LED based multispectral film scanner for accurate color imaging

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***Abstract*—LED (Light Emitting Diode) based spectral imaging is advantageous for its fast computer controlled switching ability, availability of many different types of LEDs and cost effectiveness. It has been used in some applications like biometrics and arts; however, it has not been explored in film scanning. Here in this paper, we have proposed a LED based spectral film scanner that allows acquiring spectral data and at the same time producing more accurate digital color images. Such a system, in practice, is constrained by the limit in the number of LEDs to be used. We have studied the performance of the system also, under the influence of the number of LEDs. Simulation experiments show that the system is capable of acquiring accurate color images with a fairly reasonable number of LEDs. We have also investigated the influence of noise on the number of LEDs, and it shows that the noise plays some part on the number of LEDs to be used.**

I. Introduction

The tremendous growth of digital technologies has dramatically increased the demand for clear, colorful and high quality digital images. Digital images can be stored electronically and manipulated on a computer. One can add them to documents, share them over the Internet and print them on the color printers. However, a large number of images and movies are only available as conventional silver halide processing films. With time, degradations occur on those films and nowadays, curators often proceed to film digitization for preservation. In this case, accurate color film reproduction is very important. A film scanner is used to convert these film images directly into digital images. A typical film scanner uses three color (usually RGB) line sensor which scan a film strip line-by-line over the entire width of the filmstrip, while the film strip is fed in a lengthwise direction [1].

A number of film scanning technologies have been proposed, and many commercial products are available in the market. Abrahamsson [2] proposed a computer controlled film scanner which is used to determine reflection coordinates and integrated intensities of X-ray single crystal films. Kurtz et al. [3] proposed a film scanner illumination system having an automatic light control. The illumination system comprises a light source and optics for providing a line of light on a film. Light transmitted through the film is imaged onto a CCD sensor. Swinson et al. [4] proposed a high resolution film scanner which scans a frame of film three times by reciprocating a clapper gate assembly holding the film past a solid state line array sensor. Successive scans are in an opposite sense to the previous scan and R,G,B filter wheel is placed in the optical path and advanced for each scan so that separate high resolution R, G and B scans are produced.

All the film scanners discussed above produce either monochrome or three channel (usually RGB) color images. In this paper, we have proposed a LED (Light Emitting Diode) based film scanner capable of producing spectral images that allows obtaining more accurate digital color images. There are many advantages of spectral image over a classic RGB image: environment independent, free of metamerism, beyond visible range and more accurate color. LED based imaging is one of the techniques of faster acquisition of spectral images, and it has been proposed [5] and has already been used in some areas like arts [6], [7], medical [8], biometrics [9], spectral analysis [10] and color proofing [11]. However, to our knowledge, no application has been proposed in film scanning.

A question may be raised on why multispectral is necessary when the original is film which has three layers, and it has been suggested in some literatures [12]–[14], that a three LED system where the LED have most power where the absorption of the dyes is the highest could achieve a good reconstruction of color images. However, they produce higher colorimetric error. Moreover, each film has different dyes and the diversity of films in museum is huge, from the beginning of cinema to nowadays. We will not find one single triplet of LEDs that will fit all the film dye's maximum absorption. Each artist's film is unique, and we need the best possible digitization. Furthermore, the films are often degraded, so we really don't know where is the useful information. The multispectral scanning can play an effective role in this situation. A research program about film preservation with digitization has been conducted in C2RMF since 2008 [15]–[18]. Within this context, the accuracy of the construction of a multispectral film scanner for patrimonial purpose has been studied. Because C2RMF is working with artists films preserved in museums, we tested here the scanner on positive films.

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In the proposed LED based multispectral film scanner, a subset of LEDs has been selected from a given set of LED lights and a LED cluster is constructed. Each of these LED is lit in sequence and the image through the film is captured on a monochrome camera sensor. The camera responses of the images under a number of different types of LEDs are used to estimate the spectral transmittance of every pixel of the image on the film, and which in turn can be used to obtain more accurate digital color image. The proposed system has been investigated through simulation based experiments which confirms the effectiveness of the system.

We present next in Section II the proposed LED based film scanner. We then present the experiments and results in Section III. And finally we conclude the paper in Section V.

II. LED BASED SPECTRAL FILM SCANNER

Figure 1 illustrates a proposed LED based spectral film scanner. The scanner uses a cluster of different types of color LEDs, and these LEDs are lit one type at a time. A diffuser could be used on top of LED panel in order to produce a diffused uniform illumination. A film strip or slide is illuminated using a sequence of distinct LED illuminations diffused by the diffuser, and an image is then captured by a camera. A monochrome camera is used to capture images. The lighting of the LED sequence and the camera acquisition are synchronized and controlled by a computer. This allows high speed capture of the spectral image.

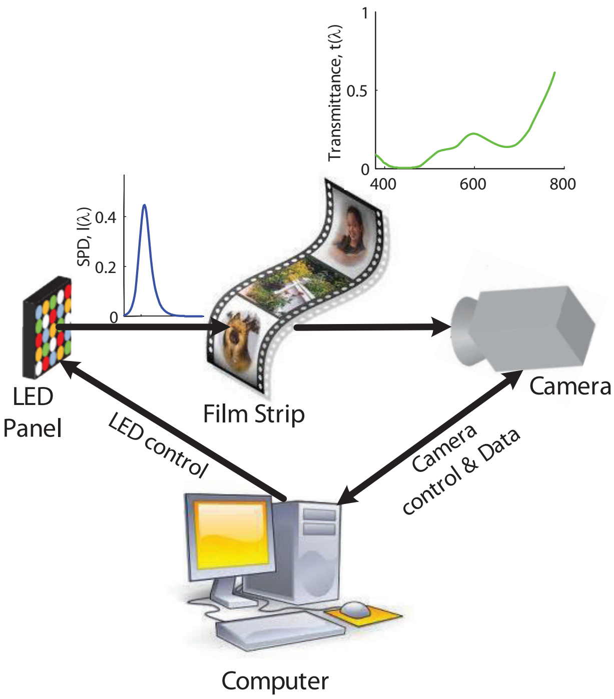


Fig. 1. Illustration of a LED based film scanner system

The subsections below present the system model, spectral estimation methods used, system evaluation and the selection of LEDs.

A. System model

Let n be the number of different types of LEDs used, then the camera response c_n at a pixel corresponding to a point in the film scene is given by:

$$c_n = \int_\lambda l_n(\lambda)t(\lambda)s(\lambda)d\lambda + \eta, \qquad (1)$$

where $l_n(\lambda)$ is the spectral power distribution of the nth LED illumination, $t(\lambda)$ is the spectral transmittance of the scene point in the film, $s(\lambda)$ is the spectral sensitivity of the camera and η is the camera noise. The camera responses C_n for the whole scene corresponding to ith LED illumination can be expressed in a matrix equation form as:

$$C_i = S'\text{Diag(L)}T + \eta;\ \ i = 1...n \qquad (2)$$

where L is the spectral power distribution of the illumination, T is the spectral transmittance of the scene (of size $p \times q$) in the film, and S is the spectral sensitivity of the camera. S' denotes the transpose of the matrix S. The camera responses of the whole scene for all n LED types can be expressed in a single matrix (of size $n \times pq$) form as:

$$C = \begin{pmatrix} C_1 \\ C_2 \\ : \\ C_n \end{pmatrix} \qquad (3)$$

B. Spectral estimation

The estimated spectral transmittance ($\tilde{T}$) is then obtained for the corresponding original transmittance (T) from the camera response C using a spectral estimation method. Among several widely used spectral estimation methods like Imai and Berns (IB) [19], Linear Regression, Polynomial (PN) [20] and Neural Network (NN) [21], we have used the polynomial method as it produces better results and relatively fast [22], [23]. A 10-fold cross validation method is used to select training and test patches from a test chart. Training targets are the database of film transmittance functions from which basis functions are generated and test targets are used to validate the performance of the system. Let C_{train} and C denote the camera responses of the training and test targets respectively. Then, the estimated transmittance with the polynomial method is given by the following equation:

$$\tilde{T} = MC_p \qquad (4)$$

Here $M = T_{\text{train}}C^+_{p,\text{train}}$; C_p is the polynomials of degree 2, formed from the channel responses in the camera response matrix C.

A simulated color image of a scene acquired by an RGB camera (of known spectral sensitivities) under a standard illuminant D65 can be obtained from the estimated spectral transmittance $\tilde{T}$ using the classic color equation.

C. System evaluation

The system can be evaluated using spectral and colorimetric metrics. Two different spectral metrics: GFC (Goodness of Fit Coefficient) and RMS (Root Mean Square) error, and a colorimetric metric: ΔE_{ab}^* (CIELAB Color Difference) have been used. These metrics are computed using the equations:

$$GFC = \frac{\sum_{i=1}^{n} T(\lambda_i)\tilde{T}(\lambda_i)}{\sqrt{\sum_{i=1}^{n} T(\lambda_i)^2}\sqrt{\sum_{i=1}^{n} \tilde{T}(\lambda_i)^2}} \quad (5)$$

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[T(\lambda_i) - \tilde{T}(\lambda_i)\right]^2} \quad (6)$$

$$\Delta E_{ab}^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (7)$$

The GFC is a positive value from 0 to 1, with 1 corresponding to the perfect estimation. The RMS and the ΔE_{ab}^* are positive values, with 0 corresponding to the perfect estimation.

D. Selection of LEDs

The number of LEDs corresponds to the number of channels of the multispectral film scanner system, and the quality of an image acquired by the system depends very much on the number and type of channels. Therefore, selection of LEDs is one of the important issues to be addressed. We need to select the LEDs that produce a high quality spectral image which in turn can be used to obtain accurate color image. In practice, the selection might be under the constraint of a predefined maximum number of LEDs that can be used in the system, maybe due to cost and/or manufacturing limitations.

A straightforward approach of selecting LEDs to be used in the LED cluster would be to determine the optimal subset of LEDs through an exhaustive search, under a given criteria. Since we are interested here in accurate color image, the criteria is the most accurate color reproduction. The exhaustive search method, however, is computationally very expensive. For N number of LEDs, the total search space will be of size $\sum_{k=1}^{N} {}^{N}C_k$, where ${}^{N}C_k$ is the combination of N LEDs taken k at a time. When the number of LEDs in a given set is large, the search space could be so huge that it might be impracticable (computationally intractable) to use the approach.

Since a subset with a reasonably small number of LEDs would be chosen from a large set, a computationally tractable alternative approach would be the forward stepwise selection. In this approach, starting with empty selected list, we add LEDs to the list one at a time. At each step, each LED that is not already in the list is tested for inclusion in the list. The LEDs added previously may not be significant anymore, and in such a case they are deleted from the selected list. The most significant of these LEDs is added to the list, so long as the criterion is fulfilled (i.e. the color difference is below a predefined threshold value). Even though it is not guaranteed to find an optimal subset with the forward stepwise selection, it has been found to have reported good results in practice [24]. We have also obtained reasonably good results with the approach in the selection of the LEDs.

III. Experiment

In this section, we discuss the experimental setup and then present experiment and results obtained.

A. Experimental Setup

The experiment is carried out through simulation, and the experimental setup comprises of spectral data of LED lights, and film transmittances. A monochrome camera with 12-bits depth, and 35 LEDs (including the 9 from Herrera et al. [7]) whose wavelengths are within the visual rage (380nm-780nm) have been used. Among the 35 LEDs, there are several LEDs that have same or almost the same nominal wavelengths and the shape. We remove 10 such LEDs and use the remaining 25 distinct LEDs. Figure 2 shows the relative spectral power distributions of these LED lights, where individual LEDs are numbered for identification. The CIE D65 illuminant, and the CIE 1964 10° color matching functions are used for color computation. A test chart with 405 patches printed on a 35mm Kodak Vision Color Print Film 2383 with an Arrilaser shooting device has been used for testing. The chart was prepared by cutting an RGB cube into $7 \times 7 \times 7$ values [25]. And for accuracy, a gray scale was added with a primary and secondary color scale, in 21 steps. The duplicate values were removed and thus obtained 405 patches. The spectral transmittances of these patches have been measured with an Ocean Optics - USB4000 spectrometer. Training and test patches are selected from the 405 patches through 10-fold cross validation. An RGB camera (Nikon D70) with known spectral sensitivities has been used to compare the results from the proposed system with the classic 3-channel RGB camera. Figure 3 shows the spectral sensitivities of the Nikon D70 camera.

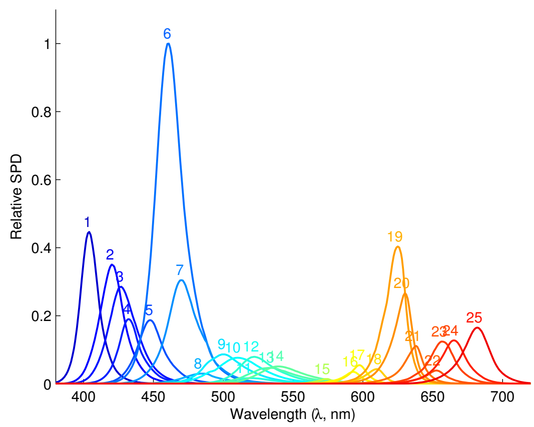


Fig. 2. Spectral power distributions of 25 LEDs used

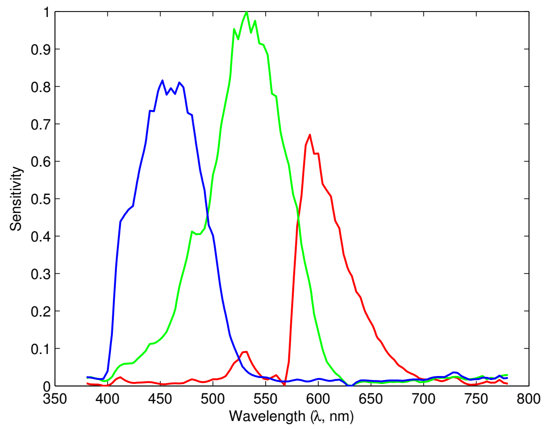


Fig. 3. Sensitivities of the Nikon D70 camera

As there is always acquisition noise in the camera outputs, simulated random shot noise and quantization noise are introduced, in order to make the simulation more realistic. Barnard et al. [26] investigated the noise in trichromatic cameras and came to a conclusion that a realistic level of shot noise in a trichromatic camera is between 1% and 2% [26]. Therefore, 2% normally distributed Gaussian noise is introduced as a random shot noise in the simulation. And 12-bit quantization noise is introduced by directly quantizing the simulated responses after the application of the shot noise. In order to study the influence of noise, the systems with three different amount of random shot noise (2%, 5% and 8%), and one without the noise have been used.

The polynomial estimation method and the three evaluation metrics discussed above are used for estimating the spectral images and evaluating the systems.

B. Experiment

The simulation experiment computes the camera responses, for a number of LED combinations, then estimate the spectral transmittance from the camera responses using the polynomial estimation method, and finally compute the simulated color images from the estimated spectra. The selection of LEDs has been carried out with both the exhaustive search and forward stepwise selection methods. It would be computationally quite expensive to find an optimal subset from the 25 LEDs using exhaustive search. In order to reduce the possible combinations, we set a constraint of 6-9 as the allowable number of LEDs to be selected. An optimal LED combination is selected, under these constraints, which produces the minimum color difference, ΔE^*_{ab}. We have also investigated the selection of LEDs for the optimal spectral output, and for this LEDs are selected that produces the maximum mean GFC. Forward stepwise selection approach uses all 25 LEDs to find the subset of LEDs to be used in the system. The method selected a subset of 7 LEDs out of 25 LEDs, for the minimum color difference. Taking this number as a hint, we have used 6-9 as the constraining number of LEDs for the exhaustive search method, and this method selected 9 LEDs. We have also tested the performance of the system with the intuitive selection of 7 LEDs based on uniform spacing of the peaks throughout the visible spectrum. For the maximum GFC, the forward stepwise selection method chose 8 LEDs, while the exhaustive search method selected 9 LEDs.

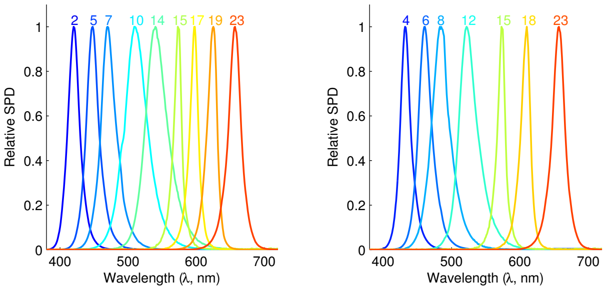
IV. Results and Discussion

Table I shows the statistics (min/max, mean and standard deviation) of the estimation errors obtained with the proposed LED based film scanner system using the LEDs selected by the three LED selection approaches; along with the corresponding results from the classic 3-channel RGB system using the Nikon D70 camera. The results are shown for both the accurate color and spectral output. The table also shows the illuminant used in the 3-channel system, and the subsets of LEDs selected by the three LED selection approaches. The results show that the proposed LED based film scanner, even with the intuitively selected LEDs, produces much more accurate color image compared to the classic 3-channel RGB camera system. The performance is similar in terms of spectral quality (RMS and GFC) as well. As expected, the LED based system using exhaustive search method produces the minimum mean ΔE^*_{ab} of 0.177 along with the GFC of 0.998 and the RMS of 0.003 for the accurate color, and it produces the maximum mean GFC of 0.999 along with the RMS of 0.004 and the ΔE^*_{ab} of 0.391 for the accurate spectra. The forward stepwise selection produces slightly worse but reasonably good results with the ΔE^*_{ab} value of 0.204, the GFC of 0.999 and the RMS of 0.012 for the accurate color, and produces mean GFC of 0.999 along with the RMS of 0.003 and the ΔE^*_{ab} of 0.888 for the accurate spectra. It is to be noted here that we have introduced the random noise and the quantization noise in order to make the results from the simulation more realistic.

TABLE I
STATISTICS OF THE ESTIMATION ERRORS PRODUCED BY THE SYSTEMS

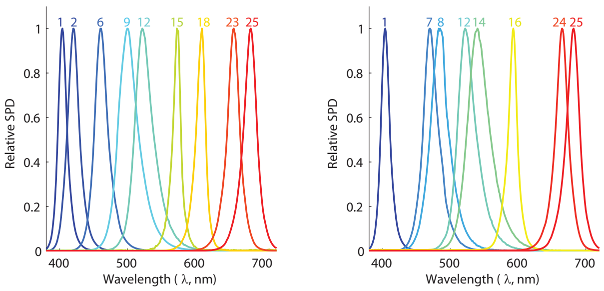
Metric		GFC			RMS			ΔE^*_{ab}		
Statistical Indicators		Min	Mean	Std.	Max	Mean	Std.	Max	Mean	Std.
3-channel system		Illuminant Used: D65								
		0.973	0.994	0.006	0.067	0.029	0.013	10.868	2.707	2.339
LED based system	NA	Uniformly Spaced LEDs: 1, 5, 8, 12, 15, 18, 22								
		0.979	0.998	0.005	0.015	0.006	0.003	0.931	0.384	0.204
	For max. GFC	LEDs from Exhaustive Search: 1, 2, 6, 9, 12, 15, 18, 23, 25								
		0.995	0.999	0.001	0.009	0.004	0.002	1.307	0.391	0.267
		LEDs from Forward Stepwise Selection: 1, 7, 8, 12, 14, 16, 24, 25								
		0.992	0.999	0.002	0.013	0.005	0.003	2.292	0.888	0.508
	For min. ΔE*ab	LEDs from Exhaustive Search: 2, 5, 7, 10, 14, 15, 17, 19, 23								
		0.975	0.998	0.006	0.016	0.006	0.003	0.494	0.177	0.095
		LEDs from Forward Stepwise Selection: 4, 6, 8, 12, 15, 18, 23								
		0.974	0.998	0.005	0.019	0.007	0.004	1.163	0.326	0.209

Figures 4 and 5 show the LEDs selected by the exhaustive search and the forward stepwise selection methods, for the minimum ΔE^*_{ab} and the maximum GFC respectively. Figure 6 shows the 7 intuitively selected LEDs.



(a) Exhaustive search (b) Forward stepwise selection

Fig. 4. LEDs selected for the minimum ΔE^*_{ab}



(a) Exhaustive search (b) Forward stepwise selection

Fig. 5. LEDs selected for the maximum GFC

The results show that the exhaustive search method increases the color accuracy, however at the cost of two more LEDs. There is no significant change in the mean GFC with the 7 LEDs from the forward stepwise selection and the 9 LEDs from the exhaustive search method, however with some differences in the maximum and standard deviations. This indicates that forward stepwise selection of LEDs could be an appropriate method of LED selection.

Different methods selects different LEDs for different optimization criteria, however, they are reasonably well spaced in all the cases. This is explained by the fact that the results from a uniformly spaced intuitive selection of LEDs are comparable with results from the forward stepwise selection. However, the intuitive selection works only in the case where there is a large number of LEDs throughout the visual spectrum. If we carefully look at the LEDs selected in case of color optimization and spectral optimization, we can see that LEDs span from 400nm to before 700nm in the case of color, while it spans beyond 700nm. This is expected as the color calculation is done using CIE color matching function which has quite low sensitivity beyond 700nm, however the spectral optimization considers the whole spectrum.

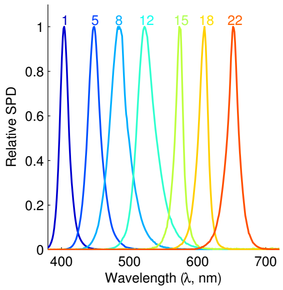


Fig. 6. Intuitively selected 7 uniformly spaced LEDs

We now show the spectral estimation from the LED based spectral scanner, in case of the color optimization for illustrations. Figures 7 and 8 illustrate the estimated spectral transmittance of 9 randomly picked test patches along with the corresponding measured transmittance using the LEDs selected by the forward stepwise method, for the color and spectral accuracy respectively. We can see the better fitting of the estimated and measured spectra in the case of spectral optimization compared to the color optimization.

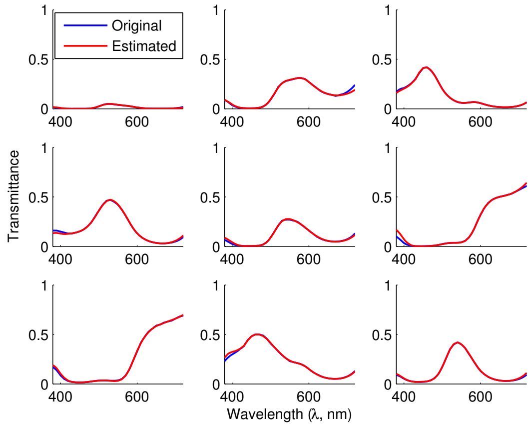


Fig. 7. The original and the estimated spectral transmittance of 9 random test patches for the color accuracy

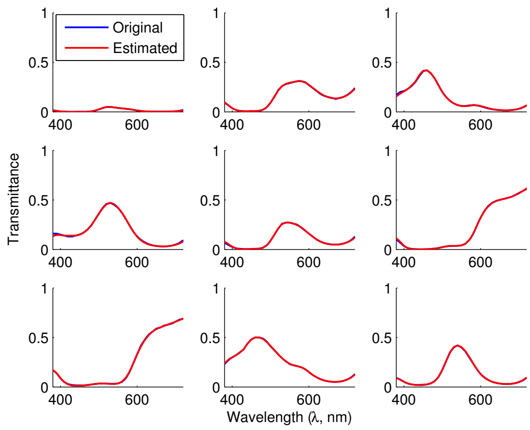


Fig. 8. The original and the estimated spectral transmittance of the 9 test patches using the LEDs for the spectral accuracy

Next, we study the performance of the system with the number of LEDs. The influence of the noise on the number of LEDs and hence the performance of the system has also been investigated. Figure 9 illustrates the plots showing the change in the performance (color difference, ΔE^*_{ab}) of the system with the increase in the number of LEDs, and also for three different amount of random shot noise (no noise, 2%, and 8% noise). The plots are based on the results from the forward stepwise selection of LEDs. The x-axis indicates the maximum number of LEDs allowed from 4 to 25 (all LEDs).

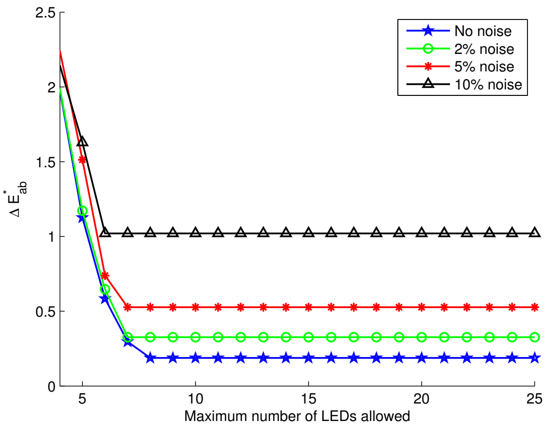


Fig. 9. Change in the system performance with the number of LEDs, for 3 different noise levels

The plots show that the ΔE^*_{ab} decreases sharply from 4 LEDs, and after few more LEDs the curve flattens indicating no change in the performance. As expected, the curves for the higher noise are above the lower noise curves. The flat part indicates there is no change in the LEDs selection and hence the ΔE^*_{ab} even though the constraint is set to the higher number of LEDs. As for example, in the case of no noise, the ΔE^*_{ab} drops sharply from around 2 downto about 0.6 with the increase in LEDs from 4 to 6. The error reduction slows down and the curve becomes flat when the number of LEDs becomes 8. This means it chooses only those 8 LEDs even if it is allowed to select more LEDs. In other words, there is no improvement in the performance of the system by increasing the number of LEDs after 8. With the 2% noise, the curve gets flattened at 7 LEDs and with 10%, it gets flattened at even lesser number of LEDs, 6. This shows that increasing the number of LEDs does not always increase the performance of the system. This indicates that the influence of noise gets more prominent with the increase in the number of LEDs. We normally prefer to have the minimum number of LEDs as it reduces the cost, manufacturing limitations and memory requirements. This number, in general, depends on the dataset, noise model and the noise level, as in the case with the sensors [27]. By setting an upper threshold value of $\Delta E^*_{ab} = 5$ (say), we can use a reasonably small number of LEDs (7) that allows to acquire color images within this accuracy, for the noise below 5%.

V. Conclusion

We have proposed a spectral film scanner using a multiplexed LED illumination. The system can be used to digitize the images from the film with accurate color. The simulation based experiment has confirmed the effectiveness of the system. The experimental results show that the proposed LED based film scanner produces accurate color image and/or spectral image with a reasonably small number of LEDs. The forward stepwise selection of LEDs produces comparable results to the exhaustive search method. It has been found that the influence of noise increases with the increase in the number of LEDs and this leads to the decrease in the performance, after some point, when the number of LEDs is increased further.

Construction of a real film scanner and experimenting with the real system in order to validate the promising simulation results would be an interesting future work. We haven't considered possible dust and scratches on the films. However, as a future work, the system could be extended with infrared LED(s) in order to detect and correct them.

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