameter ($Ki = 1/Ti$)

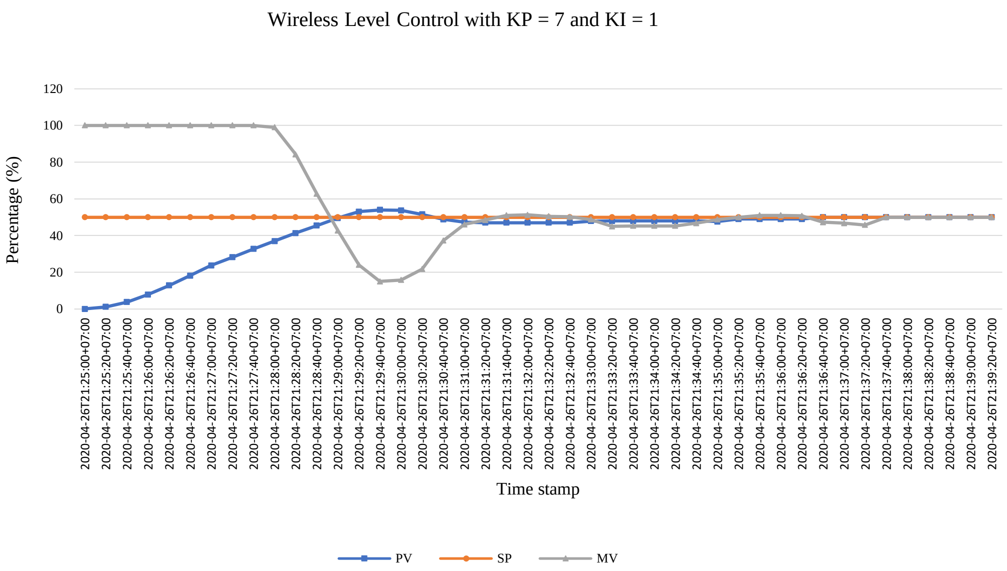
The Ziegler-Nichols rule, a heuristic PID tuning rule that attempts to produce good values for the 3 PID gain parameters, was applied for tunning PI controller in this paper. This method has reliability in the field of control engineering [28].

Server connection loss and redundancy

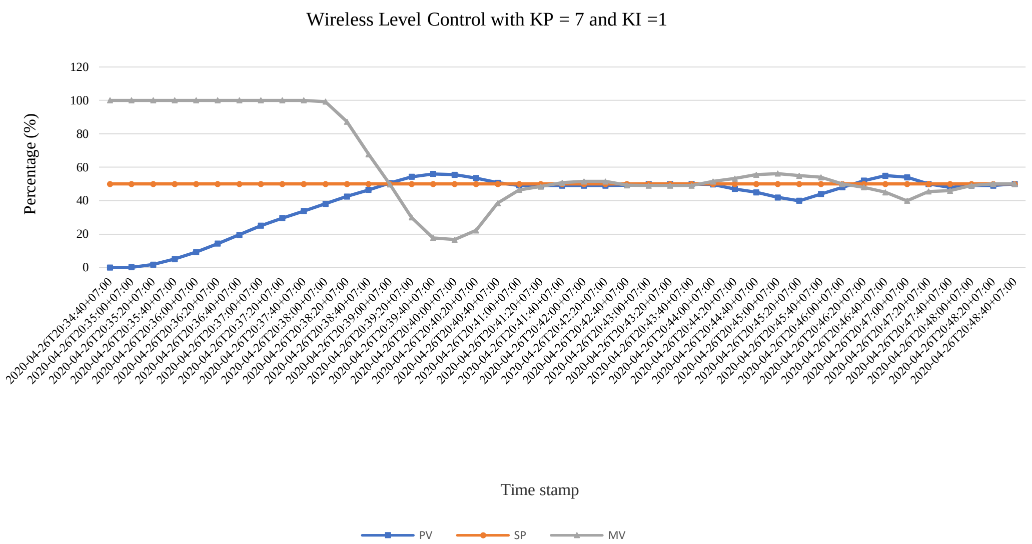
To increase reliability, the IIoT system for water level control also provides backup communication if server communication is lost. The backup system must have the capability to automatically replace the missing primary system to maintain water level control. A mesh network, capable of communication between nodes without external communication, was therefore designed as a backup if the main system malfunctioned. An advantage of a mesh network is data sharing of every node in the communication circle that is created with independent communication without the need for a central processor. This means that when any node is missing, the redundant node can still replace the missing node. Users are confident that IIoT is safe enough if the WiFi signal is temporarily disconnected. Accordingly, the mesh network programmed in NodeMCU is called to communicate when NodeMCUs do not receive messages from the server at the specified time. The mesh network as shown in **Figure 8** is created for secondary communication using 3 NodeMCUs divided into a measurement node and 2 control valve nodes. In this phase, the main and backup algorithm is defined for NodeMCU on the mesh network, while server connection loss is shown as Algorithm 1.

Figure 7 Grafana dashboard display.

Figure 8 Prototype of the IIoT water level control system.



(a)



(b)

Figure 9 Wireless level control (a) No disturbance, (b) Disturbance.

Algorithm1

```
IF ((Node A AND Node D) CONNECT Server < 5 s)
        THEN    SET             MQTT Network
                INPUT           Node D publishes a topic and PV value to the server
                INPUT           The server receives the topic from Node B
                COMPUTE         Error = Setpoint - PV
                COMPARE         MV = Output of PI Action
                OUTPUT          Publish the topic to Node A with subscribe
                WRITE           Node A shares MV and SP to Node C by serial communication
ELSE
        THEN    SET             Mesh Network
                OUTPUT          Node B asks for the MAC address from all nodes in the mesh network
                IF   ((Node A AND Node C) CONNECT Node B WITH MAC Address < 5 s)
                        THEN    OUTPUT  Node B sends MV message to Node A and Node C directly
                                IF ( Response FROM (Node A OR Node C) > 5 s)
                                        THEN    OUTPUT  Close the control valve to safety by Node
                                                 A,C
                                ELSE
                                        THEN    COMPUTE Node A,C use SP to compute MV
                ELSE
                        THEN    DISPLAY Node B shows blink lamp to show that mesh network has failed

END
```

Figure 10 Alarm display on Gafana dashboard when server connection was lost.

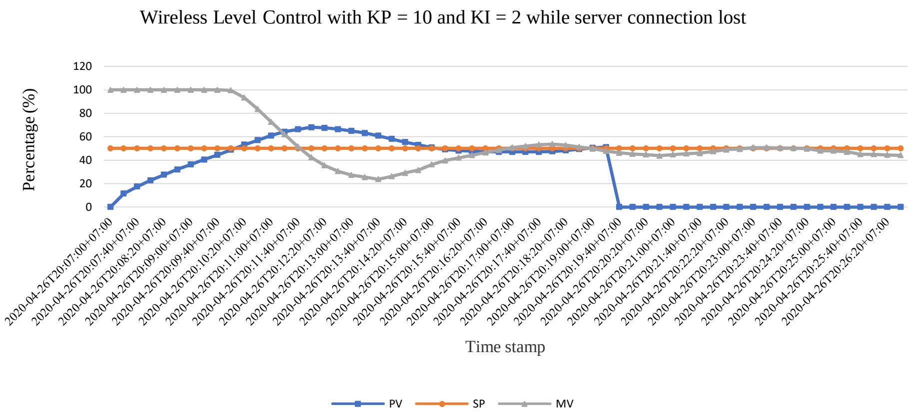


Figure 11 Wireless water level control when server connection was lost.

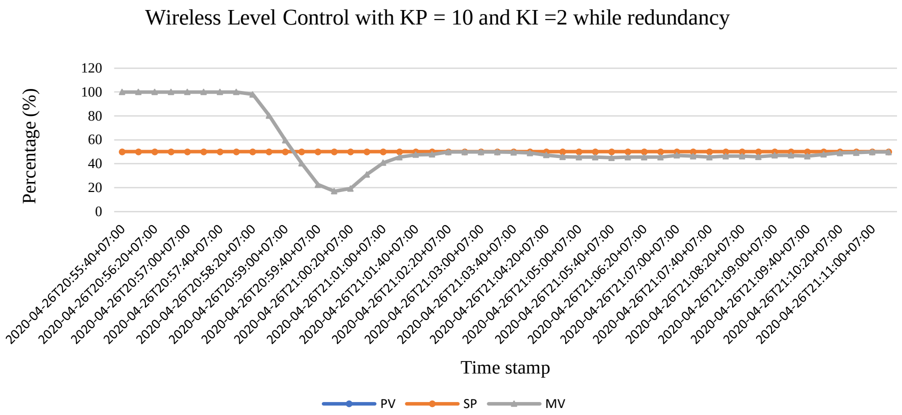


Figure 12 Wireless water level control during redundancy.

Results and discussion

The prototype of the IIoT water level control system was designed using industrial measuring tools consisting of water levelling devices, electric linear valves and a water tank as shown in **Figure 8**. The IIoT devices are shown in **Table 1**. SP was selected on the dashboard of the Experiments were run with 2 sets of different PI parameters for both online and offline server connection. Comparison of the response as shown in **Figure 9** is the desired value (SP) that was set at 50 %, a process response (PV) and a control valve movement (MV). **Figure 9(a)**, presenting the process response with wireless control, was found to be stable at 7 min of settle times and had a 5 % overshoot. Disturbance in **Figure 9(b)** was interrupted as soon as 10 min passed and the desired value also remained stable. Next, reliability of the wireless water level control was verified by unplugging the server from the network. Simultaneously, the mesh network was connected to replace the server connection. In **Figure 10**, a window shows the status of the network on the Gafana dashboard while the server was offline. PV in **Figure 11** disappeared after 12 min had elapsed since the wireless water level control started running. The measurement node then sent a message that contained the PV values to the control valve node with KP = 10 and KI = 2 to drive the linear control valve. Based on server connection loss testing, the effect of water level control was still stable using PI action on the NodeMCUs of the mesh network. In the redundant mode, a NodeMCU of the control valve was removed and the behavior of the water level in the tank was observed as shown in **Figure 12**. The result confirmed that the proposed system had the ability to retain the water level. Experimental results of both server connection loss and redundancy can be viewed from the clip of supplementary materials [29-31]. Finally, if the redundant node did not receive a message from the measurement node within 5 s, the linear valve was ordered to be immediately closed.

Table 1 Deployment parameters.

Device	Type	Value
NodeMCUs	-	5 V
Server	-	5 V
Level sensor	Radar	24 V
Control valve	Electrical	24 V

Table 2 Comparative evaluation.

Case	Desired level maintaining
Normal situation	Possible
Main communication failure	Possible (observe MV)
Emergency	Possible (observe MV)

Conclusions

This research discussed the use of IIoT in the wireless water level control process. This prototype was free from any controllers in the wireless network and controlled variables were transmitted via the server. This wireless control system consisted of the main network as communication of the MQTT protocol. Whenever the main network failed, it was automatically replaced by the secondary network as the mesh network. The proposed system also provided redundancy for backups to increase the reliability of wireless control.

Firstly, in a normal situation, based on wireless water level control testing at 50 % of a target value, results of the demonstration showed that the SP value can be entered from users via a dashboard on the internet. The water level can be maintained as the desired setpoint. Secondly, in case of main communication failure on the prototype system, the mesh network, as the secondary communication, was able to maintain the water level as needed. Lastly, the control stability when an emergency occurred was demonstrated where PV and MV were shared on NodeMCU's redundancy and used as a primary control. The water level was controlled to follow the required target. The control performance was observed indirectly via the MV.

All experiments confirmed that the proposed system, designed as 2 safety layers, had the ability to protect against system failures. This research expands the opportunity to develop wireless industrial control systems that are costless of cable wire and simple maintenance to work for liquid level control reliably.

Acknowledgements

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