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ENHANCED BUILDING MANAGEMENT SYSTEM USING X-10 PLC WITH GAS SENSOR ANOMALY DETECTION

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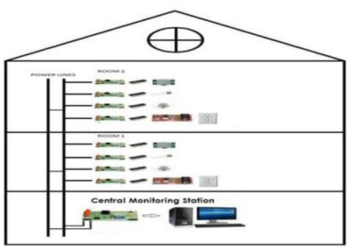
Graphical abstract



Abstract

This paper demonstrates a Building Management System that uses X-10 PLC, sensors, actuators, and microcontroller to control the lighting, the electrical outlets and switches depending on several conditions inherent to BMS. The unique feature of this BMS is the anticipation of an anomaly in the gas sensor like disconnection during renovation or malfunction which makes it inoperable thus exposing the tenants or occupants of the premises to unbeknown hazards. If an anomaly exists, the switches and the outlets are disabled so as not to cause arcing which is the common source of ignition for the leaked LPG gas. Another unique feature of this system is that it does not need to install new wiring since X-10 PLC uses the electrical wires as the communications medium.

Keywords: BMS, X10 code, PLC, gas sensor, power line communications, building automation

1.0 INTRODUCTION

Building Management System (BMS) is a collection of technologies that controls and monitors the electrical and mechanical equipment such as lighting and HVAC (heating, ventilation and air conditioning), as well as security and alarm systems in a building [1]. BMS aims in providing a safe and comfortable working environment for the occupants while some BMS are designed to reduce energy consumption. BMS relies on sensors to make a decision that mostly involve the turning on and off of devices [2]. Most BMS utilize a PC to do the monitoring and control of the different equipment and devices connected to the system. This is a centralized control system. One of the problems of the centralized system is that when the central node fails, the other nodes become inoperable [3]. In this research, a decentralized system is implemented since the intended application is in a Condominium unit.

BMS installation can be either wired or wireless. The wired BMS may use twisted-pair, coaxial cable or fiber whereas for the wireless system, Zigbee, Wi-fi, Bluetooth and Z-wave are the commonly used. Wired BMS offer high reliability compared to wireless counterpart but installation and maintenance cost are more expensive [4]. Wireless systems are easier and cheaper to deploy and can easily be reconfigured when more nodes are needed due to business expansion or when nodes are to be moved due to room renovation. However, wireless systems have their own issues which include reliability, battery life, security, and interference with other wireless networks [3]. Wireless BMS also tend to congest the channel during power outages since the devices tend to send data at the same time [5]. Power line communications (PLC) offers a viable approach that could address problems encountered in wired and wireless systems. PLC utilizes the existing electrical wiring as the physical medium in transmitting information from one device to another [6]. Its obvious advantage is that no new wires are required to be installed in the building and it can be easily integrated to other components in the Smart Grid network [7]. It also owes to reconfigurability just like wireless since the PLC modem can be connected to any power outlet. Several PLC standards are available but the popular standard in home automation and has been widely used is the X-10 code [8]. More on this is discussed in Section 2.

The sensors that are typically used in BMS are light sensor, thermal sensor, temperature sensor, heat detectors, motion sensor, and gas sensor to name a few. Regardless of whether the building has a BMS or none, the installation of sensors that are used for fire detection and alarm are mandatory in the Philippines Fire and Building Code [9]. There is no such requirement for the LPG gas leak sensor, not only in the Philippines but also abroad [10]. Although not required, Two Serendra Condominium in Taguig, Philippines opted to include gas sensor since the building is installed with piped-in gas to supply LPG to all its residents [11]. However, in May 31, 2013, a blast in one of its units caused three deaths and four injuries notwithstanding the damage to the building and nearby premises and a parked van [12]. The cause of the blast was the deflagration of the accumulated gas that leaked and was ignited by the turning off of the main switch. Further investigation revealed that a renovation was done in the unit and that the contractor of the renovation work did not reattach properly the LPG gas connection [13].

In a paper written by Ahmed [14], he envisions future buildings that would incorporate gas sensors in the BMS and send notification to the occupant through his Smart phone. In another study conducted in India [15], the proponents developed a system that detects LPG gas leaks and sends notification to the owner of the premises through GSM. The shortcoming of these systems is that the owner may be oblivious to the alert or any house member may be unaware of the alert or even those who are aware could still subconsciously reach the electrical witch either to turn it ON or to turn it OFF, thus providing the ignition source to the leaked gas. Another shortcoming is when the sensors reached their end of life and become inoperable or that they have been disconnected due to any renovation or repair as in the case of Two Serendra.

In this research, an enhanced BMS that is particularly intended for Condominiums is developed to include gas sensor anomaly alert on top of the basic gas sensing feature, light sensing, and motion sensing functions. The anomaly shall include disconnection of gas sensors, malfunction of gas sensors, and detection of excessive gas.

A retrofit of the electrical wiring is done to embed an actuator circuit in every outlet and switch. The actuator automatically disables the outlets and the switches when a gas sensor anomaly is detected. Disabling here means the switches and outlets are electrically open so as not to cause arcing if one attempts to toggle or plug something to them.

The following subsection discusses the system block diagram and components, the data and results, and conclusion.

2.0 ENHANCED BMS SYSTEM COMPONENTS

The pictorial diagram of the Enhanced BMS is shown in Figure1. The two upper divisions in the pictorial diagram represent the rooms in a condo unit. Each unit contains several modules that control the lighting and outlet. The lower division in the diagram illustrates the central monitoring station, which is typically housed either in the security office or in the building administrator's office. It's function is to monitor the status of all the modules in each unit. The following subsections discuss the different parts of the Enhanced BMS.

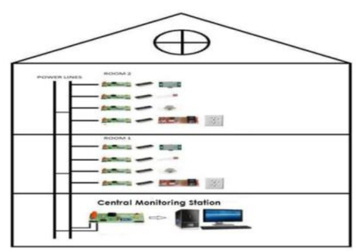


Figure 1 Pictorial Diagram of the Enhanced BMS

2.1 Hardware Components

The modular block diagram of the system is shown in

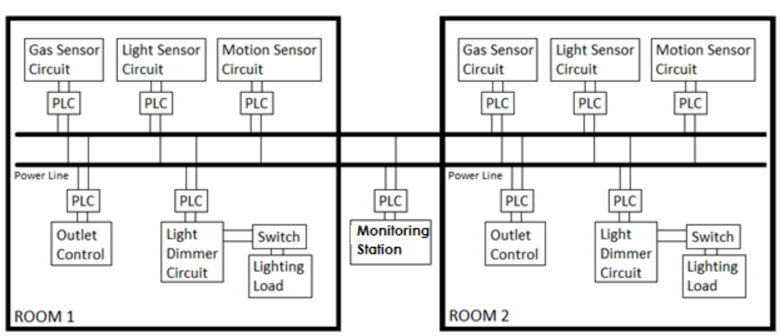


Figure 2 Modular Representation of the Enhanced BMS

Figure 2.The modular block diagram of the system is shown in Figure 2. The modules comprise the gas sensor module, the light sensor module, the motion sensor module, outlet module, and the light dimmer module, the PLC modem, and the monitoring station. All of these components are communicating with each other using the power line. The following subsection discusses each of these modules.

2.1.1 Sensor Modules

Each module contains a PIC16F88 microcontroller that is responsible in (1) generating the address of the module and (2) processing the commands that are either sent or received by the module. The generic schematic diagram for all the sensor modules is shown in Figure 3. Each microcontroller is assigned a unit code. The system does not have a master controller, however, it follows a hierarchy in transmission of commands in order to avoid collision of data. The gas sensor has the highest priority,

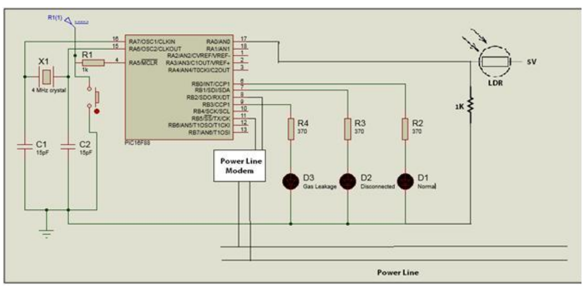


Figure 3 generic schematic diagram for the sensor modules

followed by the motion sensor, then the light sensor. Each of the modules has its corresponding function.

The light sensor module measures the ambient light and sends this information to the light dimmer circuit that consequently chooses from three possible lighting options, namely, dim, medium bright, and full bright depending on the ambient light. The sensor used is an LDR, the output of which is calibrated using the lux meter of the Samsung Galaxy S3. Both Samsung Galaxy and the LDR are positioned near the window. The common light level on a normal day near the window is approximately 1,000 Lux [16]. The light intensity of fully bright circular fluorescent lamp was measured to be 118 Lux. The measured ambient values of the light sensor positioned near the window are categorized as dark, medium bright, to bright as shown in Table 1. The LDR is powered with a 5V power supply and generates voltages at different Lux values measured by the Lux meter.

The motion sensor module detects the presence and absence of occupants in the room. When no motion is detected, the module sends the 'No motion' command to the light dimmer. This would prompt the light dimmer to turn off the lights. When motion is detected, the light dimmer automatically turns on the light and sets it to the corresponding mode that depends on the command from the light sensor module.

The gas sensor module serves as the pseudo master controller for all the modules. It operates on three modes, the normal mode, gas leak mode, and the disconnected mode. The gas sensor used in this study is MQ6 gas sensor since it is capable of sensing butane, a gas component in LPG [17] and it can measure up to 10, 000 ppm of LPG. A Sampo SPD202Ex Combustible gas detector is used to measure the actual ppm value of LPG. To determine the corresponding analog value of the three gas sensor modes, both the detector and the sensor are placed inside a safety gas chamber where LPG gas is injected through an air hole. The lower explosive limit (LEL) that would make the gas level in the confined space hazardous is 10 %. In the measurements done, the 10 % LEL shows an analog reading of 700, while 0 and 1023 are the readings for the disconnected gas sensor circuit, and for the normal gas level, the analog reading is any value below 700. These values are programmed in the microcontroller to represent gas leak, disconnected, and normal modes respectively and are sent as commands to the light dimmer and outlet modules.

Table 1 Assigned Light Level Status from the Light Sensor Module

Lux Value Measured	Status of Light Sensor Module	Setting of Light Dimmer
< 140	Dark	Full bright
141 - 600	Medium Bright	Medium Bright
> 600	Bright	Dim

2.1.2 Light Dimmer Module

The light dimmer waits for the command signal from the gas sensor, motion sensor, and light sensor modules. This module utilizes a TRIAC to control the average power that goes to the load through phase control. The schematic diagram is shown in Figure 4. The firing angle of the TRIAC is changed by varying the value of resistor R2 by means of two single-pole double throw relays. The command coming from the light sensor and motion sensor dictates which resistors will be connected. When the red wire is connected to the common point, only the 2.2 kΩ is connected thus providing higher power to the load since the firing angle is small. This is the full bright condition. When the green wire is connected, R2 is increased to 45.2 kΩ, thus producing a higher firing angle than the first thus delivering smaller power to the load. This is the medium bright condition. The connection to the blue gives the highest firing angle among the three, thereby dimming the light. If the gas sensor sends this module a 'gas leak' or a 'gas disconnected' command, the light dimmer deenergizes the solid state relay thus making the switch inoperable.

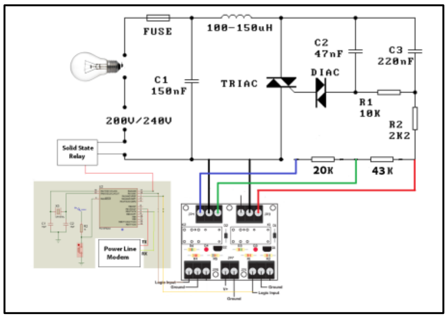


Figure 4 Light dimmer module

2.1.3 Outlet Module

The outlet module is practically a relay circuit that is embedded to the outlet so as to electrically control it. The outlet module is similar to the light dimmer module minus the TRIAC circuit. Once a 'gas leak' or a 'gas sensor disconnected' command is received, the outlet module electronically disconnects from the power line, making it unusable. This prevents arcing if one would attempt to plug or unplug something from the outlet.

2.1.4. PLC Modem

The PLC modem used in this study is the Sunrom PLC model 1187. It provides a bidirectional, half-duplex communication between PLC modems, handles up to 250V AC signal and has an Rx and Tx that directly interface with the microcontroller. It operates on a 5V dc power supply. It basically contains a coupling circuit comprised of a capacitor and inductor that couples the X-10 signal to the line. The coupling circuit ensures that the 220~V line voltage will not reach the 5V modem.

2.2 Central Monitoring System

The Central Monitoring System is a Graphical User Interface that contains the status of the different modules in each condo unit. The monitoring system runs two programs, the receiver code and the GUI code. Both programs are developed in Python programming language. The receiver acts as a server that collects data transmitted by the modules. The receiver receives the data and stores it in MySQL database. The GUI refreshes the data that is flashed on the screen every second to make the display of status of the modules in real time. The GUI displays the status of the LPG, the motion sensor, the lights, and the outlets, The LPG display will change its color depending on the state of the gas. There is also a

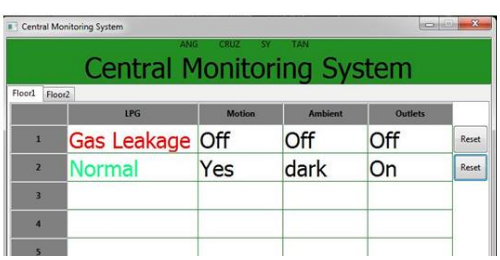


Figure 5 GUI for the central monitoring system

reset button to reset the gas state to normal when the LPG gas is already neutralized. A sample of one of the GUIs developed is shown in Figure 5.

2.3 System Process Flow

The system process flow is shown in Figure 6. In the absence of a master controller, random transmission of each module may lead to data collision. To avoid

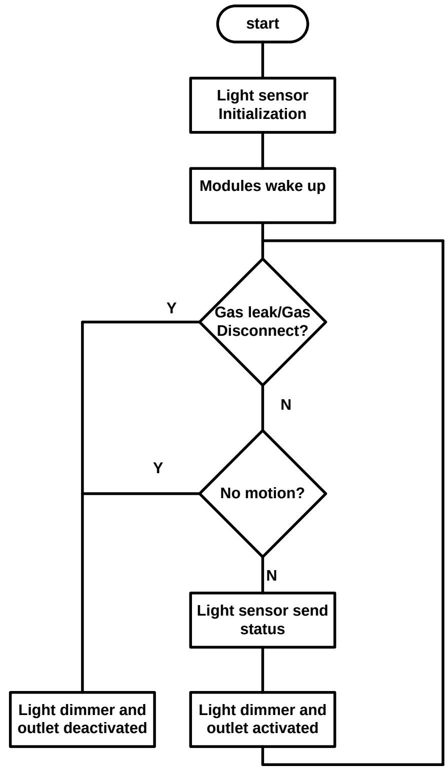


Figure 6 System flowchart

this, an initialization process is done that assigns the light sensor module to commence the transmission of the other modules. Upon deployment, all modules do not initiate transmission unless it receives the command from the light sensor module. Each of the modules is assigned a time delay that allows them to transmit at their assigned time slot. However, when a gas leak or gas disconnect happens, the gas sensor does not wait for its assigned time slot, it asynchronously sends the command to the corresponding modules. If another module is sending at the same time as the gas sensor, collision occurs. Each module assumes a collision when it does not receive any acknowledgement from the device being called. All modules except the gas sensor is programmed to keep quiet for twelve delay cycles, giving the gas sensor enough time to resend its status.

The gas leak and gas disconnect status deactivate the outlet and light dimmer modules. The other modules cannot override the command from the gas sensor module. During normal gas state, the motion sensor has the next priority in controlling the outlet and the light switches. With motion detected in the room, the light sensor has the next priority where the dimming function of the light dimmer depends on the ambient light that the light sensor detects.

2.4 X10 PLC

Power Line Communications (PLC) is the technique of utilizing the power lines as a communications medium. One of the popular PLC technology in the home automation application is X-10 codes. X-10 code sends a burst of 120~KHz amplitude modulated signal to the power line during the zero-crossing of the 220~V signal. A binary 1 is represented by the 120 kHz carrier with a 1 ms duration while the binary 0 is represented by the absence of the carrier [18]. Devices are coded with a 4-bit house code. The transmitted signal comprises of eleven cycles of the power line, two cycles for the start code, four cycles for the house code, and five cycles for key code. The key code is either a unit code or a command code, both of which are represented with 4-bits, the fifth bit is used to determine if it is a unit code (0) or a command (1). The house codes are used to distinguish different rooms in the Condo unit while the unit code represents the address of the modules. Table 2 shows the commands of the standard X-10 codes and the tweaked X-10 for purposes of this study. Most of the commands in the X-10 codes are used with a few revisions in order to accommodate the gas sensor, extra light dimming setting, and the motion sensor. The revised commands are shown in bold font.

Table 2 Standard X-10 codes command and our tweaked version

Code	Standard X10	Tweaked X10
0000	All units off	All units off
0001	All lights on	All lights on
0110	All lights off	All lights off
0010	ON any device	ON any device
0011	OFF any device	OFF any device
0100	DIM lights	DIM lights
0101	Full Bright	Full Bright
0111	Extended code	Medium Bright
1000	Hail request	No motion
1001	Hail acknowledge	Motion
1010	Pre-set dim	All units ON
1011	none	Gas leakage
1100	none	Gas neutralized
1101	Status is ON	Normal gas level
1110	Status is OFF	Gas sensor disconn.
1111	Status request	Status request

Figure 7 Test Set-up with the system in place

3.0 RESULTS AND DISCUSSION

3.1 Energy Consumption

One of the features of this project is the energy savings that the enhanced BMS can provide. To determine the savings, the power consumption of a laboratory room was measured with and without the system for two days. The test set-up is shown in Figure 7. The actual power consumption was measured using an omni power meter. To mimic the real scenario in the condo unit, the proponents do their normal activities like going to their classes or going to the restroom. Due to restriction policy on the use of the laboratory at night, the power consumption was measured for only four hours and was done in the afternoon. Nonetheless, the two days measurements gave the expected results, that is, the power consumption with the system is lower than without the system. The summary of the two-day power consumption observation is shown in Table 3

Table 3 Energy Consumption for the two-day period

Day	Energy Consumption without System	Energy Consumption with System
1	0.2041 kWh	0.1055 kWh
2	0.2002 kWh	0.0853 kWh

3.2 Effect of Heavy Loads to Transmission

In this test, several loads were connected to the line to determine the robustness of the PLC modem. The highest load plugged in to the power line was a 2200~W water boiler. For all the tests, it was observed that the data transmitted successfully.

3.3 Effect of Distance to Transmission Time

The effect of the distance to the transmission time was tested by moving one of the PLC modem away from the gas sensor and the monitoring station by plugging to the next outlet in the hallway of a Research Building. The maximum length from end-to-end is 53 meters. In all the test, a 5.1 seconds data transmission time was recorded.

3.4 Complete System Test

The complete system test involved all the modules and demonstrated the functionality of the enhanced BMS. For the safety of the proponents, the testing for the gas leak was done using a closed chamber. The gas sensor was attached inside the closed chamber together with the professional gas detector that serves as the reference. Three tests were done, the normal gas state, the disconnected gas test, and the gas leak test. In each of these tests, the setting of the lights and motion sensors were also varied. In the first test, no gas was injected in the chamber. The motion sensor sensed the movements of the proponents, thus it was observed that the lights were turned on with brightness that depended on the ambient light sensed by the light sensor. In the second test, a gas disconnect state is demonstrated by removing the wire that connected the gas sensor to the microcontroller. Just like in the previous test, the expected results were obtained. In the last test, a gas was injected into the chamber. All the modules were operating in their normal modes until the gas level of the LPG gas reached 10% LEL as indicated by SAMPO gas detector. The expected results were obtained, whereby all the lights and outlets were turned off.

4.0 CONCLUSION

The enhanced BMS developed in this project addressed the problem encountered in the Two Serendra incident whereby when a gas leakage or gas disconnect is detected, the system automatically disconnects the outlet as well as the electrical switches. The communications protocol used for the different modules connected to the system is X10 codes. The code is tweaked so as to include gas leak, gas disconnect, and medium bright functions that are not found in the original X10 code. Each module is developed using a PIC microcontroller. The microcontroller takes care of the sending and receiving of the commands as well as programming of the unit code of the module. Because of the decentralized nature of the system, the hierarchy of commands is promulgated that makes the gas sensor the priority, the motion sensor the next priority, and the light sensor the last priority. However, in the initialization process, it is the light sensor that starts the transmission, followed by the motion sensor, then the gas sensor. This is done to avoid collisions of data during the normal gas state. The enhanced BMS has also an energy saving feature because of the inclusion of the light sensors. Although, the power consumption test was done for two days only, the results show the significant reduction in the power consumption when the system is in place.

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