Portable Multi-Spectral Imaging System

Shun-Ming Lee and Chao-Hua Wen
Opto-Electronics & Systems Laboratories, Industrial Technology Research Institute
Hsinchu, Taiwan, R.O.C.

Abstract

The main aim of this study is to develop a capturing system which can record the object's visual spectral quick and accurately by one snap. The general multi-spectral imaging systems must sequentially capture five or seven images for recovering the visible spectral. Such systems are complicated and stationary. In this paper, we present the development of a portable multi-spectral imaging system that consists of a multi-image 5X prism, a set of five color filters and a digital still camera. Additionally, the algorithms of image segmentation will be disclosed to solve the problem of image overlaps by multi-image prism. Next the outputs of camera and spectral function are represented by spectral characterization. An experiment was performed to test whether this technique could be used with digital capture of real objects. Finally, results revealed that the color error were reasonable small.

Introduction

As significant improvement in material science and manufacturing technology are being made, the performance of digital image acquisition systems are gaining improved. Currently, the main requirements in advanced image acquisition systems are not only the resolution of colors, but also the accuracy of colors. When recording the image data in primary colors, there is a problem in that spectral reflectance which is the specific color characteristic of the object can not be recorded from the obtained image data since the obtained signal integrates the spectral distribution of the light source, the spectral reflectance of the object and the spectral sensitivity of the camera.

The human visual system has the ability to assign roughly constant colors to objects in varying illumination. Accordingly, this enables the accurate identification of objects visual environments. The color of an object originates from the spectrum of illuminants and the spectral reflectance function of that object surface. The spectral reflectance function is important for color constancy, color reproduction and rendering of real images. Most of current imaging capturing systems, such as digital still camera, use three different color filters, usually named R, G, and B filters, to measure the reflected spectra and use the outputs of these filters to represent the captured color information. However, the characteristics of these color filters are quite different from the characteristics of human-eye photo-receptors. Hence, even if using complicated color correction technologies, the color information captured by the present color imaging systems is still not exactly the same as the color information perceived by humans.

On the other hand, modern image reproduction systems adopt three or more primary colors to reproduce captured color images. All these systems are based on the principle of color metamerism. The "metamerism" means two color samples appear to match under a particular light source, but not match under a light source with a different "spectral power distribution". Metamersim is usually discussed in terms of two illuminants (illuminant metamerism) whereby two samples may match under an illuminant but not under another.

To improve the accuracy of color capturing and color reproduction, multi-spectral image acquisition has caught the attention of many color researchers.[1-4,6-12] Through this approach, the entire spectral information of the reflected spectrum could be recorded. Once the spectral information is fully recorded, the colors of an object can be faithfully reproduced under any illuminating conditions. The related spectral imaging system in the astronomy and the telemeter technology the research already to be divided the widespread application to record the electromagnetic spectrum, but the visual multi-spectral imaging system research only has the minority school and the research unit pays attention.

Recently, the multi-spectral imaging system almost use filter wheel type to change filter for capture multi-spectral images, like Imai and Berns proposes multi-spectral imaging, Tominaga proposes Six-color Camera System and Tunable Liquid-crystal Filter Camera System. So far, dramatic improvement has been made and the number of filters in a multi-spectral image acquisition system has been reduced from a few dozens down to a dozen or even less. Basically, all these newly developed multi-spectral image acquisition systems are conceptually similar. They all must spend long time on capturing seven or more images. Unfortunately, it is only suitable for capturing still objects and difficult for capturing vibrating or moving objects. When the target object is not fixed among capturing image frames. The results of spectral imaging will be blurred. In the next section, we will describe how to implement such a one snap and portable multi-spectral imaging system for the capture of the entire object's surface spectral information.

Portable Multi-Spectral Image System

The proposed portable multi-spectral imaging system can be decomposed into two parts, the image acquisition and post-processing unit, the spectral reflectance estimation. The image acquisition consists of a commercial digital still camera Nikon D1X, multi-image 5X prism, and a set of five color filters. A personal computer was used to develop the reconstruction software of the spectral reflectance estimation. The characteristic of the multi-image prism is decomposing light that could easy to obtain the multi-image in one image. Therefore we used the multi-image 5X prism with the five color filters to capture one picture and obtain five spectral images. A schematic view of the image acquisition part is illustrated in Figure 1, while the procedures of the reflectance estimation part are depicted in Figure 2.

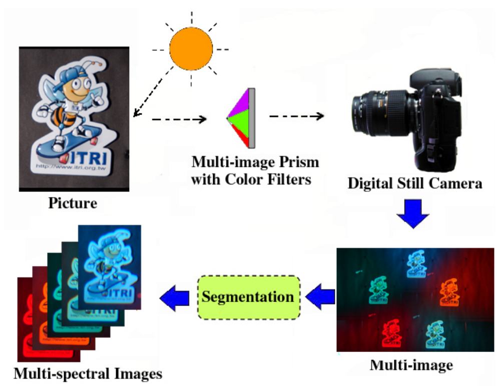

Figure 1. Schematic view of the portable multi-spectral image acquisition process.

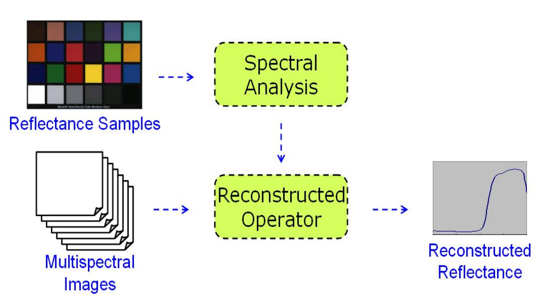

Figure 2. The illustration of the reflectance estimation processes.

The developing procedure consists of two stages. In the first stage, we analyze the characteristics of the image acquisition system in order to derive a transformation matrix, which indicates the mapping between the measurement space and the reflectance space, we obtain the spectral reflectance function in the second stage with the transformation matrix, based on the digital counts of the digital camera.

To obtain the transformation matrix, we take the Macbeth ColorChecker as the reflectance samples to characterize the image acquisition system. First, spectral reflectance functions of 24 patches on the ColorChecker are measured by PhotoResearch PR650®. Then, the principal component analysis (PCA) is performed to acquire the major principal components of these spectral reflectance functions. These spectral reflectance functions are then represented in terms of the linear combination of these principal components. The coefficients of the linear combination are called the PC (principal component) coefficients in this paper. Then we capture the multi-image of these sample patches using the portable multi-spectral imaging system and extract the digital counts of the digital camera from the multi-image. Because the relationship between the PC coefficients and the digital counts is approximately a linear transform, the measured digital counts and the corresponding PC coefficients can be used to obtain the transformation matrix via linear regression. The complete processes are shown in Figure 3.

After obtaining the transformation matrix, the spectral reflectance functions of a given object surface can be reconstructed based on this portable multi-spectral imaging system. First, five images of the object are to be captured by this system with five color filters. According to the digital counts and the transformation matrix obtained at the first stage, the PC coefficients of the object's spectral reflectance function can be calculated. Then, based on the principal components obtained at the first stage and the newly obtained PC coefficients, the spectral reflectance function can be reconstructed by calculating the linear combination of the principal components. Figure 4 presents the procedures of spectral reflectance estimation.

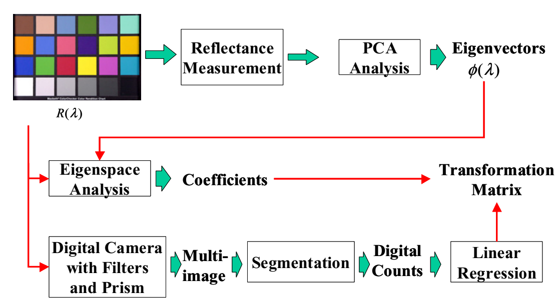

Figure 3. The analysis stages of multi-spectral image acquisition system to obtain the transformation matrix.

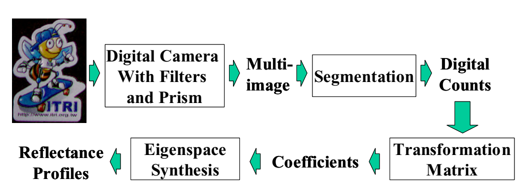

Figure 4. The reflectance estimation based on the transformation matrix and digital counts.

System Setup

Color Filters and Multi-Image Prism

After having extracted the principal components of the reflectance samples, we can start the characterization of the portable multi-spectral image acquisition system. In our system, five color filters are used. These filters are chosen to have their locations uniformly distributed from 400 nm to 700 nm in a 50 nm increment. We used the Melles Griot's visible 80-nanometer wideband interference filter set. And chose the center wavelength is 450nm, 500nm, 550nm, 600nm and 650nm from the interference filter set. The transmittances of these filters are shown in Figure 5.

In this system, we used the multi-image 5X prism, because the number of the image of the multi-image is the same as the number of color filters. We stuck the different color filter in each prism, as shown in the middle of Figure 6. When we take a picture, we could obtain five different spectral images of the multi-image to obtain the spectrum of object. In Figure 6, we show the experimental picture of the multi-image 5X prism. The assembly of the multi-image 5X prism and the five color filters that are mounted on the digital still camera is shown in Figure 7.

There are many different combinations of the color filters on the multi-image 5X prism. For example, one is gradually arrangement and the other is compartment arrangement are shown in Figure 8. Using multi-image prism will raise one serious problem, that is, each image will be interfered with each other neighbors. The Figure 8(a) is shown the overlapped transmittance of the five color filters. The Image overlaps are not easy to discover and difficult to separate. To overcome the problem of image overlaps, here used the compartment arrangement of five color filters, as shown in Figure 8(c), which could be guaranteed to get the pure transmittance outputs of each filters and could be easy to develop the image processing algorithms of segmentation multi-images.

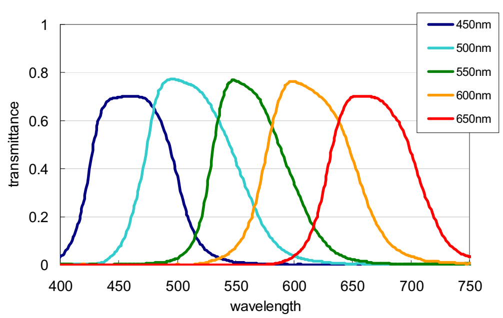

Figure 5. The transmittances of five chosen filters.

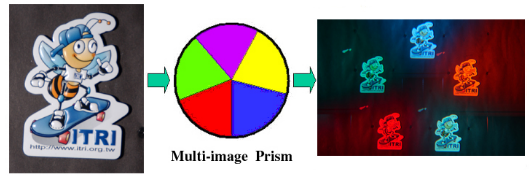

Figure 6. The picture of the multi-image 5X prism

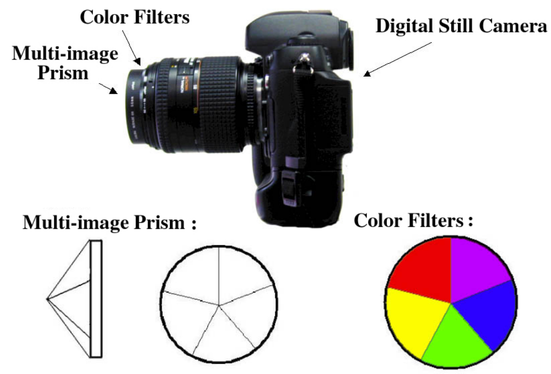

Figure 7. The laying aside way of the multi-image 5X prism and five color filters in the digital still camera

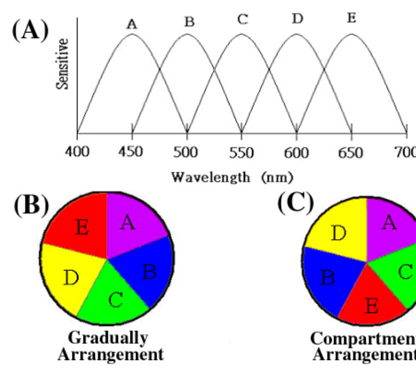

Figure 8. The different combinations of the color filters on the multi-image 5X prism

Multi-Image Segmentation Part

At once, we obtained a multi-image, and then we need to segment the multi-image overlap part for pure narrow-band images. In this study, a specified color grid chart is used to correct the capturing geometry of lens and extract the part of valid image pixels before stepping into the process of multi-image segmentation. This calibration chart contains red lines, yellow lines, green lines, blue lines, and black lines that are to composition array checker, as shown in Figure 9. When we captured the picture of the adjustment chart, we could easy to segment the parts of interesting. Because the transmittances of the five color filters are different, therefore using different color lines will help us to segmentation. For example, the red lines will be brighter than other lines in the image of the color filter that center wavelength is 600nm and 650nm. The other way, the red lines are darker in the image of the color filter that center wavelength is 450nm, 500nm and 550nm. We could easily divide the multi-image active component according to this principle.

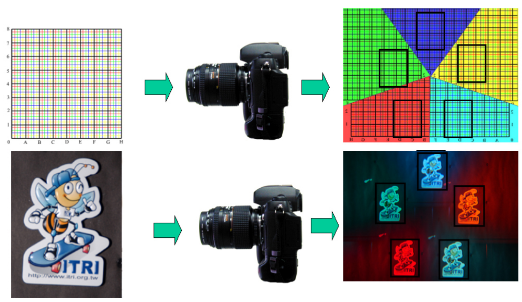

Figure 9. The multi-image segmentation part

PCA for Spectral Reflectance Samples

These 24 spectral reflectance functions were analyzed using principal component analysis (PCA). The first six principal components (PC) of these 24 reflectance functions are illustrated in Figure 10. The reconstructed spectral reflectance function of one sample is shown in Figure 11. Here, the blue profile shows the original reflectance function, while the red profile shows the reconstructed reflectance function. It can be easily seen that as more principal components are involved in reflectance reconstruction, the reconstructed reflectance function becomes a better approximation of the original one. Here, we also use cumulative contribution and the RMS error to evaluate the performance of reconstruction. The cumulative contribution is defined as the percentage of variations, while the RMS error is defined as the difference of spectral reflectance functions. The evaluation results are listed in Table 1.

Table 1. The cumulative contribution and the RMS error versus the number of PCs used in reconstructed reflectance.

Num. of PC's	Cumulative Contribution (%)	RMS Error
1	42.01	0.1015
2	65.85	0.0554
3	79.38	0.0294
4	84.45	0.0225
5	89.32	0.0144
6	91.97	0.0109
7	93.97	0.0083
8	95.53	0.0060

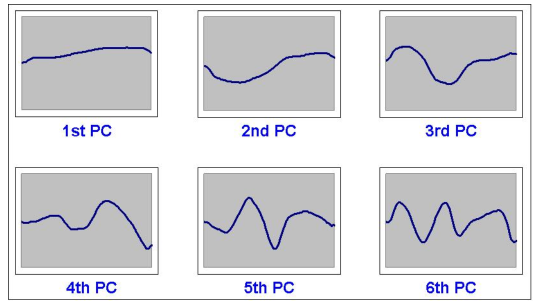

Figure 10. The first six principal components of the 24 spectral reflectance function.

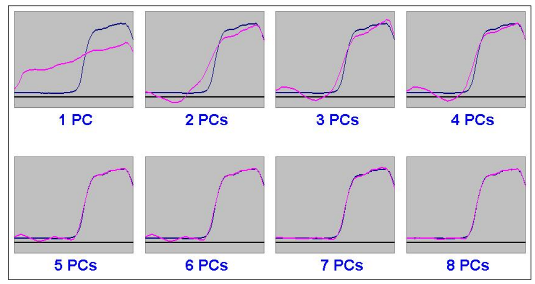

Figure 11. Reconstruction of the spectral reflectance function using different numbers of principal components.

Experimental Results

In previous study, we had accomplished a multi-spectral image acquisition system with the color filter wheel.[13] Based on the results of previous study, we adopted the Macbeth Color Checker to verify our acquisition system. The Figure 12 illustrates the real multi-images of Macbeth ColorChecker captured by the portable multi-spectral image acquisition system. After using the image processing to segment the image overlap part, the averages of digital value of each color patch are calculated from the measured intensity values at the central 40×40 pixels of each color patch for each segmented image. With this procedure, five digital counts will be measured for each color patch.

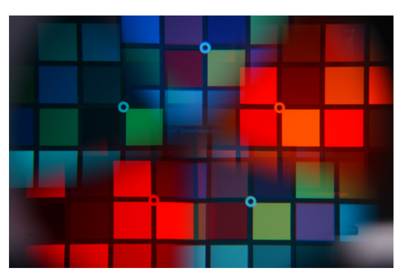

Figure 12. The multi-image of Macbeth ColorChecker.

Each digital count d_m of a color patch can be modeled as

$$d_m = \int r(\lambda) i(\lambda) f_m(\lambda) s(\lambda) d\lambda \quad (1)$$

Here, $r(\lambda)$ is the spectral reflectance function of that color patch, $i(\lambda)$ is the spectrum of the illuminant, $f_m(\lambda)$ is the spectral transmittance of the m th color filter, and $s(\lambda)$ is the sensitivity function of the digital camera.

The spectral reflectance function of the color patch can be well approximated as the linear combination of the first few principal components. Assume $m(\lambda)$ denotes the mean of the measured spectral reflectance functions over all 24 color samples, we can rewrite the spectral reflectance function $r(\lambda)$ as

$$r(\lambda) \approx a_1 e_1(\lambda) + \cdots + a_6 e_6(\lambda) + m(\lambda) \quad (2)$$

where $[e_1(\lambda), \cdots, e_6(\lambda)]$ denote the first six principal components and $[a_1, \cdots a_6]$ denote the corresponding PC coefficients.

After integration, Eq.(1) can be rewritten as

$$d_m \approx a_1 \theta_{m1} + \cdots + a_6 \theta_{m6} + k_m \quad (3)$$

Here, the coefficients θ_{mn} contain the information of $e_n(\lambda)$, $i(\lambda)$, $f_m(\lambda)$, and $s(\lambda)$. k_m is the mean of the digital output of the mth color filter. We can find that the relationship between $d_m - k_m$ and the PC coefficients $[a_1, \cdots a_6]$ is approximately linear. Assume $\mathbf{D} = [d_1, d_2, \cdots, d_m]^T$ $\Theta = [\theta_1, \theta_2, \ldots, \theta_m]^T$, and $\mathbf{k} = [k_1, k_2, \cdots, k_m]^T$. We have

$$\mathrm{D} = \Theta\, \mathrm{a}^T + \mathrm{k} \quad (4)$$

Since **D**, **a**, and **k** are available for each color patch on the ColorChecker, we can estimate **Θ** by using linear regression based on these 24 color samples.

Once **Θ** is estimated, we can build the transformation between the digital counts and the PC coefficients via the pseudo inverse technique. That is, we have

$$\mathbf{a}^{\mathbf{T}} = \Theta^{+} (\mathbf{D} - \mathbf{k}) \quad (5)$$

where $\Theta^{+} = (\Theta^{\mathbf{T}} \Theta)^{-1} \Theta^{\mathbf{T}}$. Hence, for any object surface, we can use this multi-spectral image acquisition system to capture the digital counts **D**. Then, via Equation 5, we can estimate the PC coefficients **a**. With **a**, the spectral reflectance function of the object surface can be reconstructed via Equation 2.

We applied the above procedure to the color patches on the ColorChecker, using the Θ^{+} calculated from these 24 color patches. Figure 13 shows the software of portable multi-spectral imaging system, and Figure 14 shows four examples of the reconstructed reflectance functions versus their original reflectance functions. Finally, here evaluated the system performance via the color difference. The average ΔE*ab was 6.47 and the standard deviation was 4.68. The results revealed that our portable system was a bit high color difference then other previous study using wheel systems.

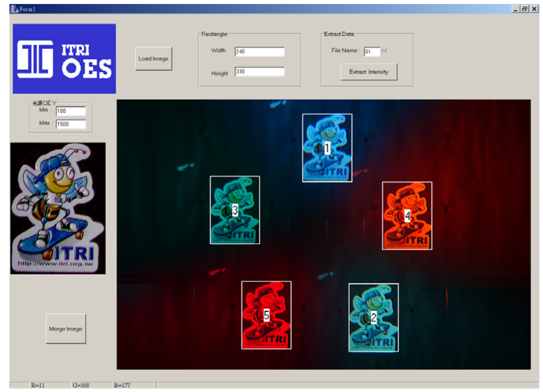

Figure 13. The software of portable multi-spectral imaging system

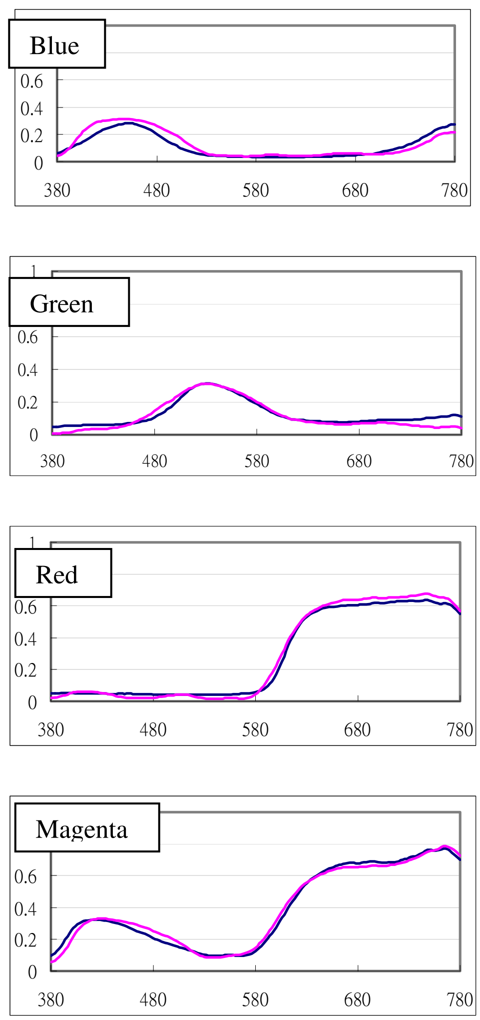

Figure 14. Four samples of original spectral reflectance functions (blue) versus the reflectance functions (magenta) estimated by the portable multi-spectral imaging system.

Conclusions

In this paper, we present the implementation of a portable multi-spectral imaging system. This systems has two important advantages. One is all of pixels in the multi-image contain spectral reflectance or transmittance functions and other is the multi-image can provide the extremely fine color to be reappeared. Based on this system, we demonstrate the capability of this system in reconstructing the spectral reflectance function of object surfaces under a controlled illuminant. The results showed that the color differences between the reconstructed reflectance functions and the original reflectance functions were reasonably small. The system performance will be further improved as following, such as increasing the number of narrow-band filters to minimize the spectral overlaps of choice filters and more accuracy geometric reconstruction of the multi-spectral image. However, the reflection estimation based on the proposed transformation matrix depends on the illumination. That is why we need capture a standard reference white before taking a multi-spectral image for objects. Automatic-white-balance method based on multi-spectral image shall also be disclosed for end users in the further works. Finally, we hope that the average of the color difference of the portable multi-spectral imaging system will be closed to the performance of the traditional wheel system.

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Biography

Shun-Ming Lee obtained his master degree in Mechanical Engineering from the National Central University of Taiwan in 2000. His interests include image quality, multi-spectrum imaging, and color image processing. He is current working in Digital Color Department of Digital Imaging Technology Division at Opto-Electronics and Systems Laboratories of Industrial Technology Research Institute. His current research interests include the automatic optic inspection for flat panel displays.