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Francesco Lamonaca

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Low-Cost Smart Living Environment Monitoring Systems from a Metrological Point of View

Juan-José Jimenez

Università della Calabria -

Dipartimento di Ingegneria Informatica,
Modellistica, Elettronica e Sistemistica
Universidad San Francisco de Quito –
Instituto de Micro-Nanoelectrónica
Cosenza, Italy
jmnjjs96h18z605k@studenti.unical.it

Domenico Luca Carni

Università della Calabria -

Dipartimento di Ingegneria Informatica,
Modellistica, Elettronica e Sistemistica
Cosenza, Italy
dl.carni@dimes.unical.it

Lionel Trojman

Institut Supérieur d'Electronique de
Paris
LISITE
Paris, France
<https://orcid.org/0000-0003-2316-4959>

Luis-Miguel Prócel

Universidad San Francisco de Quito
Instituto de Micro-Nanoelectrónica
Quito, Ecuador
lprocel@usfq.edu.ec

Francesco Lamonaca

Università della Calabria -

Dipartimento di Ingegneria Informatica,
Modellistica, Elettronica e Sistemistica
Cosenza, Italy
f.lamonaca@dimes.unical.it

Abstract —The constant pursuit of low-cost Smart Environmental Monitoring Systems (SEMS) leads to a constant use of off the shelf sensors and components. However, with a lack of validation and calibration of the sensors, the accuracy of the measurements should be question. Especially when it comes to the monitoring of living environments such as homes, offices, and classrooms, where individuals remain for extended periods of time, and where prolonged exposure to hazardous environments can lead to health problems and discomfort. The objective of this research is to shine the light on a constantly overlooked parameter, the accuracy of the measurements taken by SEMS. In particular, the presented research focuses on the measurement science point of view giving a comparison of the most widely utilized sensors for living environment monitoring and the accuracy that can be expected from them. The final aim is, in on one end, to stimulate the research in the field to define the desired accuracy in the different applicative sectors, and on the other end, to increase the awareness of both producers and consumers about the metrological aspects of the sensors they produce/use and of the overall monitoring systems.

Keywords— *Sensors, Accuracy, Living Environment monitoring, Low-cost sensor, measurement uncertainty, measurement.*

I. INTRODUCTION

Living environment is the first contact of humans with the out body. Human health and wellness depend on it.

As it has been shown on several epidemiological studies, there is a relationship between air quality and health related problems and diseases [1]. In [2] interesting research is presented pointing out that the human lymphocyte is good indicator of an unhealthy living environment. This arises an important field of study of environmental monitoring and diagnostic systems including ones based on unmanned systems [3] and internet of things [4]. For every Smart Environmental Monitoring Systems (SEMS), in order to work properly, they must be able to accomplish three main actions: (i) acquire the data from the sensors, (ii) processing it to obtain the desired measurement information, and (iii) communicating the measurement information to the user (human or automatic systems) to take the required actions. SEMSs allow for a continuous and real-time monitoring of the potentially hazardous entity of the environment [5], as well as the ability to rise an alarm (or take countermeasures if possible) so that

end users can avoid being in dangerous or uncomfortable environments [6].

Moreover, as the Internet of Things (IoT) devices are starting to become more common in our everyday life, the interest for easy deployable low-cost internet connected systems has gained attraction. Internet connection of monitoring systems can bring several improvements to SEMS. For example, there have been implementations where users can be notified of potential hazardous situations in their environment by a Short Message Service (SMS) text directly to their phones [7], by a specialized app [8] or via a website where several users can even do a continuous monitoring of the different sensors [9]. On a larger scale, several SEMS can cooperate for the monitoring of a wider area. Multiple users can access remotely the different monitoring stations within the SEMS and utilize the internet to send alarms in case a danger or a hazard occurs [10]. SEMS have proved to bring substantial improvements on several fields of research, such as: agriculture, transportation, medicine, energy, industrial automation, amongst others and will continue to develop on the upcoming years [11].

In [12], Authors demonstrate the increase of interest of low-cost living environment monitoring systems in the recent decade. The Authors searched for the following terms: “Indoor Air Quality”, “Indoor Environmental Quality” and “Indoor Air Pollution” in IEEE Xplore, Science Direct and Scopus to find all the publications from May 2012 to May 2019, leading to a total of 891 publication regarding low-cost SEMS implementations for living environment monitoring. Afterwards, the publications were filtered based on the following requirements:

- Publications must deal into monitoring device development.
- Publications that did not develop their own SEMS where not included.
- Devices that only monitor temperature and relative humidity where not considered.
- Devices that only measure a single pollutant where not considered.

- Devices monitoring of subway stations, mines, quarries, greenhouses, etc. where eliminated. While devices monitoring houses, hotels, offices, classrooms, etc. where considered.

After following these criteria, thirty-five different SEMS prototypes were studied in detail, following forty-one different academic publications. More than half of them (twenty-five) were published between 2017 to 2019, showing once again the increase of attraction to this research field in the last years. To start the comparison, a classification of the microprocessors of the different systems was done. The results are summarized on Table I shown below:

TABLE I. DIFFERENT MICOCONTROLLER UTILIZATION IMPLEMENTATIONS

Microcontroller Utilization Frequency	
Microcontroller Family	Frequency
Arduino	12
Raspberry Pi	5
Arm Cortex	3
ESP8266	3
PIC	2
Unique Implementation*	5
Not Specified	5

* This group joins all the microcontroller implementations that were used only once.

Some noteworthy comments about the table I is the appearance of the ESP8266. It is worth to note that this is a Wi-Fi module, which means that these sensing devices must be sending the data measured by the sensors for the computing to be done in another location, like with a cloud computing service. However, the most significant remark from is the wide utilization of open-source hardware for the computation and communication of the microcontrollers. In particular, the use of Arduino or Raspberry Pi individually widely surpass any other processor utilization and together they are used in almost half (48.6%) of the SEMS implementations.

When it comes to the connection of Arduino based SEMS, the models utilized where: One (33%), Pro Mini (33% times), Mega (11%) and finally Yun (22%). This furthermore highlights the utilization of low-cost hardware, as even the less expensive model is more than capable of doing the processing for a monitoring station. However, a drawback that should be taken into consideration is that for internet connectivity, most Arduino models do not integrated network connection modules. Therefore, a solution like a Wi-Fi module must be introduced to the system. Most commonly, the ESP8266 Wi-Fi module is utilized as shown on [13]. The ESP8266 is a System on Chip (SoC) with integrated TCP/IP protocol for serial communication.

Nevertheless, an advantage of Arduino is its integrated Analog to Digital Converters (ADC) which allow the connection to analog sensors, widely used in the monitoring of living environments. The Arduino One for example, can do analog to digital 10-bit conversions at a frequency close to 9600 Hz. As analyzed in [12], most SEMS implementations utilize a sampling period between 2 and 30 seconds for the different environmental parameters that are being monitored. In [12] it is also stated that even a sampling period of 5 minutes gives enough time for a response action to be taken and it is still considered an online application. Obviously,

these sampling frequencies are used for humidity, temperature, light and other low dynamic environmental parameters. Contrarywise, for acoustic emission, the used sampling frequency is much higher, in the order of hundreds of Hz, up to some MHz [10]. In this case solutions based on trigger must be adopted to reduce the data to be analyzed, local elaboration burden and data to be sent in the network. Further solution proposed by the recent literature is the compressive sampling [14].

Further problems that must be solved in SEMS is the synchronization of the sensing devices. In the case of nearby devices that requires sub microsecond accuracy, suitable solutions could be the ones based on trigger signals [15],[16]. Viceversa, message passing approaches can be used. These last deploy the communication capabilities of the sensing devices but coarse accuracy can be achieved respect to the previous ones [17],[18].

On the other hand, the other open-source hardware widely utilized for SEMS is the Raspberry Pi. From the 5 studied cases, 2 of them utilize the 2B model [19],[20], 2 use the 3B model [21],[22] and 1 of them does not specify [23]. Although this platform is much more versatile than the Arduino since it is a microprocessor instead of only a microcontroller. Some disadvantages are that depending on the model, it might not have integrated wireless network capabilities, and that its input-output pins are only digital. Therefore, the sensors these SEMS must utilize need to have digital sensors, or an external ADC conversion module. Due to this limitation, some SEMS even utilize both platforms together, like in [24].

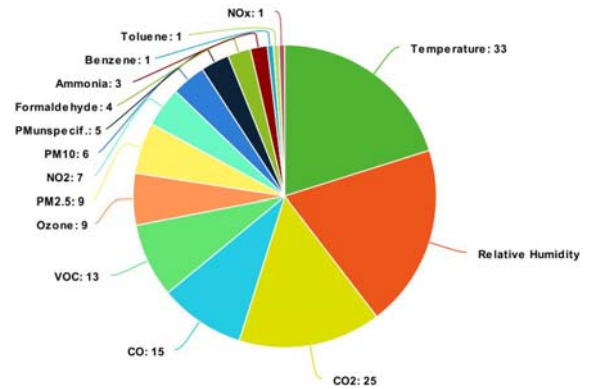


Fig.1 Monitoring Parameters Distribution

There was a large variety of the parameters that were measured by the different SEMS for living environments in [12]. Fig. 1 shows the parameters and how many times a sensor was implemented to measure it on a SEMS. It should be noted that many systems measure more than one parameter.

As shown on Fig. 1, the most common measured parameter is temperature, closely followed by relative humidity. Then air quality was monitored by measuring presence of variety of different gasses (11 in total) or particulate materials in the air. However, most studies fail to mention the calibration and validation method utilized to determinate the accuracy of the sensors utilized. Additionally, most publications fail to explain the reasons why they are opting for one sensor over another one. Since accuracy should be one of the parameters taken into account at the moment of deciding which sensor to choose for a SEMS, the next section will compare the accuracy and uncertainty of the most

commonly utilized sensors for temperature, relative humidity and air quality.

II. ACCURACY OF THE SENSORS FOR MONITORING

A. Temperature

To evaluate the different sensors utilized to measure the temperature, we will first need to determinate which ones are the most common utilized in the literature. The following table summarizes the most common sensors and how many SEMS implement them into their system.

TABLE II. TEMPERATURE SENSOR IMPLEMENTATIONS

Monitoring Parameter: Temperature	
Sensor Name	Frequency
DHT22	6
DHT11	5
SHT21	3
LM35	2
RTH03	2
Unique Implementations*	16

* This group joins all the temperature sensors that that were used only once.

As we can see in Table II, the most common used sensor for measuring temperature was the DHT22. This is digital sensor that utilizes a thermistor to measure the temperature and a capacitive sensor for relative humidity and utilizes a one-wire connection for the communication protocol. The DHT11 sensor on the other hand, works very similarly to the DHT22, however, the DHT11 has a smaller working range, as shown on Table III, a higher uncertainty but it can deliver a measurement with a frequency of 1.0 Hz compared to the DHT22 which is slower with a frequency of 0.5 Hz [25].

On the other hand, the SHT21 utilizes a band-gap sensor to measure temperature and a capacitive sensor for the relative humidity [26]. However, this sensor communicates via the I2C protocol. Lastly, the LM35 is a semiconductor-based temperature sensor, with an analog output that offers much higher resolution than its digital counterparts and does not require any online calibration [27]. On Table III, we can see a comparison between these sensors.

TABLE III. TEMPERATURE SENSORS ACCURACY

Temperature Sensors Parameters		
Sensor Name	Range [°C]	Uncertainty [°C]
DHT22	-40, 80	± 0.5
DHT11	0, 50	± 2.0
SHT21	-40,125	± 0.3
LM35	0, 100	± 0.5

As we can see from Table III, all the different common sensors have different accuracies and ranges. In [26] an extensive comparison between the sensor DHT22, SHT21 was done. In that investigation sensors were compared before and after on-site calibration to understand the performance of the sensors. Some remarkable comments that help understand the difference between the DHT22 and the SHT21 are the following:

- DHT22 sensor stayed on within the margins of the manufacturer during all the 7-day period while SHT21 did not.
- DHT22 showed reliable answers even without on-line/on-site calibration.
- The SHT21 could be more accurate with humidity calibration done frequently.

B. Relative Humidity

A similar analysis was done with the relative humidity sensors. The frequency of utilization of different sensors can be shown on the following Table IV:

TABLE IV. RELATIVE HUMIDITY SENSOR IMPLEMENTATIONS

Monitoring Parameter: Relative Humidity	
Sensor Name	Frequency
DHT22	5
HIH130	4
SHT21	3
SHT15	2
SHT11	2
Unique Implementations*	17

* This group joins all the temperature sensors that that were used only once.

For the sensor mentioned there, the DHT22 is re-used in this section as well as the SHT21, as both are temperature and humidity sensors. The SHT15 and SHT11 are of the same family of the SHT21, however, a lower precision can be achieved by them as they have either smaller operating ranges and a higher uncertainty [28],[29]. Lastly, the HIH-4000 series sensor [30] is the most used analog sensor to measure relative humidity in the researched bibliography. Table V shows a comparison between the operating ranges and uncertainty of the different relative humidity sensors.

TABLE V. HUMIDITY SENSOR ACCURACY

Humidity Sensors Parameters		
Sensor Name	Range [%]	Uncertainty [%]
DHT22	0, 100	± 2.0
HIH-4000	0, 100	± 3.5
SHT21	0,100	± 2.0
SHT15	10, 90	± 2.0
SHT11	20, 80	± 3.0

On the comparison between the DHT22 and the SHT21 done in [26] the performance while monitoring humidity was also evaluated. An important difference was that is that at 35°C, the SHT22 relative humidity readings were not inside the manufacturers range of confidence, which could be detrimental for applications on places with high temperatures. When it comes to the HIH-4000 series, it should be considered that this sensor is an analogic one, so it will provide a greater resolution. However, an advantage of this sensor is that it does not require any on-site calibration.

C. Air Quality

When it comes to air quality, as shown on Fig. 1 several approaches can be taken in to analyze a wide variety of different pollutants depending on the use-case scenario. This leads to a great variety of combinations of parameters on different SEMS implementations where different air quality parameters are monitored. For example, to measure CO₂ concentrations in [12], there were 13 different sensor implementations for a total of 16 implementations that monitored CO₂. Similar tendencies can be found on all the other air quality monitored parameters, were most of the sensor implementations on the SEMS were unique, and in case they were utilized on several systems, not one of them was used more than 4 times. Because of this, this section will only focus on the most used sensor for each of the most common parameters that are being monitored.

1) Carbon Monoxide (CO)

For carbon monoxide concentrations, twelve systems monitored this parameter with 7 different sensor implementations [12]. The most commonly sensor was the MQ-7. This is a semiconductor sensor that will detect the presence of CO from 10 to 10000ppm [31]. The material which the sensor is made of is SnO₂, which has a lower conductivity on clean air. This resistance change can then be measured with an applied voltage. This sensor goes through temperature cycles where the sensor is heated for 60 seconds with a voltage of 5V and then cooled down with 1.5V thought 90 seconds where the CO concentration is measured.

It should be noted that this sensor has an uncertainty of 5%. However, its sensitivity curve can be highly influenced by the external temperature and relative humidity of where it is placed. In worst case scenarios, (at -10°C) a variation of 20% can be present. At normal room temperature, the humidity can have an effect of up to 10% [31]. However, the manufacturer does show the effect of this parameters, so a post measurement corrective action can be taken at the moment of processing the data.

2) Carbon Dioxide (CO₂)

When it comes to carbon dioxide, a total of 18 SEMS had a module that measured this parameter. As mentioned before, 13 implementations utilized a different and the only one that was used several times (3 in total) was the SenseAir K30. This sensor's operating principle is a non-dissipating infrared that allows a detection of 0 to 5000 ppm of CO₂. If utilized in its analog sensing configuration, it can detect CO₂ from 0 to 2000 ppm, while for measuring higher concentrations, the digital output is utilized which uses I2C or UART communication protocol. The manufacturer guarantees an accuracy of ±30 ppm plus a ±3 ppm for reading [32].

3) Volatile Organic Compounds (VOC)

Some volatile organic compounds are hydrogen, methane, ethanol, and iso-butane. They can be dangerous for living environments due to their high combustibility. Only 6 of the 41 publications analyzed on [12] take VOC's into consideration and with 5 unique sensor implementations, the only sensor utilized more than once was the TGS2602.

This sensor has a similar working principle as the MQ7 where a heater voltage is applied in order to maintain the sensing element at a specific temperature for optimal for sensing. At this point the presence of VOC's will arrect the conductivity of a resistance that will be used as a sensing element. The detection range for this sensor is between 1 and 30 ppm of the organic compounds mentioned before [33]. In [34] Authors derived a non-linear empirical relationship that can reliably convert the output of a TGS2602 unit to measure CH₄ mixing ratios over a range of 1.85–5.85 ppm that agree to a high-precision instrument output to ±0.01 ppm. They also found out that the sensor could have a drift of ±0.002 ppm per day, and a higher uncertainty in the sensed value when the relative humidity is below 40%.

4) Ozone

Ozone monitoring was only done on six of the studied SEMS, and half of them utilized the MQ-131 sensor. Similarly to the carbon monoxide sensor, this is a semiconductor-based sensor that goes through temperature cycles for the monitoring of the concentration of ozone in the environment where the concentration changes the conductivity of a resistance that is later on measured. As stated on by the manufacturer on [35], the operating range of this sensor is between 10 and 1000 ppm. Although it is not clearly stated by the manufacturer, in [36], Authors compared three low-cost sensor systems and determined that the MQ-131 has an accuracy of 3%.

Lastly, Table VI summarizes all the different sensors evaluated for air quality monitoring:

TABLE VI. SENSORS FOR AIR POLUTION CONTAMINANTS

Carbon Monoxide		
Sensor Name	Range	Uncertainty
MQ-7	10 to 10000 ppm	5%
Carbon Dioxide		
SenseAir K30	0 to 5000 ppm	± 33ppm
Volatile Organic Compounds		
TGS26002	1 to 30 ppm	0.01ppm
Ozone		
MQ-131	10 to 1000ppm	3%

III. CONCLUSION AND DISCUSION

The objective of this paper was to do an analysis on the accuracy of the typical sensors that are commonly utilized on SEMS for living environments. In the case of temperature and relative humidity, as they were the most commonly used parameters, it was more important to compare several implementations of sensors as many of them were utilized on various systems. This led to a more comprehensive understanding of the accuracy limitations of these sensors, and it could be helpful at the moment of determining which sensor should be used for each particular application.

On the other hand, when it comes to parameters to measure the air quality of a living environment, the original sample of 35 SEMS had a great variety of monitored parameters but did not show a wide variety of sensor implementations for these parameters. This did not allow for a comparison between different sensors for each parameter.

However, the accuracy and operating ranges were assessed for the most common sensor for carbon monoxide (CO), carbon dioxide (CO₂), volatile organic compounds (VOC) and Ozone (O₃). This allows future users to take the accuracy of the sensors into consideration, which was overlooked, at the moment of implementing them on different SEMS. In the future, perhaps a larger number of SEMS should be considered in order to see more variety on the sensor implementations and then a comparison could be taken into account. However, this initial approach allows researchers to take into consideration the accuracy of low-cost sensors that can be implemented on SEMS for living environments, an area of research that will continue to expand on the following years.

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