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An indoor environment monitoring system using low-cost sensor network

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Abstract

Energy consumption in buildings account for a significant proportion of total energy consumed worldwide. Since humans spend about 90% of their time in buildings, it is essential that the indoor environment quality is improved and energy consumption is minimised. This paper presents the development and implementation of a low-cost sensor network system that can be used to monitor important indoor parameters to achieve high indoor environment quality. The prototype system shown in this paper has been tested in an office building and improvements made. The system, with further improvements can be used to control HVACs, and indoor environment conditions automatically and has great potentials for energy saving.

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Keywords: indoor environment, low-cost, sensor network, wireless sensor network, environment monitoring

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1. Introduction

A good indoor environment is associated with high indoor air quality and thermal comfort. The indoor air quality and thermal comfort subsequently are significantly affected by the temperature, relative humidity, airflow pattern and other parameters in the indoor space [1, 2]. In order to provide a quality indoor environment, the use of heating, ventilation and air-conditioning (HVAC) systems have been on a rapid increase in recent years, especially in developed and developing countries, along with both complex and sophisticated control systems [3, 4]. Although

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the control systems are meant to provide the required comfort while minimising energy consumption, many of these control systems have failed to satisfy the occupants' comfort need and/or reduce energy consumption [5].

This is as a result of the model being used to represent the rooms in the buildings being too simplistic with assumption of perfectly mixed (homogenous distribution) conditions [6]. In practice, in indoor environments, a temperature sensor is normally placed on the wall adjacent to doors or heating/cooling equipment and assumes that the measured parameter is representative of the whole room and is sufficient to achieve good thermal comfort. Such global sensing design would not perform well for optimal monitoring and feedback to dynamic building system operation or achieve optimal efficiency, as the measured parameter exhibit local indoor variation (e.g. indoor temperature variation) [7].

Placement of more sensors or a sensor network in the room is proposed to solve the above problem and provide more detailed monitoring or measurements. As such, better control of relevant parameters and system disturbance at multiple positions in the room can be achieved. However, professional sensors are expensive and the cost might prohibit such application, hence the need for low-cost sensor network.

Several studies have been carried out involving use of sensor networks in large scale/ citywide environment, indoor air quality/pollution, habitat, traffic monitoring with focus on various aspects like software, hardware, and middleware, and on sensor nodes, as well as on energy consumption of the sensor network [8-11]. However, focus on using multiple sensors to achieve better monitoring performance is still limited. In this paper, we present the development of a low cost sensor network comprising of sensors that can be placed in multiple locations in the room to help monitor parameters that can help achieve optimized control of HVAC system in the room.

2. Development of the low-cost sensor network

2.1. Design overview of the monitoring system

The developed low-cost indoor monitoring system employs an overall system architecture shown in fig 1. The main components include the temperature sensor nodes (digital and analogue), humidity sensor node, XBee wireless transceiver and SD shield. These nodes are all managed by Arduino microcontroller using ZigBee data protocol [8]. The recorded data is transmitted to PC for viewing. Detailed description of the components is provided in the following sub-sections.

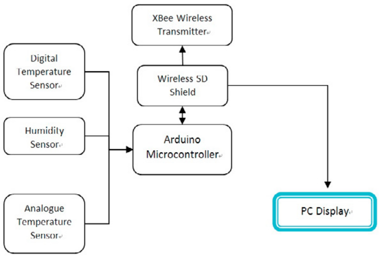

Fig. 1. Flowchart of the monitoring system.

2.2. Hardware

This subsection briefly describes each hardware component used in the monitoring system development. Table 1 provides a quick view of the entire components as can also be seen in fig 2. The equipment specifications as well as the associated costs are also shown on table 1.

- Temperature sensors

DS18B20

The DS18B20 (fig 2) is a 1-Wire bus [1] digital temperature sensor that can output temperature measurements ranging from 9-bit to 12-bit. Its operating range is from -55°C to +125°C, with accuracy of ±0.5°C above the range of -10°C to +85°C. DS18B20 is commonly used in HVAC environmental controls, temperature monitoring systems inside buildings, equipment, or machinery, and process monitoring and control systems [12].

LM35

The LM35 (fig 2) is an analogue integrated-circuit temperature sensor, with an output voltage linearly proportional to the Centigrade temperature. The LM35 is used with single power supplies, or with plus and minus supplies of 4 to 30V, as it draws only 60 µA from the supply. The sensor has very low self-heating of less than 0.1°C in still air and can be operated over a −55°C to +150°C temperature range, with accuracy of ±1°C [13].

- Humidity sensor (DHT11)

The DHT11 (fig 2) is a basic, low-cost digital temperature and humidity sensor. It uses a capacitive humidity sensor and a thermistor to measure the surrounding air, and output a digital signal on the data pin. It also uses a 1-Wire bus (no analogue input pins needed) which makes it simple to use, but requires careful timing to grab data. Its accuracy is 5% over a range of 20-80% humidity and ±2°C above 0-50°C temperature range. This accuracy adds to major downside of this sensor in addition to the fact that it also needs 2 seconds to receive a new data [14].

- Arduino microcontroller

The Arduino Mega (fig 2) is a microcontroller board based on the ATmega1280. It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analogue inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. The power for the Mega 2560 can be obtained through a USB cable or with an AC-to-DC adapter or battery [15].

- Wireless SD shield

As the name implies, the Arduino Wireless SD shield (fig 2) serves two functions. Foremost, this shield allows easy interface with XBee transceiver modules using ZigBee protocol to create wireless networks. Secondly, it comes with an on board micro SD socket which allows storage and access to large amount of data. In this particular experimental set-up, the SD storage function is of ultimate importance, as it provides the capability for data acquisition and storage for later use.

Table 1. Equipment specifications

Sensor or equipment	Model	Accuracy	Resolution	Cost ($)
Digital temperature	DS18B20	±0.5° C	0.1° C	0.50
Analogue temperature	LM35	±1° C	0.5° C	0.50
Humidity	DHT11	±5%	1%	0.70
Arduino microcontroller	Mega 2560			10.00
Wireless SD shield				15.00
Mini SD card (2GB)	ScanDisk			2.00
XBee	XBee pro			15.00
Breadboard				0.60

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[1] 1-Wire® bus by definition requires only one data line (and ground) for communication with a central microprocessor.

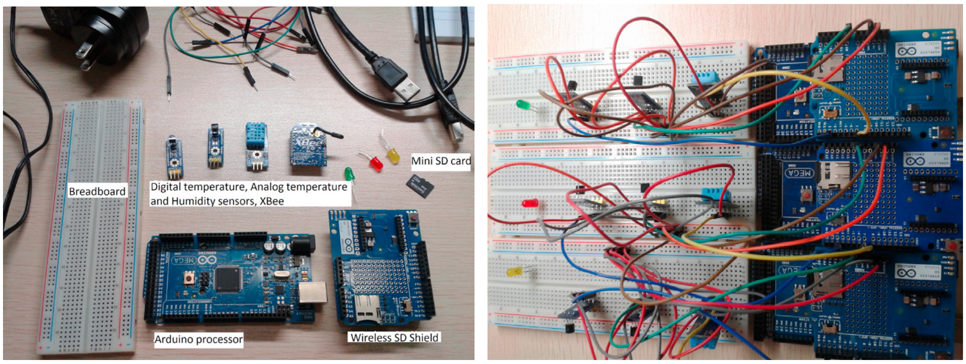

Fig. 2. (a) Pre-configuration components; (b) Post-configuration system

2.3. Software

To put together a functioning monitoring system (fig 2b), each hardware (shown in fig 2a) has to be configured correctly according to the flow chart (fig 1), and programmed to function together with the other hardware. The Arduino microcontroller serves as the processor of the entire system, it also stores the program to instruct and control the function of the other hardware. The whole monitoring system is programmed in C embedded with assembly language. The programming environment Arduino IDE is shown in fig 3 and has many functional inbuilt sample codes which can be extended to perform more advanced functions through associated libraries.

Fig. 3. Arduino IDE interface: Source [16].

3. Results and discussion

3.1. Sensor testing

To test that the configured system behaved as expected, a verification test with the systems place side by was carry out. The reading shown here is taken for only the digital temperature node every 1 minute for 80 times with the first and last 5 readings omitted to remove the error during the period the system was adjusting to the environment. The graph below in fig 4 show the readings collected over the period of close to 2 hours.

From fig 4, the highest difference in readings from the digital temperature sensors DS18B20 produced higher relative differences, which is as high as 1.5 °C between sensor A (blue line) and sensor B (red line) towards the end of the graph at point 70. The rated accuracy of the DS18B20 sensors is at 0.5 °C.

Later troubleshooting shows that the high relative difference in temperature is due to using 3 different electrical grounds (the processors in practice give different non-zero ground values) combined with having multiple Arduino processors too close to the sensors (sensors B here specifically get affected by the 3 processors as the breadboard on which the sensors were fixed is located in the middle). To resolve the problem, the ground pins are to be connected together and the sensors located further away from the Arduino processor in future systems.

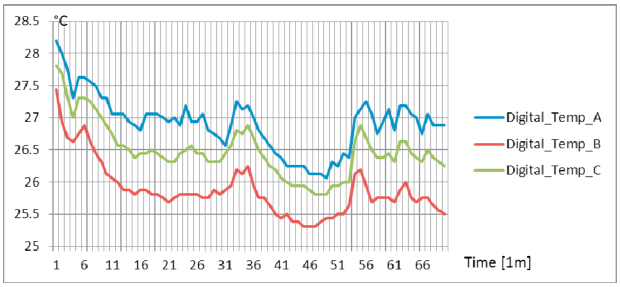

Fig. 4. Temperature readings from 3 digital sensors placed side by side compared.

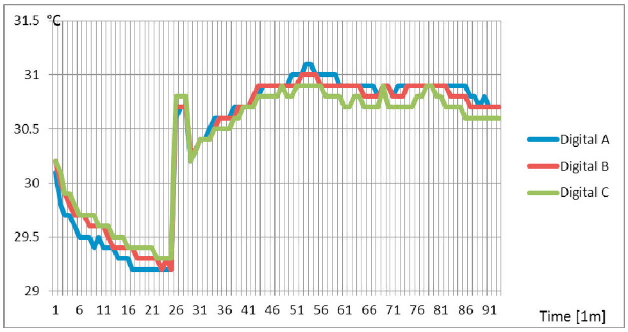

Fig. 5. Temperature readings from improved digital sensors configuration.

To solve the issues with the sensors producing large difference in relative measurements, an improved system is configured where the electrical ground of the sensors are connected together, while the Arduino microcontroller is located further away from the sensors. Having implemented these modifications, the system exhibits better performance with relative difference not exceeding 0.3°C at its highest point (period 2 at the beginning of graph in figure 5). These new readings verify that the sensors are within the 0.5°C accuracy limit rated by the sensor manufacturers.

3.2. Test room

To observe how the monitoring system performs in a real life environment, a typical staff common room at a university in Ningbo is chosen as test room. The room can accommodate multiple occupants and has multiple ACs installed as well. The dimension of the room shown in fig 6 is as follow:

Measures:
Internal = 10.6m x 9.3m x 3.0m
External = 10.9m x 9.6m x 3.3m
Window:
Glass area = 2.3m x 2.08m x 0.01m (x 2 openings)
Door:
Door area = 2.36m x 1.76m x 0.15m

Occupancy:
Multiple persons
Air-conditioning: 4-way cassette split AC (4 individual units)
Area = 0.95m x 0.95m

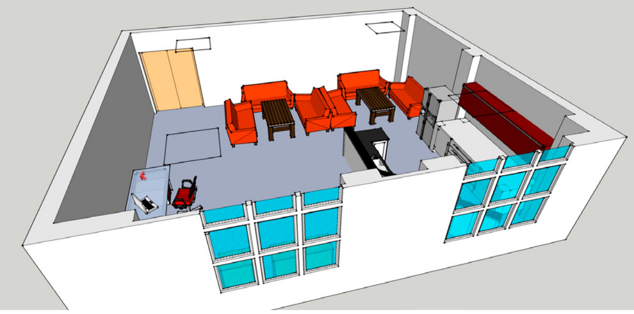

Fig. 6. 3D model of staff common room

3.3. Experiment

After improvements have been made on the system, further experiments are carried out in the test room. The monitoring system is set-up in the room with the temperature sensor nodes placed at different locations in the room. As this involves a cooling case (using AC units), with AC units operating at maximum capacity, the temperature measurement at locations 1, 2 and 3 (fig 7) could be seen to steadily decrease after initially reaching a high point of about 21.5°C at the 22nd period.

The difference in decrease rate at different locations shows promising sign that the sensor nodes captured the spatial variations at various locations within the room and show a promising potential which can be harnessed in future studies for optimal control of HVAC in rooms.

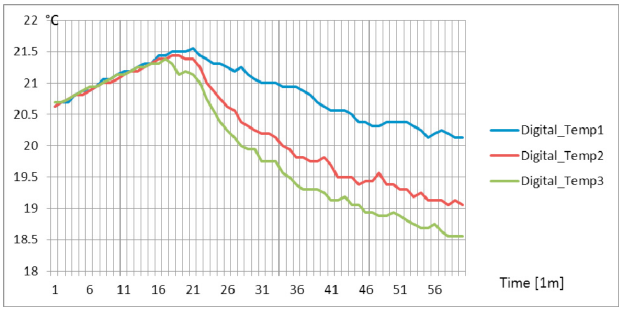

Fig. 7. Temperature readings at positions 1, 2 and 3.

4. Conclusion

At the initial testing stage of the system, several issues were encountered, but resolved after trouble shooting. Looking back at the experiments and results analysis however, further improvements are possible with the developed monitoring system. For example, on fig 5, an instantaneous jump in temperature of over 1.5°C was observed at period 26. The possible explanation is that it was likely cause by the sudden presence of an occupant in the space, the switch off of the air-conditioner or opening of the window or door. With these many likely scenarios, which are frequently encountered in real world cases, it is important to improve the initial developed monitoring system with new capabilities. These would be implemented in future development.

In the future, the focus would be on specific and detailed investigation and experiments using the improved developed systems. Priority would be placed on vigorous verification and validation of obtained results both in the controlled environmental chamber and real field tests. It is expected that, efficient placement of sensors and optimisation of existing control systems can play a major role in minimising discomfort and reducing energy consumption.

Through these studies, contribution to knowledge on understanding the effect of spatiotemporal variation on controls is anticipated, as well as quantification of energy saving potentials. These are some of the current focus of other on-going research studies by the authors.

Acknowledgements

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