An experimental study of fast multispectral imaging using LED illumination and an RGB camera

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Abstract

Active illumination based multispectral imaging using LED light sources has got much attention in recent years due to the availability of wide range of narrow band color LEDs spreading across the visible as well as infrared regions. We proposed a fast multispectral imaging using LED illumination and an RGB camera (RGB-LEDMSI) along with a novel LED selection method. In this paper, we present and analyze the results from real world experiments on the proposed RGB-LEDMSI. We built a prototype 9-band RGB-LEDMSI system using commercial iQ-LED panels and a Nikon D600 camera. The experimental results from the prototype system confirm the effectiveness of the proposed system.

Introduction

Multispectral imaging is typically used to capture spectral reflectance of the imaged scene. Because of its capability to capture much more information than a traditional color camera can, multispectral imaging has shown to be beneficial in many application domains such as cultural heritage, medical imaging, biometrics, remote sensing, food quality etc., and its scope continues to grow. Multispectral imaging provides a simpler, faster, and cheaper solution to spectral imaging compared to hyperspectral imaging. In the past decades, there has been a significant volume of research carried out in the field of multispectral imaging and many different multispectral imaging systems have been proposed. However, its use and applications are so far still mostly limited to research laboratories because of several obstacles such as cost, complexity, and speed.

In a typical filter-based multispectral imaging system, either a set of traditional optical filters in a filter wheel [1], or a tunable filter [2, 3] in front of a monochrome camera is employed, and images of a scene are acquired with each of these filters in a sequence. Filter array based multispectral imaging, commonly known as multispectral filter array (MSFA) or multispectral color filter array (MCFA), is based on the extension of the color filter array (CFA) to using more than three channels [4–6]. Another promising technique of multispectral imaging is based on multiplexed LED illumination (LEDMSI) [7–9]. LEDMSI has got much attention in recent years because of its narrow-band spectral power distribution (SPD), fast computer controlled switching ability, low power consumption, robustness, cost effectiveness, and availability of many different LEDs spreading across the visible as well as infrared ranges of the electromagnetic spectrum.

Recently, we have proposed three new promising fast and practical multispectral imaging systems: using two color cameras with additional optical filters in a stereoscopic configuration [10, 11], using multispectral filter arrays (MSFA) [12, 13], and using active LED illumination in conjunction with an RGB camera (RGB-LEDMSI) [14]. The focus of this paper is on the RGB-LEDMSI. In [14], we presented the concept and design of the proposed RGB-LEDMSI system along with the results from simulated systems. In this paper, we validate the proposed RGB-LEMSI through thorough experimentation using a prototype system we developed.

The rest of the paper is organized as follows. In the next section, we describe the concept and mathematical model of active LED illumination based multispectral imaging including the proposed RGB-LEDMSI. We then describe experimental setup and present the experimental results. We discuss the results and finally conclude the paper.

Multispectral imaging using active LED illumination (LEDMSI)

A typical LEDMSI system uses a cluster of different types of narrow band LEDs and a digital camera, and a sequence of images of the scene is acquired under each type of LED illumination. The system thus modulates the illumination and provides a multispectral light source. The lighting of the LED sequence and the camera acquisition is synchronized and controlled by a micro-controller device or a computer, which enables high-speed acquisition of multispectral images. In a state-of-the-art LEDMSI system, a digital monochrome camera is used [9, 15, 16]. With K different types of LEDs, K-band image of a scene is acquired.

Since an RGB camera can acquire 3-band image in a single exposure, use of RGB camera increases the acquisition speed by a factor of three. A $K = 3 \times N$-band image of a scene can be acquired with N different combinations of LEDs in N exposures. We proposed an RGB camera based LEDMSI (RGB-LEDMSI) system in [13]. A generalized LEDMSI system with P-channel camera and Q types of LEDs can be mathematically modeled by the following equation.

$$c_{pq} = \int_{\lambda_{\min}}^{\lambda_{\max}} l_q(\lambda) r(\lambda) s_p(\lambda) d\lambda, \qquad (1)$$

where c_{pq} is the camera sensor response at a pixel in the p^{th} channel for the q^{th} LED. $s_p(\lambda)$ is the spectral sensitivity of the p^{th} channel of the camera, $l_q(\lambda)$ is the spectral power distribution of the q^{th} LED illumination, and $r(\lambda)$ is the spectral reflectance of the surface point on the scene corresponding to the imaged pixel. Equation 1 can be expressed in a matrix equation form as follows:

$$c_{pq} = \mathbf{s}_q^{\mathrm{T}} \mathbf{L}_p \mathbf{r}, \tag{2}$$

where $\mathbf{s}_q$ is the camera sensitivity in a vector form, $\mathbf{L}$ is the diagonal illuminant matrix whose diagonal elements are the samples $l(\lambda)$, and $\mathbf{r}$ is the sampled spectral reflectance vector of the surface point. The $P \times Q = K$-channel camera response at a pixel from the P-channel and Q-LEDs can be expressed as a single vector form $\mathbf{c} = [c_{11}c_{12} \dots c_{1Q}c_{2Q} \dots c_{P1}c_{P2} \dots c_{PQ}]^T$.

An important step in a LEDMSI system design is the choice and the number of LEDs to be used. A monochrome camera based LEDMSI uses one type of LED at a time while RGB camera based LEDMSI requires a combination of two or more LEDs in every exposure. Therefore, different LED selection methods should be used in the case of a monochrome camera and RGB camera based LEDMSI systems. In [13], we proposed a novel LED selection method for an RGB-LEDMSI system. The method splits a given set of Q LEDs into three groups based on their peak wavelengths lying in the red, green, and blue regions of the spectral sensitivities of the RGB camera used. N non-overlapping optimal combinations of three types of LEDs, one from each of the three groups of LEDs are selected for the N exposures.

Another important aspect in LEDMSI is the uniform illumination over the imaged scene. In applications where the object or scene to be imaged is a small area such as the retina [17], reasonably good uniform illumination of light can be obtained by passing it through an optical fiber. For a bigger scene, a diffuser can be used in front of the LED panel to produce more uniform illumination. We proposed a LED matrix design intended for equal intensity LEDs and uniform illumination [18].

Experimental setup

In [13], we presented results from simulated RGB-LEDMSI systems, which used 19 different LEDs and a Canon20D camera. In this paper, we present both simulation and experimental results from a prototype 9-band RGB-LEDMSI system we built with a Nikon D600 camera and two iQ-LED modules from Image Engineering [19] which acquires 9-band multispectral image of a scene in three exposures. An iQ-LED module contains twenty-two different LEDs of which we used fourteen narrow band color LEDs in the visible region (Figure 1). The LED selection method picked the LED combinations 1-6-11, 2-8-14, and 4-7-10 for the three exposures.

Figure 2 shows the setup of the LEDMSI system. For better mixing of lights from different LEDs to obtain a uniform illumination, lights from the iQ-LED cluster is passed through a tube coated with barium sulphate (BaSO4), and the other end of the tube being covered with a diffuser plate. iQ-LED has a built-in temperature sensor and cooling fan in order to stabilize the operating temperature. The light modules are mounted such that the object surface at the back is illuminated by the light from both the LED modules, and illumination from the two LED

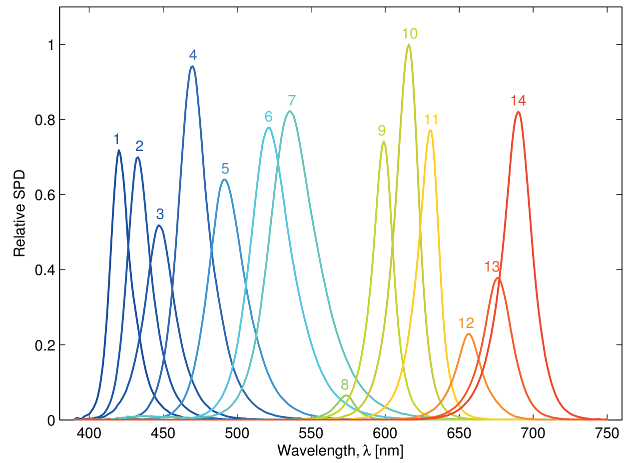


Figure 1: *Spectral power distributions (SPDs) of the 14 LEDs used from the iQ-LED.*

modules is 45° to the surface of the object. The Nikon D600 camera is fixed at the front and normal to the object surface. All the components are housed in a custom-made black case, which can be closed completely to avoid other unwanted outside light. Both the camera and the LED illumination are synchronized and controlled using a custom-built controller software.

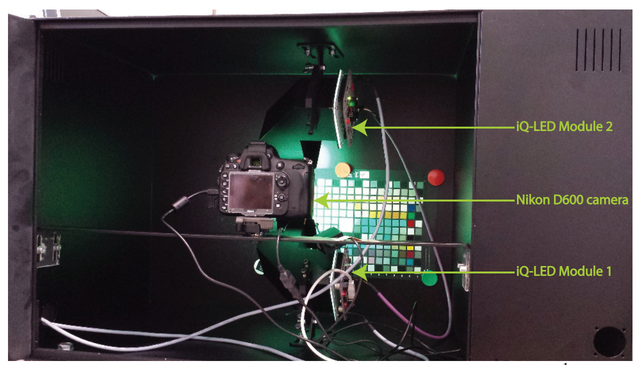


Figure 2: *Experimental setup of the RGB-LEDMSI system*[1].

Experimental results

Multispectral images of a Macbeth ColorChecker DC (MCCDC) and a Macbeth ColorChecker Passport (MCCPP) are acquired by the prototype 9-band RGB-LEDMSI system under the three optimal LED combinations in three exposures. Depending on the intensity level of the LEDs in every exposure, integration time is adjusted properly by adjusting the camera shutter speeds so that high camera response values are obtained and while at the same time any pixel saturation is avoided. We used camera shutter speeds of 1/10, 1/4, and 1/15 seconds for the first, second, and third exposures respectively. The images acquired are corrected for DC noise, non-linearity, and non-uniformity. Bilinear interpolation [20] is used to obtain a 3-band image from the raw sensor image. 9-band image of

[1]The prototype system was designed and developed in collaboration with FUJIFILM Manufacturing Europe B.V., Netherlands.

a scene is obtained by combining the three images from the three exposures. Nine camera response values for each color patch of the ColorCheckers are obtained by averaging the central 100×100 pixels.

The camera system is calibrated/trained using the most significant sixty-two patches selected from among the two hundred and forty MCCDC patches using the selection method proposed by Hardeberg et a. [21]. Spectral reflectances of the 24 patches of the MCCPP are then estimated from the nine camera response values using Wiener estimation method [22]. We tested other spectral estimation methods also. We have presented the results from the Wiener method as the method is simpler, faster, and most widely used. Figure 3 depicts the estimated and measured spectral reflectances of the 24 patches of the MCCPP. Colorimetric errors can be seen visually on the chromaticity plots shown in Figure 4. From the spectral and chromaticity plots, we see that both the spectral and colorimetric estimations are very close to the measured ground truth. Statistics of the spectral and color estimation errors are given in Table 1. The results from the corresponding simulated 9-band RGB-LEDMSI system is also given in the table. As anticipated, we see some differences in the simulation and experimental results, which we discuss in details in the next section.

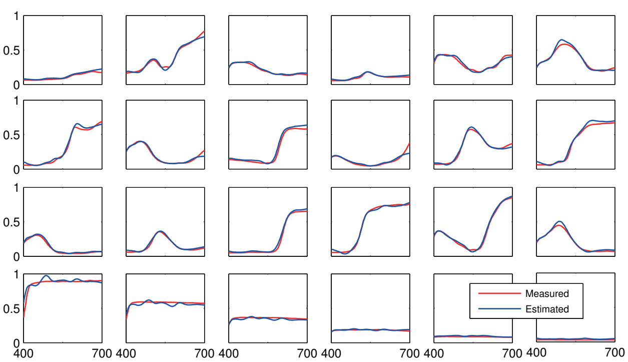


Figure 3: Measured and estimated spectral reflectances of the 24 patches of the MCCPP.

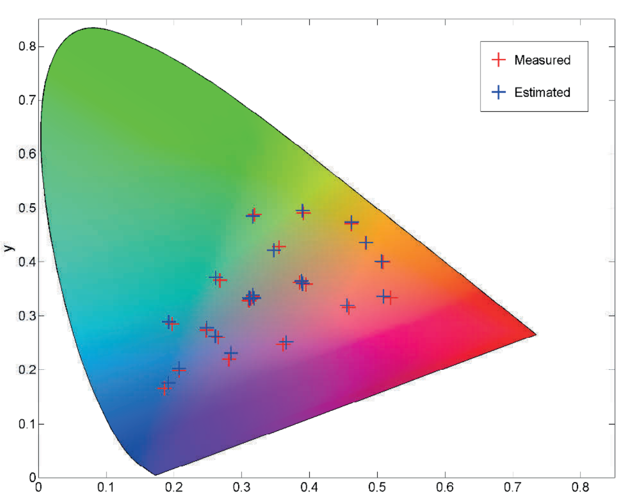


Figure 4: Chromaticity plots of the measured and estimated colors of the 24 MCCPP patches.

Table 1: Statistics of spectral and colorimetric estimation errors.

9-band RGB-LEDMSI system	RMS		ΔE^*_{ab}	
	Mean	Std.	Mean	Std.
Simulated	0.006	0.004	0.471	0.309
Prototype	0.024	0.011	2.344	1.108

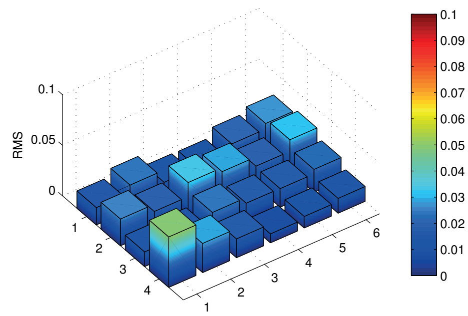
Discussion

Results from the experiments show a very good performance from the 9-band RGB-LEDMSI system both spectrally and colorimetrically. The speed of acquisition is increased by a factor of three compared to the equivalent 9-band monochrome camera based LEDMSI system. In this section, we discuss the results in more details.

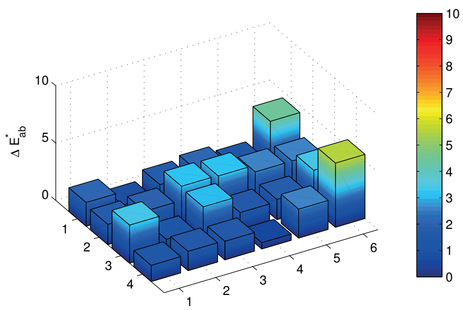
If we look at the estimation errors obtained for the individual patches of the MCCPP shown in Figure 5, we see that the largest RMS error is produced by the white patch. This might be because of some oscillations as we can see in the estimated reflectance curves in most of the achromatic patches, particularly with the higher values including the white (see Figure 3). This could be because of the limited number of narrow band LEDs that leads to some oscillations in the resulting effective illumination rather than smoother curves. The largest ΔE^*_{ab} error is produced by the black patch, which is also an achromatic color. The reason could be the same as with RMS, and the noise might also have played a role here as we can see the estimated curve slightly above the measured one. Thorough study may be required in the future to explain the behavior of estimation errors on different colors and objects more precisely.

From Table 1 we see that the prototype system produces larger estimation errors compared to that from the simulated system, which is expected since simulation is in general based on simplification. Furthermore, it might not have taken into account many factors that occur in real systems. The simulation model we used approximates the camera response through numerical integration by uniformly sampling the signals. It also assumes surfaces as Lambertian. However in reality, the natural surfaces are not Lambertian, and hence reflectance depends on measurement angles. Spectral bidirectional reflectance distribution function (BRDF) could be a solution in order to take into account the angular dependence of the reflectance [23, 24]. Moreover, our simulation model has taken into account the random shot noise and the quantization noise only, whereas in reality there could be many other types of noises that come into play in real camera systems. All these contribute to the differences in the results from the real and simulated systems. In this paper, we are more interested in the absolute results from the prototype system which is very encouraging.

We used commercially available iQ-LED modules for LED lighting in the prototype system. The LEDs in those modules were found to be reasonably stable within the operating temperature which was well maintained by the built-in cooling system. However, there were some other issues with these LEDs as the iQ-LED modules were not specifically designed for multispectral imaging. The level and uniformity of the illumination was not the best even with two iQ-LED modules



(a) Spectral error, RMS.



(b) Color difference, ΔE^*_{ab}.

Figure 5: *3D bar charts showing the spectral and colorimetric estimation errors for the individual MCCPP color patches. The bar colors indicate from the best (blue) to the worst (red) estimation.*

and flat-field/non-uniformity correction. We can anticipate better results by using a custom-made LED panel designed using a generic LED matrix design method we proposed for equal intensity and uniform illumination [18]. A general issue with LEDs is that they are spectrally unstable, peak-emissions may vary over time and even between the same LEDs. This issue can be addressed by incorporating light diffusing mechanism and also calibrating the system regularly before use. With the development of new LED technologies, we can expect more stable LEDs being produced and available in the market in the near future.

Performance of a LEDMSI system depends on several factors such as camera, number and type of LEDs, demosaicing algorithm, and noise. We have done an extensive study on the influence of these factors in [25]. Performance wise, RGB-LEDMSI shows better results compared to other equivalent fast multispectral imaging technologies such as multi-camera and multispectral filter array based systems. RGB-LEDMSI also performs comparably to state of the art monochrome camera based LEDMSI, however at a significantly high acquisition speed. For detail comparative studies of various multispectral imaging systems including the proposed RGB-LEDMSI, we refer to our papers [26, 27].

Because of the high acquisition speed and less heat dissipated from LED light sources, there are many potential applications of the proposed RGB-LEDMSI such as in cultural heritage for acquiring multispectral images of paintings, medical imaging, etc. We have also shown an effective use of the 9-band RGB-LEDMSI system in a new industrial application, for density measurement of colorants in photographic paper manufacturing process control [28].

Conclusion

The proposed multispectral imaging based on active LED illumination and an RGB camera (RGB-LEDMSI) has shown to perform very well both in terms of spectral and colorimetric estimations. We also found from other studies that RGB-LEDMSI performs better than other fast multispectral imaging systems such as stereoscopic and filter array based systems. The performance of RGB-LEDMSI is comparable to the state of the art monochrome camera based LEDMSI, but with three times higher acquisition speed. High acquisition speed makes the proposed system useful in many areas such as cultural heritage, medical and other industrial applications.

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