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Research article

Cost-Effective IoT Extensions for Existing Public Coin Operated Washing Machine Towards Smarter Apartment Complexes

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Abstract

Keywords

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washing machine extensions;

smart appliances;

state machines

Due to increasing urbanization in Bangkok, Thailand, it is observed that there are an increasing number of people who have moved into high-density apartment/condominium complexes. One common service that is provided at such complexes is the provision of public coin operated washing machines that allow tenants to do their laundry at a reasonable price. This has led to a new set of challenges, one of which is that the number of public coin operated washing machines is usually inadequate during peak hours, leading to long waits in queues for the tenants. The development of smart public coin operated washing machines has improved the quality of life of the tenants. This research proposes a smart public coin operated washing machine platform by extending the usefulness and convenience of existing washing machines using IoT applications. The infrastructure, the proposed application features, and the vacancy state detection of the new washing machine platform are discussed. Using the proposed platform, tenants using public coin operated washing machines can better plan when to do their laundry even during peak hours, improving their quality of life.

1. Introduction

It has been observed that urbanization, the process that involves population migration from rural areas to urban areas, is happening all around the world [1]. Urban areas typically provide greater

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opportunities than rural areas, which lead to high migration rates. With continual migration, cities become high population density areas and migration has led to new sets of challenges for the existing population. With increased urbanization has come an increased cost of living and other social and economic challenges [2]. One obvious impact of urbanization is the increased number of people living in high-density areas. One of the distinguishing features of high-density areas is the increased number of shared residences such as apartments and condominiums. Examining the situation in Bangkok, Thailand, it can be concluded that high-density apartment/condominium complexes are increasingly important for residents of the city.

Apartments typically cater to customers of a lower socio-economic status. To segment the market, apartment rooms [3] are usually small typically studio rooms that are usually less than 35 m^2 in area. With small rooms and sparse facilities, apartments can be rented cheaply.

The condominium market [4] has many segments that can be catered to. One of the important segments is the B condo market segment, which caters to medium income owners. The rooms are typically studio rooms that are less than 50 m^2 in size. These condominiums are usually in studio configuration, and smaller size rooms are common with newer condominium units.

When examining the tenants that live in apartments and condominium units in this segment, it reveals that many of the tenants are from medium to lower socio-economic status. Smaller room sizes cater to this segment as tenants cannot afford high rent or installment payments. It has also been observed that many tenants in this segment, for a number of reasons, do not own washing machines. The cost of a washing machine is one factor. Another potential factor is that the small room size does not usually have a suitable area for the placement of the washing machine. Some tenants change apartments regularly, and the difficulty in moving large furniture and other electronic appliances is a significant factor that has driven low washing machine ownership in the segment. Due to the low ownership of washing machines, many tenants in the segment reported that public coin operated washing machines near premises are an important factor [5, 6] in selecting which apartment to rent as it offers a cost-effective way of doing laundry.

Public coin operated washing machines come with different capacities and functionalities and are usually installed in a public area on the ground floor of the building. As the typical spaces that are provided for public amenities cannot be used for rental purposes, the public areas of many complexes are usually small. That design philosophy directly affects the tenants who are doing their laundry at these machines because the laundry area is typically cramped and provides little to no amenities to help make the wait more comfortable. During peak hours, long queues of tenants waiting to do their laundry are common. With huge laundry baskets and long distances to travel from the room to the laundry room, there have been many complaints regarding doing laundry at the public coin operated washing machines ranging from long queues, inadequate machines, inadequate service, and a myriad of other issues [7].

The tenants wanted to know when the washing machines were vacant so that they could easily plan when to do their laundry and avoid periods when the washing machines were not available for use. This research was aimed to bridge the gap by proposing possible solutions to the issue based on examining the issues toward the development of a smart public coin operated washing machine using Internet of Things (IoT) in order to extend existing devices in service. Ideally, we aimed to provide a solution that kept public coin operated washing machine inexpensive, provided vacancy status, could be used easily by tenants, and could coexist within the infrastructure of the complexes.

2. Materials and Methods

2.1 Typical apartment/condominium in Thailand

This section explores typical apartment and condominium configurations. The study focuses on the locale of Bangkok, Thailand, which is a huge sprawling metropolis. With higher population density, an increased proportion of people have moved into the apartments and lower-end condominiums that cater to lower socio-economic status tenants who have less money to spare for rent. To fit within the budget, such facilities for rent usually provide small studio rooms and have minimal facilities in the complexes. Typical facilities available may include a coin operated corner which can contain services such as coin operated washing machines, coin operated water kiosks, and mobile top-up services. The coin operated corner is usually small and in a less accessible area on the premises is shown in Figure 1. Some larger size apartments may include laundry services, mini-markets, and made-to-order restaurants on-premise. One of the common complaints is that there are usually long queues of tenants waiting to do their laundry during peak hours. For reference, Figure 1 is taken from an apartment building in Bangkok that provides public coin operated washing machine services for the tenants [7].

Figure 1. Public coin operated washing machine services offered by an apartment complex

Though the apartment and condominium complexes are not typically well-equipped in facilities, shared Internet services is one area that many complexes invest in. Many complexes have good WiFi network coverage supplying shared high-speed Internet services that are usually maintained by an external contractor. Many tenants use smartphones and connect to the Internet [8] extensively as part of their daily routines. According to a study of Poomontre [9], the availability of fast and stable Internet services is one important contributing factor for tenants in the selection of a place to rent. It was also reported that apartments that cannot provide fast and stable shared Internet services with building coverage usually have high turnover rates. This factor is not unique to Thailand and is observed in neighboring countries [10].

One unique aspect of Thailand that may not be common in other countries is the Thailand Computer Crime Act Criminal Law [11, 12]. The law has given special sets of requirements for entities that provide forms of shared Internet services. Shared Internet services are usually provided by apartments and condominiums. The law requires that Internet service providers have to collect and log Internet usage patterns for a set period of days, and should be able to provide logs when required if requested by law-enforcement agencies. Based on the requirement, many condominiums and apartments that provide shared Internet access usually have Internet gateways that control the access of the users and collect the usage patterns of the tenants. The side effect of the law has made apartments in Thailand generally a good deployment area for IoT applications due to the existing network infrastructure.

2.2 Exploring washing machines

Washing machines are considered important electronic appliances that are used to help people deal with their laundry. For consumer-level washing machines, manufacturers produce a range of washing machines of different configurations and sizes. Some of the key defining features include the drum size/capacity of the washing machine, the machine loading type, and the type of motors that drive the washing machines.

To separate the lower market from the higher market, washing machine manufacturers usually provide additional functionalities. For more affluent customers, hi-end smart washing machines are marketed and usually come with a myriad of additional functionalities. Washing machine manufacturers explore research areas in the domain to improve washing machines based on high-end consumer requirements to come up with new features that can be marketed. Design of washing machine controllers [13, 14] that are customized for the load to allow cleaner wash cycles are popular in the area. Improving the durability of washing machines by exploring damper [15] options to help alleviate the vibrations caused by washing, and explorations on different types of engines can be applied to create better washing machines. Another area of development in washing machines that is popular is the domain of WiFi-enabled smart washing machines. These machines can connect to the household WiFi network and allow applications to connect to the machine to do various tasks remotely. Examples of the tasks include remote starting, troubleshooting, and checking the status of the washing machine. Examples of smart washing machines include the hi-end LG WM9500HKA, which can be paired up with the LG THINQ application. For Bosch, Siemens, and Gaggenau hi-end smart washing machines, the Home Connect application enables users to access the smart functionality of their washing machines via a mobile application. However, exploration of high-end smart washing machines is not the focus of this study due to their high cost and unsuitability for converting into public coin operated washing machines.

In Thailand, public coin operated washing machines are typically converted from cheaper home washing machines. Lower-end washing machines are popular to convert into coin operated machines as they are cheaper and contain less complex internal circuits. Having simpler internal circuits simplifies the conversion process to coin operated machines. These lower-end washing machines do not come with smart functionalities and were designed to wash clothes with a few pre-defined settings. To be able to consistently make a profit from the coin operated washing machines, the fixed default setting is typically deployed on the machines as it makes it possible to control the cost of operation by avoiding more time-consuming modes.

To start a wash cycle, tenants have to insert a pre-defined amount of coins into the washing machines. The amount varies depending on the machine capacity. Smaller machines start at 20 THB (~0.59 USD) and range up to 60 THB (~1.76 USD) for larger capacities. These public coin operated washing machines are popular in many low-cost apartments and condominiums as many tenants do not own a washing machine, and the service provides a cost-effective way to do laundry. Figure 2 shows a washing machine that has been converted into a public coin operated washing machine.

Though public coin operated washing machines are popular, there are areas of improvement that can be studied. When deploying the public coin operated washing machines, it is possible to add smart features to the machine by attaching 3rd party extensions. In previous work [16], the authors proposed a cost-effective IoT extension that would allow users to know whether the machine was available. The cost-effective IoT extensions utilized the vibration sensors and the IoT infrastructure to enable registered users to check the status of the washing machines. Suggested

Figure 2. Example of a public coin operated washing machine

further research at the time included exploration of other alternative sensors that could be used for similar purposes, and further examination of the suitability and cost of the proposed solutions.

2.3 Internet of thing (IoT) applications

The Internet of Things (IoT) is a system of interconnected devices. Sensors are connected via a shared network infrastructure to allow IoT nodes to log and interchange data. By allowing interconnected devices to collect and exchange data, numerous applications can be implemented that can be used to solve a wide range of domains. IoT applications have been built for many domains [17] including the areas of work, exercise [18], home appliances, food production [19].

Exploring home appliances further, there are many potential areas in which home appliances can be improved by adding new features, applications, and extensions [20]. In the example of washing machines, IoT extensions can be used to detect the vacancy state [16] of the machine, and to report back to registered users in a shared user setting. For traditional home appliances, the control of the unit is usually done from the embedded microcontroller in the appliance. One interesting change would be to use cloud-based controllers [21] in which the microcontroller can be continually upgraded. Traditional washing machines can potentially be improved by IoT approaches.

With more affordable and robust microcontrollers and sensors, IoT applications have the potential to be ubiquitous. However, one of the requirements of IoT applications is the network infrastructure. Without a network infrastructure, it is not possible to deploy IoT applications. This can be an issue as it takes significant investment to get a network infrastructure set up. Apartments and condominiums in Thailand are of great interest as many complexes have existing infrastructure due to regulations; infrastructure that can be extended for use with IoT applications.

2.4 Proposed smart public coin operated washing machine platforms

The main requirement of the research was to develop a smart public coin operated washing machine platform to help alleviate the issue of long queues of tenants waiting to do their laundry. The discussion from the previous section established the assumptions that made the proposed platform viable. Public coin operated washing machines are usually developed from entry-level consumer grade washing machines, and there are a lot of potential possibilities to improve upon them further, including the adoption of IoT approaches. It was also established that there were many apartments and condominium complexes that had existing network infrastructures suitable for IoT application deployment. Based on that, the idea was to include IoT extensions to improve the public coin operated washing machines by making them smarter.

The proposed background here is an extension of the authors' previous work [16]. The suggested changes included the addition of a microcontroller node (IWASH node) and platform and features that can be added onto the existing system. The microcontroller is responsible for determining the vacancy status and using the infrastructure to log the data to the platform. The tenants can use the platform to determine the vacancy status of the washing machine, be notified when their laundry is done, and be able to queue for laundry machines. The proposed system's topology is displayed in Figure 3.

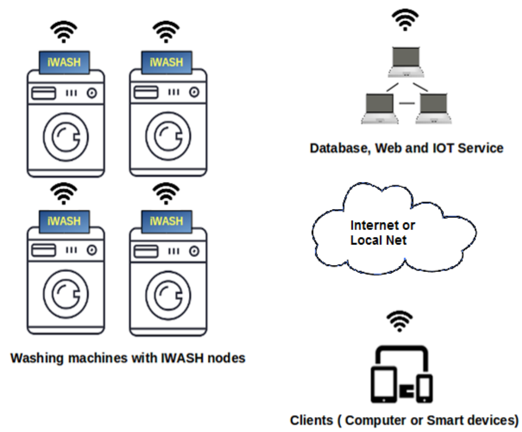

Figure 3. Topology of proposed system

2.4.1 Microcontroller node

The microcontroller node (IWASH) is attached to the washing machines and used to establish if the washing machine is active or not. The active state can be used to determine the vacancy status of the machine. Sensors attached to the microcontroller are used to log data and submit the data logs to the server to be processed. The determination of the vacancy status of the selected washing machine can be done with the data. The microcontroller node needs WiFi access to connect with network infrastructure and sensors that can log data. The cost of the microcontroller node should also be minimal to keep the cost down and make the system cost-efficient.

For the sensors, it was observed that many approaches can be used to detect the vacancy or otherwise of washing machines. Several types of sensors were tested, and these will be discussed in further detail in the next section.

The first type of sensor tested was the vibration sensor. As washing machines vibrate during the wash cycle, it is possible to attach sensors and create a data log of the vibration levels, process the data, and confirm the vacancy status. The prototype used was the ESP8266-12e, which is an affordable microcontroller that is WiFi-enabled. Attaching a vibration sensor, wiring, and casing completed the prototype unit. The completed microcontroller node is shown in Figure 4 and its installation on a washing machine is shown in Figure 5. The microcontroller node components and approximate cost are displayed in Table 1.

Figure 4. Closeup of controller node with vibration sensor

Figure 5. Controller node with vibration setup attached to washing machine

Table 1. List of components and approximate cost of microcontroller node with vibration sensor

Component	~Cost
ESP8266-12e	10.00 USD
Vibration Sensor	2.00 USD
Casing	1.00 USD
Wiring	1.00 USD
Total	**14.00 USD**

The second type of sensor tested involved detecting brightness values and using them. Washing machines usually have an LED display that displays diagnostic information. When the washing machine is active, the LED display will continually change to display the current state, and an example is displayed in Figure 6. By isolating the LED display and covering it with dark duct tape, the display is completely dark. It is possible to attach sensors such as light-dependent resistors (LDR) to check the variance in brightness level to determine if the machine is active. The prototype unit used the same microcontroller ESP8266-12e, which is an affordable microcontroller, and was WiFi-enabled. The difference was the attachment of the LDR resistor to detect the brightness level. This prototype was slightly cheaper than the previous prototype due to the sensor being cheaper. The component list and the approximate cost of the prototype microcontroller unit are shown in Table 2.

Figure 6. LED display of a top-loading washing machine

Table 2. List of components and approximate cost of microcontroller node with brightness sensor

Component	~Cost
ESP8266-12e	10.00 USD
LDR Sensor	0.50 USD
Casing	1.00 USD
Wiring	1.00 USD
Total	**12.50 USD**

The last type of sensors tested were sensors that detected the electrical current flow of the washing machine. When the washing machine is active, the washing machine draws an increased amount of current compared to the standby or off state. By logging the current flow, it is possible to derive the status of the washing machine from the patterns of current flow. For this third prototype, the cost of the unit was slightly higher than the previous approaches. The third prototype unit used the Arduino UNO R3 as the microcontroller unit. As the UNO R3 did not have WiFi access, the usage of the ESP8266 ESP-01 module allowed the unit to have WiFi access. The microcontroller depended on the ACS712 sensor that allowed AC/DC current sensing. As the ACS712 sensor was comparably more expensive than the previous types of sensors, the prototype was more expensive than other units. Its costs are displayed in Table 3. The example prototype before the WiFi module was installed is displayed in Figure 7.

Table 3. List of components and approximate cost of microcontroller node with current sensor

Component	~Cost
Arduino UNO R3	8.50 USD
ACS712 Sensor	5.50 USD
ESP8266 ESP-01 (WiFi Module)	5.00 USD
Casing	1.00 USD
Wiring	1.00 USD
Total	**21.00 USD**

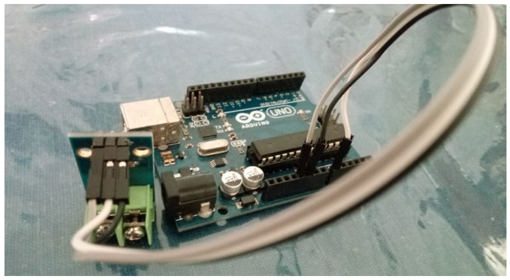

Figure 7. Closeup of controller node with current sensor

2.4.2 Software backend/frontend

For the proposed platform, the backend performs many specific roles. One of the first roles of the backend is to log the data sent from the microcontroller nodes that are attached to the washing machines in the system. The backend can process the data from the logs to determine the status of the washing machines. In addition, the backend system manages the registration of washing machine devices in the system, maintains access controls for registered users in the system, and provides other services such as user queuing.

The backend of the proposed system was created on a web stack. Apache provided the web server, the data logs were handled by the MySQL database service, and PHP was used to build the web application. The IoT nodes that are registered to the system update the data to the backend. The backend has to be accessible by the microcontroller nodes. As many apartments and condominium complexes already have existing infrastructure, it is likely the system can fit in the setup. The legal requirements dictate that shared Internet service providers are required to log all shared activities. This requirement enables these complexes to have access gateways that already provide the necessary infrastructure. As the existing infrastructure is available, there is no need to invest in additional infrastructure to implement the system.

The system can be configured in many different ways. Many apartments/condominiums only allow tenants to access the building premises and local shared network. This is done to help prevent incidents of thievery done by outside people. In this case, the public coin operated washing machines are only accessible to tenants. In this example, limiting the access of the services to tenants with local network access is suitable. In another scenario, the owners of the building might want to increase the revenue of the public coin operated washing machines. In this case, making a publicly accessible system via the Internet deploying IoT services on the cloud [22], and allowing public access might be possible.

For the tenants, a frontend was developed to allow the users to interface with the system. For the proposed system, the usage of a web interface is recommended as web browsers are common and can be used in a range of devices, from personal computers to smartphones. As most tenants in the targeted apartments and condominiums are likely to have smartphones, it is simple for users to access the system.

Users of the system would be required to register for the usage of the system. Once registered, the users can use the system in various ways. The first and most common operation would be to view the vacancy status to figure out if it would be a good time to do the laundry. This would allow tenants to avoid peak hours. Another feature that could be useful would be the display of the start time and estimated time when the machine is likely to be vacant. This factor may not be accurate, because different wash loads may affect the wash cycle slightly. Alternatively, it is possible to alert the users when the washing machine is in the spin cycle. Related to the previous feature, registration to alert tenants when the wash cycle is finished is another feature that would be useful for tenants. One additional feature that would be recommended is providing queuing services for tenants to book and queue the washing machine. There are examples of restaurant queuing systems such as QueQ [23] that provide mobile applications and queuing platform that helps manage the queues well. Implementing such features could be useful, but they are not included in the current iteration because the proposed platform separates the coin operated add-on mechanism and the proposed microcontroller nodes. Features such as authenticating the user who is queuing for the machine cannot be implemented as the mechanisms are separated. The prototype of the proposed system was implemented and the sample mobile web screenshots are displayed in Figure 8.

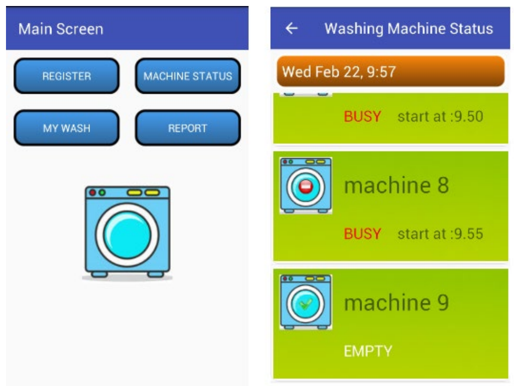

Figure 8. Proposed system - mobile web interface

3. Results and Discussion

Experiments were conducted to check if the sensors proposed could be used for the detection of the vacancy status of the washing machine via the nodes connected to the machine. Three prototype microcontrollers based on the details provided earlier were created and used for logging data from the washing machines. It was observed that different washing machines had differences in their default wash cycles. Some of the washing machine controllers were based on fuzzy logic, and it was observed that the length of the default wash cycle was dependent on the laundry load in the washing machine. The type of motor in the washing machine and the way it is loaded, either from the front or from the top, also affects certain aspects of the wash cycle. As it was impossible to isolate all the configurations, several different washing machine configurations were used, and the laundry was approximately at half-load in all the experiments.

3.1 Detecting vacancy state with vibration sensor

The first experiment was conducted using the proposed microcontroller with the vibration sensor. For the experiment, a front loading machine was selected as front-loading machines typically have lower vibration rates than top-loading washing machines, and if the patterns could be detected then the vibration sensor could be used in the detection of the vacancy status. The selected washing machine was an Electrolux EWF1074 [24]. The device was a front-loading washing machine with a 7 kg capacity. Figure 5 displays the setup of the microcontroller node. The vibration levels were recorded during the wash cycle with a half load. The results of the log are displayed in Figure 9.

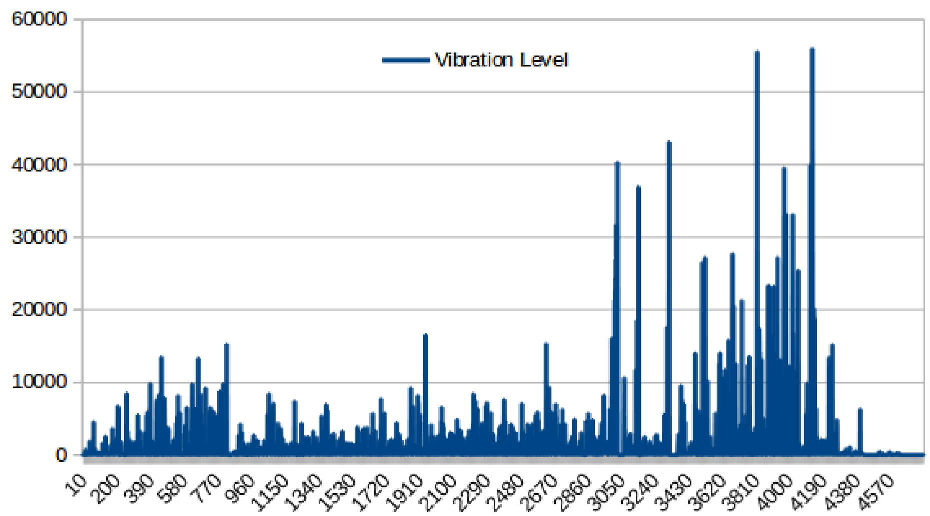

Figure 9. Complete cycle - vibration level over time(s)

The values recorded from the vibration sensor were recorded and saved to the log. The wash cycle had a distinct vibration profile during the different phases of the wash cycle, that was during the wash, rinse, and spin modes. With the default cycles, the pre-wash mode of water filling and sensing the load took about ~240 s. The next phase was the main wash cycle, which included the wash, rinse, and spinning cycle. That phase took about ~4,340 s to complete. With the main wash cycle phase completed, the machine began the post-spin period. The post-spin process lasted ~50 s and the wash cycle was completed at the end of that phase. The default wash cycle lasted about ~4,630 s, which was close to 77 min in length.

The vibration level data was saved, and an examination of it revealed specific patterns. Previous research on the vibration data showed that a series of rules were derived to form a rule-based system that was able to determine the different phases of the wash cycle [13]. Table 4 lists the details of the rules that were used to determine the phase in the wash cycle. The vacancy status could be determined by the state of the machine.

Further experiments with the same washing machine confirmed that the approach could be used to determine the vacancy state of the washing machine even in different laundry modes. However, further experimentation on the deployment of the microcontroller node with vibration sensors on different washing machines revealed that the vibration patterns could be significantly different. Due to the variation in the vibration cycles, further fine-tuning would have been done. Different machines might require different washing machine sensors, and this would not be ideal in a real-world setting where many types of washing machine configurations could be present.

3.2 Detecting vacancy state with brightness sensor

For washing machines that use LED overlays to display the status of the washing machine, it is possible to incorporate brightness detection sensors to determine the vacancy status. For this experiment, the Hitachi SF-85PJS [25] washing machine was selected. The SF-85PJS is an 8.5 kg top loading washing machine that has an LED display at the top of the machine that updates the state of the washing machine. As the brightness sensor is sensitive to ambient light, shielding the LDR sensor from the ambient light is required to help normalize the brightness values read from the

Table 4. Determining the working states of the washing machine using vibration sensors

Working State	Details of Mechanisms
STARTUP	- $Status_{WashingMachine}$ = Stop - Sampling Interval = 1000 ms
STOP	IF $vibration_{value}$>$threshold_{value}$ - Set Sampling Interval = 100 ms - $Status_{WashingMachine}$ = POSSIBLE_START - Send Message to Server -> POSSIBLE_START
POSSIBLE_START	- Sample $vibration_{value}$ for 3000 ms IF $vibration_{avg}$ > machine $threshold_{value}$ - Set Sampling Interval = 2000 ms - $Status_{WashingMachine}$ = START - Send Message to Server -> START ELSE - $Status_{WashingMachine}$ = STOP - Send Message to Server -> FAIL_POSSIBLE_START_CYCLE
START	IF $vibration_{value}$ <machine $threshold_{value}$ - Set Sampling Interval = 100 ms - Sample vibrationvalue for 10000 ms - IF $vibration_{avg}$ <machine $threshold_{value}$ - - Send Message to Server - POSSIBLE STOP - - Status WashingMachine = POSSIBLE STOP Set Sampling Interval = 2000 ms Continue START Process
POSSIBLE_STOP	- Sample $vibration_{value}$ for 60000 ms IF $vibration_{avg}$ < machine $threshold_{value}$ - Set Sampling Interval = 1000 ms - $Status_{WashingMachine}$ = STOP - Send Message to Server -> STOP

sensor. In the experiment, black-colored duct tape was used to cover the LED panel, and the LDR sensor was used to detect brightness close to the sensor. The default wash cycle was used on the selected washing machine and the brightness values were recorded.

The initial experiments were not very successful due to a myriad of related issues. Due to vibrations, the brightness sensor had difficulty producing a consistent reading from the sensor. During certain spin cycles with high vibration, the LDR sensor could not read the values consistently. Even with the sensor covered in the duct tape without external light, the extreme vibration caused erroneous readings from the brightness sensors that happened on an occasional basis. Another observed scenario was that the duct tape covering became loose, and ambient light may have sept in. This may have caused the brightness sensors to receive overly high brightness readings.

Based on the results of the experiment, brightness sensors were probably not suitable as add-on sensors. There are scenarios that can cause the sensor to get erroneous reading due to the vibration from the wash cycle. To remedy the situation, a more suitable light cover, a more stable sensor attachment, and the use of washing machines with less vibration might provide a more stable set up for the use of brightness sensors. However, based on our experiments, the results were not promising.

3.3 Detecting vacancy state with current flow sensor

The last group of experiments, we checked if current flow sensors could be used to detect the vacancy status of the washing machine. An IoT node with a current flow sensor was attached to measure the electrical current flow from the electrical outlet to the washing machine. The microcontroller with the current flow sensor was attached to the Hitachi SF-85PJS washing machine as in Figure 10 and used to record the current flow for the default wash cycle.

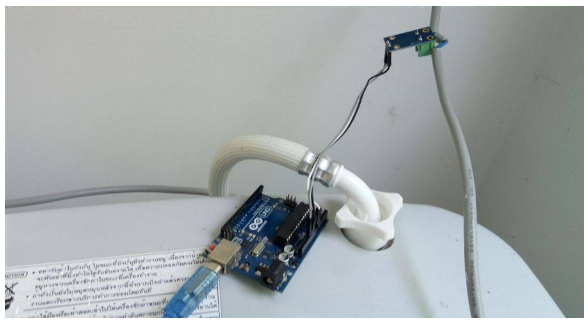

Figure 10. Microcontroller logging current draw of washing machine

The default wash cycle for a half load of laundry was approximately ~41 min. The data logs of the current flow between the electrical outlet to the washing machine from the experiment were mapped into a graph and displayed in Figure 11. It was observed that the washing machine drew upon a minimum of 0.06 amperes of current flow on standby, and the current flow fluctuated widely between the different stages of the wash cycle, depending on the requirements of the motors at different stages. Based on the patterns, it was possible to map the current flow patterns through different stages of the wash cycle well. The washing machine had to turn the drum when the load was full of laundry and water before stopping and repeating the process. This led to peak current flow before a sharp drop-off , which was repeated during the wash mode of the cycle. However, this behavior of high current flow and sharp dropout might not be as pronounced as in an inverter washing machine and might be an issue to consider when defining the states. For the spin cycle, the spinning drew a constant amount of current flow, which was lower than the wash cycle as the load was lighter and could be detected well. For the detection of the start or end of the cycle, the current flow that was above the standby threshold was sufficient to accurately detect the status of the machine.

When using the current flow sensor on heavier loads, the current flow increased. When using other washing machines, it was observed that different washing machines had different current flow profiles. However, as it was possible to check the current flow over a period to check for an active state, it was easy to use current flow to indicate the status of the washing machine without performing a lot of modifications, except for the threshold of the standby state that had to be calibrated high enough.

3.4 Selection of the proposed sensor approaches for low-cost IoT extensions for public coin operated washing machine

The goal of the research was to propose cost-effective IoT external extensions to existing coin operated public washing machines that could provide users with the vacancy state of each of the

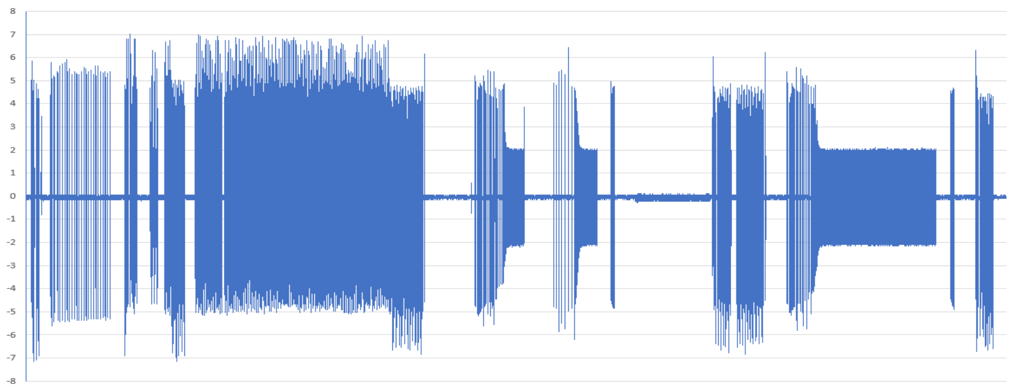

Figure 11. Complete wash cycle - current flow (A) over time (s)

registered machines. There were a total of three sensor types that were identified that could potentially be used in the IoT node to help determine the vacancy states of the washing machine, i.e. the vibration, brightness, and current flow sensors.

From the experiments, the brightness sensor was determined to be inadequate for the purpose and was rejected for use. The brightness sensor was designed to read the brightness values of the LED dashboard in order to determine the working state of the washing machine. This initial experiment determined the possibility of determining the washing machine state with the readings. However, after repeated experiments, it was discovered that the brightness sensor readings were volatile due to external factors such as the washing machine vibration that helped contribute to the unstable sensor reading. The use of more stable casing was required. Once the integrity of the casing had been compromised, the brightness sensor was no longer able to determine the vacancy state.

The vibration sensor and current flow sensor were considered to be potential candidates as sensor for the IoT extension. Based on the experiments, both of the sensors were able to detect the vacancy state of the washing machines and were able to fulfill the requirements without any major issues. The vibration sensor needed more calibrations to detect the state of the washing machine but was cheaper. The current flow sensor was more expensive than the vibration sensor node but required less calibration. If the increased cost of approximately 7 USD is not an issue, the current flow sensor would be the preferred choice. A summary of the discussion are displayed in Table 5.

Table 5. Cost, suitability, and calibration requirements of sensors for add-on IoT extensions

IoT Node Sensor	Cost	Suitability	Calibration Requirements
Vibration Sensor	~14.0 USD	Suitable	High
Brightness Sensor	~12.5 USD	Not Suitable	-
Current Flow Sensor	~21.0 USD	Suitable	Low

It is possible to create an IoT node with multiple sensors. Creating a composite IoT node with both a vibration sensor and a current flow sensor is possible. By combining the input from both sensors, it would be possible to use the data to detect the current state more accurately. This potential solution was rejected. The first factor was that the existing sensors were able to detect the vacancy states with a reasonable degree of accuracy without requiring an additional sensor. There is no requirement for a fail-safe as the detection of the vacancy state was not considered a critical task. The other factor leading to the solution being rejected was that the IoT extensions were being proposed for low-cost apartments and condominiums. They needed to be made as cheaply as possible due to the reluctance to invest unnecessary.

3.5 Test deployment and discussions with stakeholders

The proposed system was tested in a real-world scenario where the proposed IoT extensions were installed into public coin operated washing machines in an apartment complex. Due to limitation of not being able to test and calibrate the machines in the complexes by removing them out of service, the exact wash state was not determined, and only the vacancy state was determined. The base stop cycle values were determined from the machines and set as a threshold. Table 6 contains the details of the simplified mechanisms. One minute polling of the sensor was done to examine if the value has exceeded the trigger over the last 3 cycles to toggle between the states. After the real-world test, feedback was gathered by interviewing the stakeholders including the apartment management and the tenants regarding the specifics of the system.

Table 6. Simplified mechanisms for determining washing machine state

State	Details of Mechanisms
VACANT	IF ((val_i>threshold) && (val_{i-1}>threshold) && (val_{i-2}>threshold)) - $Status_{WashingMachine}$ = BUSY
BUSY	IF ((val_i<threshold) && (val_{i-1}<threshold) && (val_{i-2}<threshold)) - $Status_{WashingMachine}$ = VACANT

The PS Park apartment, a 5-floor apartment complex located in Bangkok, was selected for the pilot project with the approval of the apartment managers. In the apartment, there were a total of 4 public coin operated washing machines that had been in operation for over 10 years on the ground floor which were only accessible by the tenants. An IoT extension with vibration sensor was attached to a Samsung 8kg top loading washing machine. An IoT extension with the current flow sensor was installed on a LG 10kg top-loading washing machine. The two other machines, an LG 10.5kg and a 10kg top-loading washing machines, were left unmodified.

The backend was installed on the Internet gateway server, and users connected to the apartment WiFi infrastructure were able to access the service to view the vacancy states of both the registered public coin operated washing machines. A poster was posted in the public areas to inform the tenants of the new services provided for testing.

The system was installed and tested for a total of 6,120 min during the test period from 12:00 of May 2, 2022 to 18:00 of May 6, 2022. There was a total of 213 min of down-time during the testing period due to technical issues at the Internet gateway in which all services were not available.

During the testing period, several interesting issues occurred and were investigated. The first major issue was observed with the IoT extension with the vibration sensor from the evening of May 2 to the morning of May 3. The vibration level was not within the expected parameters. After examining the installation of the device and checking with the surveillance camera feeds, it was observed that one of the younger tenants had detached the IoT extension with the vibration sensor from the machine out of curiosity. This issue was fixed and there were no additional reported issues with the attachment during the testing period.

The next issue was the reliability of the system. There were some issues with the sensors creating erroneous values that could not be used. With repeated consecutive erroneous readings, the vacancy state of the machine could not be deduced. From the experiment, the sensor readings were sampled once a minute, in which a total of 5,907 sensor readings were recorded during the test period of both the nodes. The IoT extension with the vibration sensor recorded a total of 174 erroneous readings, which was 2.95% of the total. The IoT extension with the current flow sensor had a total of 256 erroneous readings, which was 4.33% of the total. The summary of the reliability and other issues are reported in Table 7.

Table 7. Reliability of sensor for add-on IoT extensions and other issues

Sensor	Erroneous Readings	%	Additional Issues
Vibration Sensor	174/5907	2.95%	Tenant Detached Sensor (~8 Hours)
Current Flow Sensor	256/5907	4.33%	

The erroneous readings were expected. The contributing factors to the readings could potentially be attributed to many factors. The sensors, which were not industrial grade, may not have been suitable for use for an extended period of time in a hot and humid environment. Such conditions may have contributed to the high number of erroneous readings which was consistent with observations made in other experiments conducted in the domain [26, 27]. Another potential contributing factor to the erroneous reading may have been the peak hours of usage. The usage of Internet services usually peaks around 19:00-23:00. During peak hours, due to increased usage and congestion of the network, services in apartments can be quite slow and even not available. This could have caused or contributed to the issue of erroneous sensor readings and it was previously reported that network congestion may cause readings to be less reliable than usual [28].

After the test, an interview was conducted with the management and tenants regarding the pilot test. Both the IoT extensions managed to provide the vacancy state to the tenants. Many tenants reported that they were curious about the IoT extension with vibration sensor as it was attached in the front, leading to the issue that was reported on May 2, where the extension was detached by a tenant. The tenants on the upper floors of the apartment reported that the vacancy states that were provided to them were useful as they were able to get information that helped them plan their laundry, and some of them wanted the system to be extended to all the washing machines. There were some reports from the tenants of slow service during peak hours and unavailability of the services when the Internet gateway was reported to be off-line.

The management preferred to keep the cost at a minimum and mentioned that both the proposed IoT extensions were within the budget. There was a slight preference for the current flow sensor solution. The solution did not have protruding attachments like the IoT extension with the vibration sensor, and less calibration was required. These advantages were deemed acceptable even with the slight increase in the cost of the node.

The management expressed some reservations about two other aspects that were related to the cost. The first issue was with the design of the power outlets in the public area where the public coin operated washing machines were. The original power outlets were installed by professional electricians to provide power to the washing machines, and there were not enough outlets to provide for the IoT extensions. A power extension cord was utilized to provide power to the device, which was not ideal. To change the power outlet layout, an electrician has to be hired to modify the layouts of the power outlets to account for additional devices, which will cost time and money. The second issue was about the personnel cost for the monitoring and maintenance of the new system. To keep costs low, the personnel in charge of maintaining the network services can be hired on a part-time basis. This does not include the cost of maintaining the services. This personnel cost will be much higher than the installation cost in the long run, if additional personnel have to be hired. Ideally, the management stated they do not want to incur additional personnel costs. If the criteria can be fulfilled where the personnel in charge of maintaining the network can help maintain the added system, there should be no additional maintenance costs. In this scenario, the management informed that long-term installation would be highly likely.

4. Conclusions

The research proposed a cost-effective IoT extension to improve the functionality of public coin operated washing machines in typical apartment/condominium complexes by providing the vacancy states of the devices. The IoT extensions utilized the existing network infrastructure available at many low-cost apartment/condominium buildings. By implementing low-cost microcontroller nodes with sensors onto existing coin operated mechanisms, the existing public coin operated washing machines gained new functionalities that could help alleviate the issue of long queues by allowing tenants to observe the state of the washing machines before planning when to do their laundry. The platform was deployed cheaply and provided a reasonably cost-effective solution to the problem domain.

The research explores 3 different types of potential sensors that could be used in the detection of the vacancy state of the washing machines. From the initial experiment, it was observed that each of the sensors had different advantages and disadvantages. The brightness sensor was rejected due to the issues of getting reliable sensor readings. The vibration sensor and current flow sensors were suitable for detecting the vacancy states in the initial experiments and were selected for field testing.

From the field testing, the vibration sensor solution gave more reliable sensor readings than the current flow sensor at a cheaper cost but required a protruding attachment on the washing machine and more calibration with the selected washing machines before the vacancy states were detected. The current flow sensor required less calibration to determine the status of the washing machine, but the sensor was slightly less reliable than the vibration sensor, and more expensive. The feedback from the pilot installation indicated that the current flow sensor was preferred due to the advantages of requiring less calibration with different models of washing machines and the cost being within a reasonable range. Feedback from the field testing revealed that the tenants were generally enthusiastic about the system, but the management was worried about the personnel cost incurred from the maintenance of the system.

The original design of the proposed system focused on solving the issues facing apartment/condominium complexes with several public coin operated washing machines, but there are many areas for potential improvement. Instead of targeting a single complex with several public coin operated washing machines in the same network, the problem domain can be expanded to cover a higher number of connected devices in different networks, although the polling mechanisms used thus far would not be adequate for the larger scenario. The architecture would have to be tweaked to help conserve bandwidth. One solution would be to convert the polling to the MQTT messaging protocol for connecting multiple remote devices with more optimal network bandwidth and smaller code footprint.

One of the assumptions of the research was that the coin operated add-ons and the microcontroller node extensions were two separate units. That assumption was created as the proposed platform was planned to extend existing public coin operated washing machines. This allows extensions to be built on existing systems easily, but it limits what the system can accomplish. For future work, the authors propose the redesign of the coin operated add-on for washing machines. By redesigning the coin operated add-on, it is possible to explore numerous new monetization and billing options, and to examine how they can integrate with the platform. This can extend the feature set and usability of the public coin operated washing machines in many different ways and pave the way for the inclusion of queuing systems to work for the machines. This is not possible with the current approach due to the lack of back user authentication when inserting the coins to start the wash cycle.

Other areas where future work can be implemented is in the area of tools and platforms that can help in the maintenance and management of public coin operated washing machines. When logging the usage patterns of public coin operated washing machines over a period, the trends can be studied via utilization graphs. With utilization graphs, the apartment owners can make informed decisions about whether the facilities are adequate for the premises. Another feature is that if the monitoring of the vacancy state was implemented using the current system of sensing, it would be possible to extend the system to aid in maintenance. By examining the current flow of the washing machine, it would be possible to examine the health state of the motors [29]. Being able to examine the health state of the washing machine will help in the maintenance of the systems. When significant irregularities were detected, the system could inform the maintenance team to perform corrective actions.

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