Distributed smart sensor system for indoor climate monitoring

B. Ivanov, O. Zhelondz, L. Borodulkin and H. Ruser
Universität der Bundeswehr München
Institut für Meß- und Automatisierungstechnik
Werner-Heisenberg-Weg 39, D-85577 Neubiberg b. München
Tel: +49 89 6004-4501, Fax: +49 89 6004-2557
email: boris.ivanov@unibw-muenchen.de

Summary
An important goal of smart home automation is to improve the user’s comfort and security along with a reduced overall energy consumption. A core element of this strategy is an automated decentralised indoor climate control system. The subjective perception of indoor air quality and thermal comfort in rooms is influenced by a large number of different physical parameters, the most important being the mean air room temperature, the relative air humidity, the mean air velocity, and the CO₂ concentration. For a comprehensive indoor climate monitoring and control system, multi-gas sensor arrays and person detection sensors are required. In the paper, the features of a flexible KNX based distributed sensor network, including stationary multi-gas sensor modules and wearable wireless devices, is described. Important issues for smart sensor design like self-monitoring, plausibility check and model-based self-calibration abilities have been especially devoted to. An outlook for a perspective sensor miniaturization is given.

Keywords: home automation, indoor climate control, distributed sensor network, smart sensors

1. Introduction
In recent decades, new construction techniques and insulating materials have been developed which remarkably reduce the heat loss of buildings, enabling high energy savings at the cost of a diminished natural air exchange. In this situation, sufficient indoor air quality must be guaranteed by appropriate heating and ventilation of rooms. Demand-adjusted control of heating, ventilation and air conditioning (HVAC) systems helps to establish a comfortable climate in rooms along with a reduced energy consumption [1-3]. Factors that influence the indoor air quality include:

− high CO₂ concentration due to inadequate supply of fresh air,
− contamination arising from sources within the building (e.g., combustion products, tobacco smoke and other particles; volatile organic compounds (VOCs) from building materials, fabric furnishings, carpet, adhesives, fresh paint, new paneling, and cleaning products),
− contamination from outside the building (e.g., ozone, carbon monoxide, and particulate matter) through air intakes, infiltration, open doors, and windows,
− microbiological contamination of ventilation systems or building interiors.
A decentralised HVAC system has been installed in our SmartHOME Lab which is a single-family-type living house on the University Campus [4]. The measurement system comprises of a network of a large variety of specialised indoor and outdoor sensors and actuators and a multi-bus communication and data storing infrastructure [5]. The structure of the instrumentation system is shown in Fig. 1.

The aim is to design a reliable and cheap sensor system which covers most of the demands of air quality measurement and comfort requirements. An integrated system can provide an effective means of measuring the indoor air quality and calculate the established comfort indices PMV (predicted mean vote) and CSV (comfort sensing vote) [6]. The structure of the air quality control system is show in Fig. 2.
The thermal comfort is a non-linear result of the interaction between environmental dependant parameters (the most important being air temperature, air velocity, relative humidity, mean radiant temperature), metabolic parameters (activity level, clothing) as well as subjective feelings [6]. In order to compute a value of the indoor thermal comfort, the environmental variables must be measured at a location close to the user. The activity level and the clothing insulation can be obtained from suitable person detection sensors [7].

A comprehensive air quality monitoring requires the inclusion of dust sensors and selective gas sensors in the network, which are sensitive to explosive or poisoning gases which could impose a threat to persons. In Table 1, lead gases relevant for different scenarios and typical activity (trigger) thresholds are given.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Tracer gases and activity thresholds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor air quality</td>
<td>CO₂(1000ppm), VOC (30ppm), H₂O (1%)</td>
</tr>
<tr>
<td>Outdoor air pollution</td>
<td>O₃ (20ppb), NOₓ (20ppB), VOC (30ppm)</td>
</tr>
<tr>
<td>Explosion protection</td>
<td>CH₄ (1%) bzw. C₃H₈ (0,3%)</td>
</tr>
<tr>
<td>Poisoning protection</td>
<td>CO (100ppm)</td>
</tr>
<tr>
<td>Early fire warning</td>
<td>CO₂ (1%), CO (200ppm), H₂O(2%), NOₓ (200ppb)</td>
</tr>
</tbody>
</table>

In the following, the implementation of prototypes of three technical solutions of an air quality measurement system is described:

1. Multi-gas Sensor Module,
2. Wireless Wearable Device,
3. BGA Micro-Sensor.

2. Multi-gas Sensor Module

With the Multi-gas Sensor Module (Fig. 3), the following parameters of indoor air are measured:

- concentration of carbon dioxide (CO₂), carbon monoxid (CO), ozone (O₃), hydrogen (H₂), sulfide (H₂S),
- fire gas detection (methan concentration, LEL -Lower Explosion Limit),
- dust particle concentration,
- air temperature,
- relative humidity.

Relevant parameters of the selected commercial sensors as well as the maximum permissible concentration (MAK value) of specific gases are collected in Table 2. Due to the same sensor principle for all gas sensors, the sensor output evaluation can be largely unified. The necessary signal processing is carried out on a cheap microcontroller.
The air composition in the room may vary considerably, therefore the use of broadband electrochemical gas sensors is preferred over selective gas sensors (e.g. based on IR absorption). Electrochemical gas sensors are available for a large variety of gases. The sensitivity and selectivity of the gas sensors are controlled by the value of the external voltage. Their advantages are mainly small dimensions, no heat radiation, low energy consumption and low price. A well-known problem of semiconductor gas sensors are temperature and humidity influences and a considerable baseline drift. To overcome this limitation for practical use, correction algorithms are successfully applied and the lifetime could be extended to several years [9,10].

As temperature sensors serve conventional Pt1000 Platinum resistance thermometers evaluated on a bridge circuit. The non-linear temperature characteristics is modeled by a 3-order-polynom.

The capacitance humidity sensors are built in a double oscillator configuration with a reference branch in order to reduce temperature drifts. The humidity value follows from the difference between the two oscillator frequencies.

The dust sensor is based on IR light absorption which depends on the particle concentration.

<table>
<thead>
<tr>
<th>Measurand</th>
<th>Sensor</th>
<th>Principle</th>
<th>Range</th>
<th>MAK value</th>
<th>Resolution</th>
<th>Accuracy</th>
<th>Lifetime (calibration interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>SBU [9]</td>
<td>Electrochemical</td>
<td>0-5000 ppm</td>
<td>5000 ppm</td>
<td>5 ppm</td>
<td>&lt;10 %</td>
<td>2 years</td>
</tr>
<tr>
<td>CO</td>
<td>Sensoric [10]</td>
<td>Electrochemical</td>
<td>0-300 ppm</td>
<td>30 ppm</td>
<td>&lt;0.1 ppm</td>
<td>&lt;10 %</td>
<td>3 years (6 month)</td>
</tr>
<tr>
<td>Sensor</td>
<td>Type</td>
<td>Range</td>
<td>Resolution</td>
<td>Accuracy</td>
<td>Lifespan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
<td>-------------------</td>
<td>------------</td>
<td>----------</td>
<td>----------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂S Sensoric</td>
<td>Electrochemical</td>
<td>0-30 ppm, 10 ppm &lt;0.2 ppm &lt;10 %</td>
<td>6 month</td>
<td>1.5 years</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂ Sensoric</td>
<td>Electrochemical</td>
<td>0-2000 ppm, &lt;15 ppm &lt;10 %</td>
<td>6 month</td>
<td>2 years</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₃ Sensoric</td>
<td>Electrochemical</td>
<td>0-1 ppm, 0.1 ppm &lt;0.01 ppm &lt;10 %</td>
<td>6 month</td>
<td>1 year</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEL (CHₓ) Sensoric</td>
<td>Electrochemical</td>
<td>0-100 LEL</td>
<td>6 month</td>
<td>2 years</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dust SHARP</td>
<td>IR absorption</td>
<td>0.1-8 mg/m³, 2 mg/m³, 0.02 mg/m³</td>
<td>6 month</td>
<td>&gt; 4 years</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dust Panametrics</td>
<td>Capacity</td>
<td>0...90 % rF</td>
<td>4% rF</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp. Pt 1000</td>
<td>Conductivity</td>
<td>-40...100°C</td>
<td>0.2°C</td>
<td>&lt;1 %</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The designed Multi-gas Sensor Module will be wall-mounted. The EIB bus coupler and power supply are located in a separate box to mount into a socket inlet, Fig. 4.

Data loggers scan the sensors outputs in defined time intervals (at present, every 5 min). The data is saved in ASCII format on hard disk and transferred via FTP protocol to the database computer which decodes the data and writes it into the main database (MySQL). The data from the database will be used by the Control PC for visualisation and future processing: The results are decoded and transferred to the control block to produce commands for the actuators (e.g. heater valve, ventilators).

3. Wireless Wearable Device

As mentioned, the thermal comfort is a subjective measure which is largely dependent on the position of the user in the room. Relevant is the dynamic behaviour as well as the spatial distribution of the climate parameters. Hence, the control of energy flows (heating, ventilation) has to be considered in relation to the weather conditions and to the specifications of the rooms. For optimum thermal comfort, a wearable device has been designed which measures the most relevant parameters of the surrounding air and triggers a distributed HVAC system such that the desired comfort can be established at the location of the user. In order to arrive at small and cheap devices, some compromises are necessary. Commercial sensors which measure the heat radiation are bulky and very costly. A way to get around this is to calculate the heat radiation from measured wall temperatures, weather data and known internal heat sources (electrical devices, people etc.) on behalf of a parameterized room model [13].

![Fig. 4: Wall-mount Multi-gas Sensor Module with MCM, EIB BIM, power supply](image)
For the wireless communication, a EIB-RF based communication is desired. Until the RF-UARTs and Bus Access Units (BAU) are fully available commercially (approx. 2003), a sub-optimal solution based on RF pagers which communicate with a base station (Figs. 5,6) via a radio channel has been chosen.

The developed wireless (RF) sensor module measures the following parameters:

- mean air temperature
- relative humidity
- CO$_2$ concentration

![Fig. 5: Structure and view of the pager module](image)

![Fig. 6: Structure and view of the base station](image)

From these measurements and knowledge about the room and the person’s behaviour and clothing, the PMV value is calculated, see Fig. 7 (for a 3-days-period in August 2002). Larger values of PMV indicate higher comfort, lower values less comfortable conditions (too cold, too windy etc.).
Fig. 7. Calculated PMV values from measurement

4. Micro-sensor

The success of smart sensor systems in home automation is supported by the integration of components into multi-sensor units and bus coupled sensor networks, the decentralization of functions, a general shift from analog to digital technology and the implementation in microsystem technology. The perspective are flexible, cheap multi-chip modules (MCMs): miniature devices with drastically reduced power consumption and common hardware structure, microcontroller based processing and KNX bus connectivity. The MCMs combine the physical sensors with the matching and amplifying circuitry on one chip. For enhanced flexibility, a multi-level (“stack”) structure is being developed.

In Fig. 8, a graphical model of the 3D-BGA-Module is shown. On the sensor level, all considered micro-sensors (CO₂, temperature and humidity at the moment) are combined. The signal processing and decision-making is carried out on the processing level (DSP). The stack is connected to the overall smart home environment via the communication level (TP UART, KNX bus coupler).

Fig. 8 Micro-sensor (Design study)
5. Conclusion

Energy loss estimations in residential buildings show that automated room climate control working separately for each room has the potential to reduce the over-all energy consumption in ‘Smart Homes’. The lead tasks for the realisation of the indoor air monitoring system is to maintain a healthy climate and an optimized objective thermal comfort.

The air quality assessment and the thermal comfort sensation depend on numerous variables which are difficult to measure precisely at low cost. The core of the sensor system presented here is a comprehensive monitoring system which continuously measures the indoor and outdoor air quality and through gas leakage detection and early fire warnings also addresses essential security matters. The conditions for indoor air quality control and the assessment of subjective thermal comfort are sometimes contradicting. If the CO$_2$ concentration exceeds a certain level (commonly 1000 ppm), the air quality control must have priority over the adjustment of thermal comfort.

Next research steps are aimed at improving the long-term stability and robustness against influences of temperature and humidity of existing gas sensors by means of a model-based approach. Furthermore, on behalf of extensive measurements, most suitable sensor locations have to be found sensor subsystems and reliable, fuzzy-based control strategies have to be developed.

Acknowledgement

Parts of this work have been carried out in the projects “Intelligent Instrumentation of Homes (IWO-BAY)” sponsored by Bayerische Forschungsstiftung and “telehaus” sponsored by the Federal Ministry of Education and Research (BMBF).

References