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A low-cost IoT multi-spectral acquisition device

J.S. Botero-Valencia [a,*], J. Valencia-Aguirre [a], D. Durmus [b]

[a] *Grupo de Automática, Electrónica y Ciencias Computacionales, Instituto Tecnológico Metropolitano, Medellín, Colombia*
[b] *Department of Architectural Engineering, Pennsylvania State University, University Park, PA, USA*

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ABSTRACT

Color and lighting quality assessment allow users to reliably examine the quality of light sources and the changes in the lighting conditions. Technological advance has led to an increase in the development of intelligent systems that are permanently connected to the Internet and that allow access to real time-data. Smart lighting systems have become a subject of great interest given their potential in different application areas, such as optimization for object reflectance and damage reduction to artwork. It has become necessary to develop new sensors that are aligned with the technological needs, that are easily integrated into IoT (Internet of Things) or smart lightning systems, and that allow estimating lighting quality measurements in real time. Here, a low-cost IoT multi-spectral acquisition device with wireless communication is presented. Insights into the overall system design and a validation of its operation is provided to allow reproducibility and independent testing of the proposed device. The device can be used for light source spectrum recovery and estimation of light quality and color rendering measures. The total cost of the device is below 130 USD, and customizability provides a great advantage over commercially available devices.

1. Introduction

Specifications table:

Hardware name	IoT multi-spectral acquisition device
Subject area	• Engineering • Instrumentation • Colorimetric measures • Internet of things
Hardware type	• Measuring physical properties and in-lab sensors • Field measurements and sensors • Electrical engineering and computer science
Open source license	Creative Commons Attribution-ShareAlike license
Cost of hardware	$122 USD
Source ftle repository	https://doi.org/10.17605/OSF.IO/3NA4R

* Corresponding author.
E-mail address: juanbotero@itm.edu.co (J.S. Botero-Valencia).

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2. Hardware in context

Examining the quality of a light source requires the calculation of colorimetric models or color rendering measures. These measures are based on the spectral power distribution (SPD) of the light source. Obtaining the SPD of a light source requires a spectroradiometer. However, the high cost and large sizes of lab-traceable spectroradiometers make it difficult to use them in several fields of applications. In response to these challenges, cheaper handheld spectroradiometers have recently become a low-cost alternative to lab-grade spectroradiometers, with the caveat of a trade-off between precision and cost. Today, in the market, portable spectrometers are sold around a couple of thousands of USD [1–3]. It is possible to find low-cost spectroradiometers as economical as those offered by Public Lab [4–5], where the possibility of building your own device and make measurements with ease is provided. However, these economic and simple alternatives have limitations, such as the measurement range and the level of measurement accuracy. On the other hand, commercial spectroradiometers prices may go up to tens of thousands of USD. Considering the technological advances that has led to the fourth industrial revolution, it is clear that wireless, portable devices, that allow transmitting data in real-time to the cloud, provide a great opportunity to integrate technology in a wide range of applications. Devices catalogued as IoT (Internet of Things), have become a focus of research and development due to their low-cost and versatility, compared to commercial devices. The IoT applications are increasingly adopted to lighting systems to improve energy efficiency and visual performance. In particular, smart lighting systems would greatly benefit from performing SPD recovery in real-time, and would be of great interest for architectural engineering (e.g., monitoring smart lighting systems, either to control the objects appearance or to reduce energy consumption). Real-time monitoring and analysis of the lighting quality has the potential to improve productivity and occupants' well-being. The obtained spectral information could even help prevent health problems associated with the infrared radiation emitted from the light sources. Similarly, the detection of infrared radiation has an important impact in spaces such as museums and art galleries. Since infrared and ultraviolet radiation cause damage to artwork [6], and a smart lighting system detecting SPD would prolong the life of delicate artwork. Here it is proposed a device that makes it possible to recover the SPD from the light sources, and then colorimetric measurements or light quality measures could be carried out. A similar device was proposed in [7], however, the authors employed an Arduino that does not have an Internet connection. Although the construction price is almost identical to the hardware proposed in this work, our device presents the possibility of sending data to the cloud according to the user needs.

An additional advantage of developing your own spectral-recovery device is that it can be scaled and made compatible with other IoT devices, and can be adopted to network (e.g., message queuing telemetry transport (MQTT)) or home automation protocols, such as if this then that (IFTTT), and it is a fact that IoT (Internet of Things) is one of the most relevant fields for current technological development [8–10].

Finally, the importance of light has taken on an increasingly relevant role, for example for the development and control of thermochromic smart glazing [11], it could be integrated into the development of Smart windows with suspended particle device (SPD) [12], to estimate with greater precision energy harvesting for wireless sensor systems in indoor applications [13], in the control of horticultural lighting systems [14], as an alternative to detect occupants [15] and even to study the effects of light on cognitive performance [16]. All these examples are evidence of the need to develop more devices aimed at measuring light with better characteristics, and that the data collection be integrated into systems (IoT), to facilitate the work of researchers.

3. Hardware description

The proposed device has a particle photon microcontroller unit (MCU). The MCU receives the signals from the sensors and sends the data to the internet through a Wi-Fi connection. There is also an internal memory for storing measurements when there is no Wi-Fi connection available to send the data. The signals from the AS7262 and AS7263 sensors are used as inputs for the MCU, which allows to acquire bands of both, the visible and the near infrared (NIR) spectrum, specifically 450 nm, 500 nm, 550 nm, 570 nm, 600 nm, 610 nm, 650 nm, 680 nm, 730 nm, 760 nm, 810 nm, and 860 nm. It is important to note that by acquiring several bands, the data resolution is improved and the possibility of metamerism is reduced as well, which is an advantage over the luxometers and spectrophotometers, that usually work with a single band.

Another feature worth highlighting is the device versatility, since the data transmitted to the Internet allows estimating different types of measurements, such as the color rendering index (CRI) (R_a), ANSI/IES TM-30-18 fidelity and gamut indexes (R_f, R_g), correlated color temperature (CCT), luminous efficacy of radiation (LER), and illuminance. Likewise, it is possible to use the sensed values to make particular observations, such as detection of the individual wavelengths of a polychromatic source, obtain real-time data to interact with control systems, generate safety alerts in lighting conditions. It should be noted that since there is an MCU, it is possible to perform calculations internally to convert the measurement and send these values to the cloud or to a local device. In terms of autonomy, the device is portable and does not need power for short periods, thanks to the battery that provides up to 24 h of autonomy. In addition, the battery charger is integrated. The charger and battery system works as an uninterruptible power supply - UPS, where the battery is permanently charged until it reaches its limit and the system is powered by external supply. If the external power source is disconnected, the battery automatically goes into operation. Which means that the charger supports the pass through function.

Regarding the physical design, computer-aided design tools (NX design) were employed for the enclosure design, and its parts were 3D printed. The material used for this purpose was polylactic acid (PLA), and the final result is shown in Section 5. As described in [17], multi-spectral sensors are located on the upper face of the device, but to reach the sensor the light must go through 1/16 ”film of polytetrafluoroethylene (PTFE), and a transparent glass below that protects the sensors from dust.

The proposed hardware provides several advantages:

- Facilitate light data acquisition for architectural engineering, lighting design practitioners or occupational health purposes;
- Developing systems that can make real-time decisions to improve energy efficiency and occupants visual performance and satisfaction;
- Integrate with other smart building and lighting systems for energy monitoring and control of polychromatic sources;
- Performing SPD recovery from the a wide range of environments to detect potentially harmful radiation, such as infrared and ultraviolet;
- Store the data in an SD memory, when there is no Wi-Fi connection or to save energy and make acquisitions for a longer time.

4. Design ftles

Fig. 1 shows the wiring between the electronic elements of the device. The main components are the Particle Photon Wifi Development Board, the Battery, the LiPo Charger, the OpenLog and the multi-espectral sensors.

4.1. Design files summary

- The *Box* displays an image of the finished and assembled design.
- The *Bottom* corresponds to the base (bottom part) of the device, where the MCU, the MUX, the battery and the battery charger are located.
- The *Joint* has two functions, the first is being the support for the sensors’ holder, and the second is joining the top with the bottom of the device.
- The *Plug* allows to protect USB ports from dust.
- The *Sensor holder* allows fixing the sensors to the top of the device, preventing them from moving. This piece has space for 3 sensors, but in this case only two were used.

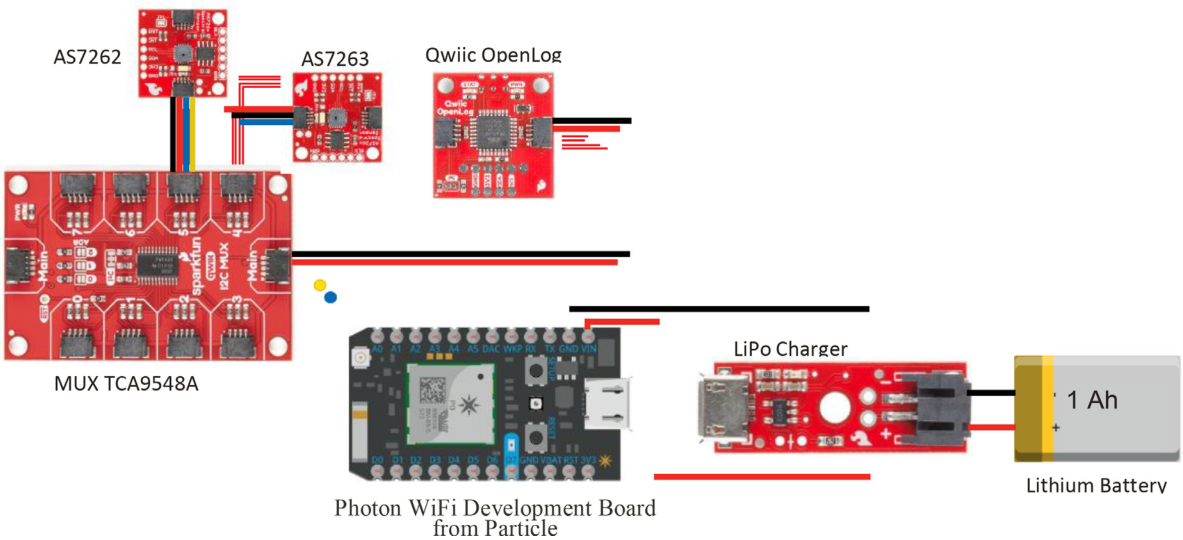


Fig. 1. Schematic.

Design ftle name	File type	Open source license	Location ftle
Box	.png	GNU General Public License (GPL) 3.0	https://osf.io/wde9j/
Bottom	.stl	GNU General Public License (GPL) 3.0	https://osf.io/u5k3b/
Joint	.stl	GNU General Public License (GPL) 3.0	https://osf.io/kc37y/
Plug	.stl	GNU General Public License (GPL) 3.0	https://osf.io/mwpn8/
Sensor|holder	.stl	GNU General Public License (GPL) 3.0	https://osf.io/vx6e9/
Top	.stl	GNU General Public License (GPL) 3.0	https://osf.io/2dfse/
Schematic	.eps	GNU General Public License (GPL) 3.0	https://osf.io/yd9s2/
main	.ino	GNU General Public License (GPL) 3.0	https://osf.io/9w5hn/

- The *Top* presents the top part of the enclosure that allows the light to reach the sensors.
- The *Schematic* shows the electronic schematic of the device, the main components and their connections.
- In the *main* file there is a C code to read the sensors and send the information to the cloud. The code can be changed for customization.

5. Bill of materials

Designator	Component	Qty	Unit cost	Total cost	Source of Materials	Material type
AS7262	Spectral sensor	1	$25.95 USD	$25.95 USD	www.sparkfun.com	Other
AS7263	Spectral sensor - NIR	1	$25.95 USD	$25.95 USD	www.sparkfun.com	Other
Photon shield	Qwiic Shield for Photon	1	$5.95 USD	$5.95 USD	www.sparkfun.com	Other
Mux	TCA9548A	1	$11.95 USD	$11.95 USD	www.sparkfun.com	Other
Cable50	Qwiic cable – 50 mm	2	$0.95 USD	$1.9 USD	www.sparkfun.com	Other
Cable200	Qwiic cable – 200 mm	2	$1.5 USD	$3.0 USD	www.sparkfun.com	Other
OpenLog	Qwiic OpenLog	1	$16.95 USD	$33.9 USD	www.sparkfun.com	Other
LiPo Charger	LiPo Charger Basic	1	$8.95 USD	$8.95 USD	www.sparkfun.com	Other
Battery	Lithium Ion Battery(1Ah)	1	$9.95 USD	$9.95 USD	www.sparkfun.com	Other
Photon	Photon WiFi Development Board - Particle	1	$19 USD	$19 USD	www.sparkfun.com	Other
PTFE	PTFE	1/15	$26.33 USD	$1.75 USD	www.amazon.com	Other
PLA	Polylactic acid	1/10	$18 USD	$1.8 USD	www.amazon.com	Other

5.1. Build instructions

Initially, the enclosure pieces must be 3D printed (files *Bottom*, *Joint*, *Plug*, *Sensor holder* and *Top*). In this case, Polylactic acid (PLA) was used as material, however, it is also possible to employ Acrylonitrile butadiene styrene (ABS). It is important to take into account the resolution of the printer so that everything fits properly, since the parts are designed in such a way that they have details that allow them to be aligned and fit perfectly. For example, file *Top* shows the design of some tabs that are intended to maintain a constant alignment of the elements.

After having the pieces printed, nuts must be located, which are assembled under pressure. The length of both nuts and bolts is used in millimeters and they are made of stainless steel. This material is chosen because it prevents corrosion and deterioration due to air humidity, even if it is not intended to use this element outdoors.

The next step is to assemble a glass on the top of the device, whose function is to protect the sensors from dust and pollution. The used glass corresponds to a microscope sample holder glass. After positioning the glass, a piece of PTFE is cut. This material is white and its located on top of the glass, as can be observed in Fig. 2. The goal of using PTFE is to prevent the sensors from receiving directional rays and avoiding distortion.

Subsequently, the sensors are assembled just above the glass and to be positioned adequately they are inserted into the sensor holder (File *Sensor holder*, element number 4 in Fig. 3). This piece is fixed with an element that provides support and that is also responsible for joining the top with the bottom of the device, i.e. it has both functions (element number 2 – Fig. 3,

Fig. 2. The proposed IoT device, sized 78 × 78 × 78 mm, has a corrective cosine filter, two USB ports, a microcontroller port and a lithium polymer (LiPo) battery.

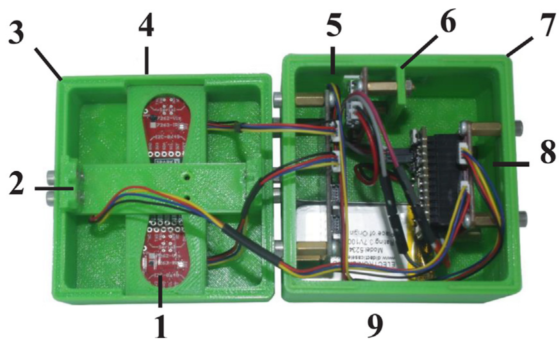


Fig. 3. Inner parts of the IoT device: (1) Sensors, (2) Joint, (3) Top part of the device, (4) Sensor holder, (5) Qwiic MUX, (6) Power card, (7) Bottom part of the device, (8) Photon Shield and MCU, and (9) Lithium battery.

File *Joint*). It is important to keep in mind that the Qwiic cables must be connected before assembling the sensors. The AS7262 and AS7263 sensors are connected to a multiplexer (Mux) using the 50 mm Qwiic cables, then, the Mux is connected to the shield that holds the MCU. This element is needed because the two sensors communicate using an I^2C interface, and for that reason they have the same I^2C address. Some sensors in the market allows the users to change the IP address, however, the ones used here do not present that option.

On the other hand, the MCU is connected to a Qwiic shield (Photon shield), whose only purpose is to be the physical support for the microcontroller unit. The shield used in this case is from Particle, nonetheless, it is possible to use a RedBear Duo, due to it supports the same programming as Particle, and it has the same pin configuration. The main requirement of the shield is that it has I^2C ports, Qwiic type connector. In case of not having a shield, the cables from the MUX would be connected directly to the MCU.

Finally, the power card, that contains the battery charger, is assembled. This card is connected to the lithium battery, which unlike the other components, is not fixed to the enclosure. In this case, a 1Ah battery is employed, however, the device has enough space to include a higher capacity battery without the need for additional connections or changes to the device. Increasing the battery capacity could increment the autonomy of the device from 24 h 10 days (for a 6Ah battery).

The complete enclosure assembly can be seen in the Fig. 2 and File *Box*, while in Fig. 3 are presented the inner parts of the proposed device, and then it is possible to observe all the electronic elements. On the figure left side are the sensors (element number 1), that finally corresponds to the upper-part of the device. On the right are shown the Microcontroller Unit (MCU), the Photon Shield, the battery and the power card (lower part of the device). The upper and lower part of the device are coupled with the help of a guide. All the parts are fixed with screws.

6. Operation instructions

The first step to operate the proposed device is registering in the Particle web site, so you are able to use its application. Secondly, the device should be included and set up in the app, and once the set up is ready the program code should be sent to the MCU. To this end, the Particle Buil IDE is employed, which allows the code edition and sending (https://build.particle.io/). The idea of using an online, browser-based portal is to facilitate the use of the device for less expert users, so that it is not necessary to install any program on their PC.

After the code is properly downloaded to the MCU, the only thing that should be done to use the device is to enter or update the Wi-Fi credentials. This procedure is also done by using the application of the MCU manufacturer, in this case the Particle app as mentioned before. However, this data is also possible to change by console.

It is important to keep in mind that the device works autonomously if necessary or can be connected directly to the energy. Another important aspect to consider is which service will be used to send the data to the cloud. In this case, the Ubidots company service was chosen. But, if you want to change the operator, then you have to update the code and libraries according to the selected cloud service. Once the device is connected to a Wi-Fi network, and is properly located to acquire the data, it is only a matter to check the information in the web and using the data according to the application. In case the user wants to make calculations directly in the MCU, the program code should be changed.

7. Validation and characterization

In order to validate the performance of the proposed device, a white light source coupled to a monochromator was used as an input. The white light goes into the monochromator (a Mini-Chrom UV–VIS–NIR), which was responsible for establishing an specific wavelength. The adjustment on the monochromator is made manually with a mechanical element (knob).

Then, the monochromator output was separated into two beams (i.e demultiplexed). One of the beams is led to a AQ6373 spectrum analyzer and the other beam was connected to the IoT multi-spectral acquisition device, where the signals are detected by the sensors, received by the Photon WiFi Development Board and sent to the cloud via WiFi. Fig. 4 shows the wavelengths measured by the spectrum analyzer, specifically the visible spectrum channels supported by the AS7262 and AS7263 sensors. The measurement with the AQ7363 was carried out to guarantee both the monochromator output wavelength and its power, because for different wavelengths the monochromator generates different attenuation, and therefore, a scale adjustment must be made in the MCU of the proposed device.

Fig. 5a and b show the response of the AS7262 and AS7263 sensor when they are stimulated by the monochromator output. 100 readings were made and averaged for each wavelength. Ideally, both sensors should detect only a wavelength at time, corresponding to the input wavelength, and in consequence each bar in the figures should have only one color. However, as can be seen, for some wavelengths nearby channels are also activated. Specifically, an input wavelength of 570 nm also causes sensor responses corresponding to 550 nm and 600 nm. This effect appears in greater proportion in the AS7262 sensor compared to the AS7263. It is important to emphasize that for the elements interconnection, achromatic optical fibre was employed to avoid signal attenuation.

Fig. 6 displays screenshots of the Ubidots platform. Fig. 6a and b shows the AS7262 and AS7263 sensed wavelengths, respectively. In both figures, the colored lines correspond to each of the sensor bands. Regarding the cloud service, the Ubi-

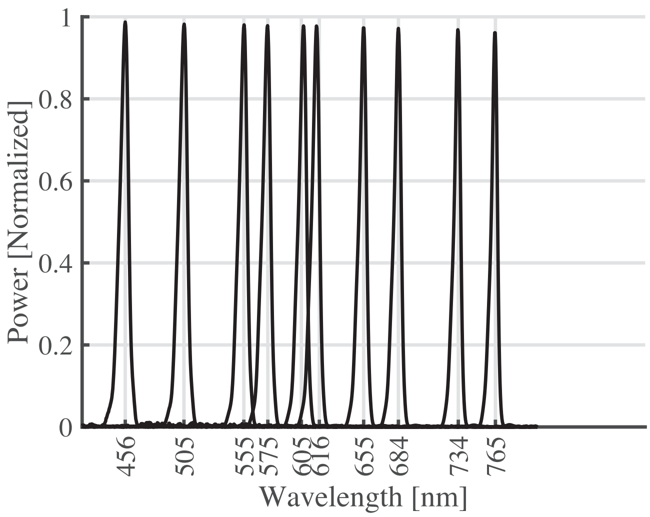
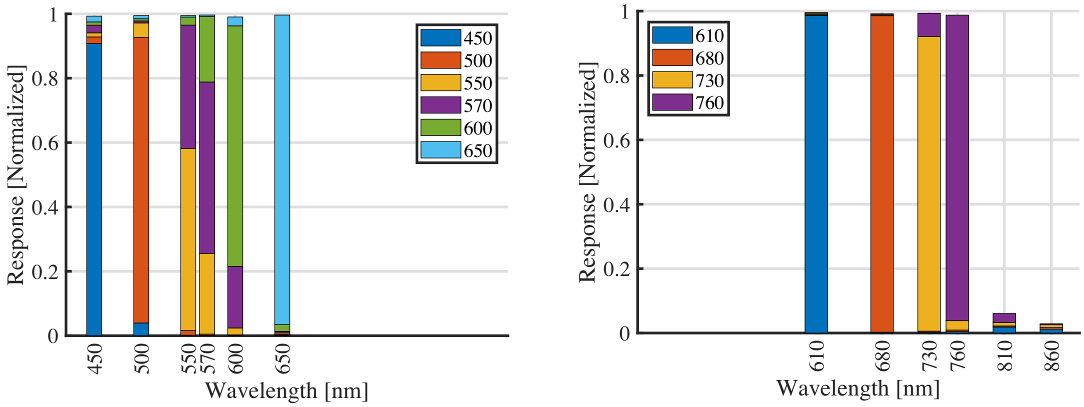


Fig. 4. Spectral response measured with the AQ6373 spectrum analyzer.



(a) Visible spectral sensor, AS7262 (b) Near infrared spectral sensor, AS7263

Fig. 5. Response in the IoT multi-spectral acquisition device.

(a) VIS sensor AS7262, Ubidots graph (b) NIR spectral sensor AS7263, Ubidots graph

Fig. 6. Screenshots of the Ubidots platform. Sun data of December 13, 2020.

dots platform allows data to be stored, viewed in real-time, and downloaded in .csv format. This last feature facilitates the subsequent analysis of the data. However, it is important to mention that the service provided by Ubidots has a cost. Additionally, there may be restrictions on communication depending on the quality of the internet connection. For this reason, the proposed device presents the alternative of storing data in an SD memory.

An important issue for IoT devices is power consumption. In this case, the Deep-sleep tool is used to turn off most of the MCU services so that it consumes the least amount of power possible. At that point, the device utilizes an average of 78mW, which corresponds to the energy drained by the sensors, the OpenLog and the LiPo Charger. On the other hand, the highest energy absorption is made by the MCU when the device is transmitting data to the Internet. For this purpose, the MCU is turned on and then it is connected to the WiFi network (this is the task that takes the longest). After that, it acquires the data, sends it to the cloud, and finally enters Deep-Sleep again. This consumption peak is at an average value of 500mW, as can be seen in Fig. 7a. The approximate time for Wi-Fi attaching, sensors reading, and sending data to the cloud (with confirmation) is 15 s, but it may vary depending on the internet connection.

Another relevant aspect of IoT is battery life. In this sense, Fig. 7b presents the State of Charge (SOC) for 24 h. As can be observed in the Figure, after 24 h the device has available approximately 40% of the battery, this for a 5 min sampling time. In case the user wants to extend the device autonomy, there are different alternatives. In the first place, a larger capacity battery can be used, secondly, the user could increase the sampling time, and finally, the user could avoid sending data to the cloud and only store data in the SD memory. According to what is presented in Fig. 7b, and considering that the device has a 1 Ah battery, the approximate consumption in 24 h is 600 mAh. Which implies an average consumption per hour of 25 mAh.

The IoT multi-spectral acquisition device presented here measures the optical radiation quickly, reliably, and efficiently, presenting a low cost alternative for smart lighting systems. The proposed device can be used, among other things, to reconstruct the spectrum from the measured wavelengths using machine learning techniques. For example in [17], this device is used to recover a light source spectrum using only the 10 specific wavelengths that are obtained by the AS7262 and AS7263 sensors. The reconstructed SPD has an error lower than 2% and allows the estimation of colour and light quality measurements, such as the International Commission on Illumination (CIE) color rendering index (CRI) R_a and R_i (1–14) [18], the color quality scale (CQS) Q_a, Q_f, and Q_g [19], and the Illuminating Engineering Society's TM-30-15 R_f and R_g [20].

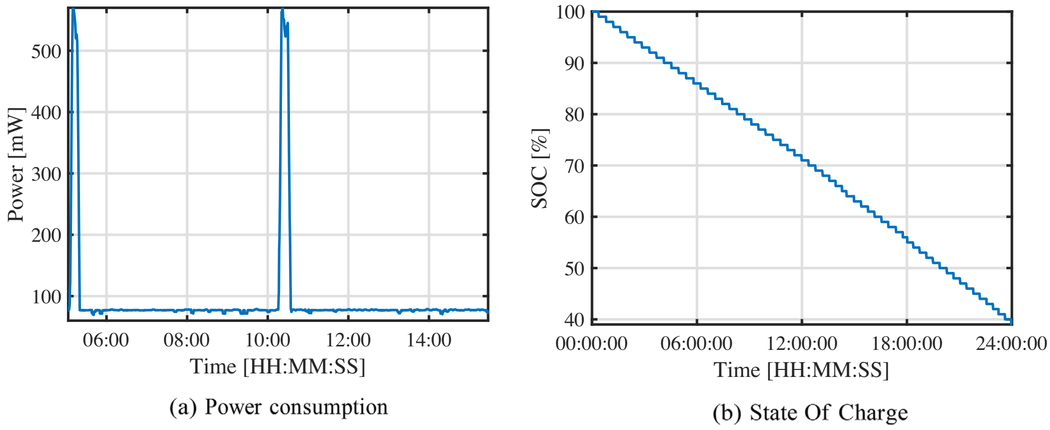


Fig. 7. Device power consumption.

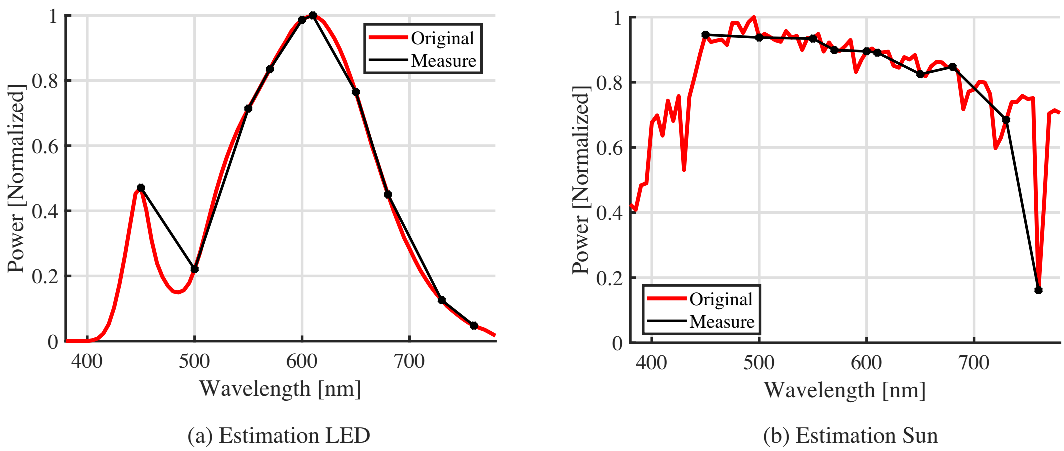


Fig. 8. Comparison with the measurement.

Finally, Fig. 8 shows the incident light spectra and the comparison with the measurement for the device after adjusting the scale in the bands using the data in the monochromator test, for more information see [17]. In the Fig. 8 it can be seen that the response of the device presented in this work is a good approximation and as mentioned above, acquiring a multispectral measurement allows other measurements to be derived, the approximation for the SPD of an LED and the Sun is presented as an example.

Some features and limitations of the device are summarized as follows:

- The device must be charged periodically, but can have a 24-hour autonomy.
- The device measures a limited number of channels, which are not evenly distributed. This depends on the detectors available on the market.
- The device can only be programmed using the Particle IDE
- The device can be used to make power measurements in the visible spectrum, according to the channels allowed by the sensors.
- The device can be integrated to other information or control systems through the wireless network.

Human and animal rights

No human or animal studies were conducted in this work.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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