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RESEARCH ARTICLE

Construction and Application of an Intelligent Air Quality Monitoring System for Healthcare Environment

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Abstract Indoor air quality monitoring in healthcare environment has become a critical part of hospital management and policy. Manual air sampling and analysis are cost-inhibitive and do not provide real-time air quality data and response measures. In this month-long study over 14 sampling locations in a public hospital in Taiwan, we observed a positive correlation between CO_2 concentration and population, total bacteria, and particulate matter concentrations, thus monitoring CO_2 concentration as a general indicator for air quality could be a viable option. Consequently, an intelligent environmental monitoring system consisting of a CO_2/temperature/humidity sensor, a digital plug, and a ZigBee Router and Coordinator was developed and tested. The system also included a backend server that received and analyzed data, as well as activating ventilation and air purifiers when CO_2 concentration exceeded a pre-set value. Alert messages can also be delivered to offsite users through mobile devices.

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Introduction

The indoor air quality (IAQ) of hospitals and medical centers has become a critical part of hospital management protocols for the well-being of both medical staffs and patients who may be both the source of microbial spreading and vulnerable to be infected through nosocomial routes. Therefore, one of the critical concerns in the design of preventive disease strategy is to establish an efficient IAQ surveillance program. IAQ mainly concerns of pollutants with physical (e.g., temperature, humidity, particulate matters), chemical (e.g., CO_2, CO, formaldehyde, volatile organic compounds, and O_3), radioactive (radon), and biological (e.g., bacteria and fungi) natures. A number of studies have indicated that indoor air pollutants with physical [1–3], chemical [4, 5] and biological [6] natures pose potential hazards to patients, medical staffs, and visitors in hospitals. For the air quality management for areas with public (e.g., lobbies, wards) and restricted (e.g., intensive care units, surgery rooms) accesses, sufficient air ventilation and purification systems are the common practices to minimize the risks of hospital acquired infection [7–9]. As frequent air sampling and analysis covering a large area is cost intensive, sophisticated simulations tools through computational fluid dynamics for indoor air contamination and control design have also been applied [10, 11].

The air quality profiles in hospitals have been comprehensively studies in the last decades [12–14], and many of the results indicate alarming IAQ especially in large-scale hospitals and medical centers. Although site-specific automated ventilation and air purification by radio-frequency identification (RFID) technology has been reported [15], most of the pre-set function of the air conditioning and ventilation systems does not adjust to the population density and degree of activities, and thus cannot always timely respond to the deteriorating air quality in the building. Consequently, development of a reliable, cost-effective, and intelligent air quality sensing network system possessing multiple functions such as sensing, monitoring, alarming, query interfacing, feedback and system activation becomes necessary.

Fast-disposing wireless sensor network (WSN) based on ZigBee technology with low power consumption has been increasingly applied for environmental monitoring (e.g., temperature, relative humidity, pressure, vibration, greenhouse gases) purposes [16–18]. ZigBee is a specification for a suite of high level communication protocols using small, low-power digital radios based on an IEEE 802.15.4 standard for personal area networks. ZigBee devices are often used in mesh network form to transmit data over longer distances, passing data through intermediate devices to reach more distant ones. This allows ZigBee networks to function with no centralized control or high-power transmitter/receiver able to reach all of the devices. ZigBee has defined rate of 250 kbit/s, best suited for periodic or intermittent data or a single signal transmission from a sensor or input device. The technology defined by the ZigBee specification is intended to be simpler and less expensive than other WPANs, such as Bluetooth or Wi-Fi.

In the present work, we have conducted a general air quality study for a public medical center in Taiwan, and constructed a prototypical intelligent environmental monitoring system (IEMS) combining a wireless sensing technique and an information platform. This study also incorporates the concept of pervasive computing, artificial intelligent, embedded systems, cloud computing, human-machine interaction, distributed computing, cognitive networks, and mobile computing. Therefore, the specific objective of the study is to demonstrate the applicability of the IEMS prototype using CO_2 as the air quality index for hospital settings. Through real-time IEMS, the facility administrators can monitor real-time air quality in the designated area, and notify medical staff via the communications system as the air quality deteriorates below a threshold level. Moreover, the information platform also has the data tracking and analyzing ability to provide the basis for IAQ improvement measures.

Materials and methods

Studied site description

This study took place in a 1500-beded public medical center in central Taiwan. Fourteen air quality sampling sites were selected, include three non-clinical area (service desk in the lobby [SL], Director's office [DO], pathology laboratory [PL]), two outpatient clinics (immunology/rheumatology wards section [IW], dermatology wards section [DW]), four medical treatment rooms (chemotherapy room [CR], emergency floor [EF], respiratory intensive care unit [RICU], operating suite [OS]), three inpatient rooms (surgical ward [SW], general wards [GW], cardiovascular ward [CW], isolation rooms [IR]), and an outdoor site on the front lawn of the outpatient building.

Air sampling and analytical methods

Month-long air sampling for 14 sites was conducted in June, 2010. All sampling activities occurred during the work-hours (between 09:00 and 18:00 h) in weekdays, with occupant population recorded during the time of sampling. For sections open to the public (i.e., SL, IW, DW, EF, SW, GW, CW), the number of people stationary within 5 m of the sampling site was recorded. For restricted areas (i.e., PO, CR, RICU, OS, SW, IR) and laboratories (PL), the number of people in the entire section space was recorded.

Air samples were collected and analyzed, as described below, for CO_2, bioaerosols (i.e., total bacteria and fungi), particulate matters (PM), total volatile organic compound (TVOC). Temperature and relative humidity were also recorded at the time of air sampling.

CO_2 Measured with a diffusive, non-dispersive infrared (NDIR) sensor (IAQ-CALC, TSI, USA) capable of measuring up to 5,000 ppmv of CO_2, with an analytical accuracy within 2 % of reading.

Bioaerosols Active sampling method was applied by drawing air through a 400-hole (0.25 mm), single-stage bioaerosol impactor (Standard BioStage, SKC Inc., PA, USA). Air was collected through a personal pump at a controlled flow rate of 28.3 l/min and a sampling duration of 2 min. The sampler was positioned between 1 and 1.5 m above ground, depending on the sampling purposes. The impactor was sterilized with 70 % ethanol prior to each sampling effort. The bioaerosols were collected on a 90 mm petri dish containing either tryptic soy agar (TSA) or malt extract agar (MEA) for non-selectively culturing bacteria and fungi, respectively. Each of the used petri dishes was sealed with parafilm immediately after sampling, and was incubated at 35 °C for 48 h at an offsite laboratory. The total counts of the bacteria and fungi were determined as the total bacteria (TB) and total fungi (TF) concentrations.

PM_{10} A personal pump (Gilair-5, Gilian, USA) was used for air sampling in conjunction with a sampler (PEM, SKC, USA) fitted with a 37 mm Teflon filter having a nominal pore size of 2 μm. During sampling, the apparatus was placed on a stand at 1.5 m above floor, using a sampling flow rate of 2.0 l/min and a sampling time of 8 h.

TVOC A vacuum chamber (Vac-U-Chamber, SKC) fitted with a 3-l Tedlar bag collected air sample which was subjected to TVOC analysis through a gas chromatography (GC 3000, China Chromatography, Taiwan) equipped with a flame ionization detector (FID) and a deactivated fused silica packed column (Alltech Associates, Inc., IL). Methane gas with a certified concentration of 10 ppmv was injected into the GC-FID (temperature settings: injector, 100 °C; detector: 200 °C, oven: 100 °C isothermal) to establish the linear CH_4 calibration. Therefore, the TVOC was expressed as the CH_4-equivalent total hydrocarbon (THC) concentrations.

System design and implementation

Figure 1 illustrates the IEMS architecture. The devices used in environmental monitoring included a sensor, a digital plug, and a RS232 connector between sensors and ZigBee Router and Coordinator which uses IEEE 802.15.4 standard to wirelessly transmit data in a range about 10 m to 100 m. When air quality data are collected by sensors, they are transmitted to the coordinator by the ZigBee Router and sent to the backend of the server through LAN for further analysis. If the detected air quality data reaches a pre-set limit, the system coordinator responds by transmitting alert signals to the ZigBee Router to trigger the front-end of the digital plug. A database which was used to monitor, record, and collect data on CO_2 concentration, temperature and relative humidity by ZigBee interface was built in this work.

The system hardware consists of CPU Intel(R) Core ^{TM} i7-2600 @3.40 GHz, eight gigabyte memory and 500 gigabyte disk. Two network interface cards (NICs) were applied to build the network environment. One of NICs was connected to internet, and the other was connected to the ZigBee Coordinator, which was linked to ZigBee Router through Zigbee IEEE802.15.4. The compiler uses Eclipse Java Version 1.4.2 to formulate ASCII (American Standard Code for Information Interchange) codes that catch the air quality data from the sensor. The database environment used Apache Web Server Version 2.2.8, PHP Script Language Version 5.2.6, MySQL Database Version 5.0.51b and phpMyAdmin Database Manager Version 2.10.3 to build.

The host server functions as data monitoring, analysis, and plug controller. The server platform was built in a distributed storage, but with a single entrance as wireless/wire sensors data integration. The platform was supplemented with HL7 format for data exchange and collection, and transmitted data in XML format to increase the consistency and readability. Through the single entrance on the platform, users can operate the system with client equipments, monitor system data from hardware devices, and plot the data for analysis using graphic software in real-time. The air quality is thus actively analyzed based on the real-time data, and signals can be sent to alert clients and activate necessary measures.

Results and discussion

Air quality profiles in the studied sites

Table 1 summarizes the recorded population density, temperature and relative humidity, as well as the measured concentrations of air pollutants including CO_2, TVOC, PM_{10}, total bacteria and total fungi, for the 13 in-building sites and an outdoor site. For the purpose of comparison, the drafted Indoor Air Quality Standards in Taiwan include the following: 8-h average CO_2 concentration, 1,000 ppmv; 1-h average

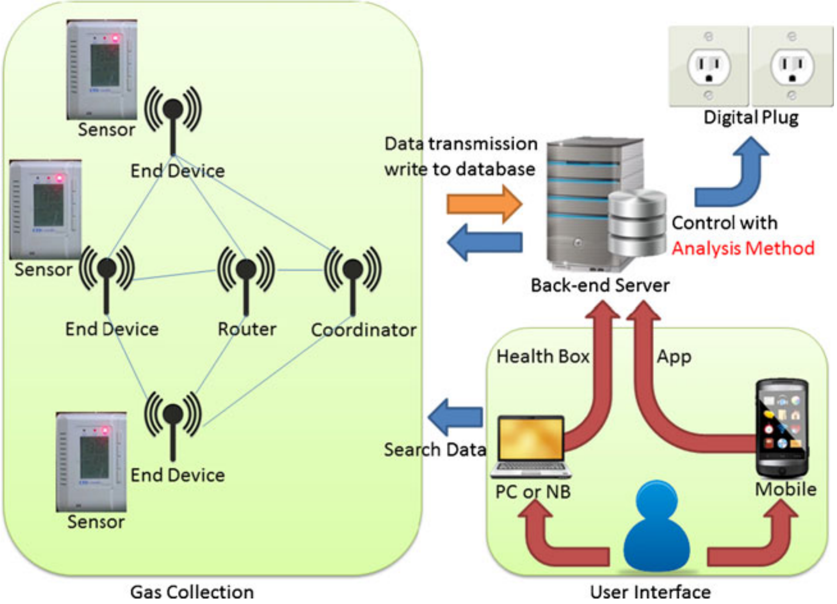

Fig. 1 A design scenario of Web service architecture for the environmental monitoring system

Table 1 Air quality profiles for the fourteen sampling sites in the studied hospital

Sampling site	[a]Population density (#/m^2)	[a]Temperature (°C)	[a]Relative Humidity (%)	[a]CO$_2$ (ppmv)	[b]TVOC (ppbv)	[c]PM$_{10}$ (μg/m^3)	[a]TB (cfu/m^3)	[a]TF (cfu/m^3)
Outdoor	NA	26.0±1.71	73.3±0.80	885.4	130	0.32	687	269
SL	1.9	26.6±0.93	75.4±0.87	1,261.6	42	0.18	1,912	197
DO	0.11	25.3±0.36	68.0±0.88	588.6	38	0.16	726	244
PL	0.92	25.4±0.92	77.3±1.08	750.3	45	NA	447	247
IW	1.6	26.1±0.81	74.5±0.79	1,474.0	41	0.24	1,429	150
DW	1.1	26.3±0.79	72.6±0.95	1,291.3	40	NA	1,105	227
CR	0.74	24.1±0.96	73.2±0.65	921.9	61	NA	850	121
EF	2.2	25.0±0.83	74.2±0.81	1,093.2	NA	0.16	1,169	101
RICU	0.13	25.8±0.75	74.2±0.59	1,056.5	NA	0.13	655	61
OS	0.4	23.3±0.14	72.9±0.52	832.7	43	0.06	503	25
SW	0.2	24.8±0.85	70.4±0.75	978.1	NA	0.17	387	84
GW	1.83	25.3±1.05	73.4±1.35	1,077.0	NA	NA	NA	NA
CW	2.2	28.7±0.98	72.5±1.90	608.1	NA	NA	864	109
IR	0.23	26.6±0.42	78.0±0.64	791.2	20	0.18	1,358	181

[a] Sample size n=28 for each site

[b] Sample size between 4 and 7 for each site

[c] Sample size n=3 for each site

NA indicates “not available. Samples were either not taken or invalid at these sites

TVOC, 560 ppbv; 24-h average PM$_{10}$, 75 μg/m^3; maximum total bacteria, 1,000 cfu/m^3; maximum indoor-to-out (I/O) total fungi ratio, 1.3.

The performance of the ventilation and air conditioning systems operated in the hospital are satisfactory, as evidenced by the improved TVOC, PM$_{10}$, and TF concentrations comparing to those measured from the outdoor site. The outdoor sampling site locates in the front lawn area outside the lobby with frequent human activities, and may have caused the escalated CO$_2$, TVOC, and PM$_{10}$ concentrations. In general, the TVOC and PM$_{10}$ concentrations, as well as the I/O ratio for TF, measured from all indoor sampling sites were well below the values indicated in the aforementioned IAQ standards. However, the CO$_2$ and TB concentrations either exceeded or approached the IAQ standards for about half the sampling locations, many of which are areas allowing public access.

CO$_2$ concentration correlations with IAQ

Figure 2 shows the correlation between the mean values of the CO$_2$ concentration and the population density for all indoor sampling sites. The mean CO$_2$ concentrations were adjusted by subtracting the smallest mean CO$_2$ value (i.e., 588.6 ppmv at site DO) from the calculated mean values for all other sites. Based on the simple regression analysis, a positive correlation was obtained between the increases in CO$_2$ concentration with the population density in the vicinity of the sampling locations. Inherent variability existed because the degree of ventilation and air purification control may be different for the sampling sites that covered various functional areas.

We also analyzed the correlations of TVOC, PM$_{10}$, TB, and TF concentrations with the adjusted CO$_2$ concentrations. As shown in Fig. 3, the linear regression analysis indicates that TVOC and TF concentrations were essentially non-correlated with CO$_2$, whereas PM$_{10}$ and TB concentrations showed moderately positive correlation with CO$_2$ concentrations. Numerous studies have shown that indoor TVOCs are primarily attributed to outdoor pollutants (e.g., vehicular and industrial emissions) and solvent leaks (e.g., surface paints, medical and laboratory solvents) [4, 19], whereas fungi are mainly attributed to airborne transmission from outdoor fungal sources and through air conduit contamination [6, 20]. These sources of TVOC and fungal contaminations are not particularly dependent of occupant density and thus CO$_2$ concentration. In contrast, the TB and PM$_{10}$ concentrations are found to be

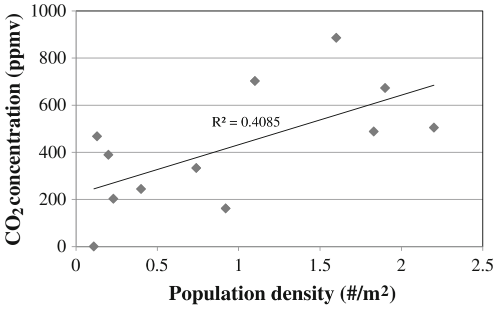

Fig. 2 The correlation between the mean CO$_2$ concentration and the population density for the sampling sites

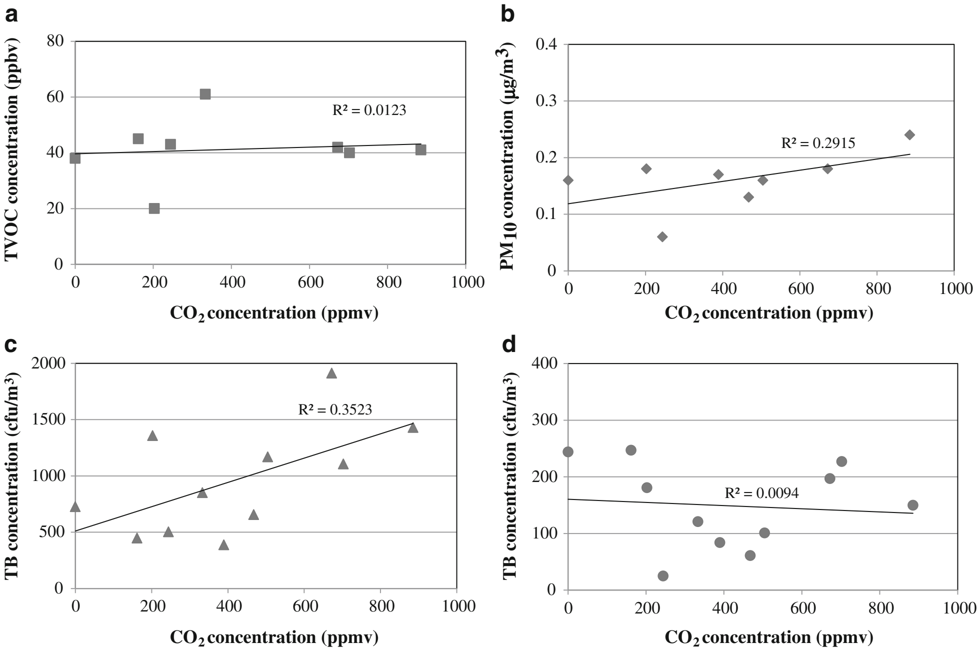

Fig. 3 The correlations between the air pollutants concentrations and the CO_2 concentrations for the sampling sites. **a** TVOC, **b** PM10, **c** TB, and **d** TF

positively correlated with CO_2 concentration. For TB, Obbard and Fang [21] reported that the bacteria identified in their study for a Singaporean hospital were representative of normal microflora of the skin, respiratory and gastrointestinal tracts, along with some opportunistic pathogens in *Acinetobacter* and *Flavobacterium* spp., and that the occupant density was the key factor influencing the level of airborne bacteria. Wan et al. [12] and Tang et al. [22] also indicated positive correlation between airborne bacterial concentration and number of persons in the studied locations. It is worth mentioning that there has not been a unified approach for the determination of microbial contamination in hospitals [23–25], though active sampling method such as the one applied in this study is generally accepted for monitoring the airborne microbial contamination. Results derived from active sampling approach are limited as the method does not measure the number of microorganisms settling on surfaces, hence does not necessarily reflect the risk of microbial infection. While there appears to be varying degrees of correlation between the microbial counts detected by active (airborne) and passive (surface-bound) sampling methods for total viable counts [23, 24] and targeted microorganisms [26], one must follow a specific sampling protocol when the microbial enumeration values are used to evaluate the air quality in hospitals.

Interpretation on the positive correlation between CO_2 concentration and the total microbial counts should be cautious, as microbial counts tend to vary significantly both temporally and spatially. The spatial variation of microbial contamination in hospitals has been reported in numerous literature [12, 21, 27, 28] as these hospital environments have vastly different medical functions and air quality characteristics. In this study, we have also noted low TB and TF counts for restricted sites (e.g., RICU, OS, SW) as compared to public accessible sites (e.g., lobby, EF and wards). The temporal variations among the sampling sites are reflected by their relative standard deviations, which ranged from 0.43 (site CW) to 1.4 (site RICU) for TB, and from 0.50 (site IR) to 2.8 (site DW) for TF. These data variations are not accounted for in the correlation analysis since Fig. 3c and d are plotted using the mean TB and TF airborne concentrations for the 11 sites from which samples were taken and measured daily (i.e., $n=28$ for each mean value) over the studied period. Consequently, the correlation between TB, TF and CO_2 concentration can only be considered as a gross one, whose spatial and temporal correlation and implication should invoke further investigations.

Based on the observed positive correlation between CO_2 concentration and occupant density, TB, and PM_{10}, it is possible that CO_2 monitoring data can be used as a general indicator of the hospital IAQ. This is advantageous because real-time detection of CO_2 is both technologically matured and cost effective. Even with the recent technological advances that have made fast-response measurement of airborne particles and bacteria possible, their reliabilities for air quality determination are still questionable. Consequently, this study will develop an IEMS on the basis of real-time CO_2 monitoring.

IEMS testing

The platform was used to collect data on CO_2 concentration, temperature and relative humidity for real-time monitoring, and to display the data on a web page by charts using Java

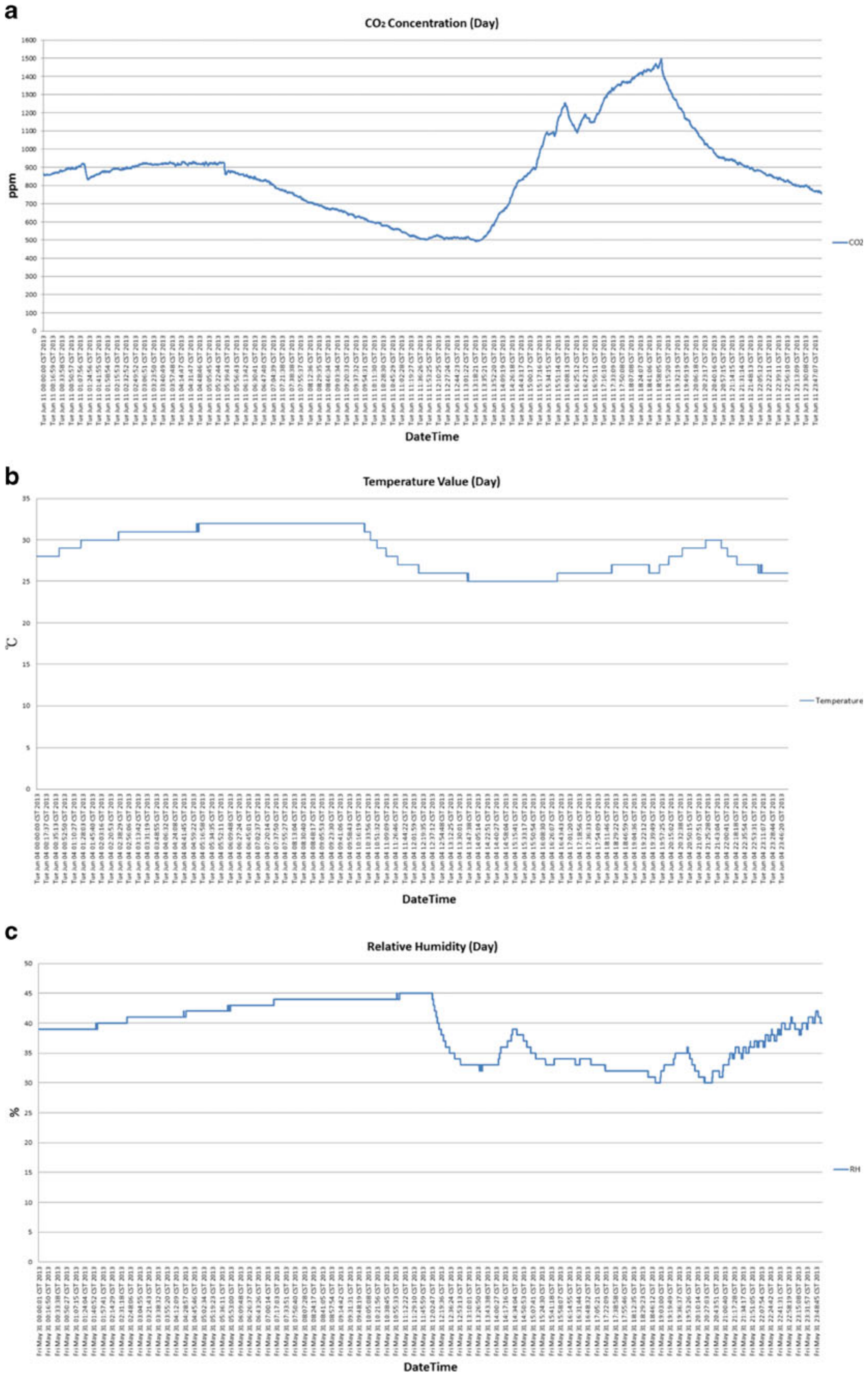

Fig. 4 Typical daily profiles of **a** CO_2 concentration, **b** temperature, and **c** RH recorded and displayed on the platform

Highcharts, an open source program. A typical set of graphical data collected is shown in Fig. 4. For example, the CO_2 concentration detected by the sensor exceeded 1,000 ppmv between 15:00 and 20:30 (shown with data for June 11), and reached a peak level of 1,600 ppmv. Additionally, the temperature was mostly over 30 °C in the morning (June 4) and briefly in late evening, whereas the relative humidity was over 40 % from 3:00 to 12:00 (May 31). The continuous monitored data indicated that these patterns with higher CO_2 concentration, temperature and RH were relatively consistent over 3 weeks.

To air quality alert and control, a program written with java code on back-end server was developed to activate or deactivate ventilation in the local environment. Figure 5 shows the flow chart java code program. Users are prompted to log in MySql to connect the front sensor device for viewing air quality data. The entrance webpage shows the location of the buildings for the users to select and examine the data for the building. For one of the locations tested in this study, CO_2 concentration control was set on the right plug to activate ventilation, with a triggering point of 1,200 ppmv for CO_2 concentration or the period between15:00 and 20:00, as well

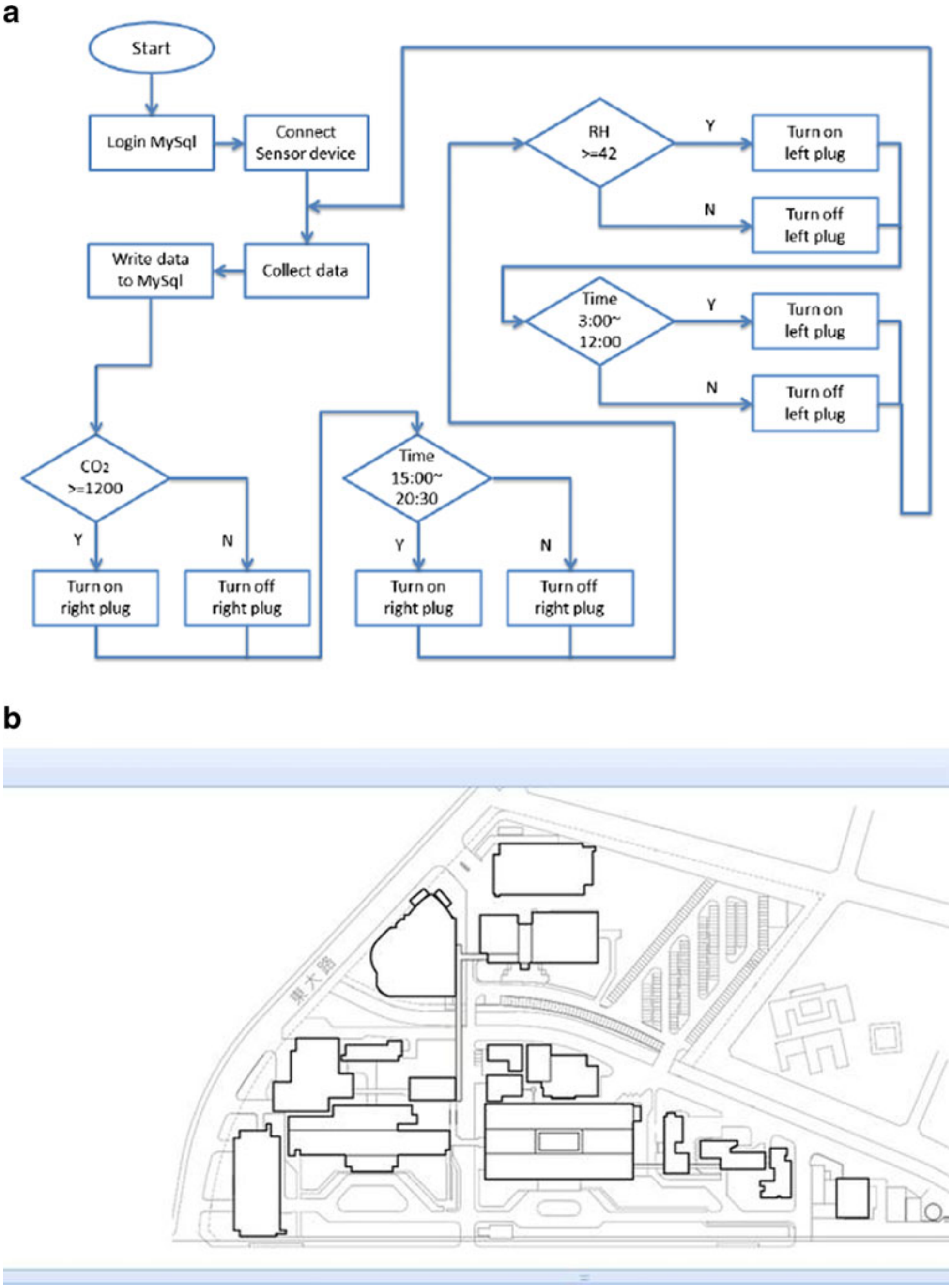

Fig. 5 **a** Flow chart of analysis method on back-end server, **b** the access webpage showing the sites of the buildings to be selected

as 42 % for RH or the period between 3:00 and12:00. It should be mentioned that the IAQ standard in Taiwan requires an 8-h average CO_2 concentration less than 1,000 ppmv. Temperature value was not used as a controlling parameter for the study, as the period where higher temperature occurred generally overlapped with that of RH.

With the IEMS detection and activation system, the red lines in Fig. 6a and b indicate the daily and weekly CO_2 concentration with the presence of the IEMS, whereas the blue lines indicate those without activation control. One can clearly observe that the CO_2 concentration has improved significantly on both daily and weekly basis. In particular, the CO_2 concentration was maintained below 1,100 ppmv during the period (between 15:00 and 20:00) which had experienced CO_2 concentration over 1,200 ppmv without control. The CO_2 concentration could have been reduced had the set point been lowered to 1,000 ppmv instead of 1,200 ppmv. Similarly, the red lines in Fig. 6c and d show the daily and weekly data of relative humidity with IEMS, and the blue lines show those without IEMS. Evidently, the relatively humidity also improved significantly and was mostly maintained below 40 %.

Real-time monitoring on mobile devices

For real-time air quality monitoring on mobile devices, we designed an Android application software (App) for smart phones. This App features both graphical and numerical displays of the real-time CO_2 concentration, temperature, and relative humidity data. This App allows off-site users to have access to the air quality conditions at a specific monitoring site. The holistic structure was implemented in a private cloud. Slight time delay of response from the frontend devices to the backend host was noted. Our current solution is to use more sensitive sensors and rewrite the monitoring App on the smart phone.

Light-weight demand is another design factor to make the device application more flexible. One of the alternatives is to use Intel Atom PQ7-C100XL, a popular 3.5” ESB-based board, to replace the backend server. Figure 7a shows a built-in VGA port, a LVDS port for dual independent display, a Gigabit Ethernet port, 7 USB port, a SATA, a SDIO socket expand through a Mini PCI-E socket and a 12V DC power supply connect to DC circuit for the demand of DC-in application. PQ7-C100XL presents an ideal alternative for low power-consuming devices such as outdoor embedded systems. The board functioned as a substitute server capable of accessing and analyzing data through windows 8 OS. Because of its x86 architecture, the composition shown in Fig. 7b can meet the light-weight demand. However, technical issue concerning the connectivity between mobile devices and the board needs further modifications.

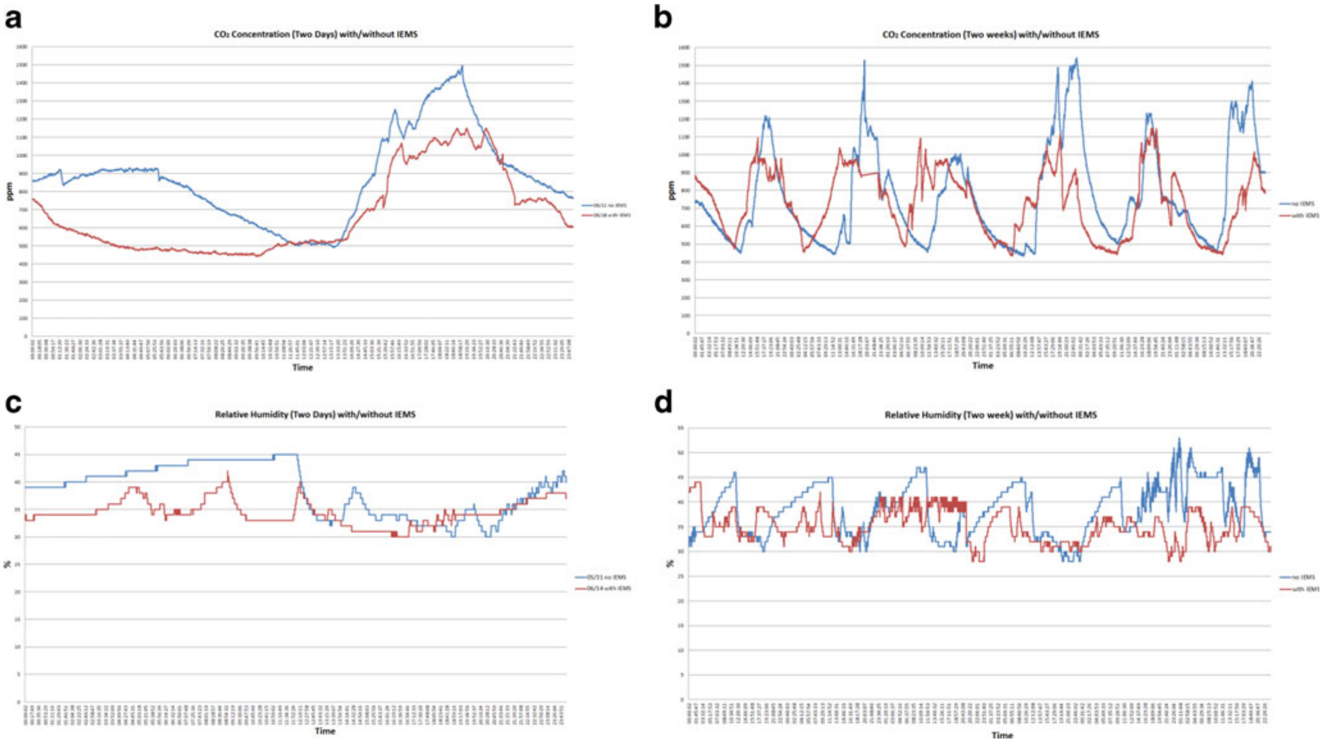

Fig. 6 CO_2 concentration and relative humidity with **a**, **c** daily, **b**, **d** weekly profiles with (*red*) and without (*blue*) IEMS

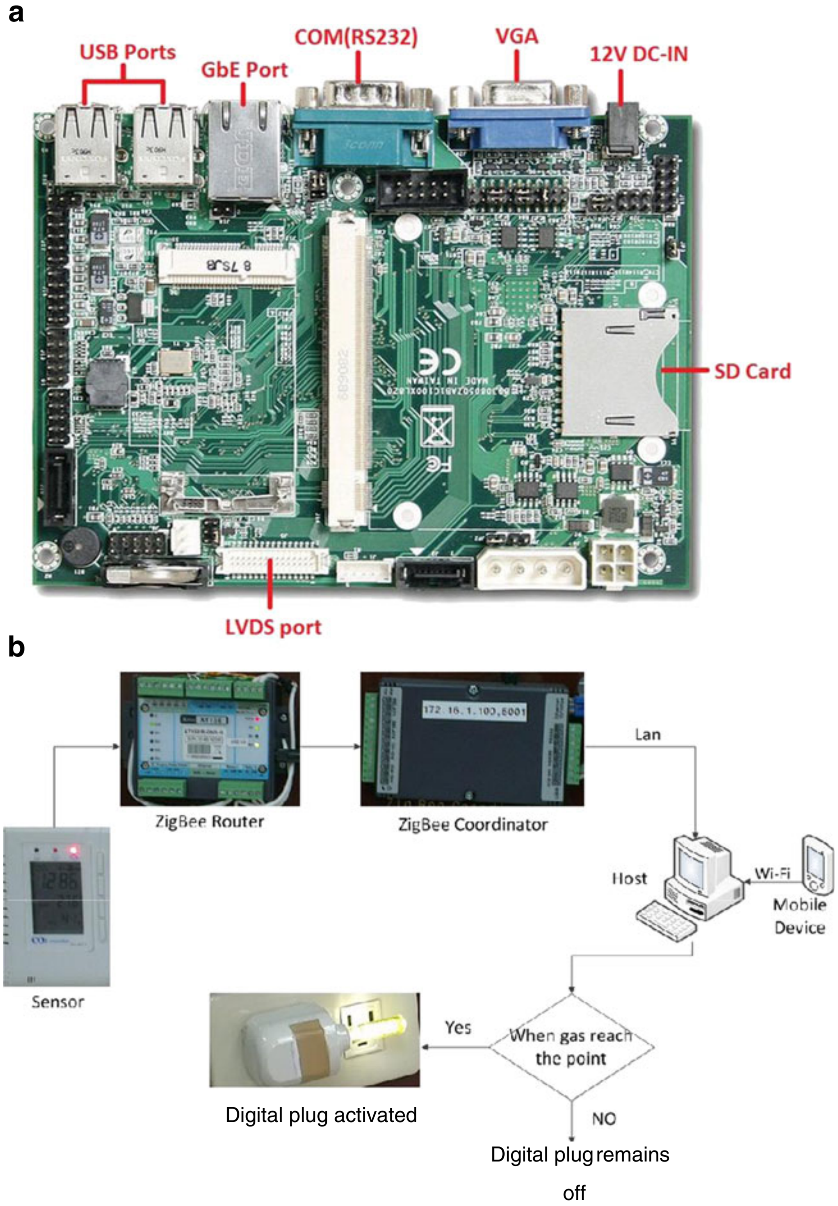

Fig. 7 **a** The Intel Atom PQ7-C100XL board design, and **b** the testing system flow design incorporating the board

Conclusions

Over this long-month air quality monitoring study, we have noted that using CO_2 concentration as a basic indicator of the indoor air quality in a hospital could be possible. The implication of this result is the feasibility to perform real-time air quality monitoring through the matured CO_2-sensing devices connecting to a Zigbee-based wireless network, and to subsequently send out signals to activated air ventilators or purifiers. Alert messages to off-site users can also be attained through mobile devices in a private cloud. The entire system combines applications of grid computing and cloud technologies to create an efficient, low-cost, fast, and lightweight indoor air quality control network. A source code community was formed to provide users a safe and convenient platform for data analysis, file access, and transmission. Future efforts to improve the intelligent environmental monitoring system include incorporating "big data" method to store and analyze the large volume of data collected from sensors, and to predict the indoor air quality through data mining technique.

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