Development and Metrological Characterization of a Multi-sensor Device for Indoor Environmental Quality (IEQ) monitoring

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***Abstract* — Indoor Environmental Quality (IEQ), which affects people's health, comfort, well-being and productivity, combines thermal, visual, acoustic and air quality conditions. This work deals with design, development and metrological characterization of a low-cost multi-sensor device that is able to detect the quality conditions of indoor environments for IEQ purposes. The device, hereafter referred as PROMET&O (PROactive Monitoring for indoor EnvironmenTal quality & cOmfort) embeds a set of low-cost sensors that measure air temperature and relative humidity, illuminance, sound pressure level, carbon monoxide, carbon dioxide, particulate matter, formaldehyde, and nitrogen dioxide. The basic architecture of the device is described and the design criteria that are related to the measurement requirements are highlighted. Particular attention has been paid towards the traceability assurance of the measurements provided by PROMET&O by means of specifically conceived calibration procedures, which have been tailored to the requirements of each measurement quantity. The calibration is based on the comparison to reference standards following commonly employed or *ad-hoc* developed technical procedures. The defined calibration procedures can be applied both for the single sensors and for the set of sensors integrated in the multi-sensor case. For the latter, the effects of the percentage of permeable case surface and the sensors allocation are also investigated. A preliminary uncertainty evaluation of the proposed multi-sensor device is reported for the carbon dioxide and the illuminance sensors taking the defined calibration procedures into account.**

Keywords—Indoor Environmental Quality, metrological characterization, multi-sensor

I. INTRODUCTION ON IEQ MONITORING

Indoor Environmental Quality (IEQ) concerns thermal, lighting, acoustic and indoor air quality (IAQ) domains, and affects occupants' overall comfort, well-being, health, and work productivity in offices [1]-[2]. Interest in this research has increased in the last decades since people spend about 90% of their time in closed spaces and most of the time at work. Nowadays, there is an increasing search for methodological approaches for the evaluation of IEQ conditions that can appraise all the domains simultaneously, without addressing them as independent entities, thanks to the implementation of low-cost wireless sensor networks and cloud software platforms [3].

Tiele et al. [1] developed an IEQ monitoring device for indoor working environments that monitors temperature, humidity, illuminance, sound levels, particulate matter, total volatile organic compounds, carbon dioxide and carbon monoxide, with a sampling period of 10 minutes. It is a low-cost battery-powered device, with an estimated battery life of 68 hours and with an enclosure of 165 mm × 105 mm × 55 mm. The CO210 Extech commercial system was used for the calibration of temperature, humidity and carbon dioxide sensors. The temperature and carbon dioxide readings did not respect the uncertainty declared by manufacturers, thus were adjusted by 1.9 °C and 70 ppm, respectively. Subsequently the IEQ device was put inside a sealed plastic enclosure along with the CO210 Extech and exposed to zero air, with the aim of understanding the baseline characteristics of the IEQ unit.

Parkinson et al. [3] developed an IEQ monitoring device as well, to be put on office desks. It is a low-cost device known as SAMBA and monitors air temperature, relative humidity, globe temperature, air velocity, sound pressure level, illuminance, total volatile organic compounds, formaldehyde, carbon monoxide and carbon dioxide. It is made up of two separate units, linked by means of an ethernet cable. The satellite unit contains all the temperature sensitive transducers, to not make the other heat wasting components affect their measurements. The calibration of thermal sensors is performed in a small-scale wind tunnel. A sealed chamber was used for the calibration of indoor air quality sensors: reference gases were supplied inside the chamber by means of an intake port and the sensors and reference devices monitored the concentration. The calibration of illuminance sensors consists in the positioning of a dome on top of SAMBA with an RGB LED module (WS2812, Worldsemi) mounted as a point-source controlled via PWM. The microphone was calibrated locating it with a reference SPL meter (Type 1; NL-52, Rion) near a monitor generating a noise signal in the frequency range 100 Hz – 16000 kHz.

PROMET&O device (PROactive Monitoring for indoor EnvironmenTal quality & cOmfort) is thought as a system that allows for continuous in-field monitoring of IEQ parameters through many sensors. It is expected that its outcomes can be implemented within the BACS (Building Automation and Control Systems). It also acquires the occupants' feedback on their comfort perception. In fact, it embeds an *ad-hoc* questionnaire which can allow to correlate objective and subjective data. To this aim, a high reliability of monitored data is required, thus a verification of the uncertainty stated by manufacturers is performed and calibration procedures are carried out whenever needed.

II. IEQ REQUIREMENTS

This study presents the development and metrological characterization of PROMET&O multi-sensor. A universally recognized group of parameters and indexes for IEQ assessment is not available yet [4], thus standards for single domains are the main reference. Tab.1 shows the parameters included in the multi-sensor and their thresholds for offices.

TABLE 1. MONITORED PARAMETERS AND THRESHOLDS SET BY STANDARDS.

Parameter	Threshold for offices	Reference
Air temperature (T)	WINTER: (20-24) °C	ISO 7730:2005
	SUMMER: (23-26) °C	
Relative Humidity (h)	(25-60) %	EN 16798-1:2019
Illuminance (E_v)	Writing, typing, reading, data processing ≥ 500 lx	EN 12464-1:2021
	15 min. mean ≤ 100 mg/m^3	EN 16798-1:2019
Carbon monoxide (CO)	1 h mean ≤ 35 mg/m^3	
	8h mean ≤ 10 mg/m^3	
	24 h mean ≤ 7 mg/m^3	
Carbon dioxide (ΔCO_2)	≤ 800 ppm	EN 16798-1:2019
Nitrogen dioxide (NO_2)	1 h mean ≤ 200 μg/m^3	EN 16798-1:2019
	Annual mean ≤ 20 μg/m^3	
Particulate matter ($PM2.5$)	24 h mean ≤ 25 μg/m^3	EN 16798-1:2019
	Annual mean ≤ 10 μg/m^3	
Particulate matter ($PM10$)	24 h mean ≤ 50 μg/m^3	EN 16798-1:2019
	Annual mean ≤ 20 μg/m^3	
Formaldehyde (CH_2O)	30 min. mean ≤ 100 μg/m^3	EN 16798-1:2019
Sound Pressure Level (SPL)	≤ 45 dB(A)	NF S 31-080

III. PROMET&O DESIGN

A. Multi-sensor architecture and case

The measurement requirements summarized in Section II have driven the design of the PROMET&O multi-sensor, which is based on a set of low-cost off-the-shelf sensors. The basic architecture of the device (Fig. 1) can be subdivided in the sensor array (on the right), the power/conditioning circuitry of the sensors, and a micro-controller that acquires the sensor outputs and implements the calibration function of each measuring chain. A WiFi module is also present that is responsible for transmitting the acquired data to a cloud platform for visualization, post-processing and storage purposes. Low voltage DC-DC converters are included to supply the previous sub-blocks through an external power adapter. All the components are integrated inside a single-case device and the embedded sensors allow the measurements of the quantities listed in Table 1. The sensor array is thermally separated by the other part of the system to minimize the effects of self-heating of micro-controller and WiFi module (power dissipation around 300 mW).

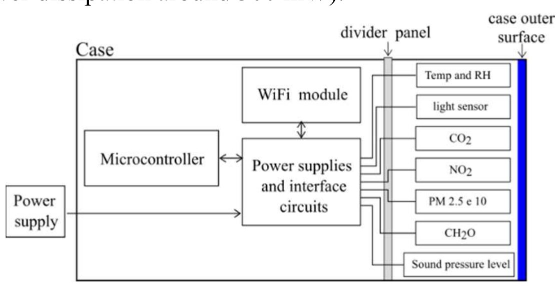

Fig. 1. Block scheme of the PROMET&O device.

Fig. 2 shows the internal structure of the device: the sensors are placed in the front and the remaining blocks at the back. The air-quality sensors are placed on an *ad-hoc* vertical mount to get the sensitive elements as close as possible to the case drilling. In such a way, their measurements are expected to be representative of the indoor environment to be monitored. On the contrary, the illuminance sensor and the microphone are placed on the top of the device to negligibly affect their spatial responses.

The PROMET&O external case is a PA12 structure, which is characterized by a cylindric shape (height 18 cm, diameter 12 cm). The 3D rendering is shown in Fig. 2(b). The perimeter of the top cover is slightly smaller, leaving a split in the ring for the dissipation of the heat generated by the operating sensors. Both the openings for the illuminance sensor and the MEMS microphone are also located on the top cover. On the perimeter, the case has a series of holes in both the front and back sides to provide additional ventilation and prevent components from overheating. Above the holes there are ten openings on each side housing ten LEDs, which indicates the percentage of IEQ calculated through specific algorithms accounting for the monitored parameters. At the base level, the case has two significantly larger openings that allow the PM 2.5 and PM 10 sensor to draw in and expel air through its supplied fan. Two jacks are provided to connect the external power supply to the power board, one on the side (multi-sensor installed on a desk) and one at the bottom (pole-mounted or wall-mounted installation).

B. *Selected sensors and nominal specifications*

From the documents cited in Section II, a set of sensors was selected with the main characteristics that are summarized in Tab. 2. The selection criteria include range and measurement uncertainty, as well as cost, power consumption, physical dimensions, and response time. Temperature and relative humidity are provided by a digital ultra-low power sensor. The illuminance sensor is a photodiode characterized by a spectral response close to the human eye photopic curve. The microphone is an omni-directional MEMS microphone built with a capacitive sensing element. Nitrogen dioxide and formaldehyde sensors are based on electrochemical cells. The carbon dioxide sensing element is based on the Non-Dispersive InfraRed (NDIR) technology, and the particulate matter sensor implements on optical particle counter (OPC).

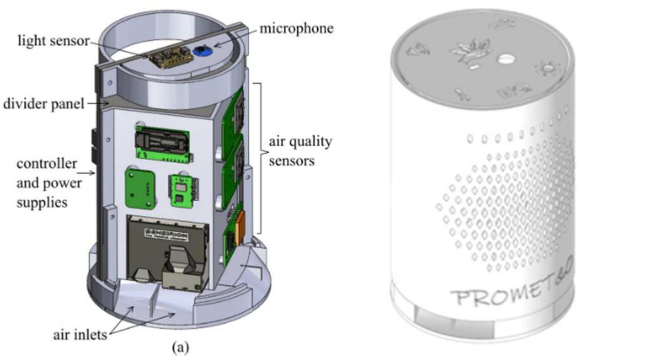

Fig. 2. (a) Placement of the PROMET&O sub-blocks shown in Fig. 1 inside the case. In (b), 3D rendering of the designed case.

C. *Calibration requirements*

The traceability assurance of the measurements provided by the designed multi-sensor requires suitable calibration procedures to be defined for the measurement chain of each quantity of interest. Two different conditions can be identified for each quantity, which are related to the metrological characteristics of the selected sensors. If the uncertainty stated by the sensor manufacturer meets the requirements, the whole measurement chain is subjected to a verification procedure. Such a procedure, which is performed by comparison against a reference standard, is aimed at evaluating the error of the whole chain and verifying if this error conforms to the target maximum admitted error. If instead the sensor specifications do not meet the uncertainty requirements, it is necessary to modify the calibration function of the measurement chain by means of a metrological characterization, which still requires a reference standard. The two conditions are highlighted in Tab. 2 by means of different background colors in the column "U": white color means that the sensor is nominally able to meet the uncertainty requirement (first condition), while a gray color identifies sensors that require a suitable characterization (second condition). The required uncertainty is taken from International Standards or from building certification schemes. The procedures designed for the different quantities are described in Section IV.

TABLE 2. MAIN CHARACTERISTICS OF THE SELECTED COMMERCIAL SENSORS FOR EACH MEASURED PARAMETER (P): SENSOR MEASUREMENT RANGE (SMR) AND UNCERTAINTY U VALID IN THE RANGE R. REQUIRED UNCERTAINTY (RU) BY STANDARDS AND BUILDING CERTIFICATION SCHEMES. GREY BOXES: SENSORS THAT REQUIRE A METROLOGICAL CHARACTERIZATION; WHITE BOXES: SENSORS THAT ARE NOMINALLY ABLE TO MEET THE UNCERTAINTY REQUIREMENT.

P	SMR	U	R	RU
T	-40 °C to 125 °C	± 0.2 °C	(0-60) °C	±0.5°C (BS EN ISO 7726:2001)
h	(0-100) %	± 1.8 %	(30-70) %	±5% (ANSI/ASHRAE 55:2017)
E_v	(0-120) klx	15 % measured value	-	±5% (WELL)
CO	(0-1000) ppm	± 2.75 nA/ppm (sensitivity)	-	1 ppm at values between 0 and 10 ppm (WELL)
CO_2	(0-40000) ppm	± (30 ppm +3% mv)	(400-10000) ppm	10% at 750 ppm (WELL)
NO_2	(0-5) ppm	±30 % mv	(0-5) ppm	20% (WELL)
PM2.5	(0-1000) μg/m^3	± (5 μg/m^3 + 5% mv)	(0-100) g/m^3	≤ 15% (WELL)
PM10	(0-1000) μg/m^3	± (25 g/m^3)	(0-100) g/m^3	-
CH_2O	(0-1) ppm	±20 % mv	(0-200) ppb	20 ppb (0-100 ppb) (WELL)
SPL	122.5 dB (SPL) AOP	Not declared	-	±0.5 dB (1 kHz) (WELL)

IV. CALIBRATION PROCEDURES

A. *Air temperature and relative humidity*

The verification procedure of the temperature and humidity sensor (Sensirion SHT41) is implemented placing the device inside a climatic chamber and comparing the readings of the sensor to the values provided by a reference thermo-hygrometer, which ensures an uncertainty of 0.1 °C (temperature) and 1.5 % (relative humidity) in the ranges of interest. Furthermore, a Pt100 is also used as a reference, as suggested in the E220-19 [5]. For the temperature verification, tests are carried out at three different set points: 10 °C, 20 °C, 30 °C. Sampling interval is set at 60 s in all the devices and the first recording starts when the climate chamber reaches the set temperature (10 °C). Then, the conditions are manually modified to the next temperature set-point and recording is not stopped, thus collecting enough measurements both in steady conditions and in the transient among them. About the verification of the relative humidity measurements, the temperature is set at 23 °C and four different relative humidity values are tested: 22 %, 39 %, 75 %, 94 %. The same sample interval of 60 s is used to collect data from the sensor under verification and the reference device, starting the acquisition once the required thermo-hygrometric conditions are reached and collecting data for a time interval longer than 1 hour for each test point.

B. *Sound Pressure Level*

The MEMS microphone is verified both as separate and integrated sensor, to account for the contributions of acoustic diffraction effects due to the mounting configuration of the multi-sensor case. Secondary free-field calibration based on the comparison method is performed. Free-field calibration by the comparison or substitution method is performed in an anechoic or hemi-anechoic chamber (Fig. 3) according to the IEC 61094-8 Standard [6]. By this method, the free-field sensitivity of the microphone under-test is determined from the free-field sensitivity of a reference microphone (known by primary free-field reciprocity calibration or derived from primary pressure reciprocity calibration by applying the appropriate free-field corrections), when both microphones are sequentially exposed to essentially the same free-field sound pressure. The stability of the sound source and possible changes in the acoustic field during measurements are considered by a monitor microphone kept in a fixed position inside the chamber. Furthermore, the acoustic pressure is measured in a region of the test environment where sound generated by the loudspeaker approximately propagates by plane progressive waves, and the acoustic centers or reference points of both microphones are positioned at the same measurement point with the specified angle of incidence. The free-field sensitivities of both the separate and the case-integrated MEMS microphone are evaluated by comparison or substitution calibration, in the frequency range from 500 Hz to 12.5 kHz in a small anechoic chamber (volume ≈ 3.5 m^3).

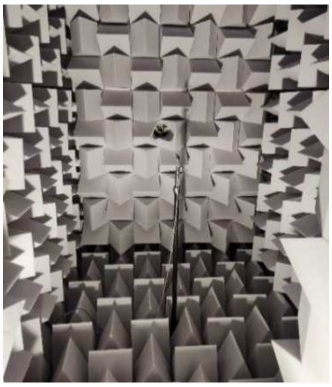

Fig. 3. The anechoic chamber used for the MEMS calibration.

C. Illuminance

The calibration of the illuminance measurement chain is performed through comparison to a reference standard PRC Radiolux 111 luxmeter, which is equipped with a photometric head certified in class B according to DIN 5032-7 [7]. The calibration method consists in measuring illuminance in a test box under a stable light source dimmed at several light output (Fig. 4). In the first step, the standard measures the reference illuminance and in the second step it is replaced by the sensor under calibration, thus obtaining its indication in each test condition. Specifically, the calibration method is carried out in the following test conditions:

- 3 LEDs with different spectra and Correlated Color Temperature of 2700 K, 4000 K, 5700 K (warm white, neutral white and cool white, respectively) are used as light sources in the box to assess the spectral response of the sensor under calibration;
- each LED is dimmed obtaining illuminance values in the range from 2.5 lx to about 3500 lx on the measuring plane inside the box;
- besides the horizontal position, the sensor under verification is tilted to assess the cosine response for different angle of light incidence (30° and 60°);
- the sensor under verification is tested without and with the PROMET&O device case, with different window opening and thickness of the cover upon it.

The distance from the light source to the sensitive area is maintained unvaried during all the tests, ensuring a uniform light distribution on the measuring plane. The correct positioning of the sensitive area under the light source is checked by a laser beam pointer. The test box contains the LED source, and the measuring plane is put in a blacked-out room under stable thermal conditions. The tests are randomly repeated, and the reproducibility of the results evaluated.

D. Carbon dioxide

The selected low-cost sensor of CO_2 concentration (Sensirion SCD30) is verified by comparison to the following reference instruments:

- Photoacoustic Gas Monitor - Innova 1512;
- Testo 400, associated with the Bluetooth humidity meter probe 605i.

The test is carried out in a plexiglass theca (Fig. 5) that is linked to the Photoacoustic Gas Monitor through two rubber pipes. The probe 605i and the sensor under verification connected to its core board are placed in the same theca. The core board is connected to the PC via USB cable through a hole at the corner of the theca. The red pipe injects air into the theca, while the white pipe extracts air from the theca and leads it to the Innova 1512 for analysis. The instrument is set with a sample integration time of 5 s. The first test refers to baseline condition (about 500 ppm), that will be achieved by opening the windows for a few minutes. Second and third settings (1500 ppm and 2500 ppm) which will be achieved by insufflating CO_2 into the theca by steps through an air-inflated balloon. Silica gel inside the balloon is used to reduce humidity. Data is acquired until the CO_2 decays below the set thresholds.

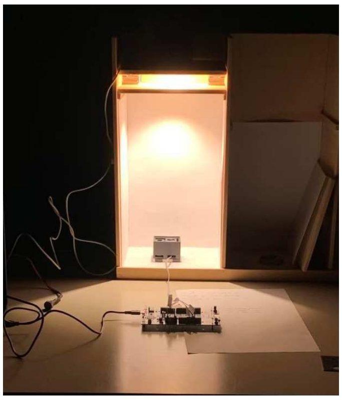

Fig. 4. Data acquisition phase of the naked sensor with LED 2700 K without optical filter.

E. Particulate matter

Low-cost light-scattering PM sensors are miniaturized version of traditional optical particle counters, to be used in IoT solutions [8, 9]. Calibration and verification methods for light-scattering airborne particle counters (LSAPC) are defined in ISO 21501-4:2018 [10], but most low-cost sensors do not follow this standard. Low-cost light-scattering sensors shine a laser beam on the air sample and detect the intensity of scattered light with a photodiode positioned at a specific angle with respect to the laser source. By using Mie theory, it is possible to determine particle diameters and count the number of particles in different size intervals. From particle diameter, the volume is computed by considering an ideal spherical shape [9]. From the total volume, the total PM mass is computed by assuming a density coefficient, that can change for each size interval. The PM concentration can be computed dividing the total mass by the analyzed air volume. The measurement procedure assumes spherical particles, which is not true for environmental pollution. In addition, the density coefficient is specific to the particulate used in factory calibration but may not be the same in the real working environment. For this reason, it can be useful to re-calibrate the sensor using PM particles similar to the ones found in the deployment scenario. Literature provides different models for calibration [11, 12, 13]. One of the simplest model is linear regression, which is used in this work to correct the large errors due to factory calibration of the sensor. Since sensors calibration is strongly dependent on particulate composition, two particulate types will be considered: cigarette smoke and outdoor pollution in the area of the installation. The former calibration is performed in a sealed climatic chamber against a high-precision reference sensor. For outside monitoring, sensors are positioned near official monitoring stations. Additional correction can be introduced in the model by measuring temperature and humidity.

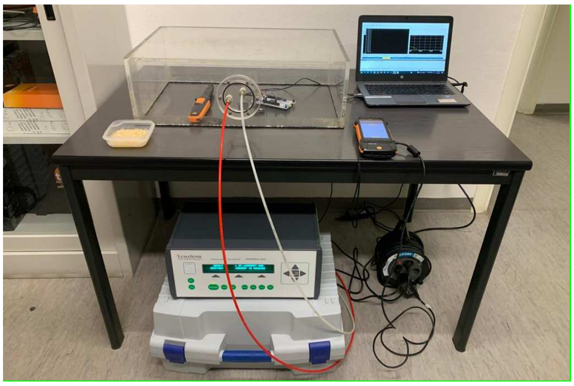

Fig. 5. Overall setting for CO_2 monitoring.

V. EXPERIMENTAL RESULTS

Preliminary examples of experimental results are reported for two of the involved measurement chains, which refer to the measurement of CO_2 concentration and illuminance E_v. According to the classification described in Section III.C, a verification is performed for the CO_2 concentration, while a characterization of the E_v measurement chain is required.

The results that refer to the verification of the measurement chain of CO_2 concentration are summarized in Fig. 6 for the baseline set-point (about 500 ppm). The top chart shows the reference concentration provided by the Photoacoustic Gas Monitor (PGM, green line) and the concentration measured by the device Sensirion SCD30 (red line) during a time interval of about 70 min. The bottom chart reports the measurement error (blue line), which is the difference between the indication of the sensor under verification and the PGM. In the same chart, the maximum admitted error of the sensor SCD30 is also reported (red lines) as Upper Limit (UL SCD30) and lower limit (LL SCD30) and the confidence interval of the measurement error (95% of confidence level) is shown (green lines). The expanded uncertainty *U*(Error) has been evaluating taking into account the contributions related to the PGM uncertainty and the resolution of the sensor under verification. One should note that the measurement error is within the tolerance interval and then the CO_2 measurement chain under verification can be considered conform to its nominal specification. A complete statement of conformity will be provided once the verification procedure is performed in the whole range of interest.

About the measurement chain of the illuminance E_v, a preliminary characterization is required because of the large maximum admitted error (± 15% of the measured value) stated by the manufacturer. For this reason, the calibration function of the illuminance measurement chain has been evaluated starting from the results obtained using the LED with the correlated color temperature of 2700 K (warm white), which exhibits a spectral response with a maximum sensitivity that is near to the maximum of the photopic human sensitivity $V(\lambda)$. The results are summarized in Fig. 7, where the red circles in the top chart represent the couple of experimental values (reference vs measured) and the blue line is the linear calibration function identified by minimizing the root square sum of the difference between the function and the experimental values (intercept –35 lx; slope 1.22 lx/lx).

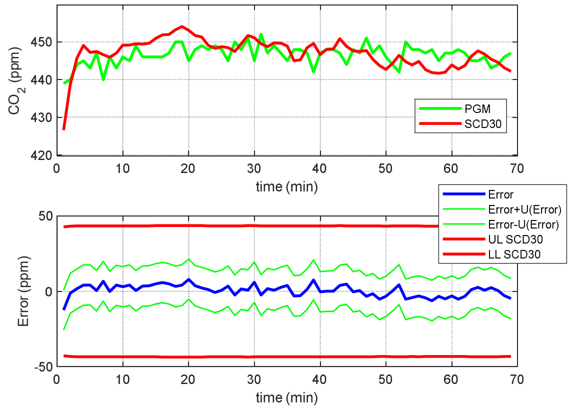

Fig. 6. Verification results obtained for the CO_2 concentration measurement chain in the baseline set-point.

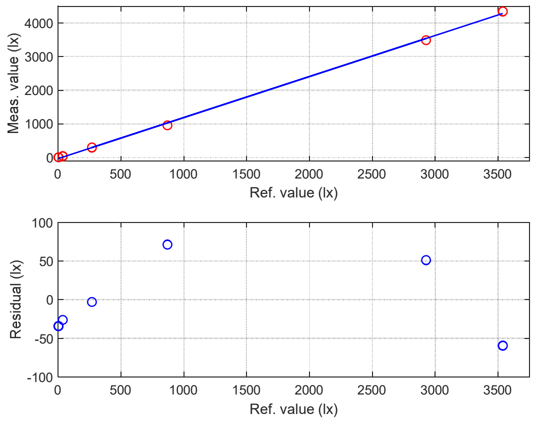

Fig. 7. Characterization results for the illuminance measurement chain obtained using the LED with the correlated color temperature of 2700 K.

The residual fitting errors (bottom chart) are characterized by a negligible mean value and a root mean square error of about 50 lx. This uncertainty contribution has been combined with the one related to the uncertainty of the reference luxmeter, thus obtaining the expected uncertainty of the characterized chain of the illuminance, which can be expressed at a confidence level of 95% as:

$$U_{adj}(E_v) = (60 + 4\%\ \text{measured value})\ \text{lx} \qquad (1)$$

Then, the illuminance measurement chain has been verified by comparison to the same reference device using the other two LEDs with correlated color temperature of 4000 K and 5700 K (maximum sensitivity of spectral response in the violet region of visible light) and the LED at 2700 K after one month from the characterization. The obtained results are reported in Fig. 8, where the red symbols refer to the errors obtained using the indications (unadjusted) of the illuminance measurement chain, while the blue symbols represent the errors that result implementing the identified calibration function (adjusted). In the same figure, the continuous red lines are the expanded measurement uncertainty of the characterized chain. The main outcome is the effectiveness of the proposed characterization procedure, which allows the illuminance E_v to be measured with an acceptable uncertainty with respect to the requirement indicated in Table 2. On the contrary, if the illuminance sensor is not adjusted, the measurement error also exceeds the stated uncertainty (±15% of the measured value), as can be observed by the unadjusted errors at illuminance values higher than 3500 lx.

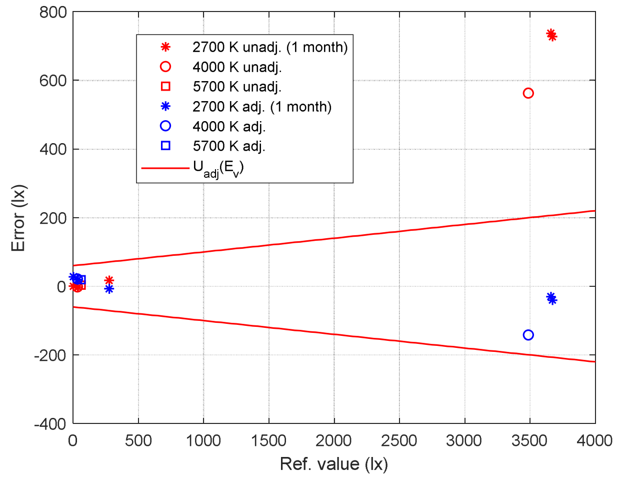

Fig. 8. Verification results obtained for the illuminance measurement chain using its indications without any correction (unadjusted, red symbols) and using the identified calibration function (adjusted, blue symbols).

VI. Conclusions

Indoor Environmental Quality (IEQ), that combines thermal, visual, acoustic and air quality conditions, affects people's health, comfort, well-being and productivity. The design, development and metrological characterization of a low-cost multi-sensor device for the monitoring of indoor conditions is presented in this work. The multi-sensor, named PROMET&O (PROactive Monitoring for indoor EnvironmenTal quality & cOmfort) embeds a set of low-cost sensors that measure air temperature, relative humidity, illuminance, sound pressure level, carbon monoxide, carbon dioxide, particulate matter, formaldehyde and nitrogen dioxide. Specifically conceived calibration procedures, based on reference standards, will provide the traceability assurance of the measurements provided by PROMET&O. A verification procedure of the whole measurement chain for each quantity is performed to verify whether the error conforms to the uncertainty stated by the sensor manufacturer. If the sensor does not meet the uncertainty requirements, it is necessary to modify the calibration function of the measurement chain by means of a metrological characterization, which requires a reference standard. Preliminary examples of experimental results are presented for both the procedures: a verification is performed for the concentration of carbon dioxide, while a characterization of the illuminance measurement chain is required, since uncertainty requirements are not met. Measurements will be performed for all the monitored parameters with PROMET&O to verify whether if a verification is enough or a metrological characterization is required, with the aim of ensuring measurements traceability for all the involved quantities.

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