Calibrating Raspberry Pi v2.1 Camera as an Absolute Luminance Meter for Smart Luminaire System Sensing Applications

Nebyu Yonas[1*] and Enyew Adugna[1]

School of Electrical and Computer Engineering, Addis Ababa institute of Technology,
Addis Ababa University, Addis Ababa, Ethiopia
**Corresponding author's E-mail address: nebyu.yonas@aait.edu.et; nebayoni@gmail.com*

DOI: https://doi.org/10.20372/zede.v42i.10186

ABSTRACT

This article presents the conception and realization of a self-contained, absolute luminance level measurement device using a Raspberry Pi v2.1 camera system and single-board pocket size Raspberry Pi computer for a smart luminaire system sensing applications. The work presents Raspberry Pi v2.1 camera module footage in raw Bayer data formats, radiometric characterizations, raw Red, Green, Blue (RGB) to absolute luminance meter calibration and validation results. The developed absolute luminance meter is very simple, efficient, compact and suitable for absolute luminance level sensing measurement. Results obtained from the luminance meter calibration validation experiments showed that the proposed absolute luminance meter has the capability of measuring wide range of absolute luminance levels quickly with an average deviation of less than 2 cd/m^2 from actual measurements or with 97.48 % accuracy.

Keywords: Absolute Luminance, Raspberry Pi v2.1 Camera, Smart Luminaire System.

1. INTRODUCTION

Light, which is a necessity for humans and vision, is a form of electromagnetic radiation that travels through space within the visible electromagnetic spectrum as a wave that can be perceived by human eye [1]. Light from a light source reflects off a surface reaching human eye passing and proceeding in cornea and pupil forming images in retina. Human eye is therefore sensitive to wide range of light intensities for its proper function.

As human brain perceives light and geometry at the same time and interprets it as vision, many scientific and engineering applications in image processing are supposed to be capable of detecting both photometry and geometry at the same time [2]. This is useful in many applications including, smart luminaire systems, glare computation, light quality assessment, natural light harvesting, light control and so forth. Especially in smart luminaire systems, where absolute luminance level measurement is focal, its use is indisputable.

Generally, there are two types of light measurements, illuminance and luminance [3]. Measurement of light from a source that falls on a surface is known as illuminance. It is measured in Lux and devices used to measure it are cheap and easily available. Luminance is measure of light reflecting back from a surface and corresponds to human eye sensation of brightness of a source and is measured in units of cd/m^2. When humans look at the world, their eyes actually detect brightness (the arbitrary sensation of luminance), not illuminance.

The word camera comes from the Latin word 'Obscura', meaning a dark chamber or dark room [4]. Since its invention, camera has been in a continuous evolution and currently it has reached the age of digitalization. Digital cameras compared to their analog counterparts offer better resolution, minimized noise, better dynamic range, speed, price, size, portability, convenience and etc. [5]. However, the main advantage of digital camera lies in its output digital signals which can easily be attained, analyzed, processed, interpreted, manipulated and stored [6].

Digital cameras evolved quickly, offering tremendous opportunities and enjoying a great market penetration and success in the last few decades. Especially the rapid evolution of Complementary Metal Oxide Semiconductor (CMOS) technologies in the last few decades yielded a very powerful, miniaturized, easy-to-manipulate digital cameras for commercial purposes in a much cheaper price than ever before [5]. These days, digital cameras operate and function as optical instruments in the similar way the human eyes do.

Digital cameras operate based on the principle of sampling light reflected from objects and directly mapping that into sequence of pixel values [7]. They possess a series of lenses which are used to focus light into a semiconductor device to record light intensity electronically. Digital cameras also possess array of sensors, also called photosites, which are used to convert light falling on them to equivalent electrical charges. Photosites are light sensitive tiny sensors which convert light (photon) in to electrons (electric charge). Photosites are sensitive to lights and hence will result in creation of large electrical charge when exposed with brighter lights.

Today, as artificial lightings are solely responsible for a significant portion of global power consumption and environmental pollutions, cutting energy consumption and boosting users' comfort in artificial lighting systems are some of the major research targets. To accomplish visual comfort and reduction in energy consumption in these luminaires systems, absolute luminance measurement is an absolute necessity. Hence, since the last few decades, there are several ongoing efforts underway to calibrate digital cameras as a compact, simple, affordable luminance meter for wide-range of applications. However, the progress made so far is either limited or failed to avail and make the final transformation matrix public. This article deliberates an absolute luminance sensing using Raspberry Pi v2.1 camera for smart luminaire system applications.

2. MATERIALS AND METHODS

2.1. Raspberry Pi v2.1 Camera Overview

Raspberry Pi v2.1 camera module is a mini sized, high-performance, 8 Megapixels' digital camera which is based on Sony IMX219 back-lit CMOS sensors [8-9]. It offers the possibility of multiple character alterations through a software control. It is widely applicable in applications of high dynamic range imaging, remote sensing, computer vision, bio photonics, security and surveillance, light measurement, medical imaging, remote sensing and many more. The main reason for this is the fact that its ability to deliver raw Bayer data formats, which can easily be accessed and used for many different motives.

The Raspberry Pi v2.1 camera used in this study was 3 grams in weight and 25 mm×25 mm×9 mm in size [10]. It could be directly attached to the Raspberry Pi 3 module B single board computer through the Camera Sensor Interface (CSI) port. Its characteristics could easily be controlled and monitored via the Raspberry Pi firmware. The firmware has gone through several development stages in time and currently it has an extended functionality and robust controls. The camera is capable of delivering 3280 × 2464 Bayer data of 8 megapixels. The Bayer data pattern of the camera was Blue Green Green Red (BGGR) and operated only in the visible light spectrum, i.e. from 380 nm up to 700 nm [8].

Many scientific and engineering applications require raw sensor data to be extracted so further analysis can be carried [9]. Raspberry Pi v2.1 camera is not only fit for this purpose but also one of the best in the market with a reasonable price. The camera requires only 250 mA to run and operate. It is also compact in size and low in weight [8]. This makes it ideal for low-cost application consumptions compared to the highly expensive and bulky digital commercial cameras available in the market.

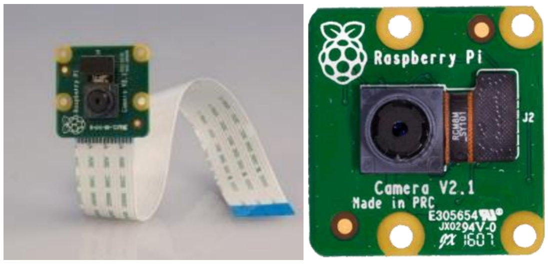

Figure 1 Raspberry Pi v2.1 camera

2.2. Smart Luminaire Systems

Smart luminaire systems are lighting systems that tailor and deliver artificial illuminations automatically, according to user tasks, responses, comfort, and wellbeing with appropriate luminaire color temperature, brightness level and energy consumption reductions [11]. They use different sensors, electronics, circuitries, actuators, gadgets, and communication protocols in a closed-loop control manner to realize that [12]. These lighting systems are created to considerably cut lighting energy consumptions while simultaneously improving user comfort and experience. Additionally, Solid-State Lighting (SSL) devices like Light Emitting Diodes (LEDs) have become more common, and they can now provide the right illumination levels, with suitable luminaire color temperatures in line with users' visual comfort and activities [13]. At present with the rapid evolution of wireless sensor networks and LED luminaire technologies and state of the art LED driver circuitries, delivering different illumination level and color temperature are easier than ever before [14-16].

Smart luminaire systems typically contain three main parts; measurement module: which is the front-end part of a smart luminaire system which is responsible for monitoring real-time situations according to design specification including illumination level and activity to deliver vital information in for decision making. Here is where real time light measurement devices play a crucial role. They are used to measure the actual light levels at the scene. The information processing and decision-making part is the middle part of any smart luminaire system and is responsible for information processing and decision making on the luminance level of luminaires. The last part of any smart luminaire system is the luminaire lighting system, which consists of luminaire drivers and luminaires that are responsible for the artificial illumination. A typical smart luminaire system based on LED luminaires and with its main components is shown in Figure 2.

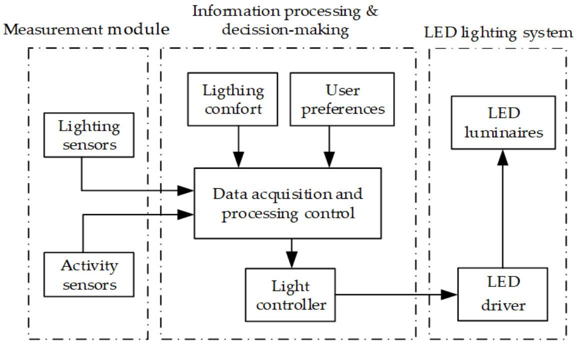

Figure 2 Typical smart luminaire system [14]

2.3. Digital Camera to Absolute Luminance Sensing Calibration

There are several digital cameras that are made specifically for luminance level measurements with very high standards. However, due to their high precision, accuracy and complex analytic solutions, these cameras are extremely expensive and not commercially practical for many luminance measurement applications. Despite having a history of high reliability and precision, meter-based measurement is a time-consuming, point-by-point process with poor measurement resolutions. Furthermore, given their poor measurement speed and the time intervals between readings, these luminance meters are ineffective for measuring dynamic light scenes and integration with smart luminaire systems.

Today, easily affordable and accessible digital still cameras are opening up the possibility for an absolute luminance level measurement in a wide range of applications. Consequently, several past related works [17-21] showed that relatively cheaper digital cameras can be used to measure actual luminance levels with tolerable precision. However, before utilizing these digital cameras for absolute luminance level measurement, they must be characterized and calibrated. This calibration process will directly affect the reliability, accuracy and precision of such systems.

Hence, the current readily available digital cameras, which use either Charge Coupled Device (CCD) or CMOS light collection technology, can be practical and affordable luminance measurement instruments with proper calibration. Via acquiring the real luminance level of a space, a range of architectural smart lighting applications, such as automated daylight harvesting systems, dynamic lighting control, lighting simulations, and glare assessments, can be made more easily and effectively.

The luminous atmosphere of an architectural space for different tasks cannot be deciphered using illuminance-based metrics and measurements from the perspective of human eyesight. Instead, measurements that are based on luminance level would be more appropriate. Some examples of luminance-based metrics in smart luminaire systems include ambient luminance, target luminance, luminance uniformity, background luminance, luminance contrast, and task/background luminance ratios. Such luminance-based indices have been extensively utilized in lighting applications that are important for vision, including different tasks (reading, surgery, office, recreation, gaming etc.) and road lighting system, which have a significant impact on, vision, visibility, safety, comfort, psychology and efficiency.

However, due to the fact that still digital cameras employ various image-processing techniques which change the digital cameras' default responses, has led to difficulties in direct luminance measurements. These various image processing techniques cannot be completely changed or manipulated by the end user. However, Raspberry Pi v2.1 camera allows that, making it one of the best potential devices in the market for the purpose of absolute luminance level measurement consumptions in different applications.

2.4. Raspberry Pi v2.1 Camera Characterization

2.4.1. Raw Bayer Data Acquisition

One of the main advantages of a Raspberry Pi v2.1 camera is its ability to deliver raw Bayer data values which are significant for scientific and engineering applications [9]. Raw Bayer data are simple data captured via the camera CMOS sensor and prior to processing by the camera Graphical Processing Unit (GPU). The main GPU processes include white balancing, defected pixels' correction, smoothing, metamerism, vignetting compensation, dark frames correction, compression, color adjustments, etc.

By turning off the auto white balance and activating the Bayer data mode on, a 3280 × 2464 raw Bayer data can be acquired from a Raspberry Pi v2.1 camera. Usually, the raw data RGB and YUV data formats of Raspberry Pi camera are GPU post processed data and hence not the real sensor outputs suitable for luminance measurement calibration purposes [8].

2.4.2. Linearity

The linearity test of the Raspberry Pi v2.1 camera was conducted to investigate the Raspberry Pi camera response as a function of shutter speed (exposure time). To excite the camera for this test, a 10 × 10 cm Lambertian flat surface Organic Light Emitting Diode (OLED) light source was positioned perpendicularly 1 m below. Different Shutter Speeds (SS) were used and the corresponding central 80 × 80 data Bayer array outputs were recorded and analyzed. This was done to prevent the data being affected by the vignetting effect of the camera, which is a common phenomenon in digital cameras [22-24]. The OLED luminance level was adjusted from 1 cd/m^2 up to 850 cd/m^2 at different intervals for each shutter speed and raw data readings were recorded.

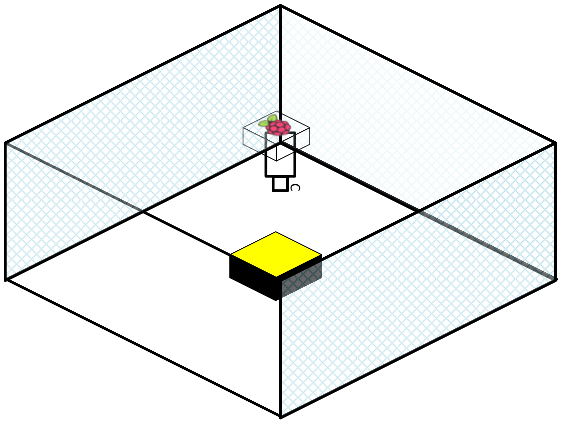

Figure 3 Linearity experiment set up

2.4.3. Uniformity/Vignetting Test

Vignetting effect is a phenomenon noticed in many digital cameras and optical activities where the output data values fade out towards the edge [22-25]. It is the consequence of light intensity fall-off of the camera lens towards the periphery of image. It is clear that both resolving and transmission of a lens are higher at the center and fall off towards the edge. Vignetting correction is manipulation of the raw Bayer data array values in a fixed fashion in order to regenerate the original intensities at the center of an image. To investigate the vignetting effect of the Raspberry Pi v2.1 camera lens, uniformity test with an excitation of a constant luminance level with the OLED light source was used across the entire camera Field of View (FoV). The experimental setup used is given in Figure 4.

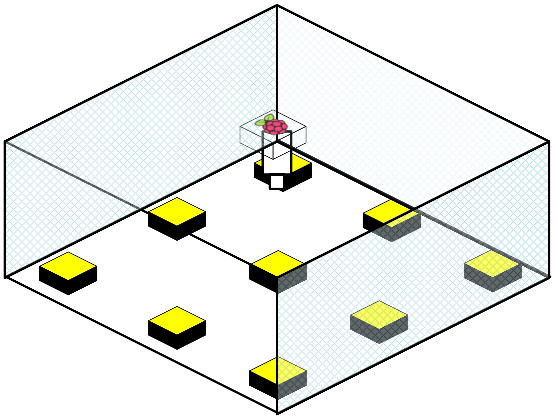

Figure 4 Uniformity test experiment setup

The camera was fixed 1 m above the table and its field of view was initially divided into 9 different zones and each zone's Bayer data responses to a constant luminance level were recorded. Further, to have a better response information on the area close to the center of the camera, additional four extra sub-regions were taken into consideration. This experiment was also done with different shutter speeds to check its uniformity and results showed the camera has similar vignetting responses. Therefore, by fixing the excitation at a constant level, any difference in the Bayer data was accounted for the vignetting effect of the lens. Again, here also 80 × 80 center data Bayer array outputs were used for the analysis.

2.4.4. Spectral Response

A spectrum response test experiment was carried out to investigate the absolute and relative spectral response of the Raspberry Pi v2.1 camera to various different wavelengths. In this experiment the Raspberry Pi camera was placed in front of an integrating sphere illuminated by an illumination wavelength of a laser light source from 360 nm to 720 nm. The camera was made to target the aperture of the integrating sphere at its center. The laser light source was made to pass through a monochromator (Bentham TMc300) so that only the wavelength of interest makes it to the integrating sphere.

The spectral radiance values, in W/m^2.sr.nm units, were recorded using spectrometer and results were integrated over wavelength in order to get radiance values in units of W/m^2.sr in Matlab. Then the Raspberry Pi camera red, green and blue Bayer data values were recorded to get its absolute spectral response. Then for the relative spectral response, these data values were normalized and plotted against the wavelength. For this task two different experimental setups were used with two different shutter speeds (400 ms and 30 ms) and results recorded were found to be identical.

Therefore, absolute and relative radiance calibrations, raw data value to radiance conversion, were accomplished successfully.

2.4.5. Dark Frame Rate Analysis

For the dark frame rate analysis test, the Raspberry Pi v2.1 camera aperture was covered by a dark material in a dark room around room temperature. Since raw data values depend on temperature, the room temperature was kept constant thorough out the experiment and the camera were warmed up before acquiring the images so that it will not affect the dark frame values recorded. This experiment was conducted to get the Raspberry Pi's constant dark frame (noise) added to the raw data so that it will be considered before further processing. Different shutter speeds were used for this analysis.

3. RESULTS AND DISCUSSION

3.1. Raspberry Pi v2.1 Camera Characterization

The Raspberry Pi v2.1 camera linearity test experimental findings demonstrated that the shutter speed of the Raspberry Pi camera is linear with each of the three channels' raw data Bayer values. However, opposed to the work in [9], the Raspberry Pi cameras red Bayer data responses were found to be higher than that of the green channel. The blue raw Bayer data showed the smallest data values compared to the other two. Hence, based on the results obtained and shown in Figure 5, it was found that the camera response is linear with shutter speed (exposure time).

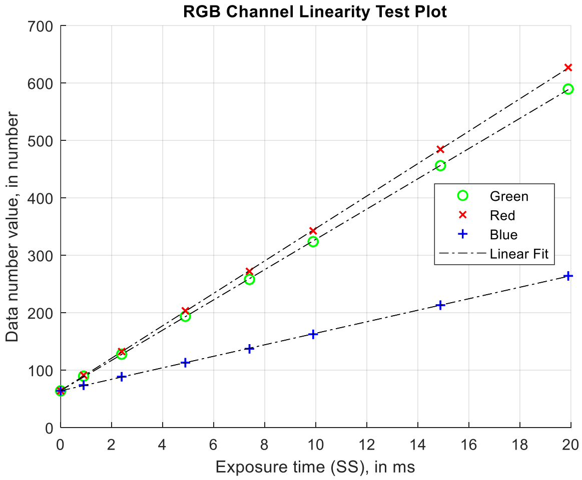

Figure 5 R, G, B typical linearity response

Further, the experimental findings for the Raspberry Pi camera uniformity/vignetting test, based on the recorded data for 3 different shutter speeds (1, 5, and 10 milliseconds), a flat fading surface response towards the periphery in the camera was observed. There was a significant drop in the intensity of the Bayer data values, up to 75 % around the edges. Moreover, the results obtained showed that the camera shows optical symmetry in both diagonals (top left to right bottom and top right to left bottom). The blue and green Bayer data show almost identical responses whereas the red channel showed a little different response with an increased vignetting effect. This result was identical to a previous work [9]. Uniformity test results obtained are shown in Figure 6.

Supplementary, based on the results obtained above, two-term Fourier series expansion lens correction or compensation coefficients were computed in Matlab. The following were vignetting correction equations used for the red, green and blue Bayer data, respectively.

$$F(r) = -1.234 + 1.962\cos(w.x) - 1.751\sin(w.x) + 0.2604\cos(2w.x) + 0.079\sin(2w.x) \quad (1)$$

$$F(g) = 0.49 + 0.4123\cos(w.x) + 0.185\sin(w.x) + 0.0908\cos(2w.x) - 0.057\sin(2w.x) \quad (2)$$

$$F(b) = 0.493 + 0.4216\cos(w.x) + 0.173\sin(w.x) + 0.081\cos(2w.x) - 0.0615\sin(2w.x) \quad (3)$$

where:

w equals; - 0.0007905 for r, 0.001312 for g and 0.001284 for b.

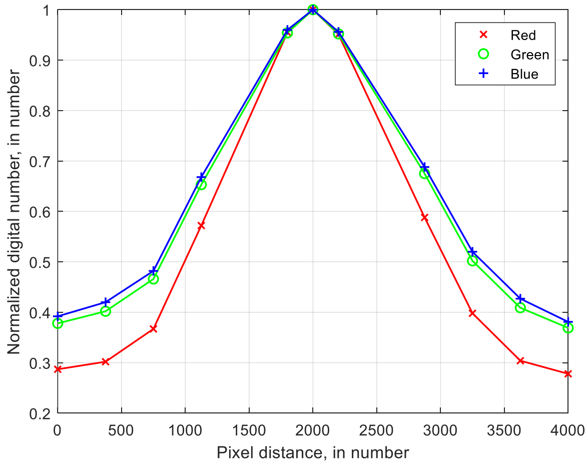

Figure 6 Uniformity test response

After applying the vignetting effect correction, the following results, displayed in Figure 7 to 9, were obtained for each channel. As it can be seen from the plots, the reconstruction exhibits RMSE of 0.0109, 0.0068 and 0.0038 for the red, green and blue channels, respectively.

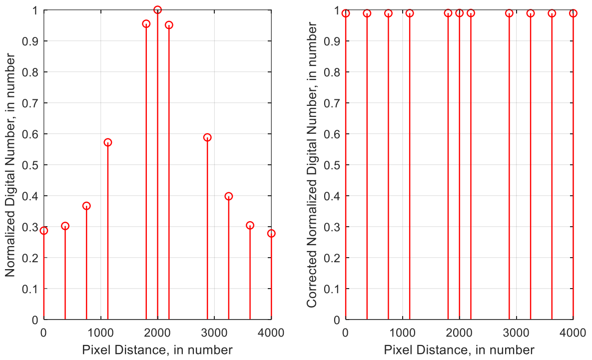

Figure 7 Red channel vignetting correction

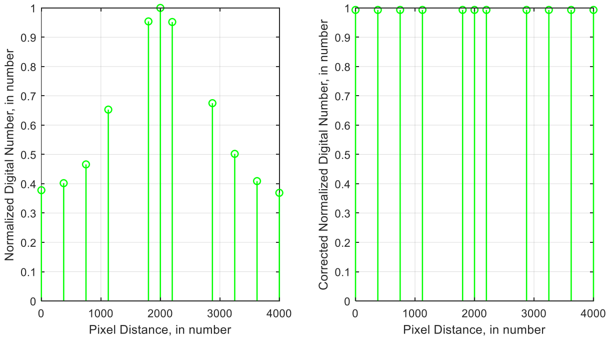

Figure 8 Green channel vignetting correction

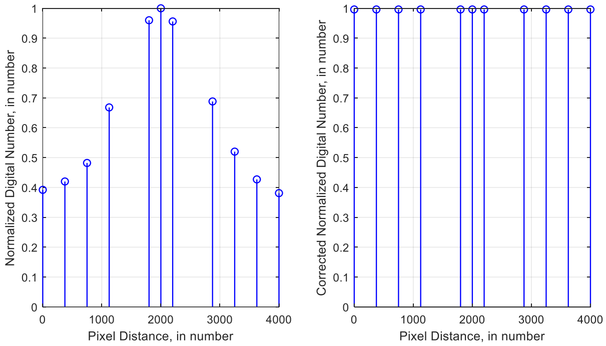

Figure 9 Blue channel vignetting correction

The Raspberry Pi v2.1 camera spectral response characterization experimental setup results for absolute and relative spectral responses are shown in Figures 10 and 11, respectively. Note that the shutter speed used for this experiment was 400 ms.

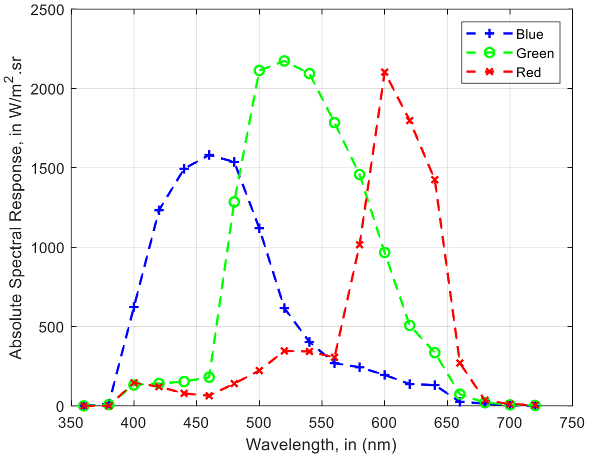

Figure 10 Absolute spectral response

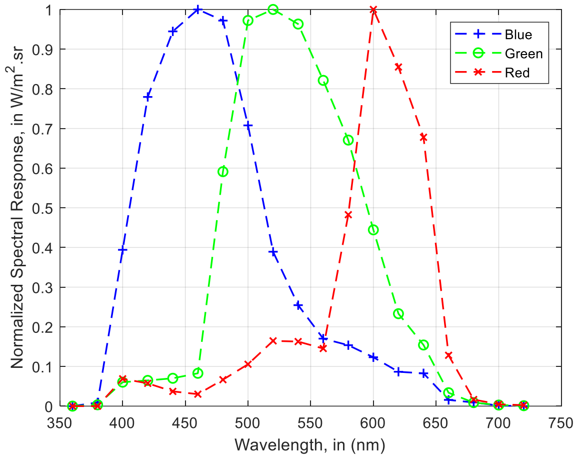

Figure 11 Relative spectral response

Furthermore, results obtained from dark frame rate analysis experiment are shown in Table 1.

Table 1 Dark frame rate test results

SS (μs)	**R** (number)	**G** (number)	**B** (number)
898	63.96	63.97	63.84
2391	64.04	63.88	63.89
4887	63.90	63.94	63.89
7401	63.95	63.93	63.90
9896	63.94	63.96	63.92
14887	63.92	63.93	63.94
19896	63.99	63.91	63.89
Average	**63.96**	**63.93**	**63.90**

As shown in Table 1, there is a very close resemblance between the r, g and b channels. Therefore, the dark frame values are consistent and very close to 64 data number values. This implies that, these values should be deducted from the raw Bayer values before further analysis. Additionally, it should be noted that it is not possible to obtain raw Bayer data values lower than the dark frame rates at any given time while attempting to calibrate the Raspberry Pi v2.1 camera as an absolute luminance meter.

3.2. Absolute luminance meter calibration

The Raspberry Pi v2.1 camera was made to be excited via OLED light source luminaire, with different shutter speeds and luminance level values in this work. By putting the OLED at the center of the camera Field of View (FoV), R, G, B to luminance mapping was computed as a function of SS, r, g and b raw data Bayer values. The calibration was done based on the principle of converting digital image raw data to luminance level. Knowing that the camera response is linear with the luminance scene functions, a 3X1 linear transformation matrix from RGB to Luminance level estimation was computed via a linear regression model. Please note that the central 80 × 80 Bayer data were used for this scrutiny.

Therefore, the final task of calibrating the Raspberry Pi v2.1 camera raw data to absolute luminance level was carried successfully in Matlab. Hence, the Raspberry Pi v2.1 camera was made read and measure absolute luminance levels. The transformation matrix is given in equation4.

$$L = (0.0046 \times r + 0.0064 \times g + 0.008 \times b)/SS \quad (4)$$

where:

SS is the shutter speed given in second and r, g and b are Bayer data values after the dark frame correction.

Results obtained showed an average of 1.6 cd/m^2 difference from the real luminance value measured using Konica Minolta Luminance Meter and 5.1 cd/m^2 and 0.1 cd/m^2 maximum and minimum deviations respectively, under different light sources.

Therefore, via activating raw Bayer data of Raspberry Pi v2.1 camera and deploying vignetting correction and absolute luminance transformation matrix, given in equations 1-4, the device can be used as a simple, compact, affordable and efficient absolute luminance meter for different absolute luminance measurement applications.

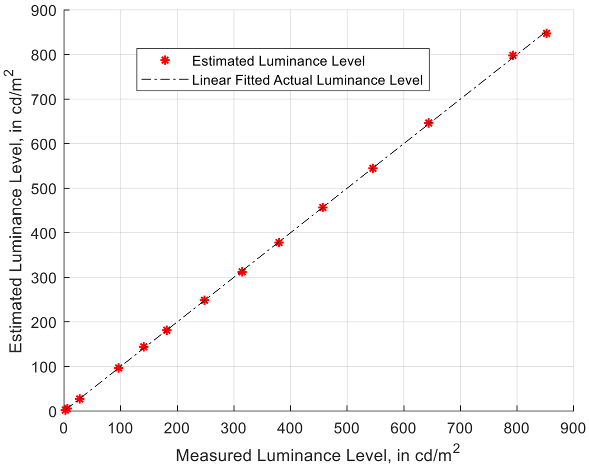

Figure 12 Measured vs estimated luminance

3.3. Absolute Luminance Meter Validation

Different luminance levels, from 3 to 850 cd/m^2, with a variety of light sources with different spectral properties including day light, Philips Hue LED lamp, incandescent lamp, florescent lamp, halogen lamp and combination of the above-mentioned light sources were used to assess the raw Bayer data-based absolute luminance level estimation accuracy. Results obtained from the validation assessments yielded an average deviation of less than 2 cd/m^2 from actual measurements with mean square error of 8.18, root mean square error of 2.86 and 97.48 % accuracy. Further, the device exhibited a capability of providing quick response compared with the traditional actual luminance meters. Figure 13 and Figure 14 show the validation results.

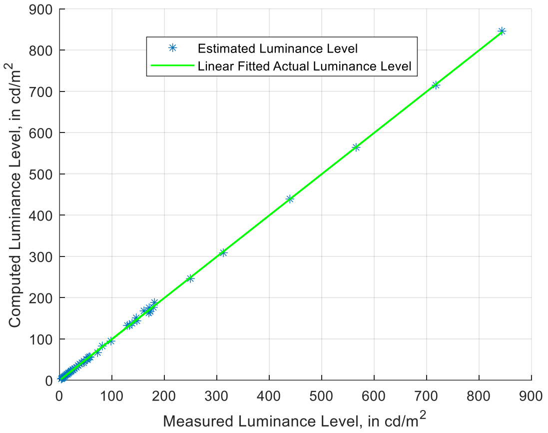

Figure 13 Validation for 0 – 900 cd/m^2 range

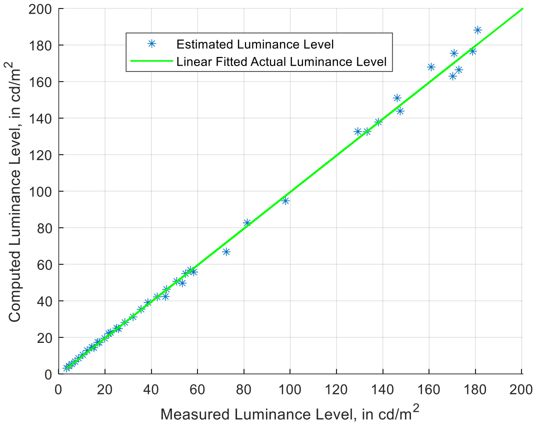

Figure 14 Validation for 0 – 200 cd/m^2 range

4. CONCLUSIONS

Results obtained from this work showed that, Raspberry Pi v2.1 camera can be calibrated to be used as a simple, compact, affordable and efficient absolute luminance meter. Using this device, a smart artificial luminaire system which does not only target power consumptions minimization but also user comfort, humans' psychological boost, and illumination level adjustment can be realized. This in turn, will have positive effects in humans' productivity and quality of indoor lighting environment. This luminance meter can also be used in embedded systems, which deal with real-time absolute luminance level measurements for analysis and decision making. Hence, there is no doubt that the proposed calibrated absolute luminance level measuring device usage will be tremendous and can be readily used as a focal part of the measuring unit in typical smart luminaire systems and other similar applications.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ACKNOWLEDGMENTS

This study was undertaken in the School of Electrical and Computer Engineering, Addis Ababa Institute of Technology. The authors are grateful to Addis Ababa University for its financial support and KU Leuven University for availing its laboratory facility.

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