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A 360° Omnidirectional Photometer using a Ricoh Theta Z1

Ian MacPherson, Richard F. Murray, and Michael S. Brown
York University, Toronto, Canada

Abstract

Spot photometers measure the luminance that is emitted or reflected from a small surface area in a physical environment. Because the measurement is limited to a "spot," capturing dense luminance readings for an entire environment is impractical. In this paper, we provide preliminary results demonstrating the potential of using an off-the-shelf commercial camera to operate as a 360° luminance meter. Our method uses the Ricoh Theta Z1 camera, which provides a full 360° omnidirectional field of view and an API to access the camera's minimally processed RAW images. Working from the RAW images, we describe a calibration method to map the RAW images under different exposures and ISO settings to luminance values. By combining the calibrated sensor with multi-exposure high-dynamic-range imaging, we provide a cost-effective mechanism to capture dense luminance maps of environments. Our results show that our luminance meter performs well when validated against a significantly more expensive spot photometer.

Introduction

Lighting conditions are an important property of outdoor and indoor environments, particularly for visual perception. Almost all retinal images are highly ambiguous, and human vision relies on stable lighting properties to overcome this ambiguity and infer the properties of objects and surfaces [1]. As a result, having a good statistical model of an environment's lighting from omnidirectional measurements is useful for research in this area. In addition, such lighting information is useful for interior designers and architects to better understand the environmental lighting conditions inside a building. To accurately measure perceived brightness in terms of luminance (i.e., candela/meter^2 or nit), specialized spot photometers, such as a Jadak SpectraScan PR-655 [2] or a Konica Minolta LS-160 [3], are required. These devices operate in a point-and-shoot manner and measure the light emitted or reflected from a small surface patch in the scene. Measuring a "spot" in the scene can take up to 6 seconds, depending on the device's settings. In turn, multiple measurements are required to understand only a small fraction of the lighting in an environment. Moreover, spot luminance meters can be expensive, costing upwards of several thousands of dollars.

Consumer cameras also provide a convenient and intuitive way to record the light in an environment. Human observers can quickly interpret camera images to reveal relative brightness in an environment falling within the camera's field of view. Recent advances in lens technology, sensor size, and optical path folding allow cameras such as the Ricoh Theta [4] to capture a full 360° omnidirectional field of view in azimuth and altitude as shown in Figure 1. However, digital cameras do not aim to reproduce an accurate recording of scene luminance, but instead strive to produce

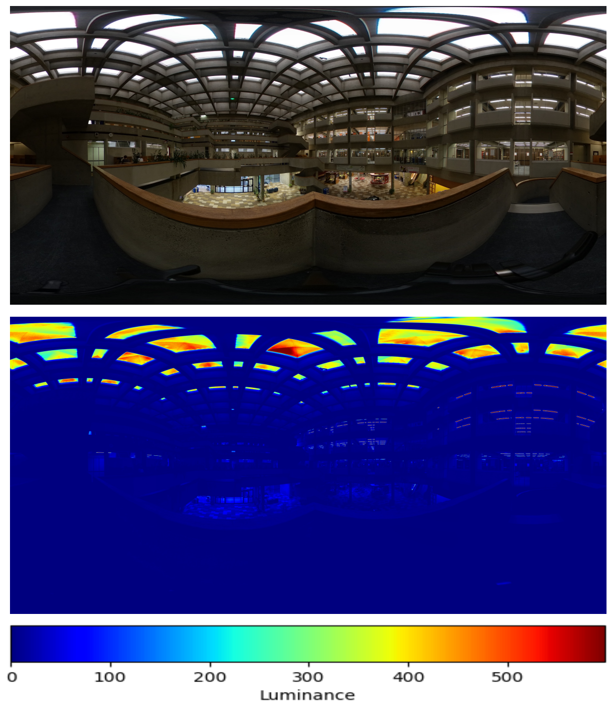

Figure 1. *(Top) The output of a single omnidirectional 360° JPEG image from a Ricoh Theta Z1 camera. (Bot) The corresponding omnidirectional luminance map computed from calibrated RAW images using multi-exposure fusion.*

visually pleasing photographs in a display-referred color space such as sRGB [5]. As a result, onboard camera hardware performs proprietary image processing routines to enhance the image's contrast and colors such that the final pixel values have a complex and indirect relationship with the real environment. Furthermore, most digital camera sensors have a limited dynamic range compared with photometers, and the final output JPEG image is further reduced to 8-bit for compatibility with display technology.

However, when cameras allow access to the unprocessed sensor RAW image, there is an opportunity to calibrate the sensor such that each pixel's digital value (often referred to as pixel intensities) can be interpreted in terms of physical or perceptual measurements. In fact, spot luminance meters use silicon photodiodes with photopic filters that are similar in nature to CMOS sensors used in consumer cameras. Recently, the manufacturers of the Ricoh Theta provided a software API [4] that allows access to RAW images on certain Ricoh devices, including the Z1 camera. The access to this omnidirectional RAW image is the impetus for the work in this paper.

Contribution We demonstrate a working proof of concept for a 360° omnidirectional luminance meter based on a Ricoh Theta Z1. Specifically, we describe a calibration procedure to estimate the Ricoh sensor's response to scene luminance at different ISO and shutter speeds. To overcome the limited bit depth of the CMOS sensor, we use simple high dynamic range (HDR) imaging techniques to translate pixels from multiple images with different shutter speeds to their corresponding luminance values (i.e., cd/m^2). The result is a photometric device that can quickly measure the scene luminance in an entire environment. When the device is used within our calibration range, we show good performance compared to measurements made with a more expensive spot photometer.

Related Work

Omnidirectional Luminance Estimation Pioneering work by Tominaga and Tanaka [6] proposed a catadioptric system for omnidirectional imaging using a conventional camera observing a spherical mirror. This work established many of the geometric warping techniques needed to map between a planar sensor and a spherical world coordinate system. While the work in [6] did not explicitly calibrate the sensor to obtain luminance measurements, their findings undoubtedly influenced later technology, such as the Ricoh Theta, that replaced spherical mirrors with wide-angle lenses.

Towards omnidirectional luminance measurements, Mury et al. [7] proposed a custom device dubbed the "plenopter," capable of capturing an omnidirectional radiance map. The plenopter is composed of twelve photocells, each with a 74° solid angle field of view capable of capturing an entire environment. Dense omnidirectional measurements from the sparse photocell readings were obtained via harmonic interpolation. Morgenstern et al. use a similar device to investigate observer's assumptions on the diffuseness of light [8].

Ricoh Theta Z1 The Ricoh Theta family of cameras contains two CMOS sensors that use wide field of view lenses to capture two hemispheres of the environment, as shown in Fig. 2-A. The sensor images share a small overlapping region that is stitched together to create a single 7296×3648 image. The captured image can be viewed as a spherical or equirectangular image through accompanying software.

The advantage of the Theta Z1 model for our application is that the images can be captured in RAW format with minimal image processing. The ability to capture RAW is unavailable for most other models of the Ricoh Theta product line at the time of writing. The Ricoh Theta has already garnered academic interest as a scientific measurement device from Aghayari et al. [9] who provided a geometric calibration of the Ricoh Theta noting its applications for photogrammetry, robotic, and machine vision applications. Their approach uses an enclosed room with targets placed across known distances in the scene to determine the device's intrinsic and extrinsic parameters.

High Dynamic Range Imaging High dynamic range (HDR) imaging is a well-studied approach that fuses multiple exposed images to produce a composite image with a larger dynamic range than possible from a single exposure [10]. Early work in HDR required a calibration step to model the nonlinear photo-finishing applied by the camera [11, 12]. Access to the minimally processed RAW image makes HDR significantly simpler to perform; however, calibration is still necessary to learn the relationship between different ISO and shutter speeds to scene luminance. HDR will be necessary for our application to expand the range of measurable luminance values.

Method

In this section, we provide details regarding how we calibrate the Ricoh Theta Z1 camera to produce luminance measurements. Figure 2-B illustrates the basic setup in which an LCD monitor is used as a planar illumination source with a known luminance output. By using the Theta to take photographs of the monitor at a range of luminance values we can establish a mapping for RAW pixel intensities captured under various settings to corresponding luminance values. We also describe our HDR procedure using multiple exposures.

Monitor Calibration

In our prototype, we used an LCD monitor to serve as a controllable light source with known luminance output. Specifically, we used the Psychtoolbox MATLAB library [13], which comes with a calibration utility that interfaces to a wide range of luminance spot meters. For our work, we used a SpectraScan PR-655 [2] that is connected via a USB to a computer that also controls the monitor's output. The Psychtoolbox tool runs a routine in which the monitor sweeps a series of patterns of varying intensity and records the measurement of these patterns using the spot meter to establish a lookup table (LUT). Once the monitor's calibration is completed, we used custom software to display a range of RGB values at specified luminance values.

Sensor Response to Luminance Mapping

To calibrate the Ricoh Theta Z1, a MATLAB script is used to display a series of images on the LCD monitor with increasing luminance output that are imaged by the Ricoh camera. The Theta Z1 has a fixed aperture and sensor exposure is controlled by adjusting shutter speed and ISO (i.e., sensor gain). The Ricoh Theta device has built-in wi-fi and runs an onboard web server that allows camera settings and capture to be controlled remotely. As previously mentioned, the Ricoh's software API allows RAW image capture for this particular device, in addition to the photo-finished JPEG image. The RAW image includes both sensor images side by side before geometric correction has been applied (see Figure 2-A). From our observation, the two sensor images appear to have lens shading and defective pixel correction applied before saving the RAW image. Lens shading and defective pixel correction are processing steps applied early in the in-camera pipeline and are beneficial to our calibration procedure, as it ensures a uniform sensor response [5].

Our calibration procedure is performed for different ISO and shutter speeds. For each exposure setting, we image a range of luminance values ranging from 1 to 400 nits (the maximum output of our LCD monitor). For each luminance value, we capture five RAW images that are averaged to mitigate problems arising from sensor noise and potential LED flicker. The RAW images are in their Bayer format in which each pixel is associated with a single color channel based on the sensor's color filter array. For the prototype in this paper, we use only the green channel pixels as the spectral sensitivity of most sensor's green channel is similar to the photopic luminosity response used to calculate lu-

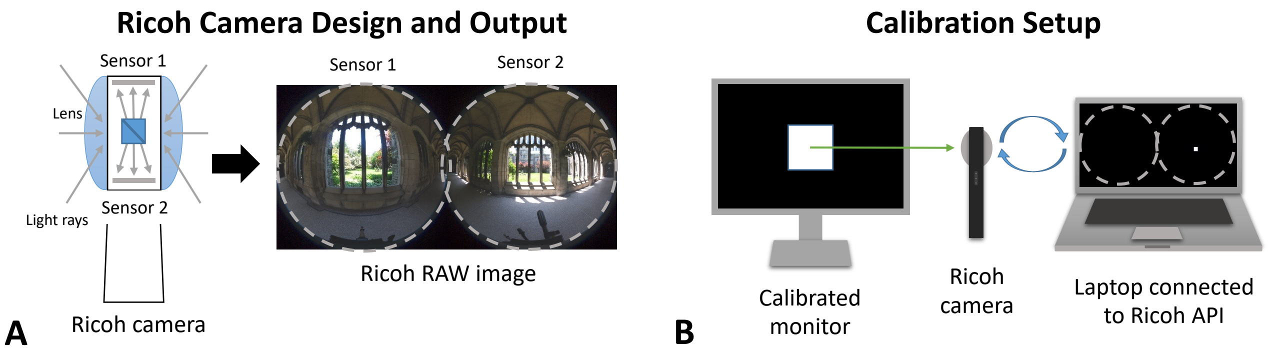

Figure 2. (A) An illustration of the Ricoh Theta Z1 device is shown. The optical paths of two fish-eye lenses are directed to two separate sensors. The camera is capable of outputting a single RAW image in which the two sensor images are concatenated side by side. (B) A calibration procedure is used to map the sensor intensities to luminance values. A calibrated LCD monitor displays images with specified luminance values, which are imaged by the Ricoh camera using varying ISO and shutter speeds.

minance [14]. The range of shutter speeds was limited to a lower bound of 1/60 s due to the refresh rate of the LCD monitor, and a maximum of 1/2.5 s due to rapid over-saturation of the pixels in the known luminance region.

Fig. 3 shows plots from our calibration procedure. The Ricoh's sensor has 12 bits of dynamic range, resulting in a maximum digital value of $\tilde{4}096$. The plot shows that the sensor responds linearly to increasing luminance. This linear relations allows us to use simple line fitting to model digital value conversion to luminance. In principle, we expected to see a linear relationship between the increase in shutter speed, and increase in response. For example, if the camera outputs a digital value of $\mathbf{x}$ when observing a fixed luminance pattern at shutter speed 1/60, we expect the digital value at shutter speed 1/30 to be $2\mathbf{x}$, since the exposure time is twice as long. Unfortunately, we did not observe this relationship between shutter speeds, which can be attributed to either the Ricoh API only providing an approximation to the true shutter speed or nonlinear quantum efficiency of the sensor. As a result, it was necessary to establish mappings between the sensor's digital values at different shutter speeds.

High Dynamic Range Imaging

For most environments, a single shutter speed is not sufficient to capture the dynamic range of a scene. When this is the case, certain pixels become overexposed or underexposed, reaching either end of the discrete sensor bit-depth. HDR can be used to help overcome this situation.

To construct an HDR image, we capture three RAW images with different exposures. In particular, we first select the shutter speed that gives the overall best coverage of the scene in terms of dynamic range and fix this as our base exposure value (EV), denoted as EV0. Once the EV0 has been established, we take two additional images at EV-1 and EV$+1$, which corresponds to a halving and doubling of the shutter speed respectively.

For any pixels in our base EV0 image with a digital value below 500, we use the luminance reading from EV+1; for pixels in our base EV0 image with digital values above 3500, we use the luminance reading from EV-1. The luminance value for these different images are computed using the linear fit calibrated for

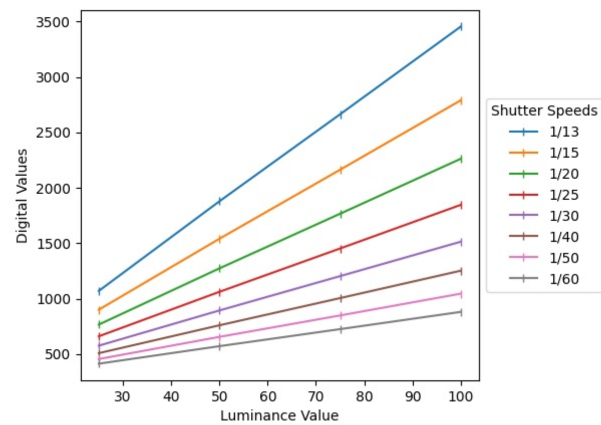

Figure 3. The RAW image's response (digital values) with respect to the luminance for different shutter speeds. This plot is for ISO 80, the default ISO of the camera. The sensor responds linearly to incoming scene luminance.

the particular shutter speed and ISO setting. Our combined luminance image is then processed by the Ricoh software to unwarp the fisheye views to produce a rectilinear output.

Results

Digital value to luminance linear fit We performed an experiment to test the use of a linear model to convert RAW pixel digital values to luminance measurements for a given ISO and shutter speed. In particular, we captured RAW images of the LCD monitor displaying luminance values ranging from value 25 to 400 nits at an increment of 25 nits per step. We then fit the linear model using approximately half of the samples (i.e., 25,...,100 nits at an increment of 25 nits). This fitted model was used to predict the observed values at remaining samples (i.e., 200, 300, ..., 400 nits). The accuracy of our model was approximately 93%, confirming that the sensor behaves linearly to scene luminance.

Omnidirectional luminance measurement We captured several scenes with the calibrated Ricoh Theta Z1. Because of the use of HDR imaging, we targeted environments mostly free of scene

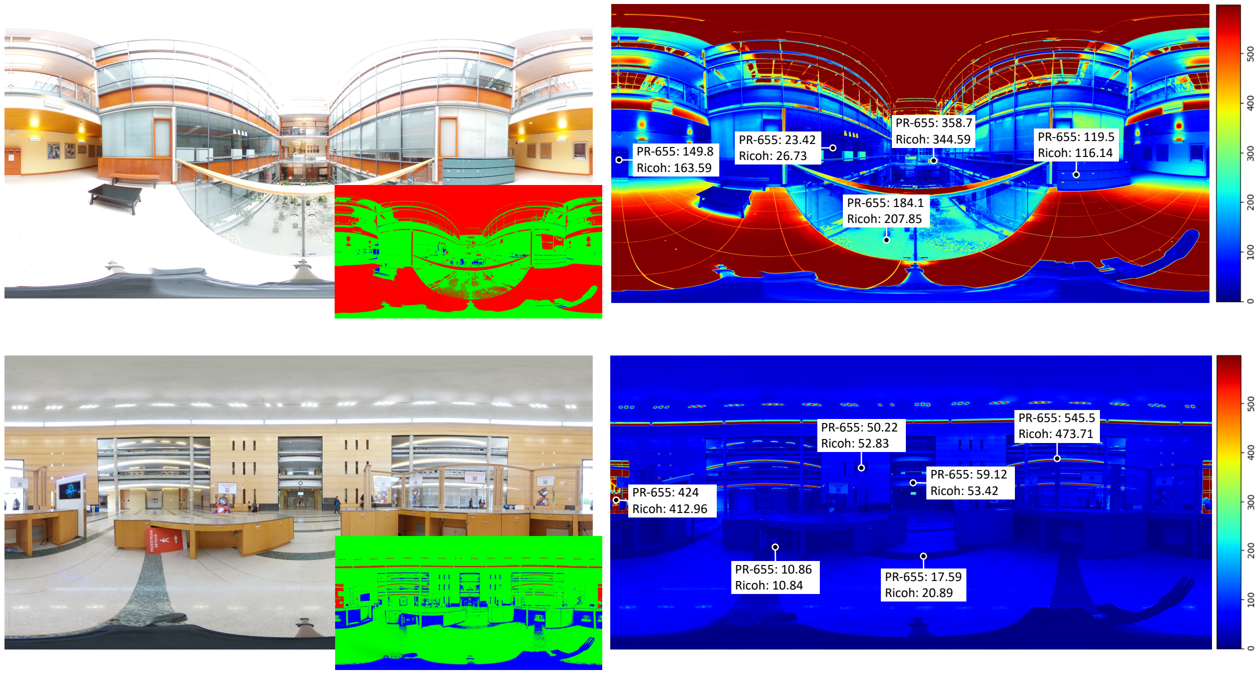

Figure 4. *Luminance maps computed for two scenes. Shown is the JPEG image for the EV0 image which has been mapped to its rectilinear format. While the processed JPEG image appears bright, these scenes were relatively low-light as evident by the low luminance values. The inset shows the HDR composite map, where green is EV0, red is EV−1, and blue is EV+1. The corresponding luminance map is also shown. Readings using the SpectraScan PR-655 spot luminance meter were taken for reference against our results (see Results for description of the slight discrepancies between measurements).*

motion. Because our LCD monitor had a maximum luminance output of 400 nits, we focused on capturing scenes with lower luminance to be closer to our calibrated range. The Ricoh was placed on a tripod and RAW images within the calibrated shutter speeds were captured. The optimal exposure value (EV0) was determined for each scene as described in the previous section. We then select the corresponding EV−1 and EV+1 images and composited the results to produce the final luminance map.

Fig. 1 depicts an indoor scene of a natural environment. Fig. 4 shows two scenes in which we also collected sparse luminance readings using the SpectraScan PR-655 for comparison. Fig. 4 depicts two natural environment scenes with a mixture of artificial light, and natural lighting from skylights above. Also shown in Fig. 4 are insets showing which EV image was used for individual pixels.

We can see that our luminance measurements are similar to those captured by the SpectraScan device with deviations around 20%. While the differences between our Ricoh measurements and the luminance spot meter might appear high, this can be attributed to several factors. First, given the large form factor of the SpectraScan device, we can only position it approximately in the same location as the Ricoh Theta—small deviations in location can produce different luminance readings. In addition, in the real scenes, there are slight changes in the environment lighting between the time when the scene was captured with the Ricoh and later with the spot meter. However, even with these small discrepancies, we find the results obtained with our prototype compelling.

Concluding Remarks

We have demonstrated a 360° omnidirectional luminance meter that leverages the availability of RAW image capture for the Ricoh Theta Z1 camera. We described a simple calibration procedure to convert the RAW digital values captured by the Ricoh's sensor to luminance measurements. Our prototype allows dense environmental luminance measurements not possible with existing spot meters, and at a fraction of the cost. We note that the work in this paper serves only as a proof of concept. The reliance on an LCD monitor for calibration significantly limited the range of luminance that we could reliably calibrate. We also had to limit the range of shutter speeds that we could calibrate due to the monitor's refresh rate. A better illumination source void of flicker and capable of much higher luminance values is needed for future designs. In addition, validating the results using an auxiliary device is difficult, given the challenges in physically aligning the optical centers of the devices. Establishing a calibrated environment with controllable luminance is necessary for robust validation. Nonetheless, we expect that our proof of concept will spur further interest in developing 360° omnidirectional luminance meters with existing commercial hardware.

Acknowledgements

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