Development of a microcontroller-based interactive monitoring system for indoor environmental quality

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Abstract: A holistic determination and improvement of the quality of the indoor environment includes, in addition to the “classic” parameters such as air temperature and humidity, other influencing variables such as air quality, noise, and lighting conditions (brightness, color temperature). Since Covid-19, air quality came back into focus. The interaction of these factors in their entirety has an effect on people and significantly determines their well-being and performance. This paper presents the implementation of a monitoring system for these indoor comfort variables (temperature, humidity, wind speed, CO_2, VOC, lighting, and noise) based on the Arduino microcontroller ecosystem and corresponding sensor technology. This setup is complemented by the development of a graphical user interface (GUI) with an interactive feedback system. Via touchscreen or the accompanying app for desktop PCs, users can monitor real-time measurements and change settings such as the model of thermal comfort, algorithm parameters that are used to predict comfort indices, database connection, application programming interface, or the language of the software. Feedback can be augmented by using system notifications, color notifications in the GUI, and changeable animated images according to user preferences. Furthermore, user tests were conducted to investigate the system usability and to explore the differences between these two interaction possibilities. During the user testing phase (N = 4), two questionnaires based on the usability metric for user experience lite (UMUX-LITE) and the system usability scale (SUS) proved the high usability of this monitoring system. Additionally, it was found that users increasingly prefer to use the touchscreen as the testing phase progressed.

Keywords: Indoor Climate, Indoor Environment, Indoor Environmental Quality, Indoor Air Quality, Sensors, Monitoring, Interaction, Internet of Things, Microcontroller, Arduino

1 Introduction

Humans spend nearly 90% of their time indoors, and since Covid at the latest, the indoor environmental quality (IEQ), particularly indoor air quality (IAQ), usually measured by CO_2 concentration, has come back into focus [1]–[4]. At the same time, given the growing interest in human's productivity, well-being, and health, the indoor environment has also received increasing attention in recent years [1], [5], [6]. The use of low-cost sensor technology to monitor IEQ, especially IAQ, has come a long way in the last decade, particularly after 2017 [6]. Chojer et al. [6] reviewed 35 relevant projects from 2012 to 2019. The monitored indoor environment parameters vary from study to study. Most projects only include sensors to monitor temperature, relative Humidity, and CO_2, as showed in Figure 1. Only very few studies monitored the wind speed, the acoustic and visual environment.

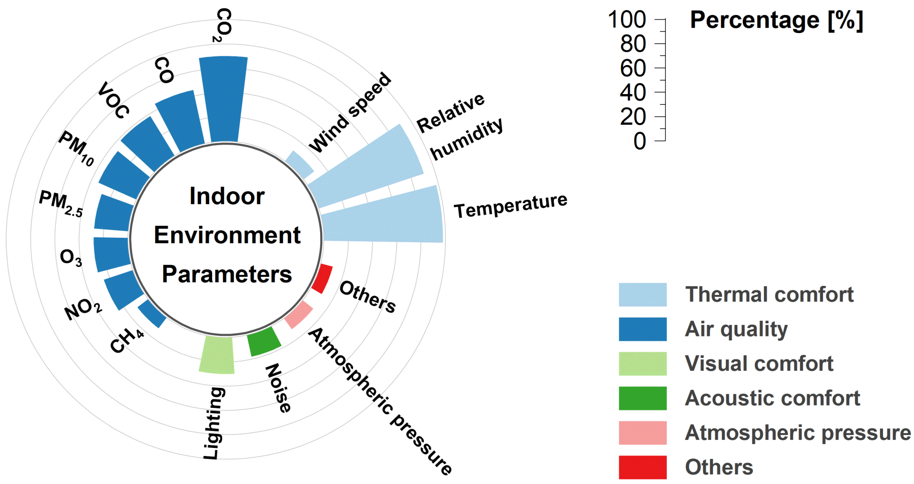

Figure 1: Monitoring parameters of the sensors used in the relevant projects, based on [6]

Most systems in these projects support both real-time access to sensor data and access to historical data [6]. The project of Tiele, Esfahani, and Covington [7] provides the user with real-time IEQ assessment on the hardware display, but beyond that, no software has been developed to view and analyze historical data. Only Parkinson et al. [8] developed both the hardware and software for the end user and offered the analysis and evaluation of IEQ.

The aim of this work is to develop a microcontroller-based monitoring system including hardware, software for the monitoring of the IEQ parameters (temperature, humidity, air pressure, wind speed, CO_2, VOC, lighting, and noise) using Arduinos and the corresponding sensor technology. Since there are very few IEQ algorithms that take all these parameters into account, the development of a new algorithm for the indoor environmental quality index (IEQI) in multi domain by integrating and extending existing algorithms is also an important goal of this work. In this paper, we propose a new multi-domain IEQI algorithm, a highlight of which is that the counterweight can be adapted to various populations in different domains.

2 Materials and Methods

As the central component, the Arduino Nano microcontroller (MC) controls all sensors and actuators. In addition, the MC organizes the communication of the measurement device with the computer and the touchscreen. A Nextion 3.5" touchscreen (NX4832K035) is used to display the GUI.

2.1 Sensors

In order to control all components in the best possible way and for meaningful monitoring, the status of the system must be known at all times, which means that the IEQ needs to be continuously monitored, not just a single measurement at a certain point in time. The MC can retrieve the system status in real time using the sensors and display it in the GUI.

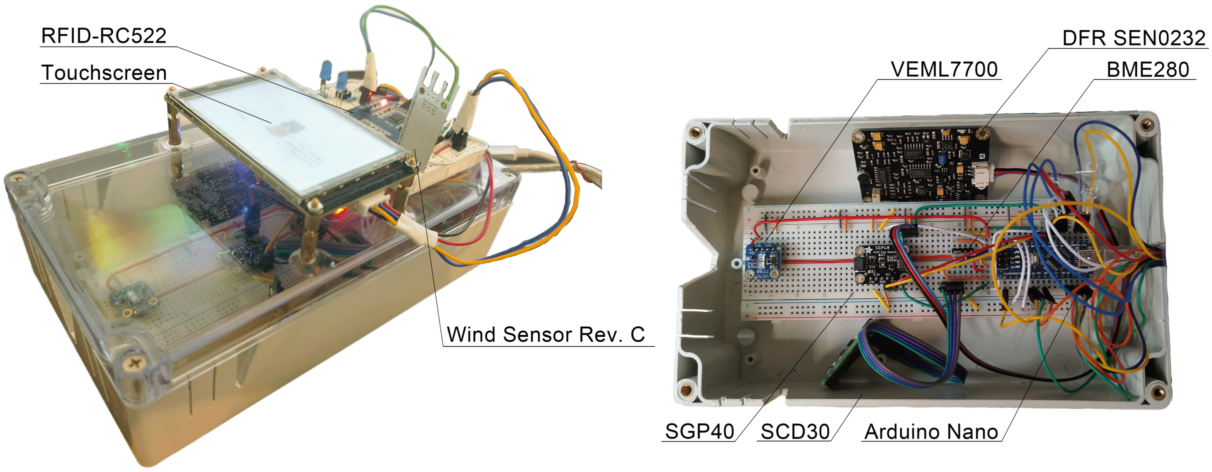

Figure 2: Prototype of the monitoring system

2.2 Algorithms

In this work, the IEQI consists of the thermal comfort index (TCI), acoustic comfort index (ACI), barometric comfort index (BCI), visual comfort index (VCI), and indoor air quality index (IAQI). To allow an individual comfort prediction, the constant k_i is used to facilitate adaptation by the user.

$$IEQI = \frac{k_{TCI} \cdot TCI + k_{ACI} \cdot ACI + k_{BCI} \cdot BCI + k_{VCI} \cdot VCI + k_{IAQI} \cdot IAQI}{k_{TCI} + k_{ACI} + k_{BCI} + k_{VCI} + k_{IAQI}} \tag{1}$$

The default value for the constant k_i is 1.0 with value range from 0 to 3. A larger value of k_i means that the index accounts for a larger percentage of the IEQI, which means that it is more important for the user. To predict the thermal comfort, the user has a choice of two thermal comfort models, the static PMV (predicted mean vote) / PPD (predicted percentage of dissatisfied) model according to ISO 7730 standard [9] and the adaptive model according to DIN EN 16798 [10]. For both models, the algorithm from the Python package pythermalcomfort developed by Tartarini and Schiavon [11] was used in this work. The PMV/PPD model outputs the PMV index values directly, while the adaptive model only gives threshold values of categories I - IV. Therefore, it is necessary to subdivide and define them uniformly. In this work, a total of four comfort zones were defined, as shown in Table 1. Each zone has a corresponding PMV/PPD interval and thresholds for the different categories of DIN EN 16798 [10].

Table 1: Definition of the comfort zones for TCI

Zone	PPD	PMV	Threshold value	Definition
1	≤ 6	$\lvert PMV\rvert \leq 0.2$	Category I	very comfortable
2	≤ 25	$\lvert PMV\rvert \leq 0.7$	Category III	comfortable
3	≤ 70	$\lvert PMV\rvert \leq 2.0$	Category III $\pm$ 2 °C	uncomfortable
4	> 70	$\lvert PMV\rvert > 2.0$	-	extremely uncomfortable

For ACI, BCI, VCI and IAQI, similar classification criteria were used to calculate the corresponding comfort index (CI) and quality index (QI), respectively, by setting the corresponding thresholds for each zone. To compare indoor environment data more intuitively, the PMV index and sensor data are converted to CI and QI, see the equations 2 to 6.

$$TCI_{PMV/PPD} = 3 - |PMV| \tag{2}$$

$$TCI_{adaptiv}, BCI = \begin{cases} 3 - \dfrac{|x - \frac{x_{1,max} + x_{1,min}}{2}| \cdot 2}{x_{1,max} - x_{1,min}} & \text{if } x_{1,min} \leq x < x_{1,max} \\ I_{i,max} - |x - x_{i-1,min}| \cdot \dfrac{I_{i,max} - I_{i+1,max}}{x_{i-1,min} - x_{i,min}} & \text{if } x_{i,min} \leq x < x_{i-1,min} \text{ for } i = 2 \text{ and } 3 \\ I_{i,max} - |x - x_{i-1,max}| \cdot \dfrac{I_{i,max} - I_{i+1,max}}{x_{i,max} - x_{i-1,max}} & \text{if } x_{i-1,max} \leq x < x_{i,max} \text{ for } i = 2 \text{ and } 3 \\ 0 & \text{if } x < x_{3,min} \text{ or } x \geq x_{3,max} \end{cases} \tag{3}$$

$$ACI, IAQI_{VOC/CO_2} = \begin{cases} 3 - |x| \cdot \dfrac{3 - 2.8}{x_{1,max}} & \text{if } x < x_{1,max} \\ I_{i,max} - |x - x_{i-1,max}| \cdot \dfrac{I_{i,max} - I_{i+1,max}}{x_{i,max} - x_{i-1,max}} & \text{if } x_{i-1,max} \leq x < x_{i,max} \text{ for } i = 2 \text{ and } 3 \\ 0 & \text{if } x \geq x_{3,max} \end{cases} \tag{4}$$

$$IAQI = \frac{IAQI_{VOC} + IAQI_{CO_2}}{2} \tag{5}$$

$$VCI = \begin{cases} 0 & \text{if } x < x_{3,min} \\ I_{i,max} - |x - x_{i-1,min}| \cdot \dfrac{I_{i,max} - I_{i+1,max}}{x_{i-1,min} - x_{i,min}} & \text{if } x_{i,min} \leq x < x_{i-1,min} \text{ for } i = 3 \text{ and } 2 \\ 3 & \text{if } x \geq x_{1,min} \end{cases} \tag{6}$$

Where:

x	data value from sensor
$I_{i,max}$	maximum index value of comfort zone i, with $I_{1,max} = 3.0, I_{2,max} = 2.8, I_{3,max} = 2.3, I_{4,max} = 1.0$
$x_{i,min/max}$	minimum / maximum threshold of zone i, the thresholds can be adjusted in the settings page of the software

Once all CI and QI are calculated, user comfort can be predicted. Due to the veto power of thermal and acoustic comfort [5], user comfort is deemed uncomfortable if TCI or ACI is below 2.3.

2.3 User test

Users were asked to fill out a questionnaire every evening. To avoid too many questions repeatedly each day, a questionnaire based on the usability metric for user experience lite (UMUX-LITE) was used [12]. At the end of the test, a 20 minute interview was conducted in which the users were asked to complete a more detailed questionnaire based on the system usability scale (SUS) developed by Brooke [13]. To ensure the validity of the collected data and to avoid the effects of different operating systems on the data mentioned by Lewis [14] in his study, all test users used the Windows 10 operating system with a screen resolution of 1080p. There were also no additional instructions for the test users. They were only informed about how to power the monitoring system and where to find the manual.

3 Results and Discussion

As shown in Figure 2, a touchscreen is installed on the box, which includes a total of four screens (see Figure 3). As Figure 4 shows, the accompanying desktop app provides the information on user comfort prediction, system status, outdoor weather, indoor environment analysis, and the level system. The desktop app performs an analysis of all sensor data collected since the app was launched and makes appropriate suggestions to the user to improve comfort, depending on the state of the indoor environment. Also, the desktop app will inform the user via the notification center which parameters of the current indoor environment have exceeded the threshold value. The user does not have to constantly keep an eye on the data. In addition to comfort prediction, it is also important to provide feedback and interaction to the user. Depending on how long the user has been using the app and what the current state of the indoor environment is, the level system gives the user the appropriate experience points (EXP). When the EXP reaches the pre-set threshold, the user's level will increase and the content of the animated images will become more varied and have more detail at the same time.

However, it should be noted that since the system only implements monitoring functions and is not connected to other personalized conditioning systems, although it can provide users with predictions

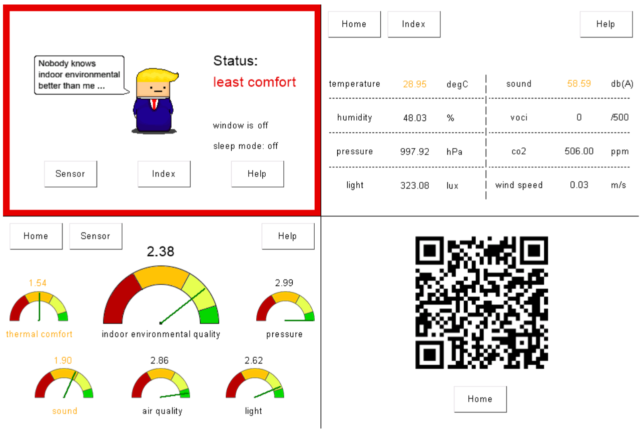

Figure 3: Top: home screen (left) and sensor screen, bottom: index screen (left) and help screen

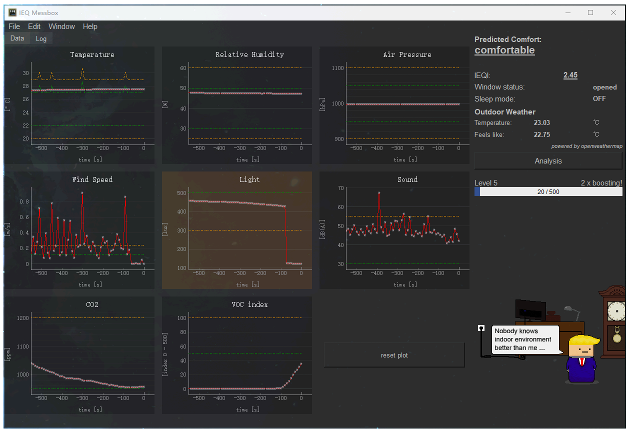

Figure 4: GUI of the accompanying desktop app

of comfort and tips of how to improve the indoor environment, users still need to decide whether and to what extent to change the current environment.

Four testers used the monitoring system for five days each. The average usage time is 3.8 hours per day, but differed strongly between users (Figure 5). With regard to usage habits, it can be seen from the user responses to the question "I use display on the box more often than the desktop app" in Figure 6 that the longer the test users use the monitoring system, the longer they use the touchscreen.

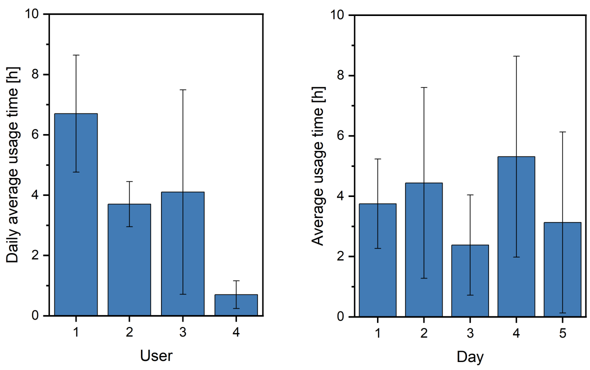

Figure 5: Average usage time incl. standard deviation, left: for each test user, right: for each day

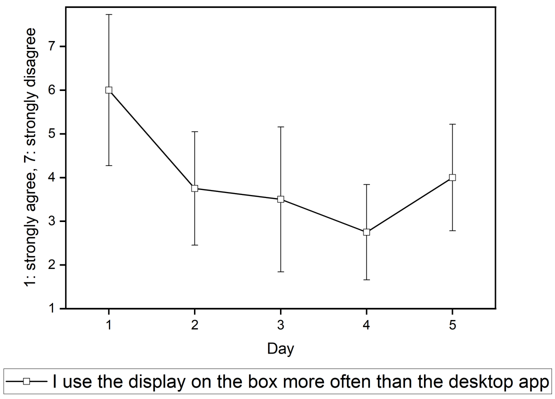

Figure 6: Responses to display vs. desktop app use (error bars show standard deviation)

This could indicate that experienced users prefer faster and easier access to basic IEQ data, and that the desktop app enables users to understand the system faster. This does not mean that touchscreen is a better solution for human-machine interaction. Three test users stated in the interview that they liked some functions offered by the desktop app, such as the notification function running in the background. Touchscreen and desktop app should be complementary: The touchscreen can offer simpler interaction possibilities, while the accompanying desktop app offers more complex and more extensive functions. Although all four test users rated the monitoring system very positively, the prototype still has some shortcomings, e.g., the GUI of the desktop app should be optimized, because the 4th tester used the app very little due to the frequent notifications, and this user did not know that the notification interval can be changed in the settings. Three users did not change the default settings because they were too complex. This may affect the accuracy of the comfort predictions, especially when using the PMV/PPD model, which requires the current clothing insulation value.

4 Conclusion and Future Work

In this work, a monitoring system including a new algorithm for IEQI was developed to monitor IEQ. Four users participated in the test phase, and the UMUX-LITE and SUS surveys indicated high usability of the system. However, it should not be overlooked that the prototype still needs improvement in some areas. Future work will be focused on minimizing the number of elements that need to be set manually by the user, as well as on associating the system with personalized climate equipment thus achieving a high degree of automation and intelligence for the entire system. The number of test users can also be further extended to obtain more accurate and reliable results. Lastly, environmental parameters are measured only at one room position. The influence of vertical temperature difference, radiation asymmetry, and measurement location is not taken into account. Therefore, how to include 3D spatial information into the system is also a focus of future work.

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