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Designing a Smart Internet of Things Solution for Point of Use Water Filtration Management System in Residential, Commercial and Public Settings

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***Abstract*— The use of water filtration Point-of-Use (POU) systems are extensive, ranging from water dispensers in public estates, to household POU water systems. Manufacturers typically recommend filtration cartridges to be changed (i) after their useful life, or (ii) when the water flow volume have exceeded certain capacity, whichever is earlier. However, filtration mechanisms are typically not changed with sufficient regularity. Overused filters can result in negative health effects, over and above the deterioration and loss of filtration benefits of the POU water system. Presently most existing water purification systems do not have smart connected Internet of Things (IoT) means of informing owners and suppliers the decline in water quality and the timely change in filters. Results of the proof-of-concept (POC) study comprises smart connected IoT sensors with integrated analytical capabilities, which will be useful to improve consumption management decisions for household consumers, building and estate managers, and government agencies managing public POU water dispenser systems. Considerations need to be given to "minimal-owner-effort" system architecture, real-time detection of sensor component failures and user-friendly issues alert dashboard, and the degree and frequency at which system monitoring and recovery would take place, among others. The modularization scalability and customizability of the solution to include more resource optimization and analytical capabilities across POU water filtration systems, will benefit POU water system owners, suppliers and manufacturers.**

Keywords—point-of-use water filtration, smart IoT, analytics, water quality, management system

I. INTRODUCTION

In Singapore, the national water agency Public Utilities Board (PUB) ensures that our tap water is within the World Health Organization drinking water guidelines and is safe for drinking without the need for further filtration [1]. However, despite PUB's continuous efforts to maintain drinking water quality, there may be occasions where Singapore's tap water may be discolored or contain visible particles, due to PUB maintenance operations, corrosion or contamination of tanks and water pipes, or internal fittings and installations, among other reasons. [2].

Increasing awareness of healthcare, aging water infrastructure, and pollution from industrialization and urbanization are among the reasons leading to an increased use of POU water filters [3]. POUs are water filtration systems designed to filtrate water from a tap or water appliances. Drinking water POUs can include faucet filters and under-sink filters, among others. This market is expected to expand at a compounded annual growth rate of 8.4% between 2016 to 2025, reaching a market size of US$110.02 bn by 2025 [4].

In Singapore, the use of water filtration POU systems for water consumption are extensive, ranging from water dispensers in buildings or estates, to POU water filters bought for domestic household or commercial consumption. POU water filters may be used to treat tap water to meet certain desired drinking purification levels, with reduced levels of contaminants, chemicals and toxins. Increasingly, households may also own POU water systems to consume purified water that brings about certain desired health benefits, such as that with certain alkalinity levels, mineral types, or aeration or oxygen levels [5] [6] [7] [8].

II. INDUSTRY CONTEXT

Typically, manufacturers recommend users to change filter cartridges after their useful life time period (e.g. six months) or when the total water flow volume each cartridge can effectively filter has exceeded certain capacity (e.g. 3,000 litres), whichever is earlier, depending on the type and capacity of water filters custom-built for different filtration devices [9]. Usually, it is up to the consumer to initiate the replacement of existing filters, but consumers tend to delay this change to save cost or forget the duration for which they have used the existing filters. Filters used beyond their useful life can result in loss of filtration benefits of POU water system, deterioration of filter sub-components, and may lead to negative health effects. Among other factors, the latter can be caused by an accumulation of harmful bacteria [10] [11].

Presently most existing water purification systems do not have smart connected IoT means of informing suppliers and owners that the water quality has declined, and the filters need to be changed [12] [13]. Many POU water systems communicate the useful life of filters to users manually; many communicate the period (e.g. visible and/or audible reminder that filter is due for a change at the end of sixth month) [14] [15]. More advanced devices typically have embedded sensors, e.g. flow sensors, to measure if the capacity of the filter has been reached. However, reminders are similarly manual visible and/or audible reminders [16]. Most existing filters also face inefficiency in determining the utilization of filters, including (i) inaccuracy in determining the utilization of filters, leading to underutilization which results in cost wastage; over-utilization may cause harm to the consumers, and (ii) lack of automated data collection and analytics capabilities to analyse the frequency of use as well as habits.

Some filters, such as Mi Purifier, provides real-time water purity information [17]. Customers are able to connect via a mobile application through Wi-Fi to find the quality of water based on total dissolved solids and frequency of use status of the Mi Purifier. The app alerts customers when filters need to be changed. However, this commercial solution is brand-dependent and only deployed in a Mi Purifier. There also exists digital flow meters that can be retrofitted to POU water systems, linking to mobile applications to deliver water consumption information [18]. However, these meters are typically limited in scope (e.g. connectivity limited to Bluetooth or Wi-Fi, and/or lack of analytics capability *etc*.)

This POC study looks to introduce a scalable smart POU drinking water filter IoT sensor-analytics solution, which will allow users to understand the status of their filters, monitor water consumption, as well as to communicate the water-usage data for multi-party/ user analytical purposes.

Users will have to undertake a consumption decision on whether if a filter is to be changed when the filter reaches its useful life or capacity limit. Whether filters are physically changed depends on consumers' knowledge of water consumption and filter useful life, and their preference and willingness to adhere to a manufacturer's prescription. It will be beneficial for multiple stakeholders, ranging from building and estate managers, to suppliers and manufacturers, to be communicated such information to reduce loss of filtration benefits, deterioration of filter sub-components, negative health effects, and lead positively to positive supplier sales outcomes and aid in management of distributed POU water systems.

The uniqueness of this solution comes in the form of transmitting the water flow rate data to a simple dashboard for owners to understand consumption patterns as well as being alerted when the filters are reaching the end of their useful lives. The solution aims to provide analytical and learning capabilities, including for instance, how seasonality trends of water consumption can affect sales and inventory levels, and whether if the use of certain POU water systems in an estate are sub-optimal. It should also be customizable, yet scalable; this means that it will be compatible with all types of water filtration systems unlike the Mi Purifier instance.

It will be beneficial for multiple stakeholders, such as consumers of POU systems, and suppliers and manufacturers of POU water systems, to be informed of their water consumption levels and be provided with analytics capabilities. The latter can include (i) daily water usage and patterns of a specific POU water system, (ii) comparison of usage of POU water system against average and/or recommended water usage and patterns, and (iii) the time period and capacity remaining of filter useful life etc. In addition, for suppliers and manufacturers of POU water systems, information can be integrated to allow (i) improved sales opportunities and sales forecasting, and (ii) inventory management. Building and estate managers who manage POU systems within the confines of their buildings or estates, and government agencies managing public POU water dispenser or water cooler systems, will find such information useful to enhance building or estate management.

III. IoT System Design

A. *Scope limitation*

The role of this research is not to determine the veracity of manufacturers' claims, and validate manufacturers' claim of usage capacity. This heuristics study is based on manufacturers' recommendations that filter cartridges are to be changed (i) after their useful life time period or (ii) when the total water flow volume each cartridge can effectively filtrate have exceeded certain capacity, whichever is earlier.

Monitoring the useful life time period is trivial. The relevant sensor modality, in this case, will be a water flow sensor that can track the flow of water to determine flow volume and if this flow volume has exceeded the filter's usage capacity.

There are varied POU water systems and water filtration methods. This study covers the following water systems and filtration methods:

1) POU water systems studied in this research: There are many kinds of POU water systems, including countertops/ under-sink water filters, faucet water filters, water filter pitchers, and whole-house water systems. In this research, we focus on countertops/ under-sink water filters, water dispenser and water cooler systems, which are prevalent in Singapore's context. Many households in Singapore also own faucet and pitcher filters. We will not be covering these latter filters in this research.

2) Water filtration methods studied in this research: There are also multiple filtration methods, including carbon, ceramic, distillation, de-ionization, ion exchange, reverse osmosis, ultra-violet (UV), among others. In this research, we will focus on filters with cartridge systems that can be changed, such as carbon filters or sediment filters. Filters, such as membrane-dependent reverse osmosis or UV-light dependent filtration, which requires solely the timely change of membrane or light components, are not part of this research consideration.

B. Considerations in sensor modality:

Requirements for water flow sensor modality include the following:

- *Flow outlet size*: Size of the water flow sensor outlets must fit a typical water tubing and/or water valve connecting to such POU water system. The typical water tubing diameter is estimated to be between 0.25 to 0.625 inches [19].
- *Measurement*: Sensitivity and precision of measurements are not critical, which would mean measurements up to one decimal points of flow rate are sufficient.
- *Durability*: Durability of sensors will be necessary, as flow measurements span over a long period of time.
- *Water pressure*: Water pressure and flow rate should be in line with typical POU water systems. According to the Public Utilities Board of Singapore, a typical basin or sink water efficient flow rate is at 2 to 5 litres per min while the water pressure is at 1.2 to 1.5 MPa [20].
- *Temperature*: As water is drawn from tap sources, and sensors are positioned between the tap-sourced water and POU water system, sensors that can operate in room temperature (25 to 35 degree Celsius) should suffice.
- *Cost*: Cost should be marginal to the cost of POU systems for the solution to gain industry-adoption [21].

C. Considerations in network architecture

- *Mobility*: Sensors mounted on POU water systems are stationary and distributed in one or more geo-locations.
- *Energy source and consumption*: Sensors are powered by a constant power source, either on a standalone basis plugged to wall sockets or are customized to tap the power source of the POU system.
- *Transmission range*: POU water systems are mainly located indoors. In building or estate deployment, including office buildings and school compounds, they can be deployed in large indoor areas where the distances between the POU systems and wireless router are significant. It is useful to consider the adoption of connectivity solutions that cater for a longer range of transmission. As an illustration, Marina One, a building in the Central Business District of Singapore where one observes use of POU water systems, an average squared configuration floor footprint can span 3700 square meters, translating to an estimated 60 meters in length or width [22].
- *Data rate and latency*: Monitoring of the water flow rate does not require real-time or frequent transmission of sensed data. Moreover, flow rate sensed data is likely to be in bytes. Amount of water consumed and frequency of transmission will determine the cumulative size of the data packet transmitted.
- *Network traffic and interference:* Wireless connectivity interference can affect data transmission; such interference would be kept to a minimal.
- *Cost*: It is useful to consider the minimization of any additional cost that may be incurred by the user for the sensor-enabled device, over and above the cost incurred for POU water systems [21].

Proposed wireless connectivity are (i) Wi-Fi and/or (ii) NB-IoT. Predilection is leaned towards Wi-Fi, due to its high penetration in developed societies including Singapore, and low cost of implementation, by tapping on existing infrastructure in the deployment locations. Typically, Wi-Fi uses unlicensed ISM radio band (2.4 GHz band), which is likely to invite interference when sensed data transmits to the wireless router(s), alongside other devices and heterogenous wireless protocols operating in the same frequency band. To circumvent this issue, several considerations can be made: (i) Transmission of data packet can be made intermittently, for instance, once every few hours in periods where Wi-Fi usage are minimal, such as early morning 2am – 5am. In an urban setting deployment, this can help reduce interference leading to transmission loss. (ii) Switching to less used channels, such as channel 1, 6 or 11, within Wi-Fi bands may result in drop in transmission efficiency and performance but is likely to lead to reduced transmission loss or failure of data packets. [23]. In an event of a lack of existing Wi-Fi infrastructure, a higher cost option of NB-IoT may be considered. While cost is markedly higher vis-à-vis Wi-Fi, there is less likelihood of interference given it operates in a licensed frequency band. Furthermore, the telecommunications license holder usually ensures good network coverage.

For both (i) Wi-Fi and/or (ii) NB-IoT, the network design involves a flat topology. Although it is a flat topology, it is still important to consider the distance between the IoT nodes and the Wi-Fi/ NB-IoT routers during deployments as a shorter distance generally leads to less chance of interference, lower transmission delay and data loss rate. A trade-off of all options will have to be considered, taking into account the cost of deployment, against optimal system reliability and throughput.

Implementation is likely to involve an event-driven protocol, as water is consumed in distributed times across the day, and non-time sensitive cumulative water usage data is required for collection. This can help can help reduce network traffic from a systems management perspective. For event-driven protocols, it is useful to consider utilizing application-level content-based publish-subscribe (pub-sub) service. In this scenario, the software, dashboard, or app that suppliers or building managers use may act as the subscriber, by specifying their interests, i.e. retrieving sensed water consumption data. The water flow sensor modalities publish their discrete data to the network in a content-based system, including sensor's water flow, timestamp, location *etc.*, without knowledge of their subscribers. Content-based system is especially necessary for large scale deployments, for instance, when suppliers have customers distributed across a region. Intermediaries, called brokers, help read and match published contents to their interested subscribers. The broker will perform the notification function, by performing interest-content matching to the subscriber list.

An illustration of a possible high-level device connection is shown below:

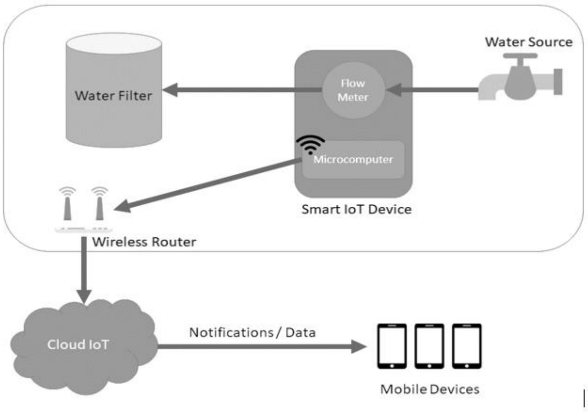

Fig. 1. Illustrative example of device connection

D. POC test implementation, algorithm and interface

POC test was coded in the Node-RED platform and the analytics interactivity interface was generated using Tableau. A relational database also exists to persist the data.

Key reasons for the specific platform and technology choice are as follows:

- *Node-RED platform:* While other options including coding in C/C++, Javascript and Python exist, Node-RED is an alternative with GUI-based option available. In the research, Node-RED was run at 2 locations - Raspberry Pi to read and publish sensed data from the flow sensor modality, and on cloud to subscribe for the message in order to persist the data to database for software dashboard visualization.

- *Message Queueing Telemetry Transport (MQTT):* MQTT messaging protocol, designed for small code footprint pub-sub connections, with data transmissions over TCP protocol, was selected.

- *IBM Watson IoT platform:* The original creator of MQTT, IBM has a free-to-use version ideal for this research purpose.

- *Tableau:* Tableau was selected for its ease of visualization.

- *Microsoft Azure SQL DB:* Good support for connectors exist both from Node-RED and to Tableau. Moreover, a free-to use-version exists suitable for this research purpose.

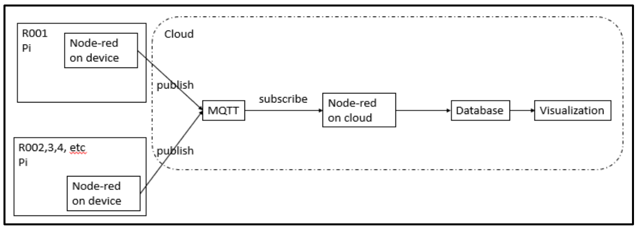

Fig. 2. High-level POC Device Connection

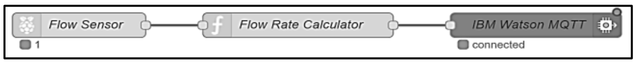

Fig. 3. Raspberry Pi Node-Red Implementation

Figure above shows the node-red implementation at Raspberry Pi:

- The flow sensor detected water flowing through and generated a payload of 0 and 1.

- The function node aggregated the payload received and, at regular period, calculated the flow accumulated.

- Flow was published to the IBM Watson MQTT with QoS set to 2.

Fig. 4. IoT Cloud Node-Red Implementation

Figure above shows the node-red implementation on our IoT Cloud:

- IoT Cloud subscribed to the same topic and to receive the published message.

- The function node formatted the payload to database specific schema.

- The formatted message was inserted into the database.

The area for POC was within the compounds of locales which generally had steady Wi-Fi network which could be utilized for the transmission of information to the IoT cloud. QoS was set to 2 to limit the possibility of lost messages, and for ease of processing by the subscriber as there were no duplicate messages.

Illustrative payload 1: Flow meter

4/11/2019, 11:08:44 PMnode: 69dbcc21.788fd4
pi/13 : msg.payload : number
0

4/11/2019, 11:08:44 PMnode: 69dbcc21.788fd4
pi/13 : msg.payload : number
1

Illustrative payload 2: Flow rate calculator

4/11/2019, 11:08:44 AMnode: 594d8f5.cb0537
msg.payload : string[98]
"{
"pulses": 9,

"liters": 0.02,
"time": "2019-04-11T03:08:44.000Z"
}"

4/11/2019, 11:08:45 AMnode: 594d8f5.cb0537
msg.payload : string[98]
"{
"pulses": 8,
"liters": 0.02,
"time": "2019-04-11T03:08:45.000Z"
}"

Algorithm 1: Flow rate calculator

Input: Continuous pulse from flow meter
Output: Flow measurement (e.g. liters per second)

```
Let x be the pulse received from the flow meter

Let freq be the frequency of flow meter
If x = 1 then
        increment pulse_counter
End
If current_time - last_message_sent > 1 then
        liters_per_second = pulse_counter / 60 / Freq
        Send message (device_Id, Liters_per_second, current_time) to MQTT server
        Set last_message_sent = current_time
        Reset pulse_counter to 0
End
```

Algorithm 2: Message formatter

Input: Message from MQTT server
Output: Database statement

```
Set cuurent_dat_time in the format 'MM/dd/yyyyy HH:mm:ss'
If message_event_type = birth or close or will then
        Construct database_statement using topic, payload, timestamp, deviceId, deviceType, eventType, currentDateTime
End
If message_event_type = update then
        Construct database_statement using topic, payload, timestamp, pulsesCount, liters_per_second, deviceId, deviceType, eventType
End
Send message (database_statement)
```

A visualization of a mockup of an analytics interface on tableau, including water consumption levels and geo-location information, is shown in the diagram below. Such interface can be customized to the needs of the user, to achieve the objective of the stakeholder.

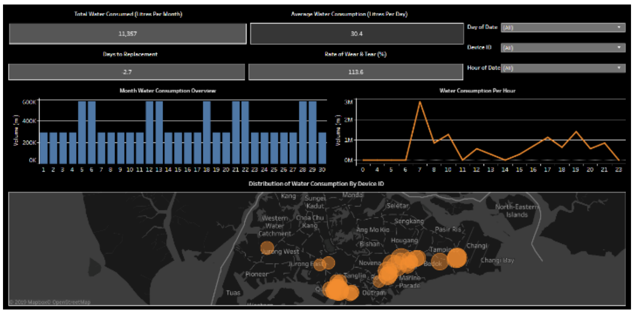

Fig. 5. Tableau POC Test Analytics Interface

IV. Discussion

A. *Considerations in test deployment*

Data quality in system deployment can be affected by system failures and downtimes. In the test deployment to ascertain if there are sufficient good quality data collected for application-level analysis, it will be useful to consider several factors, including:

(i) duration;

(ii) sufficiency of data collected; and

(iii) stableness of the sensor systems deployed, subjected to the following criterion:

(a) all test stakeholders, e.g. POU water system user and system owners, must adhere to the pre-specified duration of test deployment,

(b) any extension of deployment must be allowed and agreed by all test parties.

It is also important to consider the time taken to discover the intrinsic system failures and ascertain how system improvements and maintenance should be conducted during this test deployment stage.

IoT system deployments will have to consider the following factors:

(i) a "minimal-owner-effort" system architecture that allows remote and automated recovery, to improve data quality and lower maintenance efforts;

(ii) robust system monitoring by incorporating features of real-time detection of sensor component issues/ failures and user-friendly issues alert dashboard; and

(iii) the degree and frequency at which system monitoring and recovery would take place, taking into account availability, durability, correctness and throughput of data quality, latency of response, and the predetermined error budget.

B. *Considerations on scalability*

Due to the multiplicity/ differences in the vendor POU devices and their respective presence (or absence) of integrated sensors and gateways, it will be useful to consider the following factors when building the prototype:

(i) scalability (and constraints) when system is designed, e.g. sensor modalities and connectivity, allowing for modularization of sensor system, so customization, when required can be done;

(ii) integration of a full suite of analytics required by system owner, e.g. unified real-time system performance and recovery monitoring into owners' control dashboard from the onset, as component variety and down-time/ failure situational variety can be difficult to manage on a piece-meal basis, leading to elevated risk of system inefficiencies.

V. FUTURE WORK

For commercial POU vendors, future work can integrate a sales forecasting and inventory management system to enhance owners' user experience, customizable based on whether if this is a product or service model.

For government bodies, the data can also be useful for different purposes, including the introduction of guidelines for POU water filter use and replacement.

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