Design of a low-cost wireless data logger for monitoring the occupant's thermal perception

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Toky RAKOTOARIVELO[1], Faly RAMAHATANA[1], Steven MENARD[1] and Nour Mohammad MURAD[1], Harry BOYER[1] and Bruno MALET-DAMOUR[1]

1 : University of Reunion Island, PIMENT Laboratory, Reunion (France)

bruno.malet-damour@univ-reunion.fr

Abstract

Achieving thermal comfort for the building occupant often means increasing energy consumption. This work aims to develop an affordable, reliable, easy-to-use data logger to track occupants' thermal perception. It would allow the development of new approaches to achieving comfort by energy sobriety. This article presents the fabrication of a data logger device that allows a microcontroller-based system to measure an individual's physiological and physical parameters. The overall device is tested by comparing each sensor's mean output to assure that the physical measures have minor discrepancies. Also, the comparison was made to ensure that the two ways of data saving were reliable. The results indicated that the data logger showed no issues. The thermocouples had a reading difference of 0.05°C and constantly sent data. The oximeter needs to be closest to the wrist to return stable reading. The spectral decomposition sensors returned the same value but required to be placed perpendicular to the light source. Data were well transmitted to an online database and were well registered on the SD card. This is consistent with discoveries already made on those sensors. For the preliminary test, the measure confirms the efficiency of the design as it matches expectations and admits relatively low deviation for all units. Our finding showed that it is possible to secure the input in both ways: online and offline solutions. Also, it allows a more accessible protocol that uses more than two data loggers for online data records through Google API. Identifying individual parameters and not solely global parameters will permit further development toward fulfilling optimal thermal comfort. Despite the work done, design amelioration is needed to optimize the portability of the devices.

Keywords: wireless, sensors, thermal perception, physiological, low-cost

1. Introduction

The search for thermal comfort by the occupant is of paramount importance in terms of energy consumption in today's buildings. The individual seeks thermal satisfaction [1]–[4] with the indoor environment. This satisfaction results from the adequacy of the actual thermal conditions, the context of his presence/activity, and the expectations/demands of the users [5]. The comfort equipment regulating the temperature is then solicited, which makes them energy-consuming and responsible for a significant part of the consumption of a building [6]. Knowing how the occupant perceives his environment will allow him to anticipate his needs and thus consume as precisely as possible to meet them. The design of a system enabling the collection of the occupant's physical, physiological, and psychological parameters is the first step to reach energy sobriety.

Many works have been interested in the measurement of the thermal comfort parameters of the occupant [7]–[10]. The authors have implemented sensor systems capable of periodically measuring the ambient air temperature, humidity level, air velocity, carbon dioxide (CO_2) level, or even the air pollution of a room via the percentage of particles per million pollutants in the air. The realization of these devices using open source programming hardware is one of the most recurrent aspects of the literature. This type of project encourages the use of hardware with a lower purchase cost than the hardware proposed by industrial companies for performances in phase with the needs of the studies. The most popular projects are generally those based on the ARDUINO and Pi development platforms. They offer the advantages of an easy-to-use programming language and many development boards, sensors, and accessories that facilitate the creation of projects from the simplest to the most complex.

Several electronic communities have made it their main topic of discussion and are mobilizing to develop open-source solutions. This craze can be found in the scientific world. These sensors are commonly called data loggers. Carre and Williamson [8] designed a data-logging system to estimate indoor environmental quality using an Arduino Mega 2560 board. They presented a device using different sensors to measure: air temperature, air velocity, illuminance, noise levels, and carbon dioxide (CO_2) concentration in the air. The sensors' data was monitored with a screen, and a questionnaire, activated by a button, allowed to define the occupants' feelings. Some proximity, temperature, and relative humidity sensors were deported to follow the occupants' behavior regarding the opening and closing of sliding doors. The measurements were recorded on an SD card located on the central totem. The authors defined some limitations to their system, such as waiting until the experiment's end to retrieve the recorded data and being present on-site to monitor data fluctuations. Other techniques have been designed to use wireless technology to follow the evolution of the parameters "at a distance." This is the case of the work of Karami et al. [11], who used several Arduino Uno boards and the Zigbee protocol. A dedicated server has made the acquisition chain more reliable and eliminated the potential for data loss. However, they noted a high cost of implementation due to the need for a physical server and, therefore, the suite of associated programs. Also, they had to split the system into two boards to support the high number of sensors.

Alavi et al. [12] designed the ComfortBox to translate the perception of comfort in space. The box contained environmental sensors to measure air temperature, humidity, air velocity, air pressure, illuminance, carbon dioxide ($C0_2$) concentration, and noise levels. The measurement was taken every second and was sent to an MQTT server via WiFi, allowing for remote data tracking and storage. The ComfortBox had four mirrored sides, one of which served as a display. The latter presented the values of parameters such as temperature or alerts indicating a CO_2 level falling below a certain threshold. The box also displayed questionnaires according to pre-programmed events that could occur or be caused by the occupant. Other studies have also moved towards this same design idea. We also note the work of Ali et al. [13], who used an Arduino Uno board per sensor coupled with a wireless link system with Zigbee cards, and local storage on an SD card. Feng et al. [14] created a data logger to track the power consumption of a home using a WiFi system via an STM32F103. The work of Al-Abbas [15] also sought to develop a data logger using an ESP32 and an application-interface accessible through a browser to monitor the measurements made using WiFi.

Interestingly, this kind of data logger is not specific to each individual but concerns the area in which people live. However, it should be kept in mind that each individual perceives their comfort differently from others [16]. This assumption is further reinforced in studies of human physiology and health, disciplines in which the individuality of patients must be considered. In this perspective, several low-cost systems have been developed to address the need for quantity but also accessibility of research for laboratories with modest funds [17]. The work of Sanjaya et al. [18] sought to develop a multimodal physiological parameter telemetry system in the health context of the COVID19 pandemic. The objective of the data logger was to record oxygen saturation, body temperature, number of heartbeats, and number of breaths for an electrocardiogram. Using a third-party service, they used an ESP8266 card coupled to a WiFi data transmission protocol via HTTP. It was thus possible to consult the data sent by the sensors via any access point. The team encountered some difficulty in operating the reader to obtain electrocardiogram measurements. The accuracy level of the low-cost sensors was too low to get representative data.

Another difficulty was placing a bulky block on the participant's torso and trying to immobilize him in the supine position by imperatively limiting parasitic movements. In addition, they noted a significant latency in the transmission protocol, making the use of electrocardiography complex. Other researchers, such as Parate [19], developed a system establishing a link between two ESP32 Nodemcu. The objective was that one of the cards would send the measurements of different sensors to another, which would display them on an OLED screen. This made it possible to exploit the ESP32's pins to the maximum. Other researchers have also proposed wireless solutions: Islam [20] with an ESP32-based system to monitor the heartbeat and air parameters around the wearer, Sarierao [21] with an ESP32 module in charge of retrieving the patient's heartbeat, skin temperature, and movements, or Fadila et al. [22] with an incubator for phototherapy of newborns.

This bibliographic survey allowed us to identify low-cost data loggers' potential and limits. It also allowed us to define our specifications to develop our device for measuring the perception of an environment. It appeared essential to know how to combine an individual portable system allowing physiological measurements with a system enabling the important variables to determine comfort.

This article aims to present the design of a personal data-logging system. Compared to work where people need to assess their reaction to a centered block device, in a comfort study, the developed device will let them vote on the spot, thus permitting an on-the-go response, which will be less influenced by anticipation. It will help consider the individuality of the occupant and not solely the overall majority as thermal comfort acceptability. On the other hand, this work will permit saving the history of the user parameters for future calculation-processing and not just monitoring it in real-time. The designed hardware allows for the measurement of physiological and physical parameters necessary to assess the comfort level of an occupant.

This work has sought to implement a reliable and open access wireless data transmission with the least intrusive device possible. It will provide a new solution to save measures through two simultaneous solutions: offline on the SD card and online through an open-access database. The work will be presented as follow: we will first see the components of the data logger, the way they must be connected, and the organization of how the program is running. Then, an inter-sensor comparison phase will be presented and how the online database handled the measures.

2. Materials and Methods

The main components of the individual recorder will be presented in this part, as well as their connections. The general operation of the code will also be explained as well as the description of the data path. A protocol for verifying the operation of the sensors will also be described.

2.1. System architecture

Three main components are required to build an individual data logger: the control unit, the sensors, and the accessories (power and data transfer cables). The control unit is the brain of the data logger and is a printed circuit board equipped with a microcontroller. It is the central element responsible for coordinating the acquisition of measurements. There are different boards, and the one used in this study is the NodeMCU ESP32 WROOM from Joy It. It has better characteristics than an Arduino board: a processor as powerful as the Arduino MEGA and many pins. The ESP32 is, however, more compact, with dimensions close to an Arduino NANO board. It also integrates WiFi and/or Bluetooth without needing an extension module. Its dimensions and main characteristics are summarized in Table 1.

Table 1 - Summary table of sensors used

Materials	Parameter Measurement/Functionality	Quantity	Power supply [Vcc]	Max. consumption [mA]	Connection	Dimension [mm]	Weight [g]
DS18B20 - MAX31820	Skin temperature	3	3 – 5,5	4,5	One Wire	20 x 5 x 5	1
MAX30100 Series	Oximetry	1	1,8 – 5	2,2	I2C standard	30 x 30 x 5	4
AS726X	Spectrometry	1	2,7 – 3,6	5	I2C standard	30 x 30 x 5	3
UV Sensor	UV	1	1,8 – 5	5,5	Analog	20 x 18 x 12	2
TFT 2,8’’ TF028 shield UNO	Display/Survey responses	1	3,3 – 5,5	25	8-bit Parallel	85 x 52 x 16	38
NodeMCU ESP32	Development map	1	3,3 - 5	240	32 GPIO	55 x 26 x 11,5	10

We chose to use four different sensors whose characteristics and roles are summarized in Table 1. The measurements are of the participant's skin temperature, percentage of oxygen in the blood, heart rate per minute, and light spectrum components at the boundary between visible and infrared that could affect their thermal perception. To do this, we chose the MAX31820 sensor to measure skin temperature. It is produced by the company Sparkfun and corresponds to the DS18B20. It is a versatile thermocouple used as a skin thermometer [20] and even a thermocouple to measure ambient air [8]. We selected the MAX30105 sensor to measure the oxygen concentration and heartbeat because it is from the MAX30100 series. This oximeter is found in the literature [17], [18], [23]–[25]. It is also a Sparkfun card. To decompose the light, we chose the AS7263. This sensor is capable of decomposing light along six spectral bands. It covers a range from 610 nm to 860 nm. The next sensor is an analog sensor that measures the amount of UV arriving at the participant. The 2.8" TFT LCD screen is a 320x240 resolution screen with an ILI9341 chip as firmware. It has a capacitive touch functionality covering the entire surface of the screen. It acts as a psychological sensor because it allows the user to transcribe his perception by answering questionnaires. It also has an SD card reader for storing measurements.

The microcontroller and the sensors are connected using jumper cables grouped in wire bundles. Table 2 shows the pins that must be connected to operate the data logger.

Table 2. Cabling table between the ESP32 and other peripherals

Écran LCD		**MAX31820**	
LCD_CS	D33	VCC	3V3
LCD_RS	D27	DATA	D26
LCD_RST	D32	GND	GND
LCD_WR	D4		
LCD_RD	D35	**MAX30100**	
LCD_D0	D12	GND	GND
LCD_D1	D13	3V3	3V3
LCD_D2	D2	SDA	D21
LCD_D3	D25	SCL	D22
LCD_D4	D16 ou RX2		
LCD_D5	D17 ou TX2	**AS726X**	
LCD_D6	D15	GND	GND
LCD_D7	D14	3V3	3V3
SD_SS	D5	SDA	D21
SD_DI	D23	SCL	D22
SD_DO	D19		
SD_SCLK	D18	**UV Sensor**	
5V	VIN	AOUT	D34
GND	GND	GND	GND
		VCC	3V3

The ESP32 is powered at its mini USB port by an external battery delivering regulated $5V_{DC}$. The ESP32 manages the power supply of the peripherals. Its 3V3 output pin is a terminal providing a 3.3 V_{DC} voltage. The thermocouples, oximeter, and spectrometer share this terminal because of the same operating voltage range. Since the display requires $5V_{DC}$, its power pin is connected to the VIN pin of the ESP32. This pin delivers the same supply voltage to the mini USB port of the microcontroller. The data from each peripheral is transferred via other pins. The connection pins of the MAX30100 series and AS726X sensors are standard. These sensors use the I2C protocol to share information on the same channels: SDC and SDA. They will have different addresses allowing the microcontroller to differentiate the information received. The thermocouples transmit their data on a single standard digital pin. Due to their design, it is theoretically possible to put 64 thermocouples in parallel on the same pins because each thermocouple produced has a unique hexadecimal address. The data from the TFT display is transferred using an "8-bit parallel" connection. This standard requires 12 pins from the display to be available on the development board.

2.2. Program and wireless link

The programming of the ESP32 can be done with various languages and software interfaces. In our study, the code was written through the Arduino IDE software. It is based on the C language and is easy to access for neophytes while allowing them to realize simple actions to be broken down. The structure of the program writing is broken down into two parts or functions: void Setup and void Loop. The void Setup function contains an action that will be performed only once when the microcontroller is powered. Once the void Setup function conditions are met, the void Loop function will be launched and will continue to be launched in a loop as long as the board is powered. Figure 1 describes the evolution of the program but also how the code has been structured.

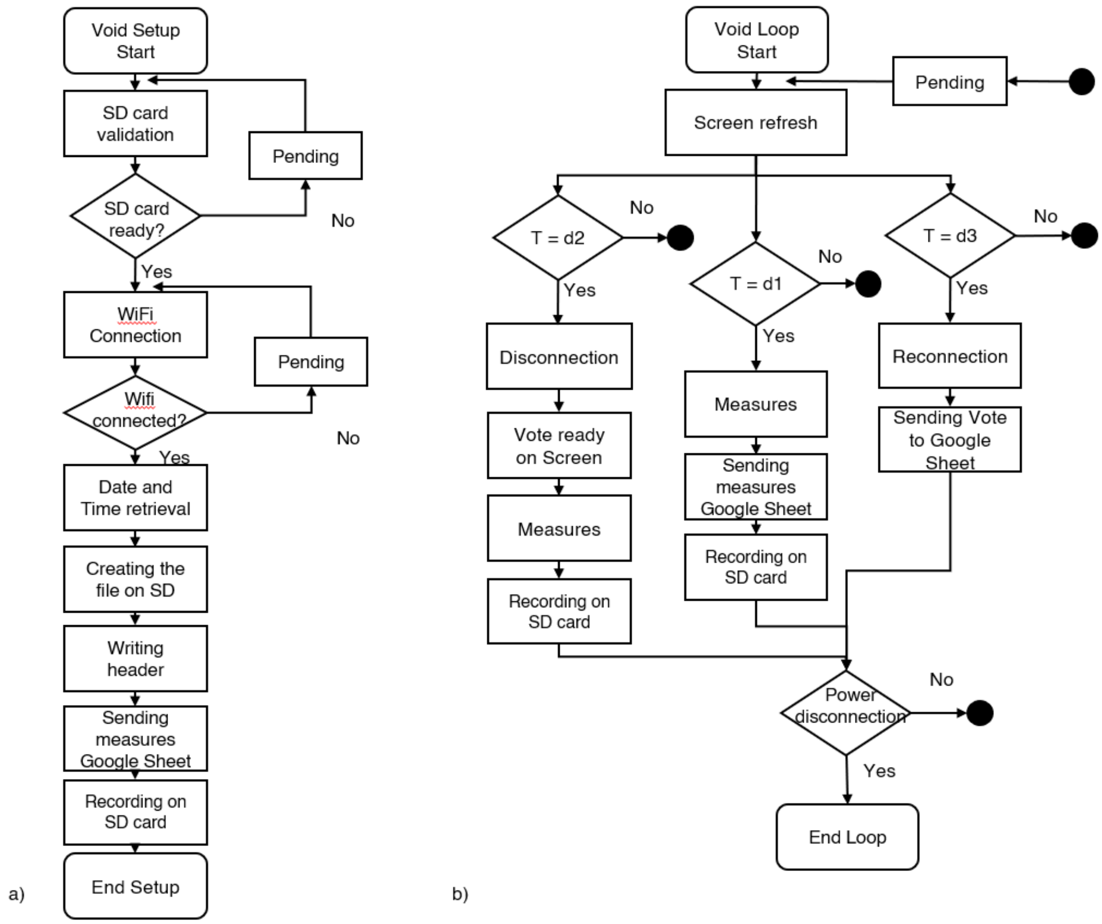

Figure 1. Program flowchart: a) Void Setup, b) Void Loop

As can be seen in Figure 1, the individual data logging system supports two modes of data logging. The first logging mode is through WiFi. As each ESP32 connects to an internet access point, they link to a Google Sheets script allowing them to write to a file on Google Drive. Each ESP32 transfers its measurements to a separate sheet in the spreadsheet. The second logging mode saves to a physical disk (SD card). The physical link is made between the ESP32 and the TFT screen. This recording mode allows the protection of data in case of WiFi malfunction. Figure 2 schematizes the structure when several data loggers are connected and schematizes the general functioning of the communication.

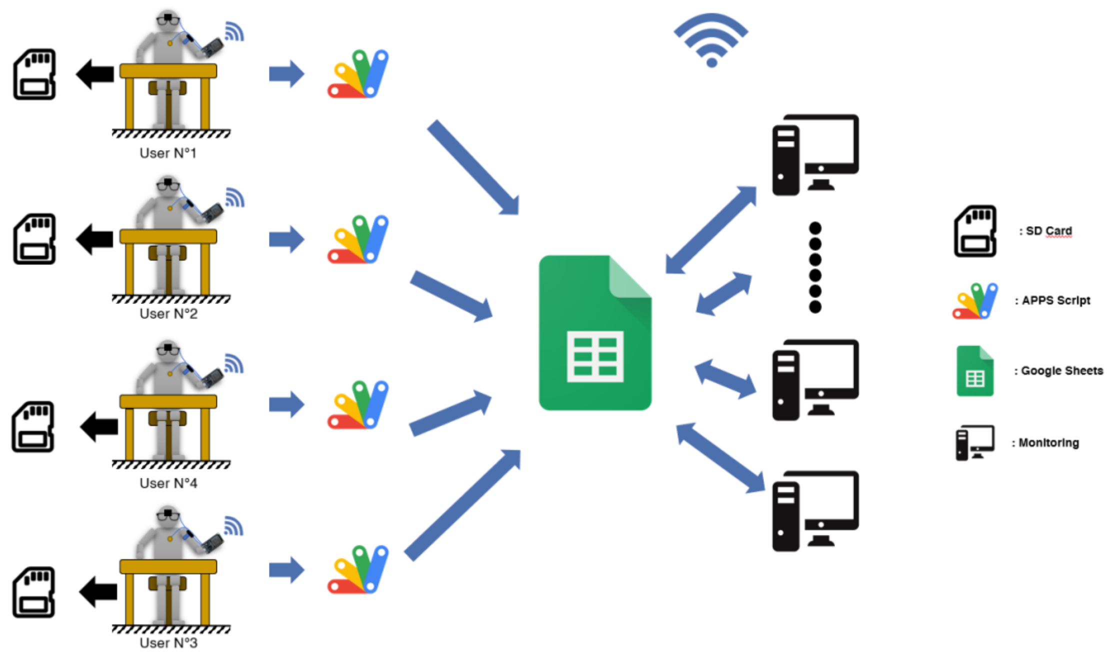

Figure 2. Schematic representation of the measurement recording architecture

This architecture has the advantage of being functional even if a user disconnects. It is also possible for several monitors to have access to the main recording file. It is possible for them to interact, whether to correct the formatting of the data, record it, or even link a graphical interface to it. This solution with Google Sheets and its APPS Script does not involve any intermediary service between the spreadsheet and the data sending. This link limits the risk of unavailability if a hypothetical intermediate service fails. Deployment with the Google Sheets service is a quick and easy solution compared to solutions like MQTT or HTTP servers. Apart from individual data loggers and tracking tools, only an internet access point is required. However, it is essential to remember that even though Google's services are free, this could change over time.

2.3. Test protocol

A test phase was necessary to verify the proper functioning of the sensors, the code, and especially the recording of the measurements. The test protocol was designed so that the sensors are exposed to the same environmental conditions to verify the output measurements' reliability. It will be necessary to determine the cause of the deviations that appear. This will then allow us to establish solutions to ensure the system's proper functioning.

The arrangement of the sensors for testing is shown in Figure 3. Figure 3a) shows the placement of the thermocouples, spectrometers, and other sensors. Figure 3b) shows the measurements in a similar environment. Figure 3c) shows the connection of the MAX30105s to a researcher's arm.

a) b) c)

Figure 3. Photographs of the set-up and progress of the experimental protocol: a) installation of the sensors on the test bench, b) progress of the experiment on day 3, c) overview of the test configuration

The experiment was conducted over three days. On the first day (Day 1), the MAX31820 thermocouples of the systems were isolated and observed. They were exposed to a 33 W halogen lamp that could emit three different radiation levels. The experiment was held between 5:55 p.m. and 7:10 p.m. Four personal data loggers were used for 12 thermocouples. Each ESP32 was programmed to return a measurement every minute. It was determined that four steps should be taken every 15 minutes:

- Step 1: Ambient temperature with the lamp off;
- Step 2: first level of illumination from the halogen lamp
- Step 3: second level of illumination of the lamp
- Step 4: maximum lighting levels.

To check their correct operation, monitoring their connection on the access point device (mobile access point via 4G network) allows knowing if the ESP32 is well connected. In the case of a bad connection, it is necessary to reboot the ESP32 and retry the connection.

On the next two days of experimentation, the sensors were turned on simultaneously to collect as much data as possible during the defined period and identify any potential overload or interferences. The second day of testing (Day 2) took place between 4:15 p.m. and 5:55 p.m. with the same halogen lamp and for the same exposure times. The ESP32s brought up all the sensor measurements every minute. The third day of testing (Day 3) took place the day after the second day between 2 p.m. and 5 p.m. An LED lamp replaced the halogen lamp with lower thermal radiation. It has three different lighting modes: warm (yellowish), natural (whitish), cold (bluish), and three different levels of illumination from the weakest to the strongest. The modules brought up the measurements every minute. The first lighting mode was set to "natural" (whitish), and the lighting intensity was changed every 15 minutes. Once the highest illumination level was reached, the lighting mode was then changed.

3. Results and Discussion

This section presents the sensors' measurements to verify the correct transmission of data and thus validate the simultaneous operation of the modules. The measurements shown are those obtained from the Google Sheets spreadsheet. Each sensor will be observed.

3.1. MAX31820 Thermocouples

The thermocouples are presented by their manufacturer as being pre-calibrated. According to their data sheet, they have a measurement tolerance of ±0.5°C in a temperature range between 10°C and 40°C in the parasitic operating mode. We could confirm this tolerance during a measurement between each sensor by placing them on an aluminum rule. Their behavior over the hour of measurement shows a slight deviation between the sensors: a difference of 0.05°C between the maximum and minimum values recorded. This deviation can be considered acceptable concerning the tolerances set by the manufacturer. By observing the curve in Figure 4, it is possible to see a trend in the measurements that tends to stabilize around 20.60°C. This slope is due to the influence of the external environment (the surrounding temperature begins to fall).

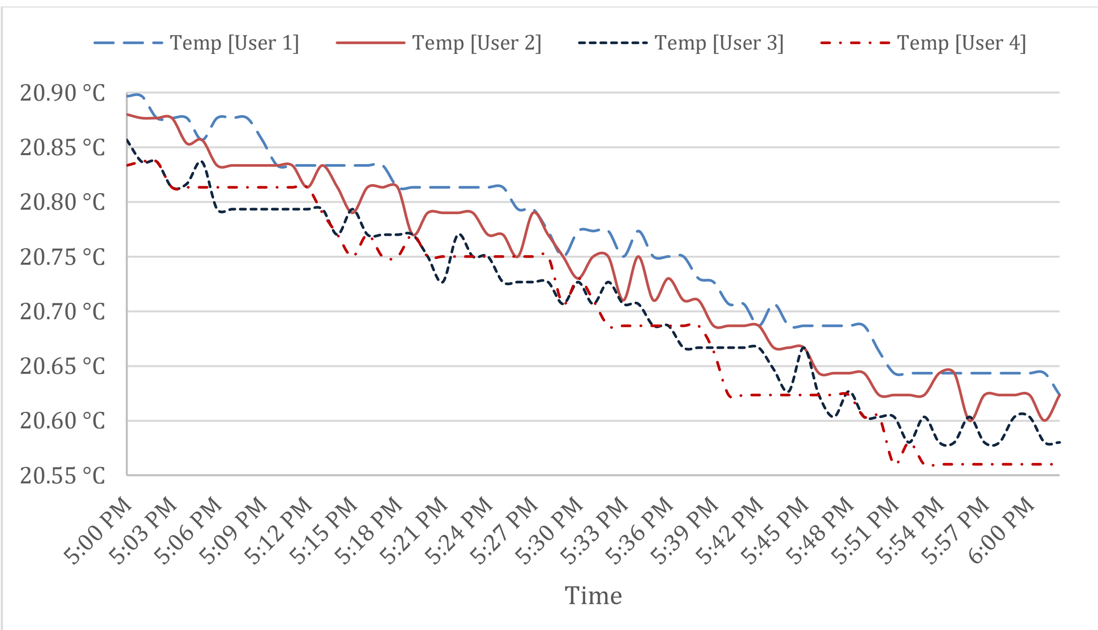

Figure 4. Calibration curve for thermocouples

The thermocouples were also tested following the Day 1 protocol. The results of the temperature averages of the three thermocouples for each user are shown in Figure 5. It is interesting to note that a cut-off between 18:24 and 18:25 is observed for User 3. This is intentional cut-offs performed to check the recovery capacity of the modules. We notice a slight delay of a few degrees with the other users after the reconnection of the module. This is induced by a loss of thermal inertia for the no longer powered sensors. The other sensors showed a similar trend throughout the experiment. The discrepancies between the values of the measurements from 18:26 onwards come from the non-uniformity of the exposure under the lamp. Some parameters, such as air movements or the angle of the lamp's reach, also influenced the measurements. Nevertheless, we can tell from these results that when one of the recorders is switched off, the others do not suffer from interference. It is also necessary to allow a certain amount of time to stabilize the reading of the sensors.

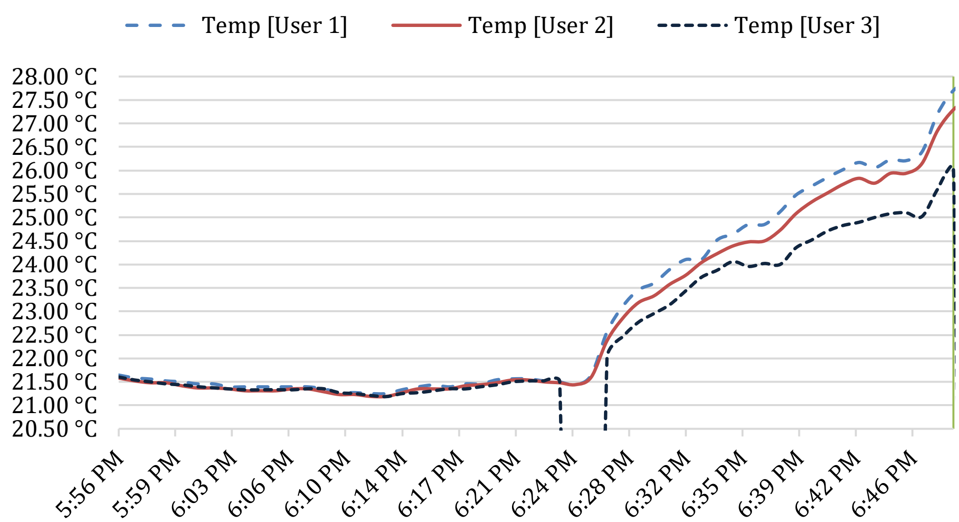

Figure 5. The thermocouple measurement curve - day 1

3.2. MAX30100 Series Oximeter

Numerous projects with heartbeat sensors [21], [24], [26], [27] indicate that it is necessary to ensure good contact with the participant's skin. The contact should be permanent and performed at constant pressure. Most often, the oximeter is placed on the tip of the finger and fixed with a clip. In our study, our prototypes are designed to pause the sensor under the forearm, as shown in Figure 66. The measurements are on a single individual at different positions along the anterior aspect of the forearm.

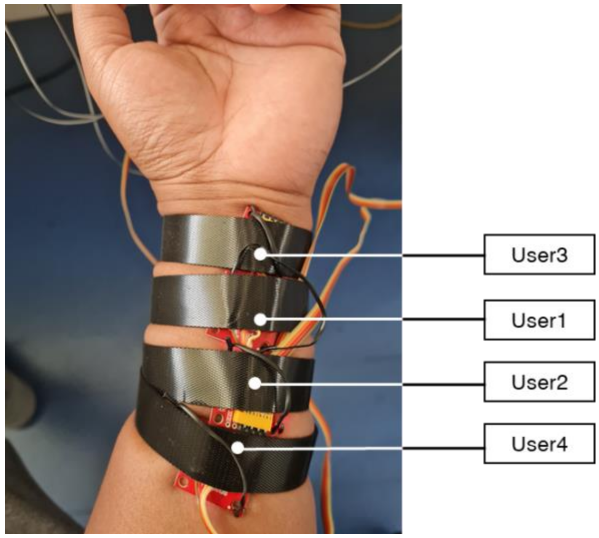

Figure 6. Photograph of a pulse oximeter installation

The interest of this approach is that it is possible to determine the best position to obtain stable values while being the least annoying for the wearer. Indeed, some places limit movement and prevent data from being taken. According to the measurements made by the oximeter, the positions of User 4 and User 2 do not ensure good contact with the skin. This results in incorrect values being returned. The sensor position of User 3 is the one with the most stable SPO2 values throughout the measurement. It is, therefore, reasonable to assume that the position of the sensor close to the inner part of the wrist is the best. From these findings, it would thus be appropriate to say that the best placement position for pulse oximeters should be between the position of User3 and User1. This positioning range corresponds to the one less far from the wrist.

3.3. AS726X Series

The spectral decomposition sensors employed could show measured values indicating their operation. Due to the frequency of the measurements, an average of 20-minute increments was performed for the Day 3 measurements. This processing resulted in Figure 7, which shows the four sensors' 610 nm±33 nm spectral band values. The sensor's value returns are the number of photons per microwatt per square centimeter. This indicates that the higher the value, the higher the component in this spectral band.

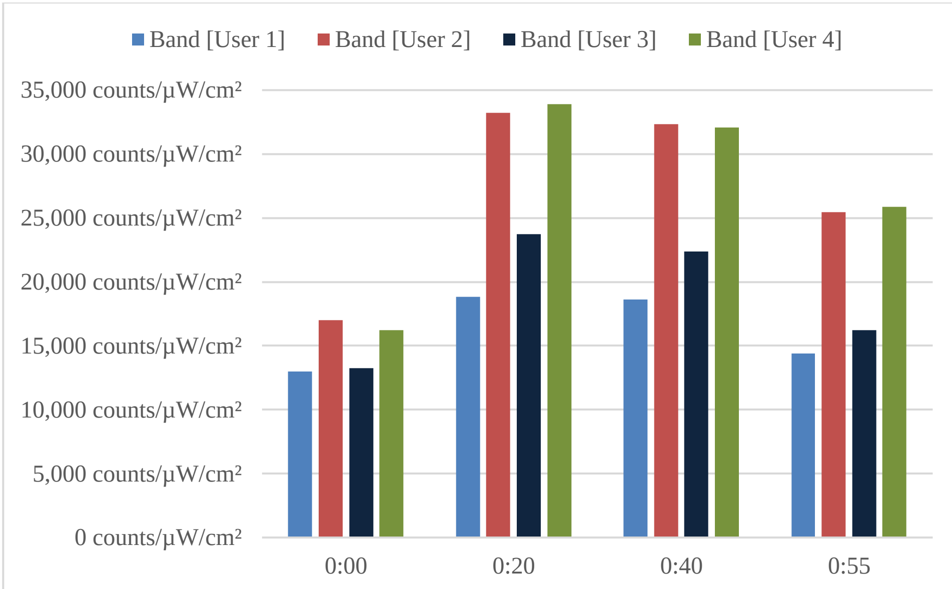

Figure 7. Representation of the 610 nm spectral bands for each user - Day 3

Figure 7 shows that when the LED lamp was not yet on, the four sensors showed a slight difference in the values captured. The light environment of the room may have influenced this difference (related to the multiple specular reflections generated by the room's walls). After 20 minutes of exposure, we notice a gap between the User 2-User 4 group and the User 1- User 3 group. The first group was placed much closer to the light source. The orientation of group 1 compared to group 2 may have caused the values to differ. Further measurements will confirm or refute these results.

3.4. Overall data transmission

Once all modules were disconnected and turned off, the SD cards were checked to see if the recorded data matched the uploaded data to the Google Sheets. In all experiments, each measurement was written correctly to the physical media. Nevertheless, considering this is a test phase, it is wise to indicate reliability to be confirmed for the quality of the data transmission through the wireless channel.

4. Conclusion et perspectives

To conclude this work, it has been demonstrated that the designed system can ensure data recording via the wireless channel or the physical medium (SD card). The system does not lose any data, thus making its operation in an environment with a WiFi access point attractive. This approach will be helpful for experimental studies that need to monitor the evolution of an individual's physiological constants remotely. The development platform used is one of the cheapest on the market, and the realization of the system is very simple, which is why we have created four functional prototypes.

Even if the objective of this work has been achieved, some points need to be improved to perfect this sensor development study. The first point is a better thought design so that each module will be more ergonomic for its wearer. A second point to improve is the choice of more efficient sensors whose precision is better adapted to indoor conditions. Finally, it would be interesting to adjust the test protocol to check the concordance of the measurements with reference material.

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