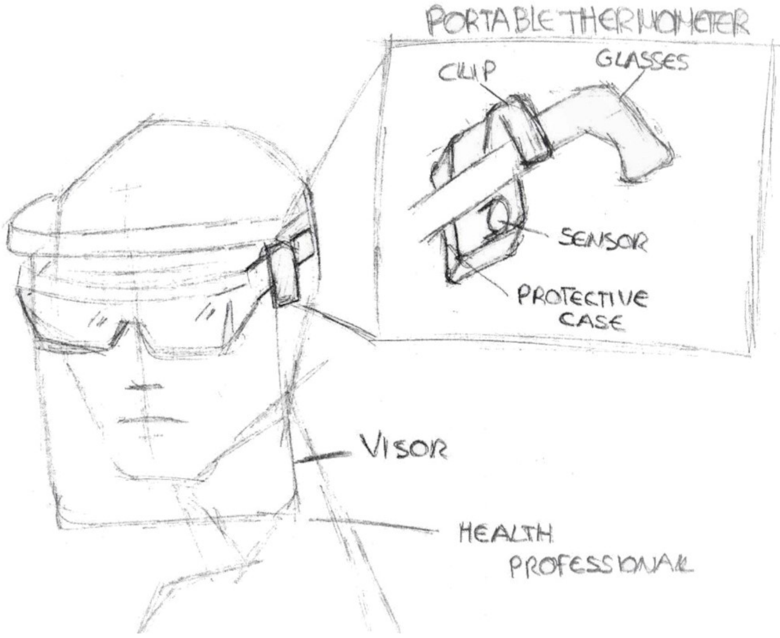

IAS Project

Portable Thermometer for Health Workers and Covid-19 Patients

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Abstract

In the first global pandemic in recent years, monitoring the symptoms of COVID-19 is essential, in order to avoid possible transmissions and to more quickly confirm the diagnosis in order to take the measures recommended by DGS and WHO. One of the main symptoms of this new virus is the presence of fever, so the identification of the pre-febrile state through continuous monitoring will be the key to early diagnosis.
Our project is focused on the development of a low-cost wearable thermometer, based on the measurement of the temperature of the tympanic artery, inside the auditory canal, using an infrared temperature sensor (non-contact sensor), and axillary temperature, using an IC sensor (contact sensor), associated with a microcontroller capable of processing the data in real time. The thermometers have two types of acquisition, namely continuous and punctual acquisition of the body temperature. These can be easily interchangeable via a switch placed in the prototype. Both of these are integrated in a web server (*Google Firebase*) that can be easily accessed in real time through a mobile phone or computer with access to Wi-Fi, after website implementation, and saved in a cloud-like ambient for further interpretation.
Since the commercial sensors are not readily adapted to be used in a human body temperature measurement context, they have a high variability in the displayed unprocessed results. Furthermore, most temperature sensors are also very susceptible to the orientation of the sensor and ambient temperature, and therefore both of these sensors had to be integrated in a processing step, done by a NodeMCU ESP32 microcontroller. Kalman and IIR adaptive filtering with dependency on the ambient temperature (the latter only for IR sensors) have shown to be great choices for processing and stabilization of the measured temperature.
The sensitivity of the various sensors was studied, with the aid of a heating pad, and compared to the temperature measured by other standard commercial thermometers. This resulted in
In view of the quality/price balance,
The current phase of the present project will only consist of a prototyping operation, where the device will be constructed with a microcontroller and a breadboard. If desired to use in real-life situations, the main circuit can then be easily adapted in a PCB board for ease of utilization.

Keywords

COVID-19, Thermometer, Fever, Wearable, Continuous measurement

Contents

1 Pandemic Context & Problem definition

In the context of the COVID-19 pandemic, there is mounting pressure on health systems globally, and health workers everywhere are themselves tragically falling victims to the disease. These professionals are working very long hours and might often miss or disregard symptoms they might have, such as cough, sore throat, headaches and fever [1]. Additionally, they might not be able to resort to a thermometer for themselves when they feel they might have a fever, one of the most common symptoms of the infection by SARS-CoV-2. It would therefore be beneficial to provide accessible, portable and continuous temperature measurement devices to health workers, in order to enable monitoring and early detection of possible cases of infection among these workers before they infect other patients or family members they may interact with.
A portable thermometer that can provide continuous monitoring might also be effective and useful for the continuous monitoring of a large number of patients at the same time, which would enable doctors to evaluate more precisely how several patients are evolving clinically, and be alerted when patients develop a fever.
Additionally, it would be useful for continuous home monitoring of patients that have not been hospitalized.
The existence of wearable, low cost, and easily programmable devices for continuous temperature measurement could, therefore, be very useful in multiple situations, in a context where prevention and early diagnose are key aspects to the control of the pandemic.

2 Introduction

A thermometer is a simple and classical device, which is common in almost every house, designed to measure temperature or a temperature gradient [2] in a punctual way, sometimes during a few minutes. A thermometer has two important and basic elements [2]:

- a temperature sensor (*e.g.* bulb of a mercury-in-glass thermometer)
- a way of converting this change into a numerical value (*e.g.* visible scale marked on a mercury thermometer)

Over the years, the way of measuring human body temperature has evolved, either for safety reasons (mainly associated with mercury toxicity, present in the classical thermometers) or for efficiency reasons (in order to take less time to measure temperature in a clinical context). Nowadays, there are various types of temperature sensors used in thermometers for human temperature measurement, and therefore different strategies to convert these changes into numeric values. A thermometer aimed at measuring the temperature of the human body should follow some characteristics, such as:

1. Be sensitive enough to detect small temperature differences, since the maximum temperature range will be between 35 °C and 40 °C, and slight changes in between this range can be associated with medical conditions
2. Do not overheat such as to cause discomfort and harm to the user
3. Fast to acquire

The main temperature sensors used in this context are NTC/PTC sensors or IC sensors, which will be detailed in the following sections. However, during the last few years, the emergence of infrared sensors for temperature measurement has changed the way temperature is measured in a clinical context, since it doesn't necessarily require contact between the sensor and the skin, and can acquire temperature data in a faster way than the previous ones. This is a major point in favor for this type of sensors. However, these sensors also have major drawbacks, which will be detailed in the next sections. A careful choice of the used sensor in any thermometer device is thus critical, and must be studied in detail.
Note that there are still other sensors capable of measuring temperature, however they are not commonly used in the biological context, *i.e.* are

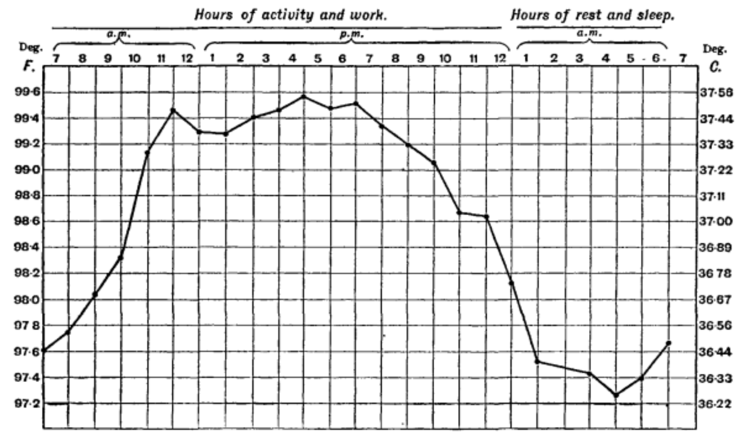


Figure 1: Average variation of human body temperature in function of the hours of the day [3]

mainly used to measure the ambient temperature, or large temperature variations associated with industrial procedures.

2.1 Temperature of the Human Body

Human body temperature can be divided into **core** and **skin surface temperature**, being the latter generally lower by a few degrees. In humans, such as for all mammals, core temperature is defined as the temperature of the hypothalamus, the regulatory center of the body, which can be estimated by taking measurements from the auditory canal, among others. By means of vasomotor, sweat and evaporation, the thermoregulatory system is capable of maintaining the core temperature of the human body in a narrow range [4]. Some natural fluctuations of the core body temperature can be due to the circadian rhythm, with the lowest value in the morning and a peak in the afternoon, with a difference of about 1 °C, as can be seen in figure 1.
On the other hand, the temperature of the skin surface is usually lower than the core body temperature, due to dissipation of heat and other factos, and is lower over superficial veins than other superficial arteries. It is also lower over protruding and markedly curved parts of the body, such as the nose, fingers, among others.
Taking this into account, core body temperature is usually around 37 °C, and skin body temperature between 33.5 and 36.9 °C, depending on the measurement site, which will be described in the following sections.
Taking this into account, general human body temperature generally varies between 35 and 42 degrees Celsius, when measured in the most common sites (such as auditory canal, forehead, under the arm, among others). A healthy temperature would be around 36.5-37.5 °C, with values lower than 35.0°C constituting hypothermia and values higher than 37.5 °C generally constituting a fever [5].
However, these cutoff values vary according to several factors, perhaps most importantly the location of the body where the temperature is measured, the circadian rhythm, whether the person performed any physical activity, the female menstrual cycle, and whether the person is hungry or sleepy.

2.1.1 Measurement site

Human body temperature is typically measured at various locations in the body, namely the mouth, forehead, ear, axilla, and rectum [6].
Generally, among the typical measurement locations, the temperature is highest when measured in ear, orally or rectally, as it is aimed to estimate the core body temperature, and lowest in the forehead and axilla, being this measurements of the skin body temperature.
According to the DGS [7], a fever is diagnosed when there is a ≥ 1 °C elevation in typical body temper-

ature at the measured location. Their basic criteria is $\geq 37,6$ °C for axillary and oral measurements, $\geq 37,8$ °C for tympanic measurements and ≥ 38 °C for rectal measurements. This is consistent with a 1 °C elevation of the average measured body temperature per location published in a review study regarding average body temperature ranges, as shown in Figure 2. As for the temporal (forehead) temperature, its range is somewhat comparable with these temperature ranges, being normally similar to the axillary measurements, and 0.6-1.2 °C lower than tympanic measurements [8].

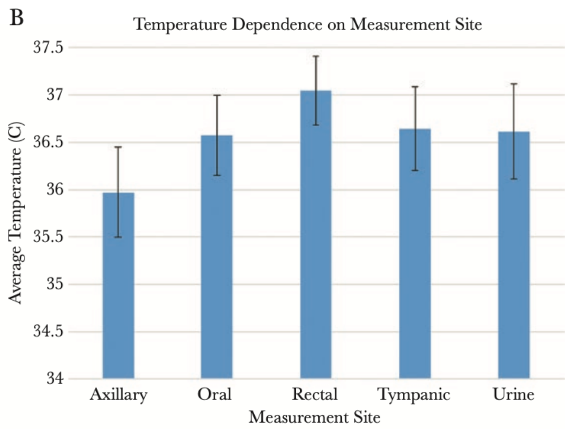


Figure 2: Average temperature range for measurements at different body locations [9]

These locations all have specific advantages and disadvantages, particularly as it relates to invasiveness, accuracy and accessibility. In this project we aim to minimize invasiveness and optimize accuracy, as well as the availability and cost of the components.

Therefore, to minimize invasiveness, we will rule out the use of rectal and oral thermometers, that in spite of optimal accuracy are unsustainable for continuous monitoring.

The two optimal measurement locations would therefore be on the forehead, specifically on the temporal artery, using contact or non-contact sensors, in the ear, using non-contact sensors, and in the axilla, using contact sensors.

The tympanic artery temperature reflects the amount of infrared heat produced by the tympanic membrane of the ear, by means of a sensor probe. The tympanic membrane shares its blood supply with the hypothalamus, the thermoregulatory center of the human body. However, this necessitates appropriate application and access to the tympanic membrane. Consequently, the probe needs to be positioned in the auditory external duct in the appropriate angle to the tympanic membrane [10]. Some studies also refer that a approximation of the tympanic artery temperature can be accessed by contact thermometers, for example behind the ear [10].

However, in the forehead, the skin temperature can be accessed by contact or non-contact thermometers. For contact thermometers, the temperature is registered by slow scanning the forehead in the temporal artery region. The thermometer thereby measures the naturally emitted infrared heat form the temporal arterial supply. This is a technique called *temporal artery scan* [10]. For non-contact thermometers, the same is applicable, meaning that one shoud aim to the temporal artery.

Finally, for the axillary temperature, the procedures are somehow easier. For this, one must only use a contact sensor, such as most thermometers in almost every home, which measures the skin body temperature. This is considered one of the safest and reliable ways of measuring temperature, namely among infants [11], being close to the best noninvasive index of core temperature for humans.

All of these have advantages and disadvantages. An in ear thermometer would perhaps be more uncomfortable, and the position would need to be very well adjusted to be accurate, however generally these generate some of the most accurate measurements. On the other hand, temporal artery thermometers are generally less accurate and less comfortable, being subjected to many artifacts, but perhaps they can be more reliable due to them not being as subject to an overly precise positioning. Finally, an axillary thermometer would need a device for properly placing it without discomfort. Therefore, we will test the accuracy and comfort of all of these measurements, and discuss which one would be best suited for the goal of this project.

2.1.2 Types of Temperature Sensors

In order to correctly measure the temperature in the temporal artery, tympanic artery or in the axilla, as previously described, we can mainly use three types of sensors. An overview of these sensors is present in the figure 3. Each sensor will be explored in the next sections, in order to complement this information.

Thermistor Sensors

These are based on thermistors, which are resistors whose resistance is dependent on their temperature. This can either be PTC (positive temperature coefficient) or NTC (negative temperature coefficient), i.e. their resistance can have either a positive or a negative correlation with the temperature. This behaviour is, however, non-linear, and these sensors have a limited temperature range (more than large enough for measurement of human body temperature though).

This is generally a metal, and platinum is often used due to its high linearity. This temperature-dependent resistance is then converted to a voltage to enable a measurement.

These types of temperature sensors are used in the most common thermometers people have at home, that usually take axillary, oral or rectal measurements. They are cheap and relatively accurate depending on where in the body the temperature is taken.

However, in the case of our project they would perhaps not be very accurate, as they are generally not very accurate for the precision needed for human body temperature measurements or continuous monitoring.

IC Sensors

An IC analog Temperature sensor is a two terminal integrated circuit temperature transducer, that produces an output current or voltage linearly proportional to absolute temperature [14].

It can be seen as an innovation in thermistors, since they supply an output that is linearly proportional to the absolute temperature. Except for that, they share all the disadvantages of thermistors: semiconductor devices, and therefore a very limited temperature range. The same problems of self-heating and fragility are evident, and they require an external power source [12].

There are two main types of IC sensors, designed for different applications:

- Immersion IC sensors - an IC temperature probe consists of solid state sensor housed inside a metallic tube.

- Transducer Type IC Sensors - very small, with a low thermal mass and a fast response type. This would be the ideal for medical applications.

In general, these are very useful in many applications, since they provide an easy-to-read output, linearly related to the temperature and whose relationship is readily defined and detailed in the manufacturer's documentation. They are also very cheap, which is a advantage for this particular project [12].

However, in the present scenario, its utility could be questionable since they require contact with the surface of the body, in order to accurately measure the body core temperature (as for the NTC/PTC sensors).

IR Sensors

IR thermometers work by measuring the black-body radiation of an object, in particular the infrared radiation that this object is emitting and its emissivity [13]. Note that this would be the only option, from the three here mentioned, suitable for the measurement of temperature in the tympanic area, since it doesn't require contact.

They are useful in human temperature measurement as they enable non-contact measurement, which might help prevent the spread of contagious diseases in pandemic scenarios: this is why IR thermometers are used to take forehead temperature measurements of incoming travellers or people entering public spaces [15]. These forehead measurements are taken at the temporal artery. IR sensors are also used in ear thermometers, which are very common in hospital settings.

In Figure 4 we can see a drawing of the inner working of an infrared thermopile sensor [16]. All ob-

	Thermistor Sensors	IC Sensors	IR Sensors
Advantages	– High output – Fast	– Most linear – Highest output – Inexpensive	– Non-harmful radiation – High emissivity of skin – Practical positioning in ear or forehead – Non-contact measurement – Minimal invasiveness
Disadvantages	– Non-linear – Fragile – Current source required – Self-heating – Contact needed for measurement	– Power supply required (for analog IC) – Slow – Self-heating – Limited configurations – Contact needed for measurement	– Low sensitivity/accuracy – Power supply required – Self-heating

Figure 3: Pros and Cons of the different types of sensors [12] [13]

jects emit infrared radiation proportional to their current temperature, being this absorbed in the surface of the detector, resulting in a gradient of temperature when comparing to the original temperature of the sensor. However, since this temperature is hard to obtain, most infrared sensors have a packaging outside the sensor itself, and the base temperature of the sensor is assumed to be equal to the temperature of this packaging. Therefore, these types of sensors are heavily influenced by ambient temperature, and must be placed in a "closed" area when used for a long time: quoting Hegen P (2012). *"When the patient is moving around and especially when going outside, the ambient air temperature will change – also affecting the packaging and therefore the measurement"*. This will introduce certain artifacts that we would not have with the other sensors, but that can also be used to achieve greater sensitivity to movement and other artifacts, as will be detailed in the next sections.

Also, from Figure 4, we can also see that, depending on the angle that the infrared radiation arives at the sensor, and its reflections and so on, this may lead to variability in the measured temperature, *i.e.* the raw data will not be perfectly stable, even with thermal equilibrium between the packaging and ambient temperature.

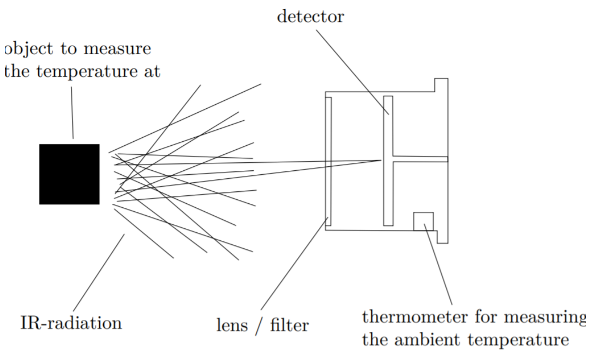


Figure 4: Schematic of the inner working of an infrared thermopile, sustaining the inter-variability of data [16]

Infrared thermometers, specifically those used to measure the temperature at the forehead, often have relatively low sensitivity but high specificity [17], which could be a problem for this project. This would mean that there would be some cases of fever that would not be accurately detected, although the vast majority of cases of fever detected would be accurate.
The particular advantage that IR sensors present to this project are the practical location.

2.2 Current Developments in Wearable Thermometers for Continuous Monitoring and Aim of This Project

Clinically, fever is a simple index of temperature change, and although representing such important information, **continuous monitoring** of body temperature remains a challenge, since it requires comfortable wearable devices and major processing in order to deal with many of the aforementioned artefacts [4].
In most patients, continuous monitoring of the temperature may not be necessary, since this may not be a critical factor to measure continuously. However, in the particular context of COVID-19 patients, since prolonged fever above 38 °C is one of the main symptoms and criteria to decide if a person has symptoms or not, and therefore being asymptomatic or not, continuous monitoring of temperature is very important. Moreover, although this particular project has been developed under the current COVID-19 pandemic, other applications of this device can be considered, such as for patients in a coma or with critical mobility limitations.
The skin is the most accepted site for temperature monitoring, but also provides unreliable measurements of core body temperature, which is the most accurate measurement, however some more sophisticated wearable devices for continuous monitoring have been arising in the last years, with infrared thermopile sensors and integrated circuits for temperature measurement. Although there are numerous wearable and touchable thermometers available commercially, for a variety of measurement sites and with integration to a Bluetooth mobile application, most of these are very expensive, which is not feasible for mass application in a clinical context, being easily put aside in favour of cheapest intermittent measurement devices. As a detailed revision of the current available wearable devices for continuous monitoring of human temperature is not the focus of our project, to have a more inside of this particular topic, the reading of *"Current Developments in Wearable Thermometers"* (Tamura T. *et al* (2018)) is reccomended.

With this, it is shown that a cheap, accurate and wearable device for temperature monitoring is a rising need under the current pandemic, which can be achieved under some basic concepts, which will be detailed in the following sections.

2.3 Common artifacts for continuous temperature measurements - biological & non-biological

As every measurement, we can expect several artifacts that can or cannot be corrected. For this, we can classify the artifacts as biological (non-reversible) and non-biological (reversible) artifacts.

Some of the most common biological artifacts, and that therefore cannot be reverted, are the ingestion of food and circadian cycle. Both of these are not "artifacts" *per se*, as they occur naturally, but that can lead to misunderstandings. When one ingests food, naturally the core body temperature slightly increases. Also, as described in the previous sections, the human temperature body changes during the day, according to the circadian cycle. This means that, one can think the temperature is increasing due to some sort of infections, but in fact this increase is totally normal. This also corroborates the fact that one can only consider to have a fever only when his/her body temperature stays high for more than a few hours, in order to take in count these "artifacts".

However, some artifacts, such as misplacement of the sensor, bad contact of the sensor itself, dependence on thermal equilibrium and influence of ambient temperature (as for infrared sensors), can be easily corrected, with simple filtering steps. This is very important in continuous measurements, since we need to have a way of ignoring these artifacts, especially in the infrared sensors, due to its high dependence on the ambient temperature, *i.e.* just by the fact that someone goes from inside to outside, this increases the "human body temperature" to values compatible with a fever.

2.4 Data Processing

As the data captured by temperature sensors generally presents a large variability, and, as mentioned, there can be artefacts caused by both biological and non-biological factors, it is necessary to apply some processing to the obtained data. This is essential in order for a clean and accurate reading of the temperature to be obtained in a continuous way.
Depending on the type of measurement being taken and the sensor being used, multiple filtering options can be used. Among these were Kalman filters, adaptive IIR filters, LMS filters and moving averages.

2.4.1 IIR filter

It is known that changes in temperature readings obtained for the object being observed with Infrared sensors are correlated with changes in the ambient temperature measured by this sensor. This fact enables the use of adaptive filters. These are filters whose transfer function contains variable parameters, which allows to tune the filters response according to variations in ambient temperature. For this purpose an IIR filter can be considered, which uses a variable alpha, varying from 0 to 1 depending on the derivative of the ambient temperature. When alpha is 0, the previously obtained temperature is used for the current value, when alpha is 1, the currently measured temperature is used. This way the current measurement will depend on all previous measurements, adjusted for how much the ambient temperature has varied.
The adaptive value of alpha is calculated using a sigmoid. This is a function that varies y from 0 to 1, when x varies from negative infinity to positive infinity:

$$\frac{1}{1+e^{-x}}$$

Where x, the input into this sigmoid, is the input variable divided by the derivative of the ambient temperature, calculated by subtracting the current value from the previous one.
When the derivative is 0, i.e. the current value for the ambient temperature is the same as the previous one, indicating stability, this input x goes to infinity, and the sigmoid returns 1.
When the derivative is very high, x will be 0. This is a problem, because a normal sigmoid would return 0.5, and we want alpha to be 0 in this case. So we adjust the sigmoid function accordingly:

$$2 \times \frac{1}{1+e^{-x}} - 1$$

This filter's output is given by:

$$y(n) = \alpha \times x(n) + (1-\alpha) \times y(n-1)$$

A schematic diagram of this filter can be seen in figure 6, as well as the adaptive alpha diagram in figure 5.

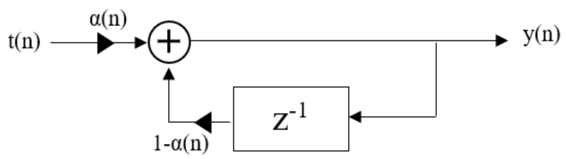


Figure 6: Diagram illustrating the IIR filter for object temperature filtering. The alpha parameter is adaptive with ambient temperature, as can be seen in figure 5.

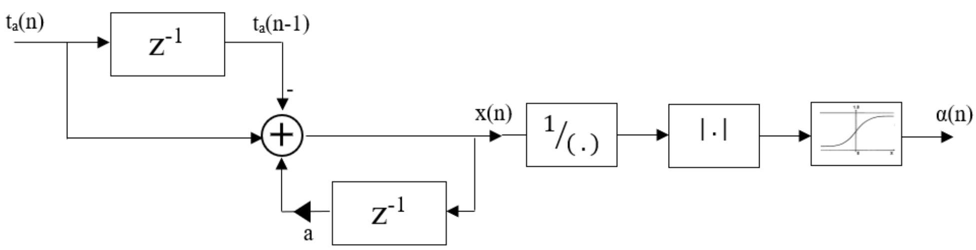


Figure 5: Diagram illustrating the adaptive alpha, with dependence on the ambient temperature.

2.4.2 Kalman Filter

Kalman filtration is an algorithm that aims to provide estimates for unknown variables given measurements over a time frame, in order to provide accurate approximations of current states. It provides a recursive solution to the least-mean-squares method without explicitly solving the problem of the minimization of errors. It is comprised by two parts, prediction and update.
The prediction consists of estimating the current state $\hat{x}_k$ using the previous state $\hat{x}_k^-$, and determining the error covariance of the current state P_k by adding a tuning parameter Q to the previous state's error covariance P_k^-:

$$\begin{aligned}\hat{x}_k^- &= \hat{x}_{k-1} \\ P_k^- &= P_{k-1}\end{aligned}$$

The update consists of the calculation of the Kalman gain K_k using P_k^- and a tuning parameter R and *a posteriori* estimates of the current state using the current measurement y_k and the Kalman gain, and error covariance using K_k and P_k^-:

$$\begin{aligned}K_k &= \tfrac{P_k^-}{P_k^- + R} \\ \hat{x}_k &= \hat{x}_k^- + K_k \times (y_k - \hat{x}_k^-) \\ P_k &= (1 - K_k) \times P_k^-\end{aligned}$$

The output of the filter, i.e. the filtered temperature corresponds to the value of $\hat{x}_k$.

2.4.3 Other types of filters

As mentioned, other filtering options can be considered for this purpose. One of these options is a simple moving average, which just averages the last N values. This approach effectively filters out high frequencies, enabling a simple filtration of noise. However, it requires the processing unit to store N values, which is not very efficient, and also introduces some delay.
Another option specific to the Infrared sensor was just the masking of samples that corresponded to high values of the derivative of the ambient temperature, and thus corresponding to non-real values of temperature. This approach is functionally similar to the previously explained adaptive IIR filter, but less sophisticated and effective at removing artefacts, since it is good only for identifying the samples affected by the ambient temperature of the sensor.
Furthermore, a least-mean-squares (LMS) filter can also implemented and studied. This adaptive filter generates filter coefficients based on the minimization of squared errors, according to the least-mean-squares method.

3 Methodology & Workflow

The aim of the project was very clear since the beginning: to create a wearable, reliable, and low cost thermometer for continuous monitoring of healthcare workers and COVID-19 patients, in order to get warning signs to what could be the beginning of the disease and its progress through time. The main workflow of this project is illustrated in figure 7, and described in the subsequent subsections.

3.1 Materials

For the current project, a careful and methodological choice of the material was fundamental, since all devices should be suited for the purpose of continuous monitoring and real-time data processing and transmission. For this, it was chosen to use **NodeMCU ESP32** micro-controller for processing and transmission of data through WiFi or Bluetooth, given its main characteristics: low price (available for 13.30€) 512 KB of SRAM memory and integrated 16MB. Also, it was chosen to use **DFRobot's IR I2C Thermometer Sensor MLX90614** [18], which uses 3.3V (operating voltage of the microcontroller) and has a resolution of 0.01 °C, being available for 18.80€. This sensor has a documented accuracu of ± 0.5 °and precision of 0.01 °C. Finally for the contact sensor, it was chosen the **Adafruit's I2C contact sensor MCP9808** [19], for its documented accuracy of ± 0.25 °C and precision of ± 0.0625 °C, purchased for 7.7€. All accessory material (jumper wires, leds, buttons, among others) was present in **Mauser's Development and Electronic Starter Sit compatible with Arduino and Raspberry Pi**, which was purchased for 22.41€. Both of these sensors are integrated in a breakout board, and therefore include amplification and regulation systems, which is a major advantage for this type of project, since there is no possibility to use oscilloscopes and function generators to study the response of the sensors in detail.

3.2 Data Visualization & processing

Since the raw data of all low-cost temperature sensors may not be suitable for human body temperature measurements, data must be first acquired and processed in a auxiliary software. For this, it was used **Matlab** Software for all the visualization and processing, prior to final implementation of the algorithms into NodeMCU breakout board, since Arduino IDE doesn't allow easy exploratory processes of the acquired data. Data was acquired using **CoolTerm** Software, which acquires data from the computer's USB port, since Matlab had troubles using this functionality. With this software, data was exported to a .csv file, which was then imported in Matlab.

3.3 Validation

The circuits were tested and validated through sensibility tests, using two different commercial thermometers and environments with controlled temperature. This step is extremely important, since the data may at first seem adequate and reliable, but the sensors and subsequent data processing may be showing temperatures different from the real ones.

3.4 Prototype & Data Export

After all data processing and validation, and making sure the data is as expected, the temperature measurement device can be changed and adapted to be wearable. It is important to note that this step will be the final step, in order to not make wrong assumptions regarding the quality of the data, i.e. temperature recordings could be wrong just by the fact that the sensor was misplaced in the developed prototype if this was an early step of the present workflow.

The main objective was to export the acquired data to an online cloud, accessed by the integrated WiFi module in the NodeMCU microcontroller. For this, the integration of the data using **Google Firebase** was studied, in order to verify the application and quality of data transmission to an online cloud, for further website development.

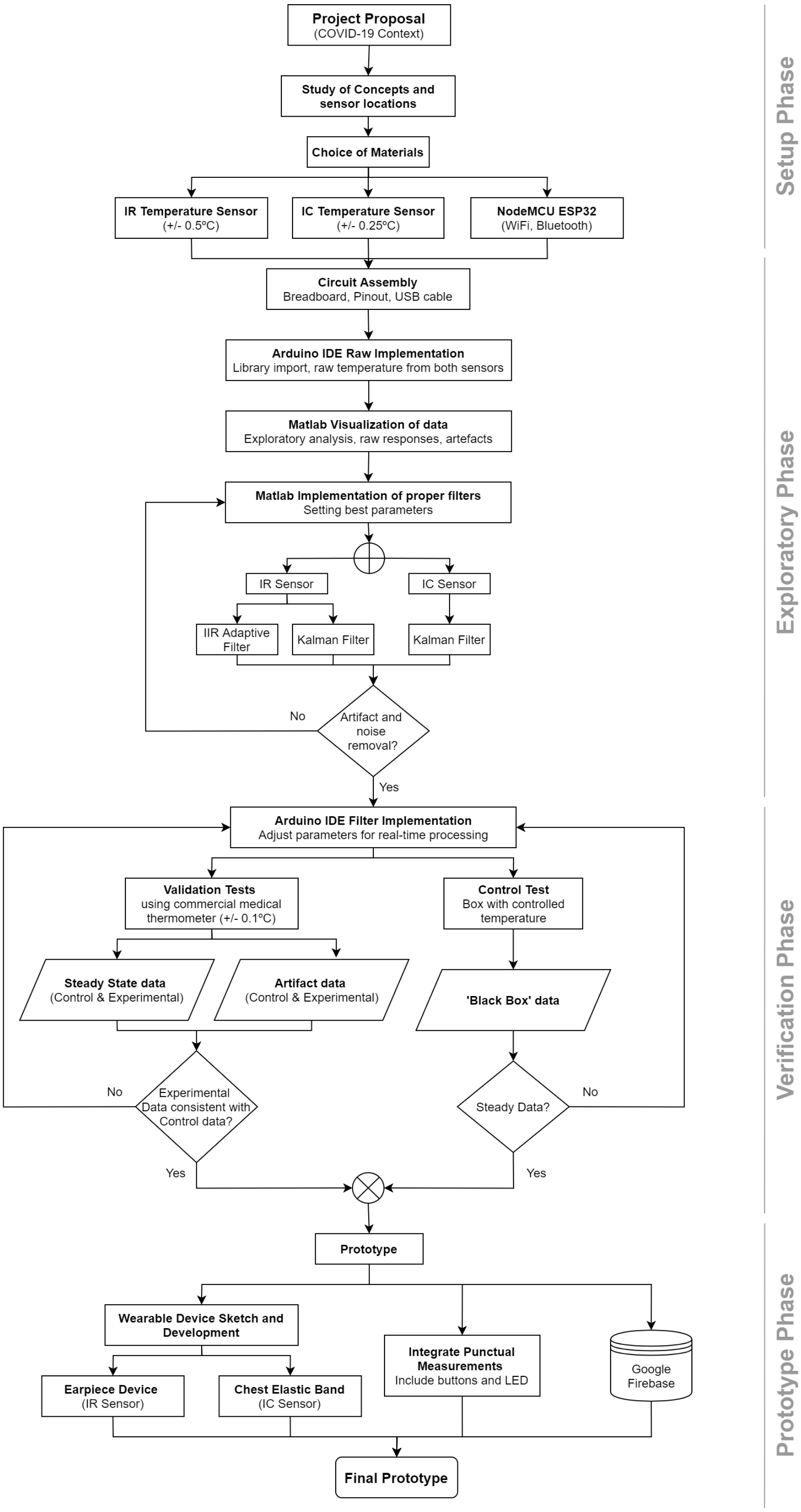


Figure 7: Workflow of the current project

4 Circuits and Results

4.1 Masked Samples & Sensor Placing

Until the code is implemented in the Arduino IDE, which is described in section 4.6, the following sections only provide an exploratory analysis of the data. For this purpose, the sensors were only connected to the computer via a USB cable, using the raw data obtaining codes available in the sensor documentation [19] [18].

4.2 Raw Signals and the Need to Process Data

As described in the previous sections, continuous monitoring is particularly demanding, since it requires to not only get accurate data, but also remove a variety of artefacts, namely movement artefacts, dependence on ambient temperature (only for Infrared sensors) and general artefacts associated with the sensor itself.

In fact, as shown in Figure 8, which illustrates the temperature registered by the chosen Infrared sensor placed in the ear for 7 minutes, the sensor itself may produce artefacts which are not corrected by the components in the breakout board, which causes the temperature to drop to non-physiological values. Also, it can be observed that this sensor is very sensitive to ambient temperature, since a brief "intended wind" around 3 minutes and a half after the beginning of the study), generated through a notebook fanned near the ear (where the sensor was placed) resulted in a change in temperature to values compatible with a fever. This puts into question the validity of the values obtained by this sensor in a continuous measurement scenario, since it shows non-physiologically compatible results when there is a variation in the ambient temperature measured by the sensor package.

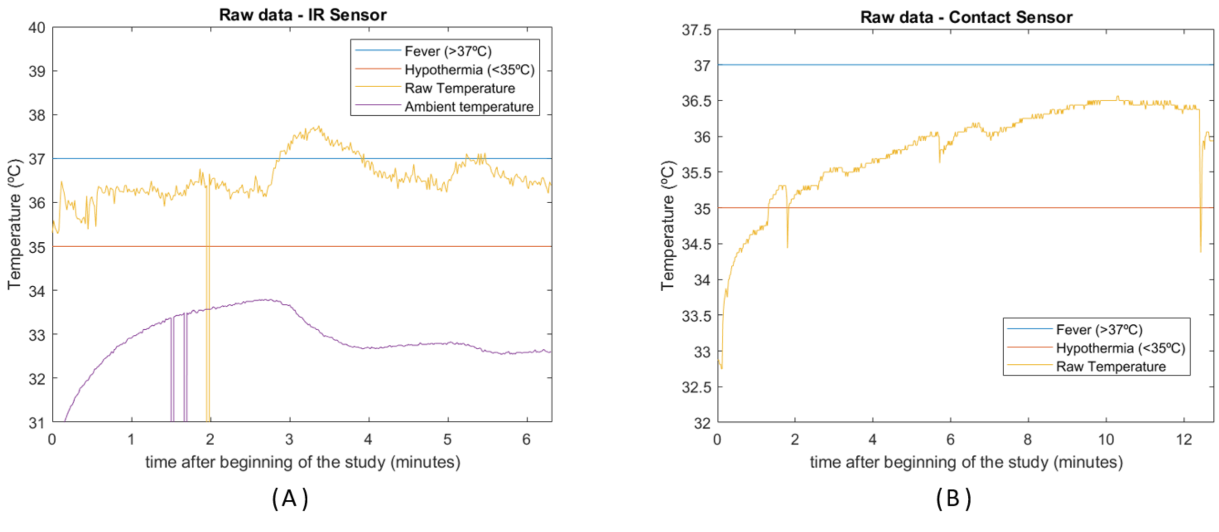


Figure 8: Raw data obtained from direct connection between MLX90614 IR sensor (A) or MCP9808 IC sensor (B) and NodeMCU ESP32, and subsequent data import to Matlab, for better analysis, using CoolTerm Software for saving the Serial data. (A) - The object temperature (yellow) is directly correlated with ambient temperature (purple), which measured in the sensor's casing, and shows spikes and movement artefacts, which are not compatible with physiological temperature variations in the human body.; (B) - The obtained temperature (yellow) shows spikes and movement artefacts, and also takes about 10 minutes to reack thermal equilibrium. which are not compatible aspects with physiological temperature of the human body.

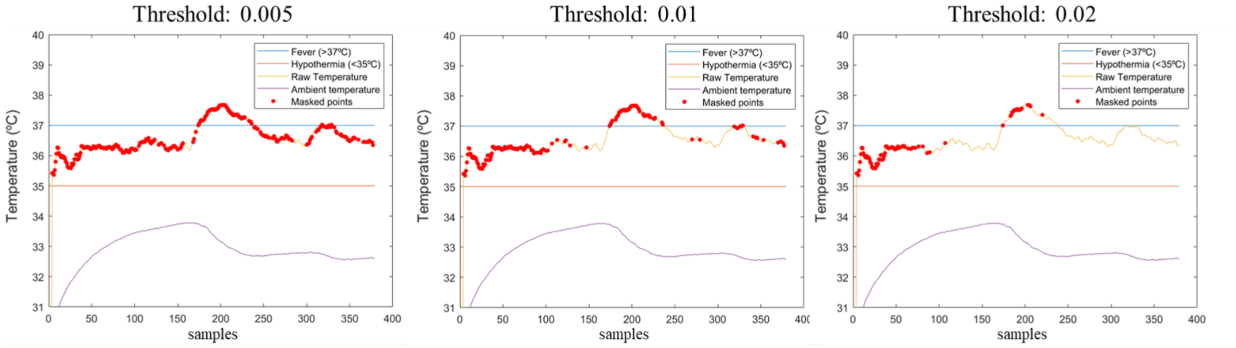


Figure 9: Masked samples, *i.e.* samples(red) that were clearly corrupted by the high variation of the ambient temperature (in purple). To be considered a masked sample, thresholds of 0.005, 0.01 and 0.02 were considered for the derivative of the ambient temperature, *i.e.* when above this threshold, the samples, which correspond to the object temperature (yellow) are marked as "masked" by the ambient temperature. In blue is represented the 37 °C warning line, and in orange the 35 °C warning line.

Finally, in this same figure, 5 minutes after the beginning of the study, the temperature rises again to values above 37 °C. In this instance, there it isn't a substantial change in the ambient temperature. This can occur due to movement artefacts. For this purpose, a threshold analysis was performed based on the derivative of the ambient temperature, in order to only consider values of the object temperature when the system is in thermal equilibrium. For different thresholds of the derivative, it can be seen in figure 9 that a large number of samples are affected by the change in ambient temperature, and effectively correspond to regions where the object temperature increases or decreases, indicating that some type of processing will be necessary to eliminate this type of correlation.

Likewise, the IC contact sensor also has intrinsic artefacts, as can be seen in the sharp decrease in temperature, in figure 8, which shows the IC sensor placed in the axilla for about 12 minutes. Also, in this particular situation, the sensor seems to take about 10 minutes to reach an equilibrium. However, it must be noted that this was not observed in later measurements, which were performed more rigorously.

All of these factors can be fairly easily corrected by data processing, using different filters. As was previously described, Kalman filters are very suitable for stabilizing data, which is necessary in the case of physiological measurements with slow rates of change, such as body temperature. It is also promising in the removal of movement artefacts and those caused by the sensor itself. Likewise, IIR adaptive filters can be used to remove the artefacts related to the correlation between ambient and object temperatures obtained by IR sensors.

4.3 Sensor Placing

In previous sections, it was mentioned that the core or skin temperature could be easily measured in the ear and temporal artery (with infrared sensors) and behind the ear or at the axilla (with contact sensors), respectively. Other locations could be considered but would be rather invasive and not comfortable for continuous measurement. However, with these initial results, it was decided that it would not be justifiable to measure the temperature of the temporal artery with infrared sensors, since it is an area that is very susceptible to variations in ambient temperature, and therefore would insert more variability and artefacts into the data.

Likewise, both the temporal artery and the region behind the ear, due to their location and the morphology of the ear surface, would not be areas indicated for this type of sensors, since they would cause unnecessary discomfort and result in increased difficulty in the conception of the wear-

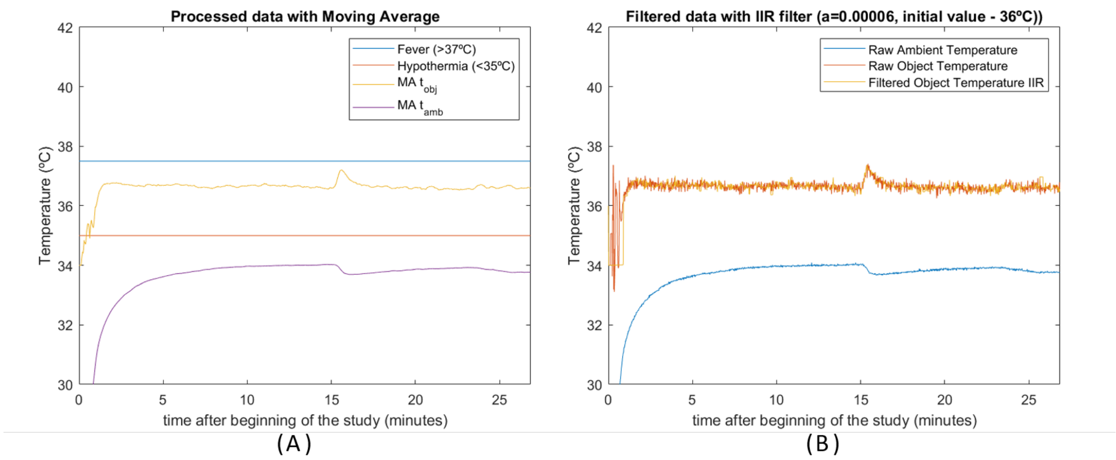


Figure 10: Removing signal noise, excessive variation and artefact attenuation (caused by bad contact within the sensor itself) by filtering smoothing, using for this (A) - Moving averages; or (B) - simple IIR filters. In yellow is represented the object temperature filtered by these two filters, respectively. In (A) is also visible the warning lines for 35 °C (orange) and 37 °C (blue), and ambient temperature (purple). In (B) we can also see the raw object temperature captured by the sensor (orange) and raw ambient temperature.

able prototype, due to the variability of dimensions across the population.
Therefore, for the following sections, only two sensor locations will be considered. For the infrared sensor, all measurements will be made at the ear, and for the IC contact sensor, all measurements will be made at the axilla.

4.4 Influence of Filters

Multiple factors need to be taken into account when designing the data processing of this device, in addition to the attenuation of artefacts and the smoothing of the data.
One such fact is that body temperature varies very slowly, so the data obtained should not vary more than what can be explained by the natural variation of body temperature. This justifies the use of very strong filtering, to eliminate high frequencies caused by noise or artefacts. Additionally, the stabilization time of the sensor and of the filters needs to be taken into account. If a punctual reading is being performed, this is vital, as it is essential that such a device does not take longer than a commercial digital thermometer to deliver an accurate reading. In the case of continuous temperature monitoring, the smoothing of artefacts and high-mid frequency noise needs to be the priority. If the temperature is taken continuously for two hours, stabilizing time is less of a factor, and the priority is that the data is smooth and accurate.

4.4.1 Non-Contact IR sensor

For this sensor, the correlation between ambient and object temperature variations makes it very suitable to use an adaptive IIR filter. This filter can respond very effectively to these types of artefacts.
In addition to artefact attenuation, it is necessary to remove signal noise and to apply pre- and post-filtering smoothing in order to obtain a signal which only contains variations that are caused by physiological characteristics. Some options that could be considered for this would be simple low-pass filters and moving averages. These can be very effective in their own right. A use of such a filter to remove noise can be seen in figure 10.
However, these usually depend on "future values" in order to be accurate, and there is a more accurate, and more memory and computationally efficient alternative, namely the Kalman filter.

4.4.1.1 Kalman

In the case of the IR sensor, it is applied once initially to the ambient and object temperatures to remove noise and therefore enable better application of the IIR filter, and applied after the filtering to eliminate variations caused by the IIR filter itself, producing a very stable signal that is much less prone to artefacts, as can be observed in figure 11.

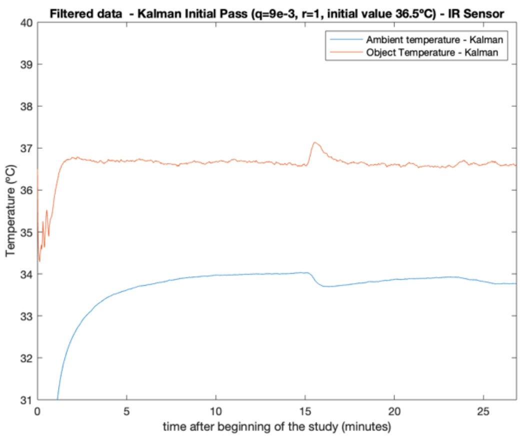


Figure 11: IR sensor - Initial pass of Kalman filter, using the following parameters: Q=9e-3, R=1, Initial value=36.5 °C. In orange is represented the Object temperature, and in blue the ambient temperature, after Kalman initial pass.

This effect is very similar to a moving average, however it requires fewer variables to be saved by the system, so it is more computationally effective. There are two tuning parameters, Q and R. These affect how "strong" the filter is, i.e. how aggressively it filters out higher frequency noise. For the Matlab implementation of this filter, in this situation we applied Q=9e-3 and R=1, but these values were adjusted subsequently when implementing and testing the device with the Arduino IDE.

This filter's stabilization time results from it being a low-pass filter, however, since it is followed up by an IIR filter this stabilization is irrelevant, because the IR filter starts from a fixed value.

4.4.1.2 Kalman + IIR

This filter is very adequate for the smoothing of artefacts, especially those caused by wind and similar causes that lower the ambient temperature. In order to obtain the best results, there should be some pre-filtering, using a Kalman filter, in order to remove high frequency signal noise.

In figure 12, its effect can be observed. The observed artefact is almost completely eliminated. This filter is therefore a very powerful tool and enables the elimination of a plethora of artefacts without causing delay or losing signal information. Furthermore, it doesn't take a lot of time to stabilize. Its stabilization time depends on when the ambient temperature has stabilized, however, since its initial value can be set as for example 36 °C, it only has to stabilize from that initial value.

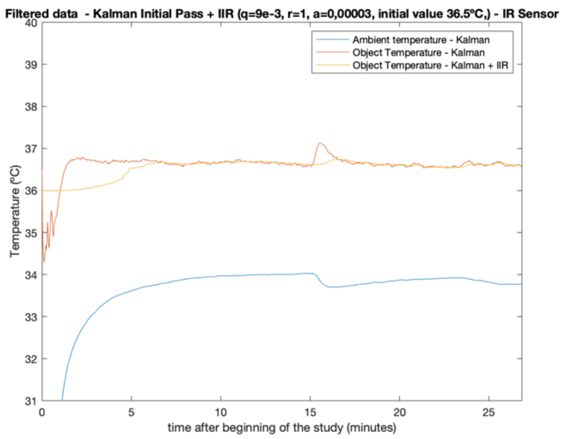


Figure 12: IR sensor - Initial pass of Kalman filter (Q=9E-3, R=1, initial value=36.5 °C) with IIR adaptive filter (a=0,00003, initial value 36.5 °C). In orange is represented the Object temperature after Kalman initial pass, in yellow the object temperature after Kalman first pass and IIR pass, and in blue the ambient temperature after Kalman initial pass.

Much like with the aforementioned Kalman filter, the IIR filter's parameters were changed when implemented in the Arduino IDE.

4.4.1.3 Kalman + IIR + Kalman

However, this isn't very smooth, so in order to obtain better results there should be some post-filtering, using a stronger Kalman filter. This way a smooth result is obtained, that ideally varies as much as the internal body temperature. This is observable in figure 13.

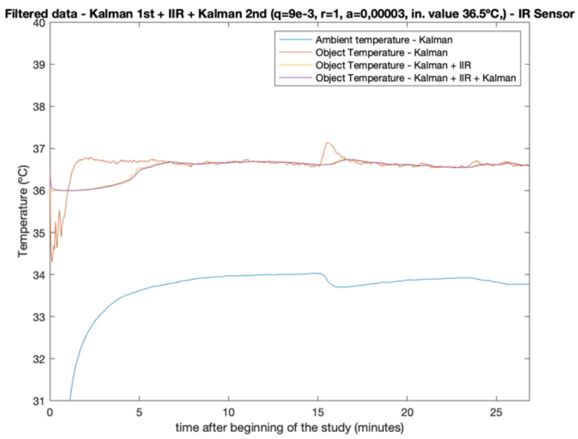


Figure 13: IR sensor - Initial pass of Kalman filter (Q=9E-3, R=1, initial value=36.5 °C) with IIR adaptive filter (a=0,00003, initial value 36.5) and second pass of Kalman filter (Q=9E-3, R=1, initial value=36.5 °C). In orange is represented the Object temperature after Kalman initial pass, in yellow the object temperature after Kalman first pass and IIR pass, in purple the object temperature after Kalman + IIR + Kalman, and in blue the ambient temperature after Kalman initial pass.

4.4.2 Contact IC sensor

4.4.2.1 Kalman

Much like was mentioned in the IR sensor, simple moving averages can be effective in removing artefacts, removing noise and smoothing out data, however, Kalman filtering is more effective and efficient. This filter is applied twice to the IC sensor data, in order to produce a clean and accurate signal, as can be seen in figure 14.

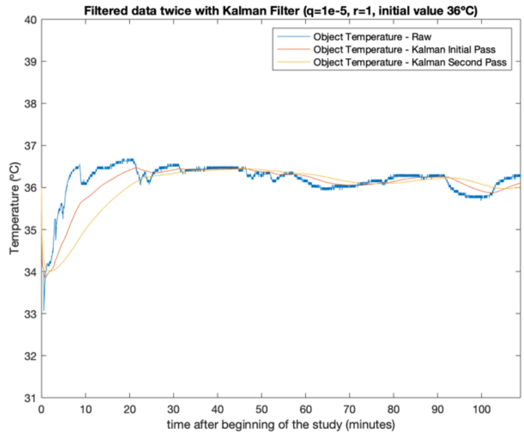


Figure 14: IC sensor - two passes of Kalman filter in object raw temperature (Q=1e-5, R=1, Initial value=36 °C). The raw object temperature can be seen in blue, in orange after an initial Kalman pass, and in yellow after two Kalman passes.

4.5 Breadboard montage

Until nothing said otherwise, only the results of continuous measurement option will be presented in the following sections, as this is the focus of the work. This study can be done by the user, through two main strategies. The first will be the simplest, through the direct connection of the sensors to the respective 3.3V, Ground and I2C pins (SDA on pin 21 and SCL on pin 22, in the NodeMCU ESP32 module used throughout this work). [1] The second strategy will be the integration of the point measurement option, using the pinout represented in figure 15, and use only the continuous measurement option for subsequent studies. The punctual measurement strategy will be just an add-on to this project, and will be explored in section 5.

Both codes can be found in the open source repository of GitHub, through the following URL: ***FALTA O LINK DO REPOSITORIO***. The available codes correspond only to the implementation of the processing in the Arduino IDE, and not of the exploratory analysis in Matlab.

[1]For more information about the pinout of this specific card, the following website is recommended: `https://randomnerdtutorials.com/esp32-pinout-reference-gpios/`

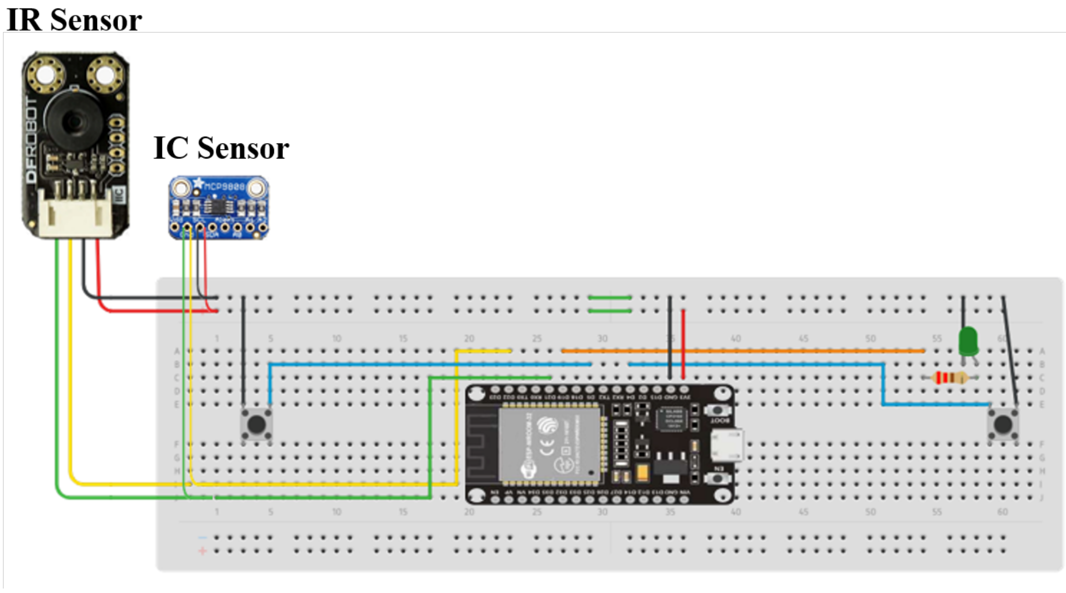


Figure 15: Schematic of the electrical circuit used after the implementation of the processing filters in the Arduino IDE. This scheme integrates the continuous measurement option, the objective of this work, and the point measurement option, which will be explored in more detail in section 5. A more detailed Pinout, buttons function, and jumper wire connections are detailed in the open-source repository of GitHub for this work.

4.6 Arduino IDE Implementation

As the data processing was previously implemented in Matlab using arrays with measurements over time, it had not been performed in real time. However, this would be necessary, in order to enable real time, continuous monitoring. Additionally, as the processing would be performed by an ESP32 board, it needed to be implemented in the Arduino IDE, which uses C++. This presented some further constrains, namely that every processing step needed to be included within the *loop()* function, which functions as an infinite while loop. Therefore, the filters were implemented as functions outside the loop and then called inside the loop. They were mostly implemented using vectors which contained the relevant variables. The Kalman filter and IIR filters were implemented as follows:

```
//Kalman:
//Initialization of global variables
double Q=0.004;
double R=1.000;
double xhat=36.500;
double P=1.000;
double xhatminus=0.000;
double Pminus=0.000;
double K=0.000;
double M=36.500;
double vm[]={xhat,P,xhatminus,Pminus,K,M,Q,R};

static void kalman(double v[]) {
    //prediction:
    v[2]=v[0];
    v[3]=v[1]+v[6];
    //update:
    v[4]=(v[3])/(v[3]+v[7]);
    v[0]=v[2]+v[4]*(v[5]-v[0]);
    v[1]=(1-v[4])*v[3];
}

//IIR:
//Initialization of global variables
//initial value for object temperature:
```

```
double y=36.000;
double alpha=0.000;
double a=0.00004;
//initial value for ambient temperature:
double tamb=1.000;
double vmf[]={tamb,alpha,y,a};

static void filtertemp(double vmIIR[],
double v[], double vA[]) {
    //derivative of ambient temperature:
    double deriv=fabs(vA[0]-vmIIR[0]);
    //calculation of alpha:
    vmIIR[1]=(2/(1+exp(-vmIIR[3]/deriv)))-1;
    double aux=vmIIR[2];
    //estimation of measurement:
    vmIIR[2]=vmIIR[1]*v[0]+(1-vmIIR[1])*aux;
    //adjusting previous ambient temperature
    vmIIR[0]=vA[0];

}
```

In the case of the IR sensor, the code for the continuous measurement essentially consisted mostly of calling the filter functions in succession.
Sometimes, poor contact in the wiring can cause very high or low values to appear. This eas fixed by using the previous value in cases where the raw temperature was displayed as being above 42 °C or below 30 °C.
"ALERT: POSSIBLE FEVER DETECTED" is displayed when the processed temperature reaches a level above 37.5, and *"ALERT: POSSIBLE PRE-FEBRILE STATE DETECTED"* is displayed when it reaches a level above 37.2.
However, in order to improve stabilization times, a short algorithm was implemented: 10 seconds are counted from the initialization of the prototype, to give it a short time to reach temperatures close to those of the body. The next 10 seconds worth of measurements are averaged into a value, and this value is used as the starting value for the IIR filter. This way, stabilization is almost instant.

```
//accounting for values caused by poor contact
double c=mlx.readObjectTempC();
      double a=mlx.readObjectTempC();
      if(c>42.0 || c<30.0) {
        c=d;
      }
      d=c;
      if(a>40.0 || a<20.0) {
        a=b;
      }
      b=a;

//waiting 10 seconds
if(counter1<10) {
    counter1+=1;
}
else {
 if (counter2<10){
  //averaging 10 measurements
  rr+=c/10;
  counter2+=1;
 }
 else {
  if(counter3<1) {
   //initializing variables
   vmf[2]=rr;
   vm[0]=rr;
   vm[5]=rr;
   vmPOST[0]=rr;
   vmPOST[5]=rr;
   counter3+=1;
 }
 else {
  //ambient temperature Kalman
  vmA[5]=a;
  kalman(vmA);

  //object temperature Kalman 1st pass
  vm[5]=c;
  kalman(vm);

  //object temperature IIR filter
  filtertemp(vmf,vm,vmA);

  //object temperature Kalman 2nd pass
  vmPOST[5]=vmf[2];
  kalman(vmPOST);
```

```
//fever alert
if(vmPOST[0]>37.5) {
 Serial.println("ALERT: POSSIBLE
 FEVER DETECTED")
}
else {
  if(vmPOST[0]>37.2) {
   Serial.println("ALERT: POSSIBLE PRE-
   -FEBRILE STATE DETECTED")
   }
}
//print
Serial.println(vmPOST[0], 3);
```

For the punctual measurement of the IR sensor, it was necessary to apply a Kalman filter, assess when the signal has stabilized to an acceptable temperature value, and average 10 consecutive values to return a measurement. Additionally, the same code shown in the previous segment for the continuous measurement is copied onto this part with the exception of the printing lines, in order to continue measuring continuously while obtaining a punctual measurement.

```
//Applying Kalman to object and
ambient temperature
vm_Pont[5]=mlx.readObjectTempC();
kalman(vm_Pont);
vmA[5]=mlx.readAmbientTempC();
kalman(vmA);

Serial.print("Measuring: ");
Serial.println(vm_Pont[0],1);

//checking for stabilization of object
temp. and ambient temp. derivative
if (vm_Pont[0]<34.7 || vm_Pont[0]>41.5
|| (fabs(vmA[0]-vmA[2]))>0.3) {
    j=0;
    kk=0;
    }
    else {
 if (j<20) {
  if ((fabs(vmA[0]-vmA[2]))<0.06) {
  j+=1;
  }
}
//averaging 10 latest values
else {
 if (kk<10) {
  Res+=(vm_Pont[0]/10);
  kk=kk+1;
  }
  else {
   Serial.print("Your Temperature is ");
   Serial.print(Res, 1);
   Serial.println("ºC");
   kk=0;
   j=0;
   Res=0;
  }
 }
}
```

In the case of the IC sensor, the continuous measurement only required the use of two consecutive Kalman filters. However, because of poor contact of some wires in the prototype, sometimes the sensor would output *nan*. This was remedied by outputting the previous measurement when the sensor would output *nan*, or indeed a value outside of the physiologically possible temperature range. When there are 10 *nan* outputs, an error message is shown, and the thermometer is switched off. Additionally, measures were taken to improve the stabilization time of the filter. Specifically, after waiting 30 seconds and averaging the values measured over the following 10 seconds, this value is saved. A weighted average of this value with the Kalman output is performed, in a way where at first this value has weight 1 and the Kalman output has weight 0, and over time the Kalman weight is progressively increased and this value's weight is decreased so that after 120 seconds only the Kalman value is being outputted. This enables the Kalman filter to stabilize while the signal being outputted is already stable. Like as is the case with the IR sensor, an alert is displayed when a temperature compatible with a fever or pre-febrile state is detected. The code is as follows:

```
float c = tempsensor.readTempC();

//detect nan
if(c>44.0 || isnan(c)){
 if(isnan(c)){
 Serial.println("nan");
 }
 c=d;
 nanI+=1;
 if(nanI==10) {
  Serial.println("There has been an error.
  Please check the connection");
  //turning off
  digitalWrite(pin_LEDON, LOW);
  LEDstatusON = LOW;
  x=false;
  nanI=0;
  }
}
d=c;

//kalman 1st pass
vm[5]=c;
kalman(vm);
//kalman 2nd pass
vmCPost[5]=vmC[0];
kalman(vmCPost);

if(counter1<30) {
 counter1+=1;
}
 else {
  if (counter2<=10){
   rr+=vm[0]/10;
   counter2+=1;
  }
  else {
   counteraux=(120-counter)/120;
   result=counteraux*rr+(1-counteraux)*vm[0];

   if (counter<120){
    counter+=1;
   }
   //fever alert
   if(result>37.5) {
    Serial.println("ALERT: POSSIBLE FEVER
    DETECTED")
   }
   else {
    if(vmPOST[0]>37.2) {
     Serial.println("ALERT: POSSIBLE PRE-
     -FEBRILE STATE DETECTED")
     }
   }
   //print
   Serial.print(c, 3);
   Serial.print(",");
   Serial.println(result, 3);
  }
```

As it pertains to the punctual measurement, the code is very similar to the IR sensor, however the stabilization factor is only the derivative of the object temperature, and not the ambient temperature. As with the IR sensor, the code for the continuous measurement is copied onto this part without the print statements.

```
if (j<10) {
 if ((fabs(vm_Pont[0]-vm_Pont[2]))<0.1) {
  j+=1;
 }
}
else {
 if (kk<5) {
 Res+=(vm_Pont[0]/5);
 kk=kk+1;
 }
 else {
   Serial.print("Your Temperature is ");
   Serial.print(Res, 1);
   Serial.println("º C");
   kk=0;
   j=0;
   Res=0;
 }
}
```

To note that the stabilization steps, presented in this section, were a last-minute add-on to this

project. All the results until the "Prototype" section were performed using a stabilization time of about 2 minutes, which represented the stabilization time of the sensors itself.
Due to time limitations, it was chosen to not re-do all the findings in the following sections using this new approach for initial stabilization. The code presented in this section is thus the final code for continuous and punctual measurements, both for IC and IR sensors.

4.7 Validation

After the filter implementation in Arduino IDE, with the parameters that best fit these sensors and context, several validation tests were done. These tests were carried out with a controlled temperature box with black tape, in order to simulate a black box with constant temperature, and using commercial thermometers. Small adjustments to the parameters initially established with the aid of the Matlab software were made, in order to adapt this problem to the context of real-time monitoring. The following sections demonstrate the temperature curves obtained through these validation tests, already using the ideal parameters (present in the previous section).
The code used can be found in the GitHub repository, since it has undergone a slight adaptation to the initial starting value, since the initial values used for the physiological context would be too high for the analyzed temperature range.
In the following sections, the blue color will be conveniently assigned to the temperature data collected with the contact sensor IC and the red color to the data collected with the infrared sensor, in order to facilitate this data analysis.

4.7.1 Controlled Temperature Ambient

In order to simulate a constant temperature environment, to study the stability of the sensors after the implemented processes, an insulated box covered with black adhesive tape was used in the first instance to better represent the emissivity of the skin.
This box was also lined with cardboard, as it was quite thin and could therefore be sensitive to punctual temperature variations. The used box is shown in figure 16.

Figure 16: Assembly of a 'black box', in order to simulate a temperature-controlled environment with similar skin emissivity. The box was covered with cardboard to increase the temperature stability on the walls of the box.

4.7.1.1 Non-contact IR sensor

In order to study the stabilization capacity of the assembly relative to the infrared thermometer, the sensor was placed inside the 'black box' for approximately 20 minutes, obtaining the temperature response that is present in the figure 17.
In general, we can infer that the sensor takes approximately two minutes to stabilize, which, according to the objective of continuous measurement for several hours, for which this device is being developed, will be negligible. On the other hand, it is shown that in general the values fluctuate very little, in the order of 0.1 °C in the instant immediately after the curve stabilizes and 0.05 °C after 6 minutes from the beginning of the study, which in a human physiological measurement will not be significant.
Still, when comparing with the raw temperature values, we can still verify that a significant improvement was achieved when compared with the initial values, which present a huge variability, for all the aspects that were previously mentioned. The small peaks observed will therefore be a mirror of the temperature measured without processing by the

sensor, which due to its small amplitude and duration, will not be significant for long-term measurements.

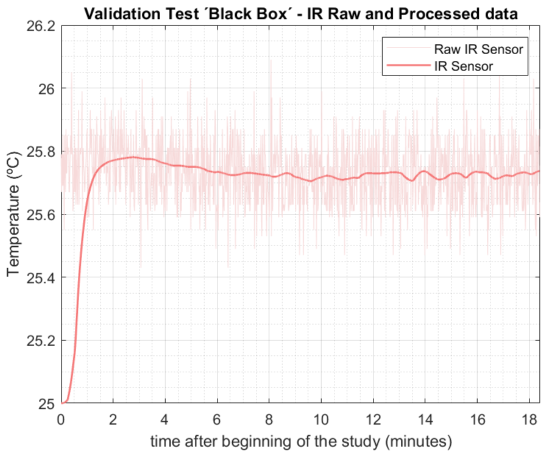


Figure 17: Raw and processed data obtained with the infrared thermometer montage inside the controlled-temperature “black box”. The precision of these measurements is of 0.1270 °C.

The precision of subsequent measurements can also be estimated from the stability of the values obtained, based on the standard deviation of a series of repetitions of the same analysis. In this case, since the temperature was measured for approximately 18 minutes, therefore not allowing for large variations in the ambient temperature, we can assume that the real value, and therefore the value of the various measurements, must be constant. Therefore, giving a sampling frequency of 1Hz and a duration of 1105 seconds, the number of measurements is N=1105. The mean of the N=1105 measurements is $\bar{x} = 25.7054°C$. The precision is, therefore, the following:

$$\sigma_{sample} = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N-1}} = \sqrt{\frac{\sum (x_i - 25.7054)^2}{1105-1}}$$

$$= 0.1270°C$$

This value is compatible with most uncertainties observed in most medical thermometer, such as the ones used in the current study, which is a good indicator of the validity of the measurements. To note that this value includes the stabilization region. If the first two minutes of the data is not considered, the obtained precision is of 0.0182 °C.

4.7.1.2 Contact IC sensor

Likewise, a test was performed on the IC sensor to study its response to a controlled temperature environment. This measurement was done simultaneously with the infrared study, for about 20 minutes, to remove any variability caused by temperature changes in only one study. The results are shown in figure 18.

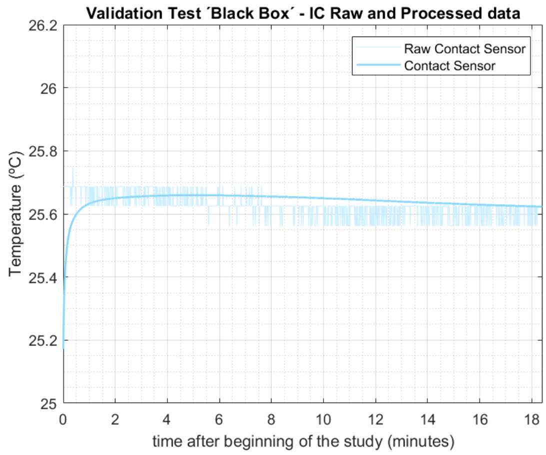
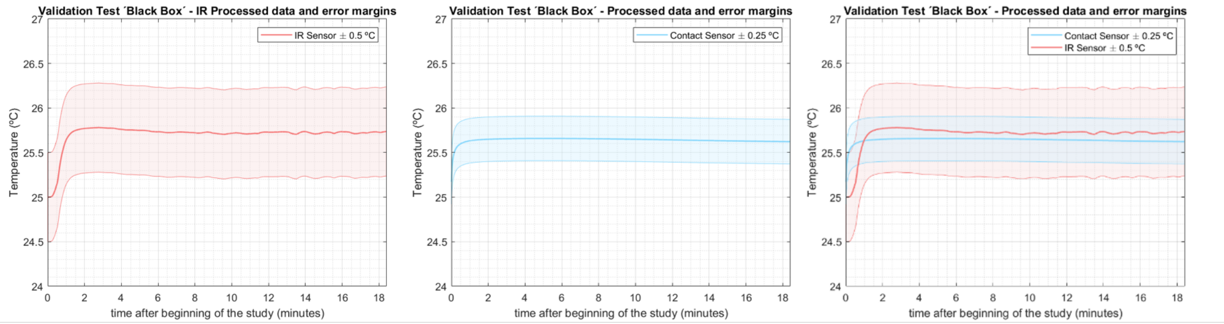


Figure 18: Raw and processed data obtained with the contact IC thermometer montage inside the controlled-temperature “black box”. The precision of these measurements is of 0.0308 °C, and the visual stability of the data is one of the main features of this results.

We were able to verify that the stabilization time for this type of test, for the parameters used, and for this sensor is quite low, being in the range of 1 to 2 minutes. In the face of a continuous temperature context, we can admit that the results are quite satisfactory in this point of view, as it approaches the stabilization time of a commercial point temperature measuring contact thermometer.
In the stability region, between approximately 2 minutes after the beginning of the study and the end of the study, we can infer that the temperature is quite stable, even more than with the infrared



(A) (B) (C)

Figure 19: Processed data with associated documented accuracy of $\pm 0.5°C$ for IR sensors (A) and $\pm 0.25°C$ for IC sensors (B). The comparison of the obtained values can also be seen in figure (C), which demonstrates a clear correlation between both sensors.

sensor, varying roughly only 0.05 °C. This change is always linear, not showing the small variations indicated for the infrared sensor, justified by the intrinsic nature of the contact sensor which not as variable as the detection of infrared emissivity in several directions.

As for the infrared sensor, it is also possible to estimate the precision of these measurements. Since the mean value of this set of measurements is of $\bar{x} = 25.6407°C$, and the number of measurements N=1105, the precision is the following:

$$\sigma_{sample} = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N-1}} = \sqrt{\frac{\sum (x_i - 25.6407)^2}{1105-1}}$$

$$= 0.0308°C$$

Likewise what was done for the infrared sensor, if we remove the first two minutes of the measurements, we obtain a value of $\sigma_{sample} = 0.0112°C$. However, the value obtained with the stabilization samples is also very small, which indicates that this sensor may be a good option for precise and stables measurements. However, to validate this option, we must also do tests of response to intentional artefacts, in order to study the stability and response of both sensors, which are demonstrated in next sections.

4.7.1.3 Limitations and Comparison between Sensors

A limitation of this analysis will be the range of values considered. Due to material limitations and movement due to the COVID-19 pandemic, the tests performed were of short duration and using only materials available at the home of the group members. Validation at controlled temperature only demonstrated stability for a range of temperature values approximately 10 °C below the physiological temperature of the human body, so it is not guaranteed that this will be true for the rest of the temperature range. However, based on the fact that the documented 0.5 °C accuracy is also valid for this range of values, it is assumed that the stability introduced by the processing will also be maintained for a slightly higher temperature range. Due to problems with the Serial Port of the group member with access to the box, longer records were not possible for this test. With that said, the following sections will only consider the documented accuracy for the sensors, namely $\pm 0.5°C$ for IR sensors and $\pm 0.25°C$ for IC sensors. The results of this section, with these uncertainty curves, can be seen in figure 19. Finally, due to the self-heating property, some variance in temperature may also be associated with this drawback, which has already been mentioned in the disadvantages of both sensors. However, for this small study, this does not seem to introduce much variability in the data, and more prolonged studies were carried out to study this hypothesis. As we can see in figure 19 (C), we can infer that the temperatures obtained by both the IR sensor and IC sensor are quite stable and compatible with each other. The IR sensor has a temperature about 0.1 °C higher than the IC sensor in most of the study, and a difference of 0.0647 °C from the average of the results. Since both temperatures are quite stable and close to each other, we can assume that the test is valid and the thermometers will be effectively measuring the temperature of the objects, even after the implemented processing, with small differences associated with the accuracy of the sensors itself.

4.7.2 Commercial thermometer

In order to assess the exactitude of the measurements, it was also chosen to carry out measurements in a so-called steady-state, in order to study the stability of the thermometers when used in physiological environments. However, because human beings experience changes in temperature throughout the day, albeit in a very mild way, it was necessary to validate the results obtained through synchronous measurement with a commercial thermometer. This test therefore has an advantage over the previous one, since we will have comparison measures that allow us to combine the stability of the data with its exactitude.

The study was carried out with care for the subject to remain as static as possible, so as not to introduce more unknown variables that would create variation in the data (such as movement artefacts, which will be explored in the next section). The thermometer used was the Geratherm medical thermometer GT-131 color with an accuracy of 0.1 °C [20], which is a contact thermometer for use in the axilla. The study was carried out for about 25 minutes, by both sensors measuring at the same time, and about two hours after eating food. The results obtained for both sensors, as well as the data collected with the commercial thermometer and with a baseline of + 0.4 °C of these values are shown in the figure 20.

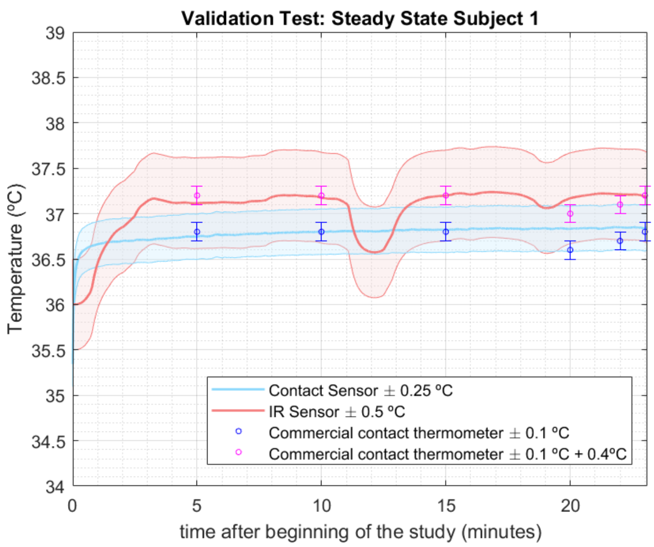


Figure 20: Data obtained through a stability test with the simultaneous use of the IC (blue) and IR (red) sensor, as well as verification through a commercial thermometer with 0.1 °C accuracy. The greatest depression in the red curve is associated with the intentional removal of the IR sensor. The IC sensor has practically the same temperature as the commercial thermometer. There is a difference of about 0.4 °C between the values of the IR sensor when compared with the results of the commercial thermometer, associated with the temperature tendency higher in the ear.

First, it is possible to note the high stability of the results, after the stabilization period of about 1 minute for the IC sensor (blue) and 3 minutes for the IR sensor (red), which corroborates the conclusions made with the box controlled temperature and indicating that the stability will be valid for a range of values close to those tested.

The depression recorded in the measurements of the infrared sensor (red curve), between approximately 11 and 14 minutes after the start of the study, was due to the voluntary removal of the sensor, and is of high importance. In fact, one of the main concerns with a filtering process that attributes stability (inserted by the Kalman filter) would be the fact that the effective value of the measure to be carried out is potentially lost, since the past values are always weighted. However, it turns out that this is not the case: the sensor was removed from the ear (approximately 10 minutes after the beginning of the study) for approximately one minute, then placed in the ear, which will not correspond to a "punctual artefact" but to an effective temperature variation. The Kalman filter behaves according to this statement, dropping its temperature about 30 seconds after removing the ear sensor, and recovering the ear temperature shortly after the sensor is replaced. The artefact verified approximately 19 minutes after the end of the study was unintentional and may possibly represent an unintentional motion artefact. This subject will be explored in the next section, but we can notice that even so the temperature varies very little (about 0.1 °C) and for a short time, which again indicates the applicability of the Kalman filter for insertion of stability.

Finally, analyzing the results in comparison with the values obtained for the commercial contact thermometer for measurements in the axilla, the results obtained are quite reasonable and comparable. As stated in the introductory section of this report, the temperature measured in the ear, when the infrared sensor is exactly aligned with the tympanic membrane (core body temperature), tends to be higher than the temperature recorded by armpit thermometers (skin temperature). However, the difference in temperature values is quite variable from person to person, as can be seen in the figure 2, hence the general body temperature is an alert when it reaches the value of about 37.5 °C, being preventively monitored from here.

In this particular case, it was found that the temperature measured by the contact sensor IC adjusted almost perfectly to all measurements made by the commercial thermometer. The slight difference in the values obtained after 20 minutes after the beginning of the study can be justified by the uncertainty associated with the commercial thermometer, since, after obtaining a value about 0.2 °C below the temperature measured by the IC sensor (20 minutes), two more measurements were made within two minutes. These last measurements made by the commercial thermometer showed a variation of about 0.2 °C in 3 minutes, which will not be a good indication of the natural variation in the physiological temperature. However, all values obtained for the IR sensor, except for the region of intentional removal of the sensor, were higher than those obtained by the sensor IC.

In order to check if there would be any standard, a baseline of + 0.4 °C was added to all measurements of the commercial thermometer, and these new measurements adjusted almost perfectly to the data obtained by the IR sensor. This small change is justified by the tendency of the temperature in the ear to be slightly higher than that of the armpit, together with the uncertainty associated with this sensor. Due to material limitations, it was not possible to accurately monitor the temperature in the ear canal.

4.8 Artefacts

Similar tests were performed on both sensors to evaluate their processing's response to punctual artefacts. The test lasted 90 minutes, and the participant's temperature was taken every 5 minutes with two commercial thermometers: Geratherm axillar digital thermometer GT-2038 with an accuracy of 0.1 °C and forehead IR thermometer KFT-22 with an accuracy of 0.2 °C. Every 20 minutes, at the 20, 40, 60 and 80 minute marks, an artefact was simulated. These were, respectively, blowing air into the sensor using a notebook to induce a

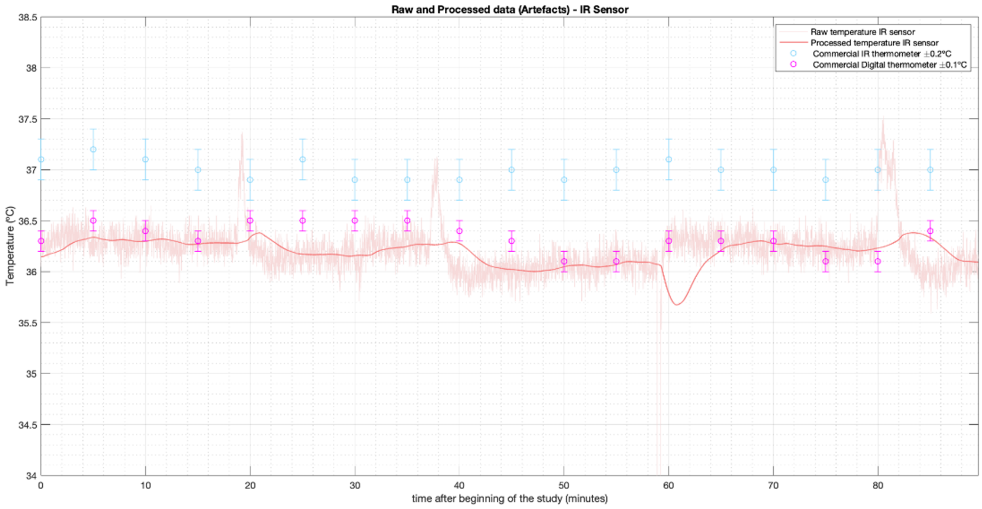


Figure 21: Artefact analysis test. Includes raw measurement data (light red) and processed data (red), as well as IR (blue) and digital commercial thermometer (magenta) validation. The performed artefacts were "blowing air into the sensor", "walking for 2 minutes", "removing the sensor for 20 seconds" and "going outside for 2 minutes", respectively 20, 40, 60 and 80 minutes after the beginning of the study.

simulated wind current, walking quickly for 2 minutes, removing the sensor for 20 seconds, and going to a window or outside for 2 minutes.

4.8.1 Non-contact IR sensor

As can be observed in figure 21, the first two artefacts produced large peaks in the raw data, roughly 1 °C above the previously recorded temperatures, reaching fever or pre-febrile temperatures. However, these artefacts were very well compensated for, and the outputted processed data only showed a 0.1 °C increase. This is due to the correlation with ambient temperature changes being used to calibrate the adaptive IIR filter, which makes the device very adequate at responding to these artefacts.

The third artefact produced a very sharp decline in the raw temperature, approximately 10 °C, while the sensor was outside the ear, due to the sensor measuring room the temperature. The processing was able to reduce this drop to a 0.4 °C drop, which stabilized after approximately 5 minutes. The fourth artefact, while similar to the first two, produced an even larger peak of 1.5 °C. The filters managed to reduce this to a 0.2 °C increase.

In summation, it can be concluded that the artefact response for these types of common artefacts is very suitable and capable.

4.8.2 Contact IC sensor

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5 Prototype

As previously mentioned, this device will be able to measure temperature both in a continuous and a punctual manner. To alternate between both of these, a button was integrated into the prototype. Furthermore, a button was also included to start and stop measurements, effectively turning its functionality on and off. Both of these buttons were integrated with a pullup resistor, i.e. using the 5V output and internal resistor of the ESP32 digital pins instead of a separate voltage source and resistor, enabling the buttons to only be connected to the ground and their digital pin. Furthermore, using a simple program, these buttons were transformed into switches, and debouncing was used to prevent small variations from acting like separate button presses, which enabled the buttons to function in a more stable manner. The code that integrates these functionalities was modified from a guide found on the website `martyncurrey.com` and is present in the GitHub repository of this project and will not be explored in this report, as it is not considered the main objective of it.

The general assembly of this prototype is present in the figure 22 and will serve as the basis for the following modifications, focusing only on the sensors and their respective positioning in the human body.

5.1 Punctual Measurement

The main objective of this project is the continuous measurement and monitoring of temperature, using IR and IC sensors. However, the decision was made to integrate a punctual temperature measurement system, in order to increase the applicability of these prototypes. For this type of measurement, the main objective is to provide a fast and accurate measurement. Filtering is not as important as determining when the signal has stabilized and averaging consecutive measurements once this is the case to obtain a suitable measurement. However, to reduce the variation between measurements and make it easier for it the stability of the signal to be assessed, a Kalman filter must be used. The Kalman filter introduces some delay in the variations observed in the initial measurements, which for long term measurement isn't a problem, but can be for punctual temperature measurement. In this case, a very light Kalman filter is applied to enable the assessment of whether the temperature has stabilized, and the final measurement is computed using a simple average of 10 consecutive stable measurements. In the case of the IR sensor, the determination of whether the temperature has stabilized is done using a threshold on the derivative of the ambient temperature. Therefore, once the ambient temperature is varying at a rate lower than

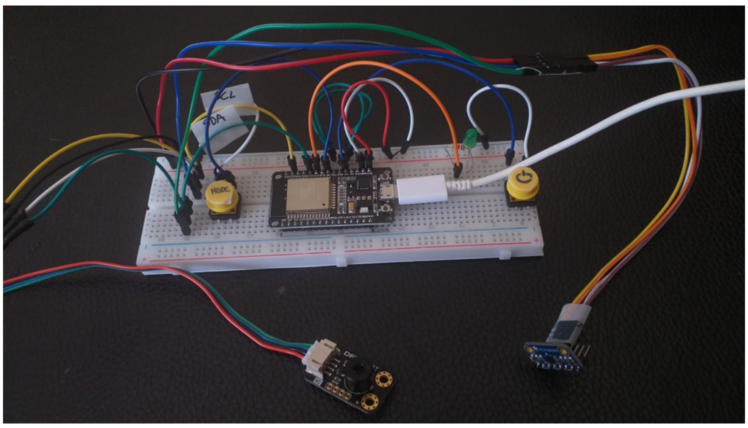

Figure 22: General assembly of the circuit used for prototype development. Only the sensor part was adapted, in order to be wearable, and thus further development to integrate microprocessor and battery in the prototype is needed.

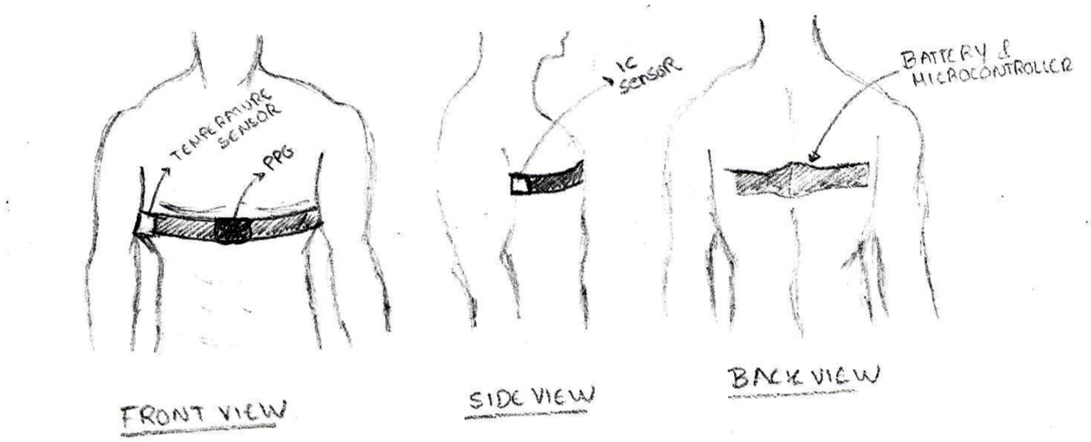

Figure 23: Sketch of a wearable device for integrating the IC contact sensor in an elastic band around the chest. The battery and microprocessor would be integrated in a lightweight pouch on the back.

an established threshold, and the object temperature is within an acceptable physiological range, after 15 seconds it is considered that it is stable. These conditions are verified throughout the measurement, in order to confirm that the signal hasn't destabilized. In the case of the IC sensor the stabilization is assessed in a very similar manner, with the exception that instead of the derivative of the ambient temperature being verified, the derivative of the object temperature is used. In both of these methods, the continuous measurements are still being taken and processed, but not being displayed, as to not have to restart the processing every time.

5.2 Contact IC sensor

For the integration of this sensor in a comfortable wearable device, to be used throughout the day, the use of an elastic band was chosen. This elastic band will be used around the user's chest, with the temperature sensor placed in the region of the axilla. In order to be compact, it would have a small lightweight compartment at the back, so as not to cause the vertical displacement of the band, where the battery and the microprocessor would be integrated. The connecting wires between these components and the sensor would be integrated between the two elastic layers that make up the band, which would be separable by velcro in order to allow washing the band for greater hygiene and in order to be a reusable device for another user. A sketch of this prototype is present in figure 23.
Due to material and resource limitations, only the contact sensor was integrated into a home-made elastic band, shown in the figure 24.

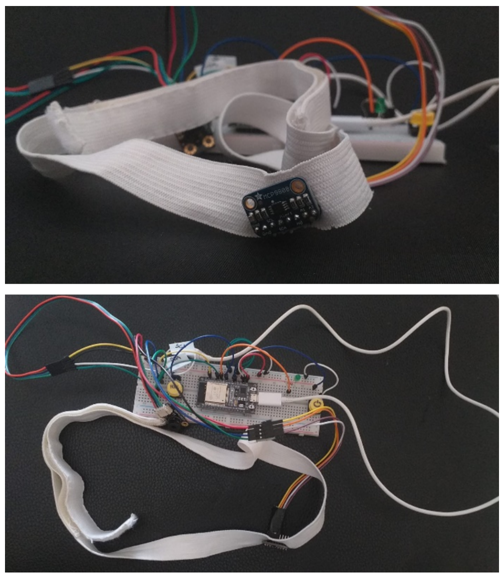

Figure 24: Integration of the IC sensor in a small elastic band. This prototype incorporates only the sensor part, so the power source and microprocessor are still external to this assembly.

The integration of the battery and microcontroller must be left for a potential continuation of the present work. In fact, this same prototype was used for all measurements made during the present work, since it made measurements easier to carry out and more comfortable. That said, the graphical results of using this prototype will not be included, since they have already been presented and can be consulted in the previous sections.

5.3 Non-Contact IR sensor

The realization of this prototype was a little more challenging, since it was desired to have a comfortable device that would cause virtually no hearing loss. This ideally would have integrated in a small protective lightweight casing the sensor, battery and microprocessor, associated with a small button to turn the device on and off, and a button for switching between continuous and point measurements. The variability between ear morphology between several people was also taken into account, trying to build a prototype relatively independent of these factors. A sketch of this prototype is present in figure 25.
Once again, due to material and resource limitations, the prototype was made based only on the modification of the sensor part, leaving the integration of the battery and microprocessor for a later phase. For this, the protective case of a lamp switch, ear support removed from a non-functional headset, and metal plates for assembly stability were used. The prototype built is present in the figure 26.

In order to verify that no additional unintended artefacts were inserted when the sensor was reassembled and positioned, further tests of stability and response to artefacts were carried out. In this way, it will be possible to compare the results obtained in this section and the results presented in the last sections, regarding the IR sensor, and check if the desired results have not been modified in any way.

Finally, since the prototype of the infrared sensor would be based mainly on the use of lightweight and low-cost materials, the possibility of integrating the sensor in a protective case made through 3D printing was also studied. For this, the OpenSCAD software was chosen, since it is a very intuitive soft-

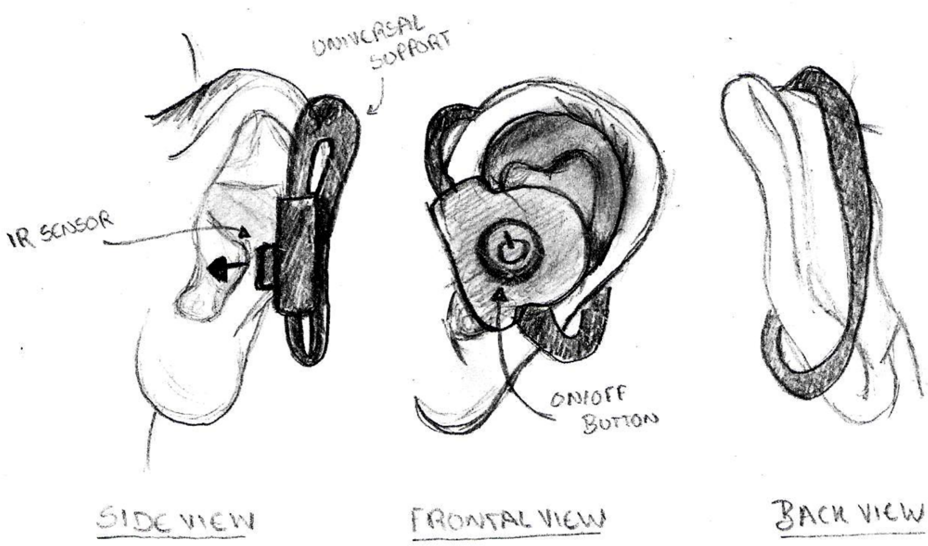

Figure 25: Sketch of a wearable device for integrating the IR sensor in an earpiece, with virtual ear loss. The battery and microprocessor would be integrated in a small compartment in this device.

Figure 26: Integration of the IR sensor in a small earpiece made with an old lamp switch. This prototype incorporates only the sensor part, so the power source and microprocessor are still external to this assembly.

ware, based on geometric shapes that are not very complex, as would be the case with this project.
The model created is shown in the figure 27, as well as the print result. This model was made just to allocate the sensor, leaving a small space for possible integration of a small battery and microprocessor. The cover was made in a sliding way, however due to the uncertainty associated with the 3D printing machine used, it will still have to undergo some improvements. Since the model created already has great precision in measurements and detailed adjustment to the MLX 90614 sensor, it is thought that this model could be a good basis for future developments in this area.

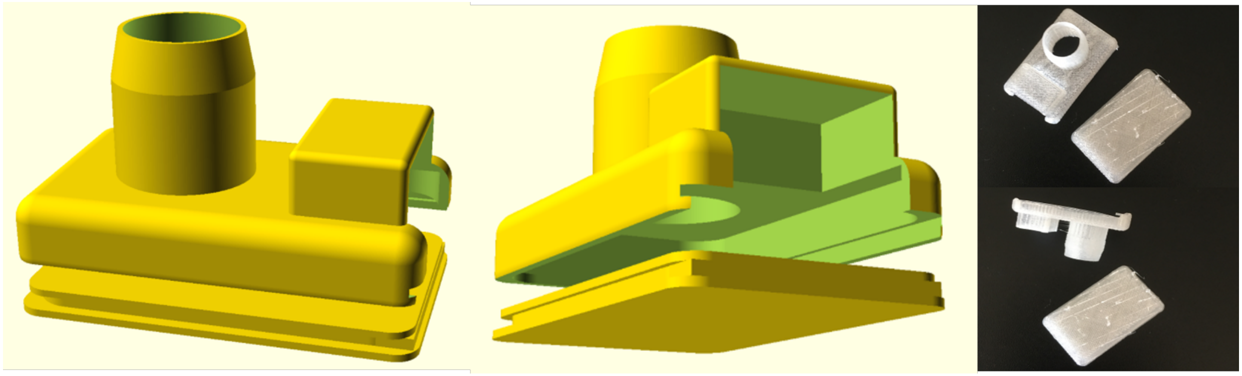

Figure 27: Sketch of a 3D model developed for this particular IR Sensor, using OpenSCAD, for 3D printing in large scale, as well as the 3D printed result.

5.4 OTA Programming

However, picturing that this could be potentially used in large-scale production, it will not be feasible to upload the code via an USB port to every microcontroller, since this port would never be used again in a real-life scale, being only a part that would consume space in the final prototype. Therefore, it is important to program an ESP through the air, i.e. have the code uploaded via WiFi and not via USB. This is what's called OTA programming (Over The Air). With this type of programming, one would no longer record the microcontroller over the USB cable, but through WiFi, which makes the process easier, since it allows us to update the software of a device that is of hard access (for example, inside a protective case and without USB port), without having to remove it from the place. There are a lot of OTA codes which will allow the upload of the code via WiFi, for several microcontrollers. In this case, it will be shown an example code for ESP32, as it is the one used in the present project, but this could be easily adapted to other types of boards, as the whole project itself. This code can be easily accessed in an opensource, by the following URL: `https://www.instructables.com/id/ESP32-and-ESP8266-Programming-in-the-Air/`. However, for the first upload of the code, it will still be needed an USB port to upload the OTA code, which may seem a bit counterproductive. However, this can be easily resolved using an FTDI Programmer. An FTDI programmer allows one to upload code to arduino-like devices which don't contain an USB port or which USB port doesn't work correctly. These devices are also very cheap, and can be used on several devices and with several microcontrollers, as long as they have available sutable libraries for this purpose. One can also use an arduino as an external programmer for other arduinos. A tutorial for this type of programming using Banggood FTDI Serial Adapter Module and ESP32 can be accessed on the following website `https://randomnerdtutorials.com/program-upload-code-esp32-cam/`. For the following code uploads and updates, the microcontroller and the computer with the respective code must be connected to the same WiFi network, in order to transfer the information "Over The Air". For a clinical context, this would mean that the code should be uploaded inside the hospital, in order to use the same WiFi network, or uploaded in a one-time trial in another environment, with the hospital WiFi specifications in the uploaded code. Other strategies could be considered, in a larger scale, such as a web page consisting on the monitoring of the sensor activity, and a option page, where it would automatically upload to the microcontroller the new WiFi's Network SSID and Password. The applications are endless in the IoT era!

6 Export Data

For a clinical context, it is very important to have a way of transmit, visualize and store the information in a Cloud environment, in order to be suited for several users, allowing for continuous monitoring and alert messages. That was why, from the start, care was taken to choose a microprocessor with WiFi and Bluetooth.
Google Firebase could be a wise choice for this. According to Google, "Firebase Realtime Database is a cloud-hosted database, where data is stored as JSON and synchronized in realtime to every connected client; When you build cross-platform apps with our iOS, Android, and JavaScript SDKs, all of your clients share one Realtime Database instance and automatically receive updates with the newest data" [21].
This means that this could be a base plattform for real-time synchronization, updated within milliseconds. These firebases are reported to remain responsive even when offline, and once connectivity is reestablished, the client device (in this case, a common server in a clinical context in a hospital or at home monitoring of COVID-19 symptoms) receives any changes it missed, synchronizing it with the current server state. This is very important in case of accidental disconnection of the device with the WiFi network, in order to not miss any data.
Therefore, this can be an easy and reliable way of storing data in a reliable and safe way, for further display in a web page or application. This Firebase is reported to be easily integrated with app development environments, such as Flutter, and Webpage servers. For ESP32 integration, there is a lot of available documentation and open-source libraries, which were tested throughout the final stage of this project, in order to test this option, as provided in mobizt repository on GitHub "Firebase-ESP32", available in the following link `https://github.com/mobizt/Firebase-ESP32`. The only drawback was that the ESP32 itself had troubles in connecting to home WiFi networks, despite detecting it. However, with a first mobile hotspot connection, as reported by many users with the same issue, it was able to connect to home WiFi networks and upload the data to the Firebase Real-time Database (which was also responsive, i.e. if the output to the firebase was an ON LED-state, it is posssible to change this variable to OFF in the firebase, and the result will be visible in real time in the ESP32.
For the sake of this project, a basic application will not be attempted for this purpose, nor to try to integrate this real-time database to an Webpage or Android Final Application, since we lack of IoT, Cybersecurrity and Cloud basics, which are very important when dealing with users personal information (such as name, age, date of admission, date of COVID-19 onset, etc) and therefore this step should be carried out by an expert in these areas.
However, to illustrate the ease of integration of the data received by Firebase, a professional in the area of application development was contacted, in order to create an application template, present in figure 28.

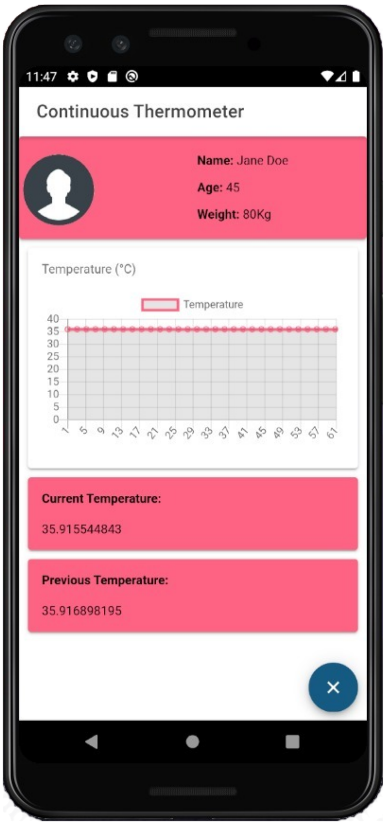

Figure 28: Template of an application with direct connection between ESP32 and Firebase. Data is displayed in real-time, without any delay.

The template found in figure 28 was made in approximately 4 hours, in Ionic (HTML), and displays the data in real time, without any delay, of the data collected by our prototype. This application also displays the temperature measured at a certain time, as well as the previous one, and has a responsive button which allows the user to start and end the data display.

For the integration of Google Firebase in the arduino IDE script, the instructions on the websites presented above were followed. An example of how to integrate this functionality is also present in the GitHub repository for this project, although censored when it comes to the passwords of the Firebase and WiFi project. The explanation of some of the lines of code used for Firebase integration in Arduino IDE is also shown below.

```
// I. Before void setup()
    // 1. This code is exclusively for
    // ESP32 Firebase Integration
    #include <HTTPClient.h>
    #include <HTTPUpdate.h>
    #include <HTTPClientESP32Ex.h>
    #include <WiFiClientSecureESP32.h>
    #include <ssl_client32.h>
    #include <FirebaseESP32.h>
    #include <FirebaseESP32HTTPClient.h>
    #include <FirebaseJson.h>
    #include <WiFi.h>
    #include <FirebaseESP32.h>

    // Name of the variable where data will
    // be stored in Firebase Real Time
    // Database
    String path = "/ESP32_Device";


    // 2. Change the following info for WiFi
    // connection and Firebase information
    //Change to your Firebase RTDB
    //project ID e.g.
    // Your_Project_ID.firebaseio.com
    define FIREBASE_HOST ...
    "XXXXXXXXXXXXXXX.firebaseio.com"
    //Change to your Firebase RTDB secret
    // password
    #define FIREBASE_AUTH "**********"
    // Change to your WiFi
    const char* ssid = "XXXXXXXXXXX ";
    const char* password = "***********";

    // 3. Define FirebaseESP8266 data object
    // for data sending and receiving
    FirebaseData firebaseData;

//II. Inside void setup()
    // 1. Connect WiFi
    WiFi.disconnect();
    WiFi.setSleep(false);
    Serial.print("Connecting to Wi-Fi");
    while (WiFi.status() != WL_CONNECTED) {
    Serial.print(".");
    delay(300);  }
    Serial.println();
    Serial.print("Connected with IP: ");
    Serial.println(WiFi.localIP());
    Serial.println();

    // 2. Set your Firebase info
    Firebase.begin(FIREBASE_HOST, FIREBASE_AUTH);

    // 3. Enable auto reconnect the WiFi
    // when connection lost
    Firebase.reconnectWiFi(true);

// III. Inside void loop()
    // To update variable \ContinuousDataRT"
    // in Firebase
    Firebase.setDouble(firebaseData, path + ...
    "/IRTemperature/ContinuousDataRT", ...
    vmPOST[0]);
    // To save value in a list
    // \ContinuousDataSave"
    Firebase.pushDouble(firebaseData, path + ...
    "/IRTemperature/ContinuousDataSAVE", ...
    vmPOST[0]);
```

7 Pros & Cons of both sensors

Both of these sensors have proven to be very reliable solutions for continuous temperature measurement applications. It is, however, valuable to compare these and explore what advantages and drawbacks they may present.

A key metric is stability and accuracy, specifically how the device can adjust for artefacts and noise in the data and provide a clear, readable and accurate measurement. This is essential in order to enable the data to be easily interpreted by medical professionals. Both of these sensors provide stability and accuracy, but the IR sensor is clearly a better choice regarding this metric, as the adaptive IIR filtering available with this sensor due to its correlated object and ambient temperatures enables this device to eliminate most common artefacts.

Another very important metric is comfort and ease of use. Since this device should be used for long periods of time, it is essential that it does not cause the user discomfort and doesn't interfere with daily activities. This is a subjective matter and may depend on the idiosyncrasies of how the final prototype would be designed. The IC sensor would, as mentioned, be placed in an elastic band around the chest. These can be used for sports and generally provide good comfort. The IR sensor would be placed in an earpiece. It is essential that this earpiece not only doesn't cause pain or discomfort when used for longer periods, but also doesn't disrupt hearing.

This device can also be combined with other physiological measurements, as will be discussed later in section 8. The IC prototype is particularly suitable for more complex applications, as an elastic band can be combined with a variety of different physiological measurements, such as heart rate, respiratory rate and volume, oxygen saturation and more. The IR sensor can be combined with photoplethysmography (PPG) in the ear lobe.

In summation, both of these provide very good performance. It is essential that, during more thorough development of a final prototype, special care is given to comfort and ease of use. Furthermore, when choosing one sensor, it is important to weigh the benefits of better accuracy and the capability of integration with other measurement types.

8 Applications

The current COVID-19 pandemic has spurred the development of the medical instrumentation necessary to tackle shortages worldwide. This device can be integrated as part of the solution in a variety of different applications and combined with different instrumentation types in projects that aim to acquire a variety of physiological data.

The main application being considered in the elaboration of this device is the home monitoring of COVID-19 patients. This device's capability of wirelessly transmitting data to databases can enable better monitoring of patients by health authorities, which can be instrumental in saving lives and controlling the pandemic. For this purpose, this device can be combined with measurements such as PPG, oxygen saturation, heart rate, respiratory rate and volume, and others to acquire as many measurements that may indicate COVID-19 progression as possible. A device that would combine these measurements could be an enormously powerful tool in tackling this pandemic.

Other possible applications include the use of this device by medical professionals. These individuals often have to work very long hours and are particularly exposed to this disease, and therefore could benefit from continuous measurement of their temperature, to assure early detection of contagion.

Another possible use would be for hospitalized patients. If the device is connected to a centralized hospital database, this can enable the continuous monitoring of temperatures of several hospitalized individuals and permit the timely detection of fever spikes. As mentioned, there are a plethora of possible applications for such a device, especially if it is possible to reduce costs to a minimum.

9 Main Ideas behind this project and Limitations

There have been studies regarding the suitability of infrared sensors for measuring the core body temperature and the correlation between the tympanic membrane temperature and the actual deep core body temperature. This work will not reconsider this aspect. Instead, we based our work on the assumption that the tympanic temperature can be expressed as a linear combination of the core body temperature, i.e., they differ only by a constant scaling factor and offset.

The temperature measured by the IC sensor in this device was observed to be practically the same as the one obtained by commercial thermometers.

As with most thermometers, a relevant limitation is the variability of body temperature between individuals, and the fact that the definition of fever is also not always exact and consistent between individuals. The threshold for fever that was decided upon was 37.5 °C. There was also a threshold set for the presence of a pre-febrile state at 37.2 °C.

Furthermore, all measurements were taken in situations where the subject was either sitting still or performing everyday tasks. This device is better suited for a clinical monitoring context that doesn't involve significant movement or physical activity, as this may disturb the accuracy of the measurements.

Due to current limitations relating to lack of proper hardware, the devised prototype isn't fully wearable yet, as it currently needs to be connected to an external microprocessor and a power source using a breadboard and cables. In order to obtain a fully wireless and wearable prototype, there needs to be a full integration of various components such as a power source and a microprocessor.

10 Conclusion & Expected Impact

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