The globe thermometer in comfort and environmental studies in buildings

El termómetro de globo en estudios de confort y medioambiente en los edificios

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Abstract

The reasons for the inferior performance of many existing buildings and associated energy systems are diverse, but an important part-cause is insufficient attention to the influence of occupant behaviour. In smart buildings it is necessary to allow for the integration of human behaviour in the HVAC system. In addition, many researchers are limited in their investigation by not having low cost tools that can provide information for their studies. This article is a review of the present state of art about the globe thermometer. It describes how to build your own globe temperature sensor and describes experiments that illustrate the feasibility of using a black globe thermometer with 40 mm diameter.

Keywords: Globe temperature, thermometer, mean radiant temperature, open hardware, sensor.

Resumen

Las razones del rendimiento inferior de muchos de los edificios actuales y sus sistemas energéticos relacionados son diversas y estas son en una parte importante causada por una atención insuficiente a la influencia del comportamiento de los ocupantes. En los edificios inteligentes es necesario implementar nuevas oportunidades para integrar el comportamiento humano en el sistema de climatización. Además, muchos investigadores están limitados en su investigación al no contar con herramientas de bajo coste que puedan proporcionar información a sus estudios. En este artículo se presenta una revisión del estado actual del arte sobre el termómetro de globo, se describe cómo construir su propio sensor de temperatura de globo y los experimentos descritos ilustran la viabilidad de utilizar un termómetro de globo negro con 40 mm de diámetro.

Palabras clave: Temperatura de globo, termómetro, temperatura media radiante, hardware abierto, sensor.

Description of the Problem

The most common environmental parameters are: air temperature, mean radiant temperature (MRT), air velocity and air humidity. In addition, there are three personal parameters: metabolism, activity, and thermal insulation of clothing. However, studies and applied research to buildings generally use different environmental indices. The current environmental indices may be divided into three categories: direct; rational and empirical (Awbi, 2013).

The globe thermometer (GT) is one of the first category, it is a good predictor of the combined effect of air temperature, long-wave radiation and air movement on human heat stress. The globe temperature responds to changes in air temperature, radiant temperature and air velocity. GT is an instrument used to determine the MRT and GT is used to measure radiant heat. It basically consists of a thermometer with its sensor located at the centre of a matt black sphere. MRT can be calculated from this result if air temp and velocity are known. The measurement of heat stress is important because loss of physical and mental efficiency occurs under definable degrees of heat stress. Severe heat stress can lead to fatigue and exhaustion.

Nowadays, many devices are expensive and inflexible, for this reason, researchers' need alternative tools. We propose using open-source Arduino and open hardware microcontroller boards as an inexpensive and flexible alternative. These boards connect to standard experimental software using a USB connection or Wi-Fi technology. In our solution, an Arduino measures the globe temperature. In addition, this system allows for the flexible integration of other sensors (air temperature, humidity, air quality, etc.).

In this paper it is proposed to use a microprocessor platform as an alternative to other more expensive systems. We also suggest how using the open hardware platform allows extending the experimental toolbox to include other measures. Thus, we describe how this platform can be used with a GT as a platform for measuring and investigation. In addition, this paper presents the results of some tests carried out between globe temperature sensors with different diameters. The mean radiant temperature (TR) is one of the most important parameters governing human energy balance. It can be used in thermal comfort assessment for public buildings (Molina & Veas, 2012). Currently, there are different methods of obtaining the TR in an indoor or outdoor space (Thorsson, Lindberg, Eliasson & Holmer, 2007). Thermal comfort researchers, designers, and urban planners require an easy and reliable method of estimating MRT, the 40 mm flat black GT proposed here, provides a good and cheap solution.

State of art

The globe thermometer (GT) is the most commonly used instrument for measuring the mean radiant temperature (MRT). The radiation and convection have an influence on the body; many instruments have been designed to meet a variety of combinations of such effects that affect the state of comfort. Prior to the GT's existence, two instruments: the kata-thermometer (Hill, 1920) and the eupatheoscope were used (Dufton, 1936) in the assessment of the thermal environment. The GT was introduced by Vernon in 1930 as a simple device for indicating the effect of radiation on human comfort (Vernon, 1932). But before the Vernon's globe, various observers have used blackened spheres as indicators of radiant heat, these have generally been filled with hot water, or otherwise heated (Bedford & Warner, 1934), for example, by exposure to sunlight and then the apparatus was removed into a darkened room and the cooling rate measured (Olson, 1970). Aitken (1887) defined a very similar globe to Vernon, he advocated the use of a blackened, hollow sphere of thin sheet metal, having a thermometer fitted to it with its bulb in the center. It consists of a hollow 15.24 cm (6-in) copper sphere, coated with matt black paint, and containing an ordinary thermometer with its bulb at the center of the sphere. Then, in 1934, Bedford and Warner used it to estimate the MRT in conjunction with air temperature and air movement; the standard of Vernon globe is a 150 mm diameter and 0.4 mm thick, black hollow copper sphere, with a thermometer with its bulb positioned in the middle of the sphere.

In the seventies, a GT has sometimes been used to measure the incoming radiation in human comfort studies (Keuhn, Stubbs, & Weaver, 1970), even in outdoor environments (Clarke & Bach, 1971). In 1987, the GT began to use the MRT; it computed from the air (ta) and globe (tg) temperatures using de Dear's equation which accounts for the globe diameter (De Dear, 1987). Over the years, investigators have used several different models of globe thermometer, varying the sphere in size; thickness and material, have been developed. But the standard GT consists of a black-painted copper sphere with a diameter of 150 mm and a thickness of 0.4 mm. However, in many instances, authors have used 38 mm, for example (De Dear, 1987; Humphreys, 1977; Nikolopoulou, Baker & Steemers, 2012).

In globe thermometers, the smaller spheres have the advantage of a shorter response time. The response time of the Vernon globe with a mercury thermometer in the middle is quite slow and needs 20 - 30 min to reach equilibrium (McIntyre, 1980). Equilibrium is reached when the heat gain by radiation equals the heat loss by convection and re-radiation, since three components must come into equilibrium: the globe itself, the air contained in it and the thermometer. A smaller globe diameter will be affected by the air temperature and air velocity, reducing the accuracy of the measurement of the MRT (Olesen, Rosendahl, Kalisperis, Summers & Steinman, 1989), but the 38 mm grey GT used in Nikolopoulou et al., (2001) had a response time of less than 5 min based on indoor tests. This is appropriate for outdoor use where a rapid response is required to pick up the rapid changes in the environment. Nikolopoulou emphasised that it is possible to reduce the response time of the instrument by reducing its heat capacity, and the heat transfer from the walls of the globe to the heat sensor is rapid and not the limiting factor. The acrylic globe thermometer was proposed because of the differences in the equilibrium temperatures between other materials and the acrylic. The thin acrylic Ping-Pong balls, their relative robustness and the need to avoid a painted metallic surface, confirms that these are a good choice for globe thermometers where response times down to about 4 minutes are required.

Chen, Lin & Matzarakis (2014) studied and compared the six direction radiation method, the GT method and three models: Rayman model, ENVI-met model and SOLWEIG model. The comparison showed that the GT method may overestimate the MRT since wind velocity is a key variable in the estimation based on these methods. In conclusion, Chen et al. (2014), found that the MRT of GT method requires stable, low wind velocity as an input. Undergo the improvement MRT of GT is more similar to MRT of six radiation method.

Currently, a GT may be used within buildings for two functions: a) To estimate the MRT of a room; in this case, it is also necessary to know the measurements of air movement and temperature. But with this measurement, a large globe is preferred because of its greater response to incident radiation (Humphreys, 1977). b) To assess the warmth of a room for human comfort. For this purpose, the globe should be of a size which responds to radiation and convection in proportions similar to those of the human body. The globe temperature is measured using a sphere, generally painted black or grey to mimic the response of the human body to thermal radiation, and is nowadays commonly about 40 mm in diameter. This is roughly the diameter of a table tennis ball. The theoretical derivation of this can be found in Humphreys (1977); In the investigation, heat exchanges between spheres and its surroundings were examined to obtain the relative responses of spheres of various diameters to convection and radiation. Höppe (2002) further highlights the different aspects of assessing indoor and outdoor thermal comfort, not only the thermo-physiological aspect, but also the psychological.

Technology

The open source software movement has had an enormous impact on today's technology. The “open hard-ware” is public so the hardware can be used freely. Everyone can implement it and learn from it, because the tools used to create the design are free, so that others can develop and improve the design. In this work the use of Arduino for an intelligent sensorization of building is proposed.

The Arduino (Schmidt, 2011) is an open source prototyping platform for AVR ATmega micro-controllers. As an open-source hardware project, all circuit board and electronic component specifications, as well as the IDE software, are freely available for anyone to use or modify. Researchers from different disciplines have begun to develop and implement successfully devices based on the Arduino platform. A discussion about the potential of applying the Arduino Platform as a low-cost, easy-to-use micro-controller and sensor kit to facilitate co-creation is presented in (Hribernik, Ghrairi, Hans & Thoben, 2011). Some cases illustrate first experiences with the Arduino platform in the co-creation of Intelligent Products.
Several features make the Arduino family an interesting tool as a measurement platform. Arduino can work while being connected to a PC or operate standalone with small batteries. It connects easily by USB to a Windows, Linux or Mac machine and can transmit data using a virtual serial port to these operating systems or via wireless technology (Xbee or Wifly) (Faludi, 2010). Different wireless transmission systems are compared in Table 1.

The wireless technologies are changing the way sensors are used in buildings. They contribute to lowering costs, are easier to install and sensing devices require no connections by wires. The sensors can provide the data required to cost-effectively operate, manage, and maintain buildings at peak performance. Wireless communication of data via WiFi (or IEEE 802.11 standards) is now routine in homes, offices and public spaces. For this reason, we recommend using wifi (e.g. Wifly shield), to send data to the network; the information can be sent via html to any database in the network or stored in global servers. As in Xively (2013) it is an online database service allowing developers to connect sensor-derived data (e.g. energy and environment data from objects, devices & buildings) to the web and to build their own applications based on that data.

Table 1. The comparison of WLAN, Bluetooth and ZigBee. Source: self-elaboration.

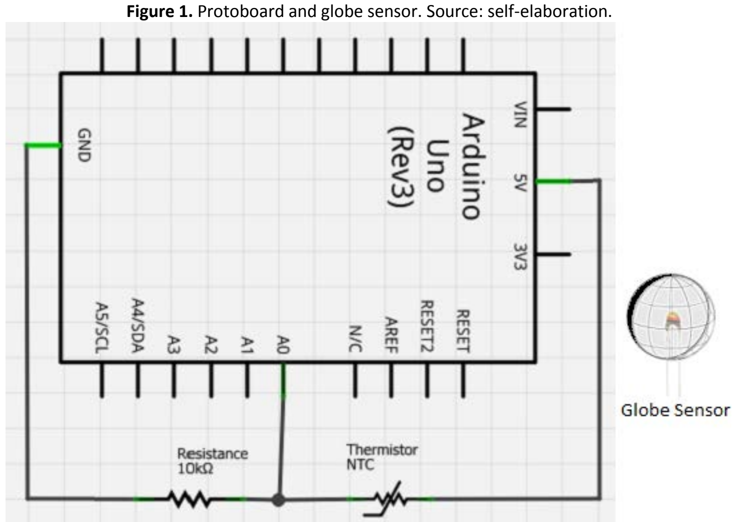
	WLAN	Bluetooth	ZigBee
Band	2.4, 3.6 and 5 GHz	2.4 GHz	2.4GHz, 868/915MHz
Power	500 mW	100 mW	30mW
Battery life	hours	Days or Months	6 months - 2 years
Range	30-70 m	10-30 m	10-75 m
Data rate	1-150 Mbps	1-3 Mbps	25-250 Kbps
Network	Ad hoc, P2P	Ad hoc, P2P, star	Mesh, ad hoc, star
Security	WEP/WPA	128-bit encryption	128-bit encryption
Wake and transmit	10 ms	3 s	15 ms

Methodology, experiment and comparison

This paper presents a comparison of globe thermometers based on Arduino. We mainly use the recent reference model of the Arduino family, the Arduino Uno. It has 32 kB of flash memory, operates at 16 MHz, features 14 digital input/output and 6 analogy input pins. Other larger models provide more of those input and output options, so we also used other models, such as Arduino Mega. The boards can be connected to actuators and sensors, either commercial or build from scratch. Many extensions of a board come as so-called shields i.e. additional small boards that are plugged into an Arduino board. Some shields provide wireless access (WLAN or Bluetooth), whereas others allow storing data on flash memory cards.

The microcontroller is connected to a PC via USB. The thermometer circuit connection is simple. It created a voltage divider (also known as a potential divider); this is a linear circuit that produces an output voltage (Vout) that is a fraction of its input voltage (Vin). This voltage divider consists of two resistors, in series, but in this case uses one resistor and one thermistor; both have similar resistant characteristics to a temperature of 24°. The signal input to the Arduino, from an outlet in the middle of both resistors. The input voltage is obtained and depends on the temperature of the thermistor environment, in our case, the inside of a black ball of a given diameter. Figure 1 shows the basic scheme.

Figure 1. Protoboard and globe sensor. Source: self-elaboration.



The sensor

The instrument consists of a thin-walled black sphere in the centre of which is placed a temperature sensor i.e. a resistance thermometer. To increase the absorptivity of the sphere the outer surface is blackened, commonly by a layer of matt black paint. In real data gathering, while taking measurements of thermal environments, the presence of the subject or other artefacts may affect the value of the immediate microclimate. For this reason, it is recommended to position the instrument at a certain distance. A GT near a subject may pick up the radiation from the subject's body besides the room surfaces. The air movement near the instrument can also be affected by the presence of the subject and so on. The GT takes some minutes to reach equilibrium. There is some merit in this in a variable environment, since it smooths out temperature fluctuations over a period. The time constant can be determined experimentally (Humphreys, 1974).

Modularity and costs

The microcontroller code is easily modified with the USB connection for various other applications. The total cost to build a basic prototype is approximately 25€. The device can also be built in various configurations. If a computer is not available near the device, local data storage to a MicroSD card can be added for 16€. In addition, if a wireless connection is desired instead of the USB cable, the Wi-Fi can be added for 35€. The thermistor, resistance, wire and a Ping-Pong ball is less than 5€. A commercial basic device costs more than 200€. Often its adaptability to the research is very limited, especially for real-time studies.

Experiment

A GT can be made up using a black or grey-painted Ping-Pong ball, with the temperature-measuring device inside also built-in or purchased ready-made. The material from which the globe is made and its thickness will affect the time it takes to come to equilibrium. The response time is also affected by the properties of the temperature sensor. The sensor should be located at the centre of the sphere and the entry point of the thermometer stem or wire should be airtight, because air flowing into the globe can affect the air/radiant temperature balance. In the experiments, the instrument is suspended within an enclosure and sufficient time elapses to reach equilibrium between convective and radiant heat transfer from the surface of the sphere. Figure 2, presents a change of the indoor ambient conditions for increased radiation (measured with the globe thermometers) which are maintained for the period of 1.5 hours presented. There is an increase of 1.5 degrees in the air temperature, and more than three degrees of radiation absorbed in the globe temperature. Furthermore, it appears that the fourth sensor (PT 150mm), located within a sphere of solid insulating material, is only affected by convection.

Figure 2. Comparative: GT 40 mm, GT 150 mm, AT (air temperature), PT 150 mm (temperature of a 150 mm diameter sphere of solid insulating material). Source: self-elaboration.

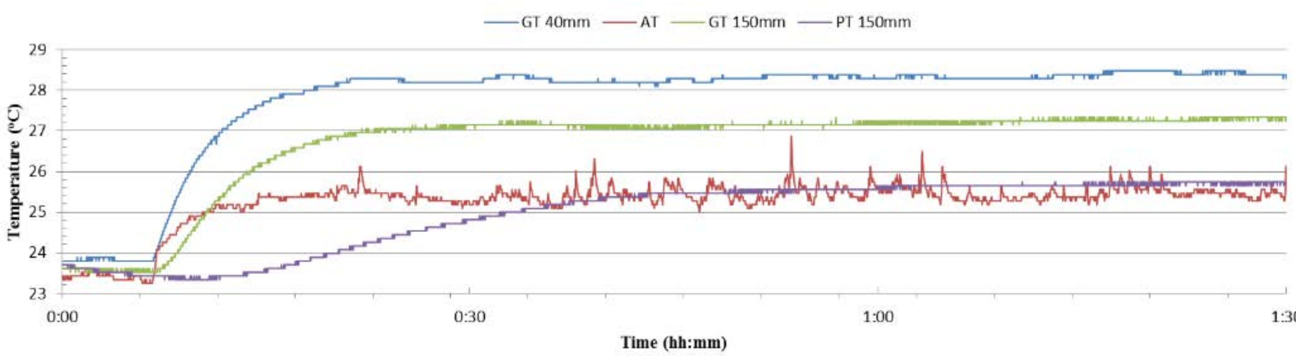


Figure 3. Comparative: GT 40 mm, GT 150 mm and AT. Source: self-elaboration.

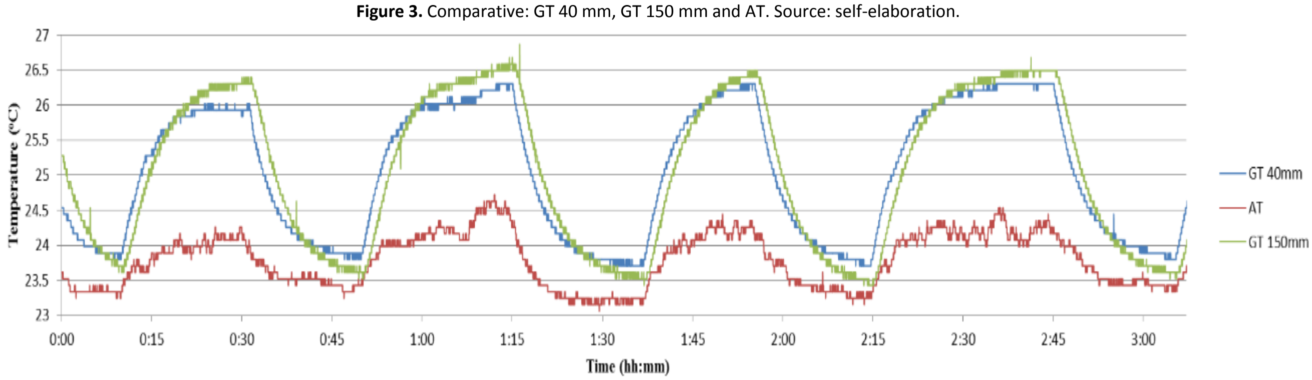


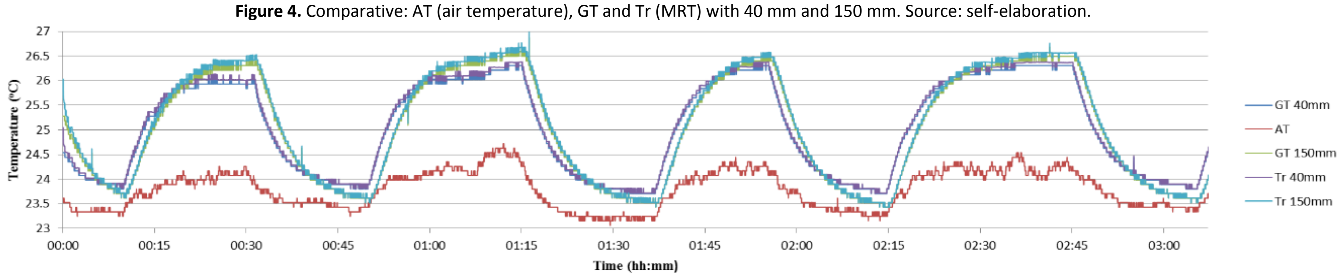
Figure 2 shows that for temperatures of 24 degrees, the GT sensors have an error of less than half a degree, however, by changing the conditions, there is a difference of about one degree between balloon 40 mm and 150 mm. This difference is produced by the relative influence of the velocity of air (Nicol, Humphreys & Roaf, 2012) and the ratio of radiation response. Depending on the value of radiant and convective heat transfer, the globe temperature lies between the MRT of the enclosure and the temperature of air surrounding the globe. The smaller the diameter of the sphere, the greater is the effect of the air temperature and air velocity, thus reducing the accuracy of measuring the MRT. Although (ISO-7726, 1998) recommends a sphere of 150 mm diameter, in general, measurements with spheres as small as 40 mm (Ping-Pong ball) seem to produce results similar to those obtained from a sphere of 150 mm diameter. An example is presented in Figure 3. The principle behind the GT is the equilibrium of heat transfer by convection and radiation from the surface of the sphere. The mean radiant temperature, tr, may be expressed in terms of the air temperature, ta and the globe temperature, tg, using the expression 1 (ISO, 1998).

$$\bar{t_r} = \left[\left(t_g + 273\right)^4 + \frac{0.25 \cdot 10^8}{\epsilon_g} \left(\frac{|t_g - t_a|}{D} \right)^{\frac{1}{4}} \left(t_g - t_a\right) \right]^{\frac{1}{4}} - 273 \tag{1}$$

Where: t_g is the temperature of a black globe, t_a is the air temperature, D is the black globe. diameter in metres and ϵ_g is the mean emission coefficient of a matt black globe (0.95).

As shown in Figure 4, the globe temperature and the radiant temperature are very similar. There is on average a variation of 0.01°C in 40 mm globe and 0.27°C for a 150 mm globe, versus the radiant temperature, in the experiments.

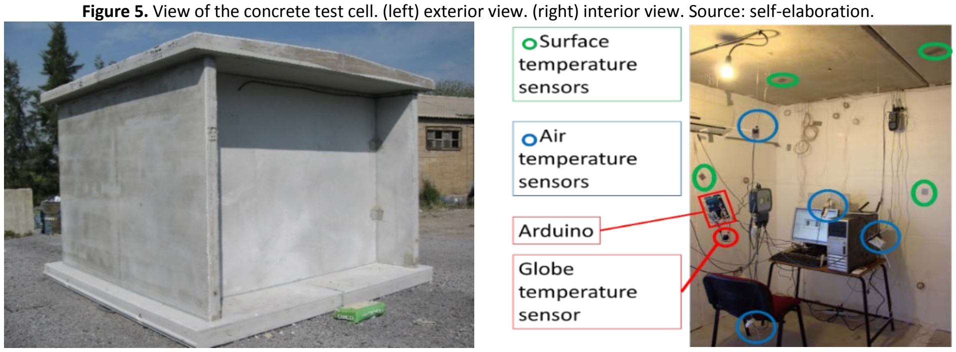
Figure 4. Comparative: AT (air temperature), GT and Tr (MRT) with 40 mm and 150 mm. Source: self-elaboration.



Experiment and results: Mean Radiant Temperature

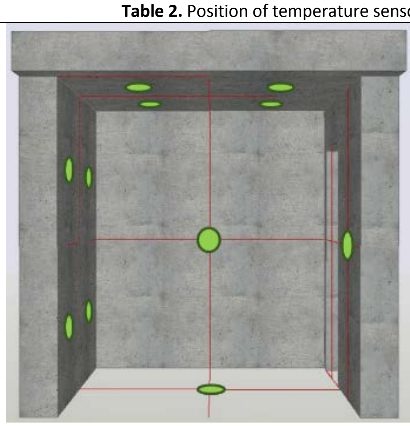
Several experimental measurements were performed in a concrete test cell located close to the small town of Alcala de Guadaira, Seville, Spain. The concrete test cell is a small building with only one room of 2.9 m width, 2.4 m deep and 2.4 m height (interior dimensions). The south wall, the roof and the floor are not insulated, so the interior surface finishing is concrete. North, east and west walls have interior insulation, so the finishing is polystyrene. A view of the test cell is shown in Figure 5.

Figure 5. View of the concrete test cell. (left) exterior view. (right) interior view. Source: self-elaboration.

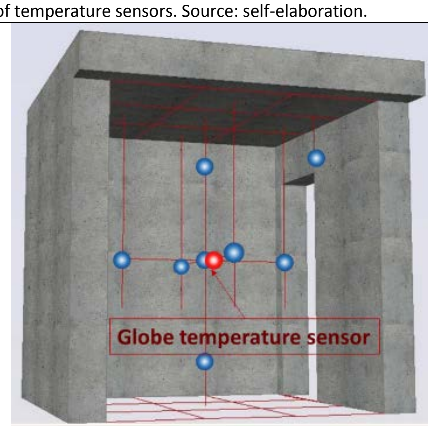


A scheme of the position of temperature sensors is shown in Table 2. South wall and roof were monitored with four sensors each, to record the non-uniform temperatures occurring in these two surfaces. In order maintain an uniform temperature in the north wall, the door was insulated to the same level. Thermographic photographs reveal that the entire north surface (including the door) was approximately at the same temperature, so it was not necessary to locate sensors on the door. The test cell was operating in a free-floating mode, i.e. the indoor temperature moves freely without any control of an air conditioning equipment. Under these conditions, indoor air and surface temperatures oscillate under the influence of the external environmental conditions, e.g. temperature and solar radiation, the air infiltration and internal heat gains.

Table 2. Position of temperature sensors and specifications of temperature sensors. Source: self-elaboration.



Surface temperature sensors



Air and globe temperatures

	Type	Datalogger	Precision
Air Temperature	PT100, 4 wires	Delta Ohm HD 32.7	+/-0.15ºC at 0ºC +/-0.35ºC at 100ºC
Surface temperature	thermocouple type T	National Instruments CompactDAQ, module NI 9214	0.5 ºC

Inside a building, there is an intimate infrared relationship of our bodies with the surrounding surfaces of the room (Ts), which is described by the mean radiant temperature (Tr, Tmr or MRT). The thermal comfort equation uses the MRT in indoor comfort studies. The MRT is a mean of expressing the influence of surface temperatures on occupant comfort.

$$T_{mr} = \frac{T_1 A_1 + T_2 A_2 + \cdots + T_n A_n}{A_1 + A_2 + \cdots + A_n} \tag{2}$$

$Where: T_N\ is\ the\ surface\ temperature\ of\ surface\ N$ and $A_N\ is\ the\ area\ of\ surface.$

The absence of windows in this test cell, assumes that the studies performed only relate to the long-wave radiation and the heat transfer between surfaces and indoor air through convective mechanisms.

Figure 6. Behaviour of the outside temperature, AT, GT 4 cm, MRT and operative temperature. Source: self-elaboration.

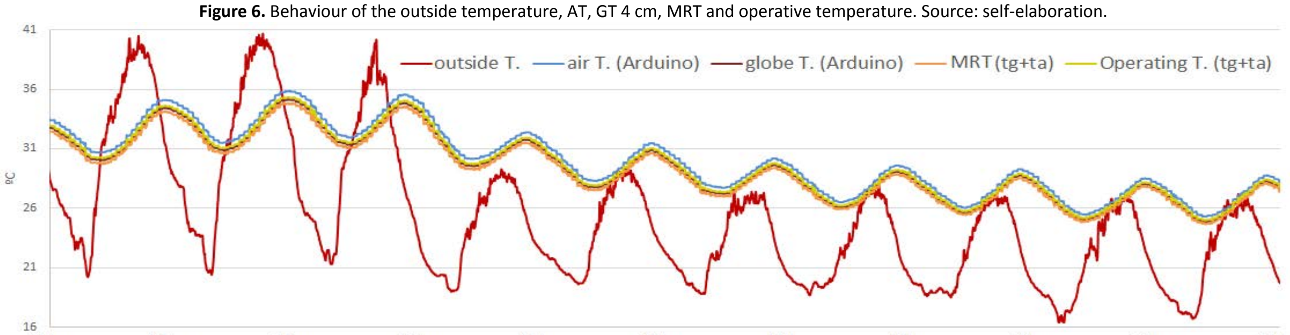


Figure 6 presents the variation of the outside temperature, with a day/night amplitude between 10 °C and 20 °C recorded for this period. The operative temperature, is obtained from the air and globe temperature, with the equation 1. The operative temperature is the mean value of the dry air temperature and MRT within an enclosure. If a more detailed calculation is required, the following formula can be used:

$$T_o = (A \cdot T_a) + [(1 - A) \cdot MRT] \qquad (3)$$

where: T_o *is the operating temperature*, T_a is the air temperature, MRT is the mean radiant temperature and A *is the* value that is a function of the relative air velocity as:

$$\left[< 0.2\frac{\mathrm{m}}{\mathrm{s}}, \mathrm{A} = 0.5\right], \left[> 0.2\frac{\mathrm{m}}{\mathrm{s}} \,\&\, < 0.6\frac{\mathrm{m}}{\mathrm{s}}, \mathrm{A} = 0.6\right], \left[> 0.6\frac{\mathrm{m}}{\mathrm{s}} \,\&\, < 1\frac{\mathrm{m}}{\mathrm{s}}, \mathrm{A} = 0.7\right] \qquad (4)$$

The operative temperature is often used in the analysis of the thermal performance of buildings and the calculation of some indices of comfort. It represents more closely the temperature that a person perceives inside an enclosure. It helps us to understand, for example, why a person in a space with walls that have a relatively high temperature, feels uncomfortable even when the air temperature is adequate.

Figure 7. Inside surface temperature on the six orientations and the average. Source: self-elaboration.

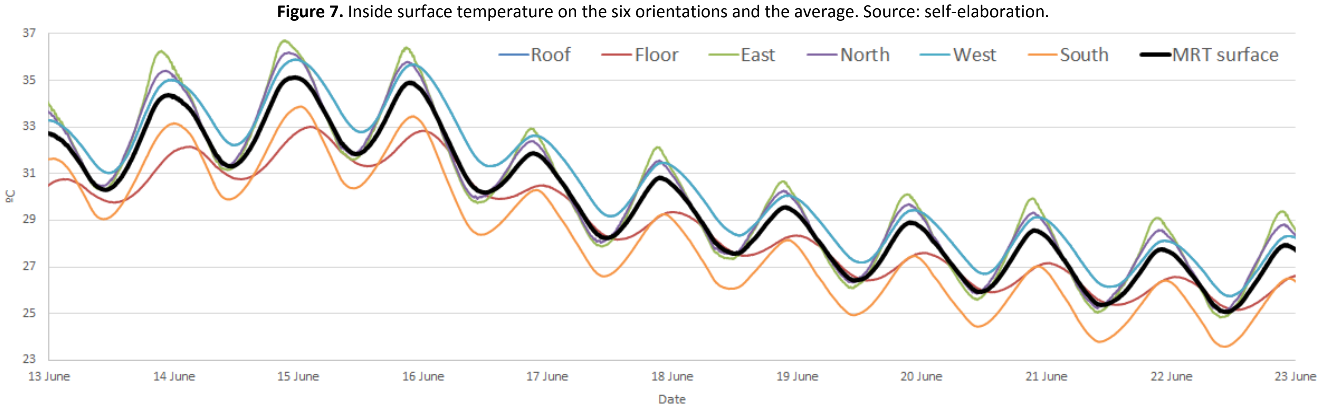
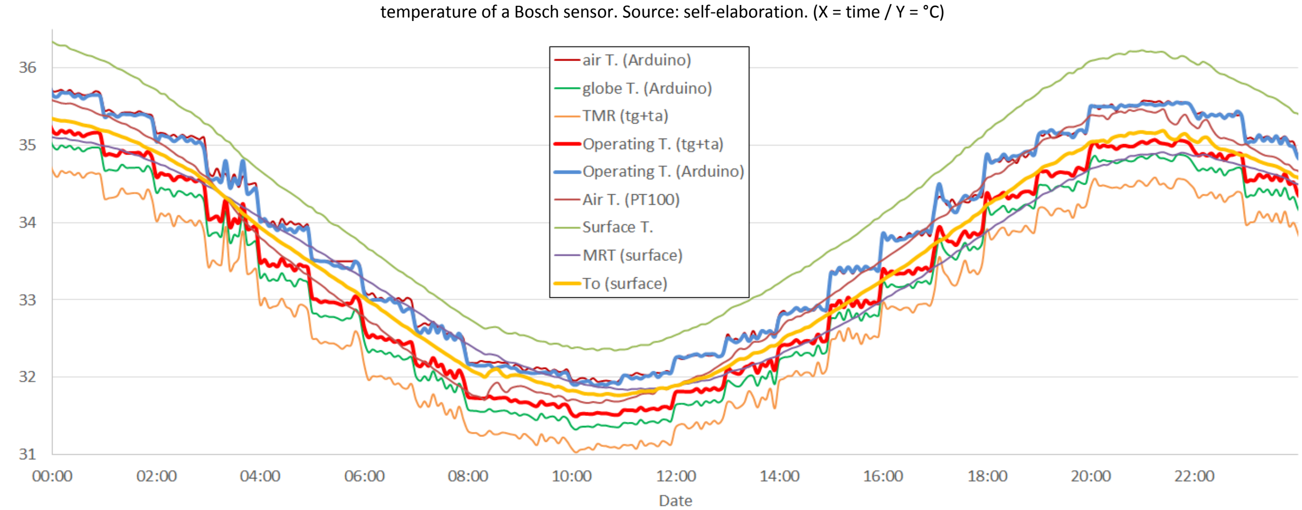


Figure 7 presents the inside surface temperature on the six orientations and the average. Figure 8 shows one day, and the results for the Arduino sensors measuring the air temperature and 4cm globe temperature. The MRT and the operative temperature are calculated from the air and globe temperature (ta + tg). The results obtained by a sensor Bosch BMP085 high-accuracy chip to detect the barometric pressure and the operative temperature are also presented in this figure.

Figure 8. Natural Behaviour: MRT and operative temperature, calculation based on the AT and GT 4cm. Theoretical operative temperature is compared with operative temperature of a Bosch sensor. Source: self-elaboration. (X = time / Y = °C)



The results compared the average air temperature of the room with sensors PT100, also called resistance temperature detectors (RTDs), and the calculated surface temperature with thermocouples type T. Finally, the MRT and operative temperature from equation 2 and 3 are calculated. There are minor differences, less than one degree, between all. The differences are due to the existing error between sensors (± 0.5 ºC). As expected, both methods are valid, although the cost of using a 4 cm GT and air thermometer is lower, with similar efficiency.

Conclusions

Nowadays, large data is obtained in the monitoring of buildings. However, black globe temperature instruments currently available are often expensive and have not been designed to generate and store data online in real time. The scientific community needs cheap and efficient tools to develop experiments. The Open Hardware allows the creation of the same tools to connect to numerous systems in the most economical solution. The manufacture of these sensors can be easily made.

This paper presents a literature review and an experimental test of globe thermometers. It has been observed that they are reliable and by using microcontrollers such as Arduino its usefulness can be extended to multiple inquiries. Finally, it validates the use of the GT with the convenient size of 40 mm as the best solution for undertaking environmental surveys of comfort temperature. Lower manufacturing costs and reaction rates with a response similar to 150 mm are presented.

An experiment with natural conditions in a concrete structure was made with GT. The experiment is performed on a windowless structure so the GT is only affected by long-wave radiation. The experiment involved calculating the operative temperatures and MRT using Arduino and comparing it with commercial sensors. The MRT and the operative temperature calculated with the GT and air temperature with the calculated surfaces were also compared. The results are similar between the different methods, irrespective of the error between sensors.

There is a demand for affordable instrumentation to monitor various parameters of comfort in buildings and to support further research in the field. In addition, there is a need for systems that develop real-time decision algorithms, hardware platform and free software to support these developments. New research projects with this platform will increase the performance of many current buildings and their related systems by taking into account the influence of occupant behaviour.

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