Designing a building automation system with open protocol communication and intelligent electronic devices

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Abstract. Building Automation System (BAS) is a microprocessor-based control network setup for controlling a building’s technical service systems such as air conditioning, ventilation, lighting, and hydraulics. BAS main microcontroller automatically handles all electronics in the building. To control the liked devices to suit the needs of the buildings’ occupants, the controller needs to be smart or intelligent. The system will be very flexible if the communication network between control and device used an open communication protocol. In this paper, we present a miniature BAS solution implemented using intelligent electronic devices (IED) as controlling devices. The system is built using 8-bit microcontrollers, sensors, and actuators. There are three IED in use, each handling lighting, air conditioning, and water pumps respectively. Communication between the devices and the human-machine interface (HMI) used the free and open Modbus TCP protocol.

1. Introduction

The main principles of smart building development are for increasing the tenants’ comfort value and reducing its maintenance costs. Building energy-efficient structures are a response to increasing human need for electronics to fulfill their needs. Efforts in smart building development are made possible by developments in information technology and automatic control engineering. More and more electronics integrated into common home and office tools pose more problems, such as increasing electricity costs.

Common structures and buildings consume about 40% of the national energy usage, and contribute about the same percentages to greenhouse gases, and also contribute to 70% of national electricity usage. The government has put efforts into developing its electricity infrastructure to match the increasing demand, but it is not enough. This pushes electricity costs up, increasing with the increase in coal, gas, or oil prices, due to the energy plants’ general usage of coal, gas or oil as its main fuel.

To reduce energy usage, the government has required governmental offices to use green building standards in planning for new buildings, with old buildings being retrofitted to help conserve energy. Energy conservation involves efficient and rational energy usage without reducing energy usage towards for important purposes. This energy conservation effort is applied in all utilization steps, starting from energy source utilization to last-mile utilization, using energy-efficient technologies, and campaigning for an energy-efficient lifestyle.

A part of energy conservation efforts is automatic control and oversight of electricity usage in a building, commonly defined as a Building Automation System (BAS). BAS are expected to be able to optimize environmental and security concerns by economical means. This aspect is reached by using computers integrated into a distributed control system. This integration is easier to achieve on buildings.
that are still in the planning stage, as opposed to older buildings that did not adopt the smart building concept on their planning step. The difficulties that arose from integrating BAS into older buildings range from difficulties in integrating sensors and actuators into existing equipment, and insufficient integration between the BAS communication network and existing communication network. Thus, it is important for a BAS to have an open and free communication protocol. In this paper, we propose a miniature BAS using an open and free communication protocol, with the protocol being Modbus TCP. The distributed controllers used in this research were 8-bit microcontrollers using fuzzy control.

2. Basic Theory
The following subsections cover the hardware and software used in this research.

2.1. Building Automation System (BAS)
The purpose of modern automation controllers is to achieve automatic control of all networked facilities. Distributed control systems integrated into electronic equipment work to oversee and control mechanical, security, fire prevention, lighting, HVAC, humidity control, and ventilation systems in buildings.

BAS’s main functions are to simultaneously control and oversee systems in a given building. A building controlled by a BAS is called a smart building. Commercial and historically important buildings use proven protocols such as BACnet and Modbus. Almost all green buildings are designed to accommodate BAS for energy, air, and water conservation. A unique function of BAS is responding to electrical demand accrued from active equipment, such as ventilation and humidity monitoring for a tighter building. Green building also use as much low-power DC devices as possible, usually integrated with power over Ethernet so as to allow control by BAS through it. A typical BAS usually has the following components:

1. Controller. Controllers used in a BAS usually consisted of one or more Programmable Logic Controllers (PLC), using specific programming. These are used to control equipment used in a building.

2. Occupancy Sensor. Occupancy is usually based on the daily schedule of the building. Override switches and sensors may be used to monitor occupancy in the internal areas of the building.

3. Lighting. Lighting may be turned off or on using BAS based on the time of the day, using timers and sensors. An example would be turning off a room’s lights half an hour after the last person left the room.

4. Air Handler. Air handlers are used to control the air’s entrance and exit to the building. This adjustment is done to keep the air quality in the building according to accepted human standards.

5. Central Plant. A central plant supplies the air handler with the needed air.

6. Alarms and Security. Many BAS solutions include alarm capabilities. If an alarm is detected, the system may be programmed to alert the authorities. The security system may also be integrated into the automation system. If there is a present occupancy sensor, it may also perform as a thief alarm.

7. Topology. A building, automation network consists of primary and secondary buses, consisting of controllers, input/output, and a user interface in the form of a human interface device. The primary and secondary bus may be in the form of fiber optic, Ethernet, ARCNET, RS-232, RS-485, or wireless network.

2.2. Modbus Protocol
The Modbus protocol was a data communication protocol using the master-slave method. In this protocol, there are only one master and one or more slaves bound together into a network. Communicating using the Modbus protocol starts from a query from the master node, with the slave nodes responding by sending data or acting out the command given by the master node. The master node may only communicate once at any given moment. The slave nodes may only communicate if there is a query from the master node and may not communicate with other slave nodes. When sending to the slave nodes, the master uses 2 addressing modes as follows. Unicast mode, the master node sends a query to a single slave node, who after receiving and processing the query sends a response to the master node. Broadcast mode, the master node sends a query to all linked slave nodes. In this addressing mode, the slave nodes did not send responses to the master nodes. The Modbus protocol forms a message format for querying and responding between master and slaves. The query-response cycle is shown in Figure 1.

![Figure 1. Query-response sending cycle in Modbus protocol](image)

3. System Design

The plan for building automation system involves both hardware and software.

3.1. System Block Diagram

The BAS proposed in this research used the block diagram shown in Figure 2.

![Figure 2. Building Automation System Block Diagram.](image)

Areas I, II and III represent 3 different rooms in different places. Each room has a piece of different electronic equipment and a local controller for all the equipment in the room. The local controllers use fuzzy logic in controlling the devices, thus the system may be called intelligent electronic devices (IED). Communication between HMI and local control uses the Modbus TCP protocol. Using this protocol allows the system to be integrated with PLC, SmartRelay or other kinds of the controller using the same protocol and physical layer.

The BAS proposed in this paper used a computer-based HMI, using EasyBuilder Pro from WINTEK Electronics.

3.2. Intelligent Electronic Devices (IED) Design
Intelligent electronic devices (IED) are an integrated solution between microcontrollers, solid state relays (SSR), sensors and signal conditioners. The block diagram for each IED used are shown in Figure 3.

![Image of a block diagram for each area]

**Figure 3.** Block diagram of IED for each area

Each system used the same architecture, with differing sensor packs. The system used the closed loop concept, and has 2 main parts, that of hardware and software

1. **Current and voltage sensor design**
   The current and voltage sensor is used to measure the grid voltage and the current used by the electronic device. A voltage sensor uses an isolator transformer, while a current sensor uses a solid state transformer, specifically ACS71205. The output of the sensors are still using AC current, with the magnitude of the current or voltage being proportional to the signal’s amplitude. To change the current type to DC and to fit with the ADC standard, the signal is conditioned with a peak-to-peak detector as shown in Figure 4.

![Image of current sensor and conditioning circuit, and voltage sensor]

(a) Current sensor and conditioning circuit, (b) voltage sensor

**Figure 4.**

2. **Temperature sensor and conditioning circuit design**
   In air conditioning devices, the controlled variable is that of the room’s temperature. Thus, the sensor used measures temperature. The sensor used in this system uses IC LM35, a solid state sensor with 10 mV/°C of output resolution. The sensor’s output signal is conditioned using a signal conditioning circuit so as to fit with the ADC standard. The circuit used has an op-amp design with a non-inverting amplifier configuration and 5x amplification. Figure 5 shows a signal conditioning circuit for sensor output.

![Image of a signal conditioning circuit for sensor output]
3. Light and Motion Sensor Design

A light sensor is used to measure the intensity of light in a room. The data is then used by the controller to control the number of lights to be turned on for optimal lighting. This sensor uses a Light Dynamic Resistor (LDR). LDR is also used to sense the condition of an information display from its given light. Figure 6a shows a light sensor circuit with LDR, using the voltage divider design. A motion sensor may also be added to an air conditioning system to detect human presence in the room. The sensor used is a Passive Infrared (PIR) sensor. Figure 6b shows a motion sensor using PIR.

![Figure 6a](image1.png) ![Figure 6b](image2.png)

**Figure 6.** a) Light sensor circuit with LDR, b) Motion sensor circuit with PIR

4. Microcontroller System Design

An IED's microcontroller functions as the main controller, and has a hand in reading sensor data, processing control algorithms and controlling devices through solid-state relays. An integration scheme between microcontrollers and other components is shown in Figure 7 and the addresses are compiled in Table 1.

![Figure 7](image3.png)

**Figure 7.** Microcontroller integration with sensors and actuators

| Supporting Components       | Arduino Pins |
|-----------------------------|--------------|
| LCD 16x2                    | 9,8,7,6,5,3  |
| Current Sensor (ACS)        | A14          |
| Voltage Sensor              | A15          |
| LDR1,LDR2 Sensor            | A8,A9        |

**Table 1.** Arduino pin integration address with supporting components
5. Solid State Relay Driver Design
A solid state switch (SSR) is an electronic switch using a semiconductor material as in a transistor. This switch type has advantages in not causing a fire or spark, compact design and not needing a large current to activate. Figure 8 shows a basic solid-state relay design.

![Figure 8. SSR internal circuit](image)

The basic components of an SSR are optocoupler and TRIAC. The amount of load that can be handled by the SSR depends on the TRIAC's specifications, while the trigger voltage stays between 3-30 VDC.

3.3. Software Design
The BAS proposed in this research has two different software, which is a control algorithm in IED and HMI in the server.

1. IED Software Design
IED’s algorithm in this system uses fuzzy lookup, which is suitable for implementation in a low-speed microcontroller due to not needing a high amount of computation. Membership function for lighting control is shown in Figure 9.

![Figure 9. Membership function for lighting control, with a) fuzzy system diagram, b) sensor input in the room, c) inner sensor input, d) output control.](image)

2. HMI Software Design
The HMI system in our proposed BAS uses a touchscreen-based minicomputer with the EasyBuilder Pro software installed. The HMI’s display design has four main screens, which is the main display, the office, the classroom, and the meeting room. The main screen and the classroom screen is shown in Figures 10a and 10b.
The HMI’s hardware aspect has 192.168.1.8 as its IP address. HMI communicates with the microcontroller using the Modbus TCP protocol, so as to be able to link with all the devices in the network as long as they also used the same protocol. There are three microcontrollers in a network with the HMI, with each unit’s address being 192.168.1.2, 192.168.1.3, and 192.168.1.4.

4. Testing and Analysis

System testing aims to find the performance characteristics of the system. The testing involves control and monitoring testing for each microcontroller as the local controller for each room.

4.1. Classroom Lighting Control Test

Classroom testing stands for lighting control testing. This testing aims to find out the capabilities of the controller to adjust the lighting for adequate reading brightness. By dividing the activation of the lamps to different switches, the appropriate amount of light is turned on for adequate brightness is made possible. The testing is done by shutting the room to adjust for outside lighting. The results of the testing are shown in Table 2.

Table 2. Room lighting control test

| NO | HMI Control | Room Intensity Level | Outer Intensity Level | Turned on Lights | Average Power (Watt) |
|----|-------------|----------------------|-----------------------|------------------|---------------------|
| 1  | ON          | 710                  | 100                   | 4                | 320                 |
| 2  | ON          | 690                  | 300                   | 3                | 240                 |
| 3  | ON          | 675                  | 400                   | 2                | 160                 |
| 4  | ON          | 640                  | 700                   | 1                | 80                  |
| 5  | OFF         | 500                  | 700                   | 0                | 0                   |

The testing results show that the lighting control system was able to respond to natural lighting changes by turning on light until optimal brightness for reading is reached.

4.2. Air Conditioning Control Test

The air conditioning control test is done by controlling the AC’s activation to reach the setpoint temperature. The setpoint value depends on the presence of humans in the room, using the motion sensor. The results of the testing are shown in Table 3.
The testing results show that the controller is able to change the setpoint temperature depending on the presence in the room. This behavior aims to reduce electricity usage. The setpoint value when unoccupied and at work, hours are set at 300°C, due to this value being the maximum temperature of the AC unit and still being better for power usage than just turning the AC off. Rapidly turning the AC on and off may damage the unit and accrue higher power penalties while starting the unit again.

4.3. Information Board Control Testing

The information board control testing aims to find out how much the system is able to know the status of the display and adjust its brightness. The results of the testing are shown in Table 4.

| NO | HMI Control | Display Status | Sensor Status |
|----|-------------|----------------|--------------|
| 1  | OFF         | OFF            | OFF          |
| 2  | ON          | ON             | ON           |
| 3  | ON          | ON             | ON           |
| 4  | OFF         | OFF            | OFF          |
| 5  | ON          | ON             | ON           |

The testing result shows that the system is able to monitor the condition of the display and control it from the control room through the HMI.

5. Conclusion

The conclusion that may be drawn from our research are as follows:

1. The building automation system allows for lower energy consumption in rooms.
2. The room lighting control system was able to control the room’s lighting to suit the needs of the occupants.
3. The air conditioning control system works to suit the current needs in the room.

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