Evaluation and comparison of multispectral imaging systems

Raju Shrestha and Jon Yngve Hardeberg
The Norwegian Colour and Visual Computing Laboratory, Gjøvik University College, Norway

Abstract

Multispectral imaging, which extends the number of imaging channels beyond the conventional three, has demonstrated to be beneficial for a wide range of applications. Its ability of acquiring images beyond the visible range and applicability in many different application domains lead to the design and the development of a number of multispectral imaging technologies and systems. Given different systems to choose from, it is important to be able to compare them in a general and in many situations specific to a certain application of interest. In this paper, we evaluate several conventional and recently proposed multispectral imaging systems, both qualitatively and quantitatively. Both spectral and colorimetric accuracies are used as the criteria in the quantitative evaluation. The systems are evaluated and compared for two specific applications: imaging of natural scenes and paintings (cultural heritage), as well as for a general spectral imaging solution. This work provides a framework for the evaluation and comparison of different multispectral imaging systems, which we believe, would be very helpful in identifying the most appropriate technique or system for a given application.

Introduction

Spectral imaging allows capture of an image of a scene called a *spectral image*, which represents an environment independent physical property of each surface points of the scene in the form of spectral reflectances. A spectral image can have information beyond the visible range, such as infrared and ultra-violet. There are basically two main types of spectral imaging techniques: hyperspectral imaging and multispectral imaging. Hyperspectral imaging (HSI), which acquires spectral images in a large number of narrow spectral bands, produces high spectral accuracy. However, the acquisition time, complexity and cost of these systems are generally quite high compared to multispectral systems. Multispectral imaging (MSI) on the other hand acquires images in a limited number of relatively wide spectral bands, and the spectral reflectance functions are obtained from the sensor responses using an estimation algorithm. Multispectral imaging provides cheaper and faster solutions compared to hyperspectral imaging with good enough quality for many applications. Multispectral imaging has widespread application domains, such as remote sensing [1], medical imaging [2], biometrics [3], cultural heritage [4, 5] and many others.

Many different types of multispectral imaging techniques and systems have been proposed in the literature. In a conventional filter-based imaging system, either a set of traditional optical filters in a filter wheel, or a tunable filter [6, 7] in front of a monochrome camera are employed, and images of a scene are acquired with one each of these filters in a sequence. The use of RGB cameras increases the acquisition speed by three times [8, 9]. Shrestha et al. [10, 11] proposed a single-shot six band multispectral system using a stereo camera (StereoMSI). Another single shot multispectral imaging solution is the filter array (FAMSI) [12–14], which is based on the extension of filter array from 3-channel as in Bayer pattern [15] further, allowing acquisition of more than three band images. Pixel value corresponding to a missing filter at a pixel position is estimated from the neighboring pixels having the filter through interpolation, the process called *demosaicing*. Another promising technique of multispectral imaging is based on multiplexed LED (Light Emitting Diode) illumination (LEDMSI) [16–19]. In a typical LED illumination based multispectral imaging system, a set of n different types of LEDs are selected, each type of LED is illuminated in a sequence, and a monochrome camera captures an image under the illuminated LED, thus producing an n-band image (n-band RGB-LEDMSI). Shrestha and Hardeberg [20] proposed a three times faster LED illumination based system which uses an RGB camera and optimal combinations of three different types of LEDs that lie on the red, the green and the blue regions bounded by the camera sensitivities. From n-band image acquired with any of the multispectral imaging technique or system, the spectral reflectance image of the scene is obtained using a spectral estimation method.

Given different multispectral imaging systems, it is important to evaluate and compare the performance and the quality of these systems. This is useful in identifying a suitable system to be used for a given application. In this paper, we evaluate the three major different types of fast and practical multispectral imaging techniques: Stereo camera, MSFA, and LED illumination based multispectral imaging systems, along with the conventional filter wheel and liquid crystal tunable filter (LCTF) based systems, both qualitatively and quantitatively. We identify important quality attributes and compare the systems based on them. Quantitative evaluation is done based on spectral and colorimetric accuracies from the spectral reflectance image, estimated from the multi-band images acquired by different systems.

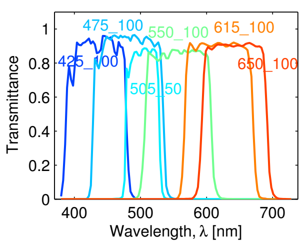
We present next the multispectral imaging systems and the setups used in our evaluation and comparison. Qualitative and quantitative evaluations of the systems will be presented in the following two sections. The results from the evaluations will be discussed next, and finally we conclude the paper.

Multispectral imaging systems and setups used

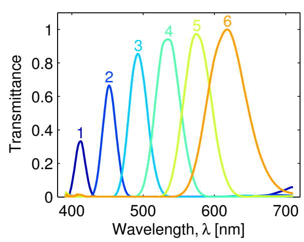
In this section, we briefly describe the three new promising fast and practical multispectral imaging systems: StereoMSI, FAMSI, and LEDMSI and two conventional systems, filter wheel and LCTF based systems.

- **Filter wheel based MSI (FWMSI) system:** In a typical FWMSI system, n number of images of a scene is acquired by a monochrome camera, with each of the filters in the rotating filter wheel placed in front of the camera sensor or the lens of the camera. It acquires an n-band image in n exposures. We use a PixelTeQ's SpectroCam UV-VIS camera (http://www.pixelteq.com/product/spectrocam-uv/) with six filters in its filter wheel. The six filters used are the band pass filters with $peakwavelength(nm)\_FWHM$ of 425_100, 475_100, 505_50, 550_100, 615_100 and 650_100. The spectral transmittances of the six filters are given in Figure 1a. The spectral sensitivity of the SpectroCam camera along with the other two cameras is given in Figure 4.

- **LCTF based MSI (LCTFMSI) system:** In a typical LCTFMSI system, n number of images of a scene is captured by a monochrome camera in n exposures, one each with a narrow (or somewhat wide) band filter activated with an electronically controllable LCTF [6, 7]. We use DVC-16000M monochrome camera and VariSpec-SN50346 LCTF filter. The spectral sensitivity of the DVC-16000M camera is given in Figure 4. The VariSpec-SN50346 LCTF filter has 33 electronically controllable filters. For a fair comparison with the other systems, we use six filters (the same number as in the most of the other systems) selected based on uniform spacing in the visible range (Figure 1b).



(a) Six FWMSI filters.

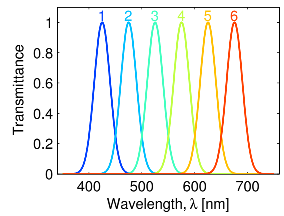


(b) Six LCTFMSI filters.

Figure 1: *Spectral transmittances of the filters used in the FWMSI and LCTFMSI systems.*

- **Stereo camera based MSI (StereoMSI) system:** This is a single shot StereoMSI system proposed by Shrestha et al. [11]. The system is built from a Fujifilm FinePix REAL 3D W1 digital stereo camera and two optimal filters, XF2021 and XF2030 from Omega Optical Inc. placed in front of the two lenses of the camera. The challenge with this system is the occlusion and the registration of the images from the two cameras. By limiting its use to flat surfaces such as paintings, and with the use of an appropriate image registration technique, the issues could be mitigated reasonably well.

- **Filter array based MSI (FAMSI) system:** FAMSI systems extend the trichromatic color filter array (CFA) employed in the conventional digital color imaging to n-bands [13, 14, 21]. This also allows single shot acquisition of a multispectral image. However, these systems require demosaicing in order to estimate missing band values in every pixel. A FAMSI setup with six equally spaced Gaussian shape simulated filters (Figure 2a) and the spectral sensitivity of the DVC-16000M monochrome camera are used in our experiments. The filters are used with their probabilities of appearance of 0.25 for the two filters (3 and 4) in the green region and of 0.125 for the others. They are arranged using the binary-tree based algorithm proposed by Miao and Qi [21], as shown in Figure 2b.



(a) Normalized spectral transmittances of the six filters.

1	4	2	4
5	3	6	3
2	4	1	4
6	3	5	3

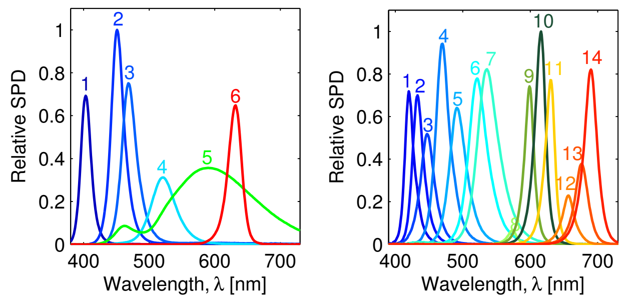
(b) Spatial arrangement of the filters.

Figure 2: *Six filters and their spatial arrangement used in the FAMSI system.*

- **LED illumination based MSI (LEDMSI) system:** Unlike the previous systems, the LEDMSI is based on active illumination, where images are captured by illuminating the scene with n different predefined narrow band color LED light sources. LEDMSI is considered a fast way of multispectral imaging, as the whole process can be controlled electronically, and speed can be increased further by three times using an RGB camera (RGB-LEDMSI) [20] instead of a monochrome camera (Mono-LEDMSI) [16, 18]. Shrestha and Hardeberg [19] presented and discussed how different factors influence the performance and the quality of LEDMSI systems. We use two RGB-LEDMSI systems, a 6-band RGB-LEDMSI which uses six LEDs from a JUST Normlicht LED ColorControl light booth (http://www.just-normlicht.de/us/articledetail.html?id=486) and a 9-band RGB-LEDMSI which uses nine LEDs selected from 14 narrow band LEDs in the visible region, from a iQ-LED module manufactured by Image Engineering (http://image-engineering-shop.de/shop/article_iQ-LED/IQ-LED.html). Both systems use the Nikon-D600 RGB camera, whose spectral sensitivities are given in Figure 4. Figures 3a and 3b depict relative spectral power distributions of the two sets of LEDs respectively. The 6-band RGB-LEDMSI system is considered as a constrained case, which has a limited number of LEDs.

  The two RGB-LEDMSI system acquires images in six and nine exposures, under a combination of three different LEDs in each exposure. Optimal LED combinations for each exposure for the two systems are selected using the LED selection method proposed by Shrestha and Hardeberg [20]. The LED combinations 1-3-5 and 2-4-6 for the two exposures of the 6-band RGB-LEDMSI, and 1-6-11, 2-8-14, and 4-7-10 for the three exposures of the 9-band RGB-LEDMSI are selected by the method.

Spectral reflectances of a scene are obtained from the multi-band images acquired with any of the multispectral imaging system, using an appropriate spectral estimation method. We use the Wiener method [22] in our experiments.



(a) LED set 1: Six LEDs from the JUST Normlicht LED ColorControl light booth.

(b) LED set 2: Fourteen narrow band LEDs in the visible region, from the iQ-LED.

***Figure 3:** Relative spectral power distributions (SPDs) of the LEDs in the two sets of LEDs.*

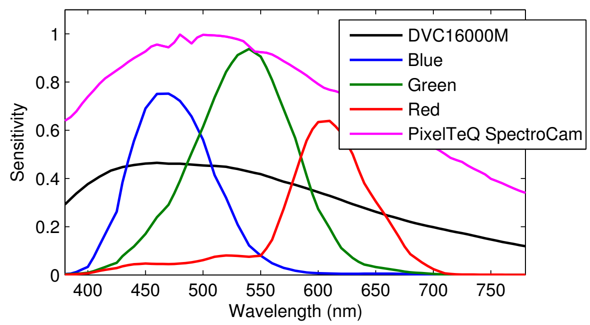


***Figure 4:** Spectral sensitivities of the DVC-16000M and SpectroCam UV-VIS monochrome, and Nikon-D600 RGB cameras.*

Qualitative evaluation

In this section, we compare the five different types of multispectral imaging systems discussed above, based on qualitative evaluations using several qualitative factors/attributes such as acquisition speed, complexity, spatial and spectral resolution, simplicity in building a system, and cost of the systems. In terms of these factors, a system is categorized as very bad (- -), bad (-), good (+), or very good (++). Table 1 summarizes the comparison of the systems. The table also shows which type of camera (monochrome or RGB) can be used, what kind of post processing is required, and technique(s) commonly used to estimate the spectral reflectance from the acquired multi-band image. Challenges with each of the systems are identified. Relevant parameters, which can be varied in a system, are also given.

From the table, we see that there is no single best system for all purposes. Every system has its capabilities, advantages, limitations and challenges. Given an application, the most appropriate one should be chosen. The comparison table would be helpful in identifying an appropriate multispectral imaging system that can be used for the given application.

Quantitative evaluation

In this section, we evaluate all the systems quantitatively based on spectral and colorimetric accuracies derived from the resulting spectral reflectance images obtained from the six simulated system setups (FWMSI, LCTFMSI, StereoMSI, FAMSI, 6-band RGB-LEDMSI, and 9-band RGB-LEDMSI). In addition, the results from a classic RGB camera are also evaluated for comparative analysis. In order to make the simulation more realistic, 2% random Gaussian noise and 16-bit quantization noise are introduced in the resulting camera responses. Surface reflectances of the sixty-two patches selected from the 240 patches of the Macbeth Color Checker DC (MCCDC) using the most significant target patches selection method proposed by Hardeberg et al. [23] are used to compute the reconstruction operator/matrix in the Wiener estimation method. The most commonly used root mean square error (RMSE) is used as the spectral metric and the CIE ΔE^*_{ab} as the colorimetric metric. In the case of passive multispectral imaging systems, CIE standard illuminant D65 and CIE 1964 standard color matching functions are used to compute color components from the spectral reflectance data.

The MSI systems are evaluated for three different applications; first as a general purpose spectral imaging, then for two different imaging applications: natural scenes and cultural heritage particularly paintings The results obtained in these three cases are presented in the last three subsections below.

- **General-purpose spectral imaging:** All the seven multispectral imaging systems are evaluated for a general-purpose imaging by using the Macbeth ColorChecker classic (MCC) as the test target.
- **Imaging of natural scenes:** In order to study how the systems perform in the case of imaging of natural scenes, we use hyperspectral images of the eight natural scenes from Nascimento et al. [7]. Simulated multi-band images are obtained with all the seven simulated systems using these hyperspectral images.
- **Imaging of cultural heritage artworks (paintings):** We also evaluate the seven systems based on how they perform in the case of a cultural heritage application, particularly in the imaging of paintings. We use the hyperspectral images of six paintings we acquired using a HySpex-VNIR 1600 camera from Norsk Elektro Optikk, Norway. The six paintings include

***Table 1:** Comparison between five different types of multispectral imaging systems/technologies, based on qualitative evaluation (subjective). - -, -, +, ++, and × are used to indicate very bad, bad, good, very good, and not applicable respectively.*

Attribute \ System	FWMSI	LCTFMSI	StereoMSI	FAMSI	LEDMSI
Speed	- -	- -	++	++	+
Spectral video	×	×	++	++	+
Complexity	-	-	++	++	+
Spatial resolution	++	++	+	-	++
Spectral resolution	++	++	+	+	++
Spectrum coverage	Mainly visible, ultraviolet and infrared possible	visible	Mainly visible, infrared possible	Mainly visible, infrared possible	visible, infrared
Camera type	Monochrome	Monochrome	RGB	Multi-band/ Multispectral	Monochrome/RGB
Post-processing	×	×	Demosaicing and image registration	Demosaicing	×
Spectral estimation	Interpolation or estimation method	Interpolation or estimation method	Estimation method		
Parameters	Number and type of filters	Number and type of filters	Number of cameras, filter types, demosaicing method	Number of bands, demosaicing method	Number and type of LEDs, demosaicing method
Simplicity in building a system	-	+	++	- -	+
Challenges	Not suitable for scenes in motion	Not suitable for scenes in motion	Occlusion and image registration	Design & fabrication of filters & sensor	LED panels of uniform and high intensity light
Cost	- -	- -	++	+	++

famous paintings such as 'The Scream' (1893) and 'Utsikt fra Fossveien' by Edvard Munch, Erik Theodor Werenskiold's 'Minner' (1891) and Frits Thaulow's 'Treschows bro' (1898). Hyperspectral images of these paintings are acquired at the National museum and the Lillehammer museum, Norway. The other two paintings are the ones available at the college.

Spectral reflectance images are then reconstructed from multi-band images using the Wiener spectral estimation method. The reconstructed spectral reflectances are evaluated with reference to the measured ground truth using the spectral (RMS) and the colorimetric (ΔE^*_{ab}) metrics. Statistics of estimation errors (mean, max, mean, and std.) produced by all the systems in the three cases of imaging is given in Table 2. We see a clearer picture of the results from the standard error plots given in Figure 5. The plots show mean estimation errors, along with the upper and the lower bounds of the 95%confidence intervals, computed from the standard error of the mean (SEM) as $Mean + 1.96 \times SEM$ and $Mean - 1.96 \times SEM$ respectively (assuming normal probability distribution of the data). SEM is computed as $Std./\sqrt{N}$, where N is the sample size.

Table 2: *Statistics of the spectral and the color estimation errors obtained with the seven MSI systems, in the three imaging applications. Minimum mean estimation errors for individual application and on the average values are shown in colored numbers, RMS in red and ΔE^*_{ab} in blue.*

MSI System	Test Image	RMS				ΔE^*_{ab}			
		Min.	Max.	Mean	Std.	Min.	Max.	Mean	Std.
RGB	MCC	0.018	0.072	0.037	0.014	0.554	15.469	5.089	3.802
	Natural	0.006	0.432	0.042	0.024	0.018	83.573	8.712	4.522
	Painting	0.007	0.747	0.036	0.014	0.007	127.884	5.441	4.666
	Average	**0.010**	**0.417**	**0.038**	**0.017**	**0.193**	**75.642**	**6.414**	**4.330**
6-band FWMSI	MCC	0.004	0.035	0.012	0.006	0.310	2.743	0.916	0.551
	Natural	0.002	0.170	0.023	0.021	0.004	33.340	2.264	1.468
	Painting	0.002	0.118	0.015	0.011	0.001	13.190	0.828	1.093
	Average	**0.003**	**0.108**	**0.017**	**0.013**	**0.105**	**16.424**	**1.336**	**1.037**
6-band LCTFMSI	MCC	0.003	0.047	0.014	0.009	0.115	0.867	0.449	0.232
	Natural	0.002	0.207	0.025	0.024	0.001	26.630	0.978	0.771
	Painting	0.002	0.146	0.018	0.011	0.003	15.018	0.945	1.133
	Average	**0.002**	**0.133**	**0.019**	**0.015**	**0.040**	**14.172**	**0.791**	**0.712**
6-band StereoMSI	MCC	0.004	0.022	0.010	0.005	0.210	1.182	0.586	0.261
	Natural	0.002	0.459	0.027	0.026	0.004	67.071	1.891	1.874
	Painting	0.002	0.701	0.021	0.016	0.003	85.801	2.419	2.504
	Average	**0.003**	**0.394**	**0.020**	**0.015**	**0.072**	**51.351**	**1.632**	**1.546**
6-band FAMSI	MCC	0.004	0.022	0.010	0.006	0.255	3.227	0.960	0.630
	Natural	0.002	0.436	0.026	0.024	0.008	62.119	2.774	2.318
	Painting	0.002	0.599	0.018	0.013	0.009	80.571	2.747	2.486
	Average	**0.003**	**0.352**	**0.018**	**0.014**	**0.091**	**48.639**	**2.160**	**1.811**
6-band RGB-LEDMSI	MCC	0.006	0.028	0.014	0.006	0.302	1.841	0.807	0.420
	Natural	0.002	0.385	0.028	0.027	0.007	75.668	2.327	2.350
	Painting	0.003	0.644	0.026	0.018	0.006	121.492	2.997	3.102
	Average	**0.003**	**0.352**	**0.023**	**0.017**	**0.105**	**66.334**	**2.044**	**1.957**
9-band RGB-LEDMSI	MCC	0.002	0.025	0.008	0.005	0.058	1.267	0.553	0.285
	Natural	0.001	0.460	0.025	0.022	0.004	86.773	2.295	2.245
	Painting	0.002	0.713	0.017	0.012	0.007	67.850	2.873	2.948
	Average	**0.002**	**0.399**	**0.017**	**0.013**	**0.023**	**51.963**	**1.907**	**1.826**

From the plots, if we compare the results for the three applications, both RMS and ΔE^*_{ab} estimation errors produced by most of the systems (except the RGB and the 6-band FWMSI) in the general-purpose imaging (MCC) are significantly smaller compared to the natural and painting imaging. Next, in terms of the spectral error, RMS errors are larger with the natural imaging than the painting imaging. However, there is no clearly better result among the two, in terms of the colorimetric estimation.

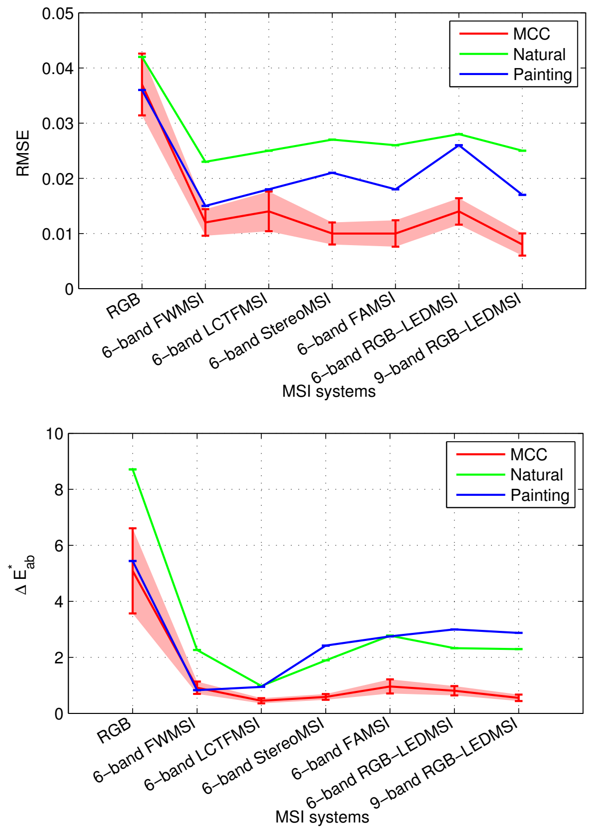


Figure 5: *Standard error plots of RMS and ΔE^*_{ab} for the estimation errors produced by the seven systems, in the three different imaging applications.*

If we compare the seven systems individually, the RGB system performs the worst both spectrally and colorimetrically. With the MCC imaging, the performance of the other six systems can be considered more or less similar. Because of the large number of sample surface points used, we see some clear distinctions in the performances in the case of the natural and the painting images, though the performance trend is not consistent in terms of both the spectral and the colorimetric errors. From the error plots, we can pick one appropriate system for a given application, based on spectral or colorimetric accuracy required. For example, we would choose the 6-band FWMSI system for the imaging of paintings for the more accurate spectral estimation. We analyze and discuss the results further in the next section.

To have a general impression about how good the estimated spectral reflectances from the seven MSI systems compared to the ground truth, spectral reflectances of the 24 patches of the MCC estimated from the multi-band images acquired with the seven systems along with the measured (ground truth) ones are shown in Figure 6. From the plots, we can clearly see more deviations of the spectra estimated from the RGB system, while the results from the other MSI systems look closer to the reference.

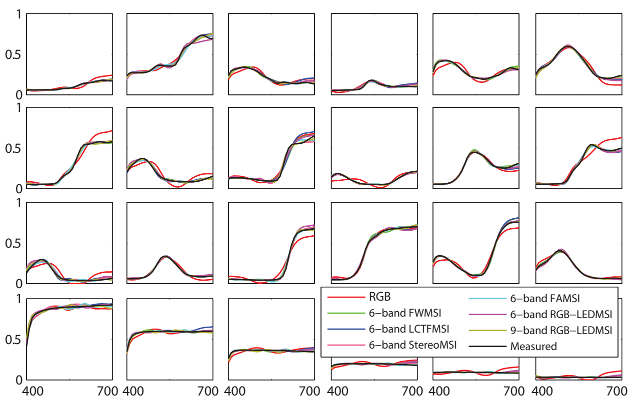


Figure 6: Estimated and measured (ground truth) spectral reflectances of the 24 patches of the MCC from the seven MSI imaging systems.

Discussion

Five different types of MSI systems are evaluated and compared based on various important quality factors/attributes we identified. Subjective evaluations based on these attributes indicate that there is no single system, which can be considered as the best for all the applications in all kinds of situations. The systems are also evaluated quantitatively based on the results from the simulated systems. In order to make our simulation experiments as realistic as possible, we introduced acquisition noise as in the real systems. However, there might still be some other issues such as other additional noise, optics that also play a role in the performance of a system. In order to minimize these factors for a reasonably fair comparison between different techniques, we have used the same cameras wherever possible.

Quantitative evaluation of the seven different simulated MSI systems based on the spectral and the colorimetric estimation errors on the three different types of imaging applications show that the conventional RGB camera system is not useful for spectral image acquisition as it produces high estimation errors in all the cases. This is because such a system can capture limited information only, which is well enough in most cases for the color information but not for the whole spectra that represent unique physical properties of the objects in a scene. Increasing the number of channels from three to six both with the StereoMSI, FAMSI, and LEDMSI systems produces reasonably good spectral images when reflectance spectra are smooth. This is true in most of the natural objects and paintings. An interesting observation is that the 9-band RGB-LEDMSI does not always perform better than the 6-band RGB-LEDMSI. One reason for this is that the influence of noise increases with the increase in the number of channels/bands. We refer to the paper [19] for detailed analysis and discussion on the influence of various factors in LEDMSI.

We found that almost all the systems perform the best with the MCC and then the performance decreases from the imaging of paintings to the natural scenes. This is because the spectra of the 62 MCCDC color patches used for the characterization (or training) of the systems are more close to the MCC patches, and then to the painting images, and even further to the natural images. This implies that it is very crucial to choose the surface reflectances of the training surfaces that are close representatives of the surfaces to be imaged.

If we look at the plots for RMS and ΔE^*_{ab} side-by-side in Figure 5, the performance trend of the systems in the three different applications is more consistent in the case of the spectral estimation compared to the colorimetric estimation. This is because, in our experiments, filter and LED selections are optimized for the minimization of the spectral estimation (RMS) error. For applications where colorimetric accuracies are more important, these selections can be done based on the colorimetric optimization, and with that we can anticipate the systems to have more consistent performance trend in colorimetric estimations.

Quantitative results also show that there is no single system, which performs the best both spectrally and colorimetrically, and for all the three applications. Therefore, it is recommended to identify an appropriate system for a given application, based on both the qualitative and the quantitative evaluations of different MSI systems. For instance, if we need to have accurate spectral reflectances of outdoor natural scenes, then from the qualitative aspects we should choose a passive, single-shot system as there is a possibility of scene movement. The potential candidates in this situation are the RGB, 6-band StereoMSI and the 6-band FAMSI systems. Since, the latter system produces the least RMS error compared to the other two; it would be a wise choice to go for this system here. For the fast and accurate spectral imaging of indoor paintings, the 9-band LEDMSI system would be preferable. Similarly, for the fast and practical general-purpose imaging, we choose an appropriate one among the four potential candidates: the 6-band StereoMSI, the 6-band FAMSI, the 6-band RGB-LEDMSI, and the 9-band RGB-LEDMSI, depending on which one is more suitable for a given application.

Conclusion

We developed a framework for both qualitative and quantitative evaluation and comparison of different multispectral imaging systems. We identified important factors/attributes for the qualitative comparison of the systems, which provides a general guidance for identifying an appropriate system to be used in an application. From our studies and experimental results, we can draw the following conclusions:

- The conventional 3-channel digital color camera is not suitable for spectral imaging.
- There is no single best multispectral imaging technology/system suitable for all purposes. An appropriate system should be identified based on its usability and performance requirement for a given application.
- For applications where scenes are static and where accuracy is more important but not the speed, classic FWMSI and LCTFMSI systems could be used. However, for a comparable quality spectral image but for faster acquisition, all the three fast and practical MSI solutions: StereoMSI, FAMSI, and LEDMSI systems are potential candidates for the consideration.
- For applications, where there is a possibility of the scene movement or for a multispectral video capture, StereoMSI and FAMSI systems are the potential candidates to choose from.

- Increasing the number of LEDs in a LEDMSI does not always lead to better results. An optimal number of bands depends on the camera and the LED set. Given a LED set, it is important to determine an optimal number and types of LEDs for a given RGB camera. It is recommended to choose LEDs from a large set of LEDs with the peak wavelengths covering the whole spectrum uniformly.

References

[1] P. H. Swain and S. M. Davis. *Remote Sensing: The Quantitative Approach*. McGraw-Hill, New York., 1978.

[2] N. L. Everdell, I. B. Styles, E. Claridge, J. C. Hebden, and A. S. Calcagni. Multispectral imaging of the ocular fundus using LED illumination. In *Novel Optical Instrumentation for Biomedical Applications IV*, volume 7371 of *SPIE Proceedings*, 2009.

[3] R. Rowe, U. Uludag, M. Demirkus, S. Parthasaradhi, and A. Jain. A multispectral whole-hand biometric authentication system. In *Biometrics Symposium*, pages 1–6, Sept 2007.

[4] P. Cotte and M. Dupouy. CRISATEL high resolution multispectral system. In *Conference on Image Processing, Image Quality, Image Capture Systems (PICS)*, pages 161–165, Rochester, New York, USA, 2003. IS&T.

[5] C. Daffara and R. Fontana. Multispectral infrared reflectography to differentiate features in paintings. *Microscopy and Microanalysis*, 17:691–695, 9 2011.

[6] J. Y. Hardeberg, F. Schmitt, and H. Brettel. Multispectral color image capture using a liquid crystal tunable filter. *Optical Engineering*, 41(10):2532–2548, 2002.

[7] S. M. C. Nascimento, F. P. Ferreira, and D. H. Foster. Statistics of spatial cone-excitation ratios in natural scenes. *Journal of Optical Society of America A*, 19(8):1484–1490, Aug 2002.

[8] E. M. Valero, J. L. Nieves, S. M. C. Nascimento, K. Amano, and D. H. Foster. Recovering spectral data from natural scenes with an RGB digital camera. *Color Research & Application*, 32(5):352–360, 2007.

[9] M. Yamaguchi, H. Haneishi, and N. Ohyama. Beyond Red–Green–Blue (RGB): Spectrum-based color imaging technology. *Journal of Imaging Science and Technology*, 52(1):10201–1–10201–15, Jan 2008.

[10] R. Shrestha, J. Y. Hardeberg, and A. Mansouri. One-shot multispectral color imaging with a stereo camera. In *Digital Photography VII*, volume 7876 of *SPIE Proceedings*, pages 787609–787609–11, Jan 2011.

[11] R. Shrestha, A. Mansouri, and J. Y. Hardeberg. Multi-spectral imaging using a stereo camera: Concept, design and assessment. *EURASIP Journal on Advances in Signal Processing*, 2011(1):57, Sep 2011.

[12] L. Miao, H. Qi, R. Ramanath, and W. Snyder. Binary tree-based generic demosaicking algorithm for multispectral filter arrays. *IEEE Transactions on Image Processing*, 15 (11):3550–3558, Nov 2006.

[13] R. Shrestha, J. Y. Hardeberg, and R. Khan. Spatial arrangement of color filter array for multispectral image acquisition. In *Sensors, Cameras, and Systems for Industrial, Scientific, and Consumer Applications XII*, volume 7875 of *SPIE Proceedings*, pages 787503–787503–9, Jan 2011.

[14] R. Shrestha and J. Y. Hardeberg. CFA based simultaneous multispectral imaging and illuminant estimation. In *Computational Color Imaging*, volume 7786 of *Lecture Notes in Computer Science (LNCS)*, pages 158–170. Springer Berlin Heidelberg, 2013.

[15] B. E. Bayer. Color imaging array, Jul 1976.

[16] J. I. Park, M. H. Lee, M. D. Grossberg, and S. K. Nayar. Multispectral imaging using multiplexed illumination. In *IEEE International Conference on Computer Vision (ICCV)*, pages 1–8, 2007.

[17] M. Parmar, S. Lansel, and J. Farrell. An LED-based lighting system for acquiring multispectral scenes. In *Digital Photography VIII*, volume 82990 of *SPIE Proceedings*, pages 82990P–82990P–8, Jan 2012.

[18] R. Shrestha, J. Y. Hardeberg, and C. Boust. LED based multispectral film scanner for accurate color imaging. In *The 8th International Conference on Signal Image Technology and Internet Based Systems (SITIS)*, pages 811–817. IEEE Proceedings, Nov 2012.

[19] R. Shrestha, R. Pillay, S. George, and J. Y. Hardeberg. Quality evaluation of spectral imaging: Quality factors and metrics. *Journal of the International Colour Association (AIC)*, 12:22–35, July 2014.

[20] R. Shrestha and J. Y. Hardeberg. Multispectral imaging using LED illumination and an RGB camera. In *The 21st Color and Imaging Conference (CIC) Color Science and Engineering Systems, Technologies, and Applications*, pages 8–13. IS&T, 2013.

[21] L. Miao and H. Qi. The design and evaluation of a generic method for generating mosaicked multispectral filter arrays. *IEEE Transactions on Image Processing*, 15(9):2780–2791, sept. 2006.

[22] H. Haneishi, T. Hasegawa, A. Hosoi, Y. Yokoyama, N. Tsumura, and Y. Miyake. System design for accurately estimating the spectral reflectance of art paintings. *Applied Optics*, 39(35):6621–6632, 2000.

[23] J. Y. Hardeberg, H. Brettel, and F. Schmitt. Spectral characterisation of electronic cameras. In *Electronic Imaging: Processing, Printing, and Publishing in Color*, volume 3409 of *SPIE Proceedings*, pages 100–109, 1998.

Author Biography

Raju Shrestha *did BSc. Engg. in Computer Science & Engineering and received M.E. in Computer Science & Technology in 2005, and M.Sc. in Color in Informatics and MEdia Technology (CIMET) under the European Erasmus Mundus program in 2010. He has several years of academic and professional experience. He is currently pursuing a PhD in color imaging at the University of Oslo and working at the Norwegian Colour and Visual Computing Laboratory, Gjøvik University College, Norway. His current research is centered on spectral imaging.*