12CNIT-2022 – FULL PAPER

Analysis of low-cost sensors for solar illuminance measurement

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Keywords: *low-cost; esp8266; Internet of Things*

TOPIC: ENERGY EFFICIENCY AND SUSTAINABILITY IN BUILDINGS AND INDUSTRY

1. Introduction

Energy efficiency is one of the biggest concerns nowadays. During the last months, a drastic increase of the electrical energy prices has been seen. The main causes are two: the strong revaluation of natural gas on international markets and the rise of the CO2 emission market prices. Therefore, reducing dependence on fossil fuels is a matter of urgency. The reduction of electricity consumption would help in following this direction. The use of natural illumination in buildings could play a vital role for decreasing the energy dependency, hence it is essential to measure the solar illuminance. Professional sensors cost hundreds of euros. This work compares several illuminance sensors for Internet of Things (IoT) projects against a professional one. The former ones cost just a few euros. The results show good precision and regular accuracy.

For the analysis of energy efficiency in buildings, knowing the values of solar irradiance and illumination is of crucial importance. The estimation of the light reaching a given work area inside a building requires knowledge of the outdoor lighting conditions. The International Commission on Illumination (Commission Internationale de l'Éclairage, CIE) proposed a characterization of skies taking into account the illuminance across the celestial dome. In it, three classes of skies (cloudy, partly cloudy or clear) are considered each subdivided into five types. Therefore, it proposes a total of 15 models of the celestial dome for different conditions of cloudiness and, therefore, illumination. At present, the most reliable way to analyze the type of sky according to the CIE is to use an expensive device that divides the dome into 145 sectors and measures the luminous emittance of each of them sequentially. For this purpose, it uses an expensive device called a "sky-scanner". Basically, it is a pyranometer that is mechanically orientated into predefined azimuth and altitude. This process, in addition to taking several minutes, puts a lot of wear on the device. Its acquisition and maintenance costs make it difficult to make it widely available. To replace this device, this work is a first step in replacing the sky-scanner by a set of pre-orientated sensors. Being able to find out which low-cost sensors perform better would help in the design and implementation of a similar device at a significant lower price.

Our goal is not only to find whether it is possible to obtain good illuminance measurements with cheap off-the-shelf sensors, but also to automate and integrate the measurement process into the so-called IoT world, i.e. send data from different locations to a centralized point, where they will be stored into a Time Series Database (TSDB), analysed, processed and finally displayed in ubiquitous web dashboards.

2. Materials and method

In this section, a series of key aspects for the development of the present study are discussed. First, the main characteristics of the selected professional luxmeter are exposed. It is the reference. Its measurements should be replicated by the low-cost luxmeters as accurately as possible. Second, the selected low-cost luxmeters will be discussed in detail. Their characteristics and limitations will be presented. Third, the prototype set up to record the measurements of the low-cost sensors is detailed. Finally, the IoT platform and the software developed for data collection are shown.

2.1 Professional luxometer

The reference sensor used is the EKO ML-020S-0. In Table 1, its most relevant characteristics for the present comparison can be found. Please, note that it produces a voltage signal in the range of millivolts. This makes it necessary to have special electronics capable of amplifying and capturing the oscillations of such low analog voltage values. This signal conditioning device adds an additional cost to the amount required for installation. It will be seen later that low-cost sensors provide digital readings, make them suitable to be directly attached to any kind of external digital logic like a microcontroller. This results in lower overall cost. In addition, an error estimate for a temperature range of -10 to 50 ºC is highlighted. Higher temperatures are to be expected in a device installed outdoors without any cooling. Although, its low value gives an idea of the accuracy of this device.

Table 1. Specifications of professional luxometer

SENSOR	OPERATING VOLTAGE RANGE	MAXIMUM ILLUMINANCE (klx)	TEMPERATURE RESPONSE -10 to 50 ºC
ML-020S-O	0 to 30 mV	150	0.4 %

2.2 Low-cost sensors

A set of six light sensor modules was chosen. Table 2 summarizes the main characteristics of each sensor. A detailed search of illumination sensors in the market was carried out. Those with the widest possible illuminance range were selected. Only three of them (VEML7700, TSL2591 and MAX44009) achieve the maximum solar luminance estimated at 120 klx. It is also noted that some models are capable of measuring the solar infrared (IR) and ultra violet (UV) spectrum, in addition to visible light. However, these measurements were not used in this study.

Table 2. Low-cost illuminance sensor modules

SENSOR	OPERATING VOLTAGE RANGE (V)	OPERATING TEMP. RANGE (°C)	MAXIMUM ILLUMINANCE (klx)	LIGHT SPECTRUM
VEML7700	2.5 to 3.6	-25 to +85	120	visible
TSL2591	2.7 to 3.6	-30 to +70	88	visible + IR
OPT3001	1.6 to 3.6	-40 to +85	83	visible
SI1145	1.7 to 3.6	-40 to +85	128	visible + IR + UV
MAX44009	1.7 to 3.6	-40 to +85	188	visible
VEML6075	1.7 to 3.6	-40 to +85	100	UV

2.3 Prototype

A PCB board (Fig. 1) is designed so light intensity values can be obtained simultaneously from six different low-cost sensors [1, 2, 3, 4, 5, 6] and will be finally compared against a professional calibrated luxometer (EKO ML-020S-O). These sensors are carefully chosen so their spectral response is that of the human eye. The board is designed around Espressif's ESP8266 microcontroller because of its WiFi communication capabilities, well documented API and low cost. The six lux sensors are connected to the microcontroller via well-known I2C protocol. Some of these sensors share the same I2C address, hence an I2C multiplexer (TCA9548A) had to be included in the system. The PCB is completed with a real time clock (DS3231) and a micro-SD slot: in the event of network failure, or in the case the device is used as a non-connected standalone datalogger, the measurements, along with their timestamp are still recorded in JSON format inside the micro-SD card. Each sixty seconds, the microcontroller sequentially polls all six sensors; the illuminance values, along with the timestamp and other values of interest (integration time, gain, etc) are included in a JSON structure that is both written to a file and sent via WiFi.

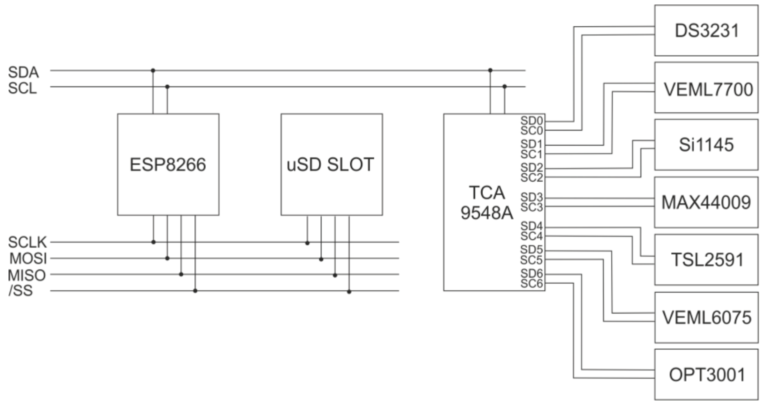

Figure 1. High level circuit schematic of the PCB sensor board

The ESP8266 microcontroller is an Adafruit Feather HUZZAH USB-enabled development board. This 32 bit RISC CPU clocked at 80 MHz, with 160 kB of RAM and 4 MB of external flash memory, besides the customary general purpose I/O pins and SPI, UART and I2C peripherals, includes full IEEE 802.11 b/g/n Wi-Fi compliance thanks to its integrated TR switch, low noise amplifier, power amplifier, impedance adaptation network and antenna. Since the selected microcontroller does not provide an internal real time clock (RTC), we included an external one, so in the event of a network failure that prevents from network time synchronization, a local timestamp can be still generated. For this task we chose a module that integrates Maxim DS3231 high accuracy RTC (thanks to a temperature-compensated internal oscillator) and Atmel AT24C32 4 kB EEPROM, both sharing the I2C bus and backed up with a CR2032 lithium battery. To be fully resilient to a network outage, sensor data must also be stored locally, so a 32 GB micro SD card is included. This card is inserted into holder module that talks to the microcontroller by means of the Serial Peripheral Interface (SPI) protocol, which allows for synchronous serial two-way communications. An I2C multiplexer (Texas Instruments TCA9548A) is used in order to address sensors with the same I2C address which would otherwise overlap, as it can be seen in Table 3. Lastly, the prototype was powered using a Traco TSR 1-2450 step-down switching regulator, capable of providing a steady output of 5V at 1A with an input voltage ranging between 6.5V and 36V. It has a 94% efficiency, so it is suitable to plug into a 12V DC power supply or a 12V NiMH battery should it be needed.

Table 3. I2C slave devices in the circuit

PART CODE	I2C ADDRESS
clock DS3231	0x68
eeprom AT24C32	0x57
multiplexer TCA9548A	0x70
sensor VEML7700	0x10
sensor SI1145	0x60
sensor MAX44009	0x4A
sensor TSL2591	0x29
sensor VEML6075	0x10
sensor OPT3001	0x44

2.4 Internet of Things

The diagram in Fig. 2 shows all the IT infrastructure involved in managing the data produced by the sensor board. By means of the TCP/IP layer 7 protocol MQTT (Message Queue Telemetry Transport), the data is sent to a centralized message broker (Mosquitto). This method enables the seamless addition of extra sensor boards across several locations. Node-Red acts as a data bridge, between the message broker and the database. It also allows the preprocessing of the received data, should that be required. The data is then stored in InfluxDB, a Time Series Database (TSDB), which is especially suitable to store and perform real time analysis of big volumes of time series. Finally, there is Grafana, a web environment capable of displaying rich visual dashboards and graphs based upon queries on the TSDB. The data displayed on such graphs can easily be exported to CSV to perform further mathematical modelling and analysis.

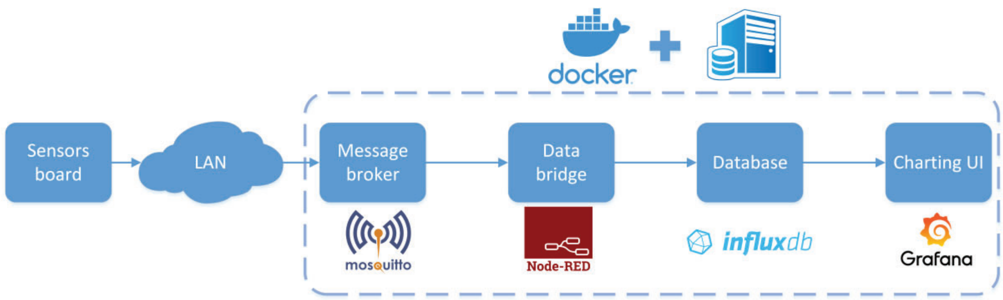

Figure 2. Full diagram of the system.

Since the tested sensor are heterogeneous, for each one a variable of type *struct* is defined, whose members are the different parameters provided by the sensor under test (e.g.: lux, human-visible ambient light, IR…). In order for the board to be able to work offline, besides sending the measured values through WiFi (and getting the current timestamp via Network Time Protocol -NTP-), the embedded micro-SD card slot and real time clock can be used as a network-isolated datalogger, which will save one text file per day with the same JSON-formatted information as it would be sent via wireless network should it be available. The program developed for the ESP8266 microcontroller in C++ language using Arduino API is briefly described in the flowchart from Fig. 3. In the initialization section (which is only executed after microcontroller boot up), several functional groups are configured or given operational values: microcontroller's serial and I2C internal peripherals, light sensors and external RTC. The latter is configured with the program's compilation date and time, which will be held thanks to the customary CR2032 coin cell battery. A timer interruption is set to rise every 60 seconds. In its Interruption Service Routine (ISR) a global boolean variable is toggled so when the program waits for the next measurement cycle it does not have to do an active wait, thus letting WiFi routines not to starve and keep the connection up. The microcontroller's WiFi internal card (RF PHY + MAC) is configured in Station mode (ST) so it can connect with the Access Point (AP) generated by the server. Once network layers 1 to 4 from OSI model are established between the microcontroller and the server, an MQTT (Message Queue Telemetry Transport) client is enabled in the former. This layer 5-7 protocol will be responsible for sending sensors data to the server (which will act as an MQTT broker) in an efficient way (in terms of computational resources, bandwidth and energy consumption). In the measurement stage, every sensor is polled and its information temporarily saved to its data *struct* variable. Once the polling is finished, the next stage begins, in which all data from every sensor is structured into a JSON object. This let us to both send it via an MQTT Publish message to the central broker and also be saved in the on-board micro-SD card (one file per day, one JSON-formatted line per multiple-sensor measurement). Finally, the program reaches a stage in which it is waiting for either the timer interruption (which will trigger a new measurement) or any interruption from the network stack.

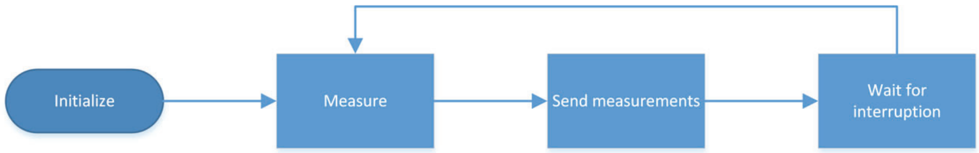

Figure 3. High level flowchart of the program running in the microcontroller

3. Results and discussion

Figure 4 shows the finished device, with all the components already soldered onto the PCB: (A) TRACO TSR1-2450 step-down switching regulator, (B) VEML6075 light sensor, (C) TSL2591 light sensor, (D) SI1145 light sensor, (E) Micro SD card reader populated with a 32 GB card, (F) TCA9548A I2C multiplexer, (G) OPT3001 light sensor, (H) VEML7700 light sensor, (I) MAX44009 light sensor, (J) Adafruit Huzzah ESP8266 development module and (K) Real time clock module (DS323+AT24C32+CR2032 lithium battery).

Figure 5 shows the measurements recorded by all sensors for June 11, 2021. The limitation of illuminance range in the recorded measurements is clearly visible. While the professional luxmeter reaches to 100 klx without any problem, the low-cost sensors hardly reach that figure. They suffer attenuation as the Sun increases its altitude and, consequently, the illuminance value increases. The smallest errors are obtained at sunrise and sunset. The most anomalous behavior is experienced by the OPT3001 sensor, since it stops measuring at 75 klx. Therefore, its use would be ruled out in view of these results. However, it could be due to an error in the assembly or to an operating mode that can be modified.

Figure 6 shows the comparison of the low-cost sensor measurements against the calibrated one. Only the sensors that measure illuminance are brought into the comparison. Data of UV radiation is disregarded. One of the sensors, the SI1145, did not survived the testing phase. The case containing the PCB board experienced humidity issues that may have caused a premature death. That could also explain some of the isolated measurements in the survival ones. They have a very consistent precision. However, the accuracy is average. It can be clearly seen that they measure below the calibrated sensor. This bias could be alleviated using some type of transfer function. However, such mathematical approach was not considered in this first stage of the work.

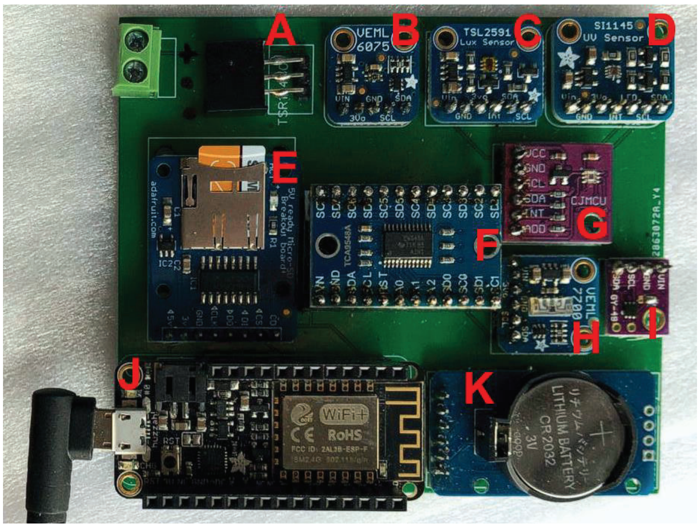

Figure 4. Finished PCB

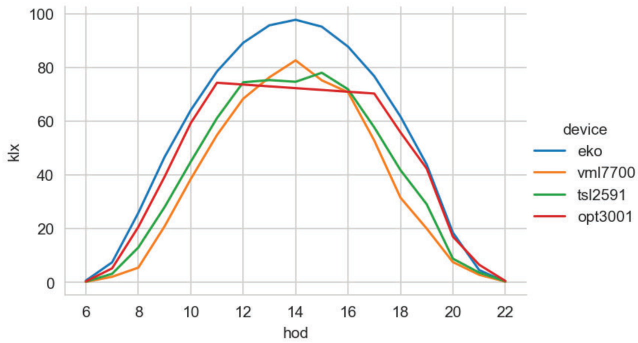

Figure 5. Illuminance measures of Jun 11, 2021

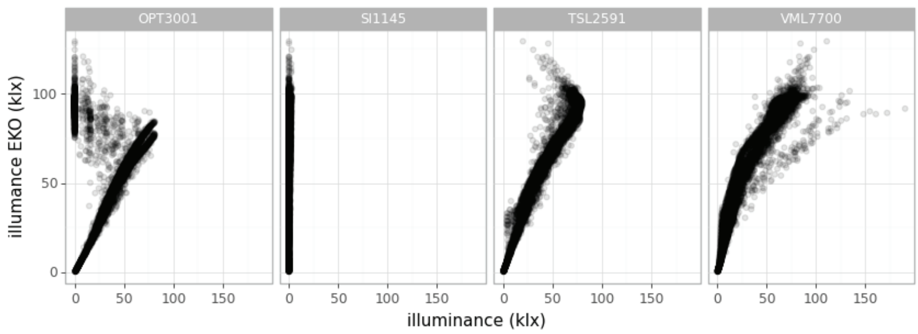

Figure 6. Illuminance low-cost sensor measurements versus professional one

4. Conclusions

The proposal hereby presented is very promising. The low-cost sensors analyzed show a good precision. Also, there is a bias that could be corrected using a mathematical function. The use of these types of sensors could vastly improve the collection of illuminance data: not only the costs will be radically reduced but also the use of IoT tools will leverage the recording and treatment of the collected data. Both aspects will help in the modelling of the solar energy available for natural illumination inside buildings.

Acknowledgements

The authors gratefully acknowledge the financial support provided by the Spanish Ministry of Science & Innovation under the I+D +i state program "Challenges Research Projects" (Ref. RTI2018-098900-B-I00). Diego Granados-López thanks grant PIRTU Program, ORDEN EDU/556/2019, for financial support.

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