

Design Results for a Set of Thin Film Color Scanning Filters

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Abstract

Accurate scanning of a color image, which is absolutely essential for good colour reproduction, depends upon the creation of a set of filters matched to the optical system of the scanner. Previous work developed a measure of goodness for a set of color filters. The measure provides an optimization criterion which can be maximized to obtain optimal scanning filters of arbitrary spectral shapes. This paper reports on the results of fabricating and testing filters designed by this method. The results show that the filters can be fabricated accurately enough to produce increased accuracy in color measurement over existing filters.

KEYWORDS: Color, Scanning, Filter Design, Color Reproduction

1 INTRODUCTION

It is well known that the scanning filters need not be exact duplicates of the CIE color matching functions but need be only a nonsingular transformation of them. The measure of goodness, which was developed in previous work [3], [4], [5], measures the goodness of a set of filters rather than each individual filter. The measure is based on the closeness of the vector space spanned by the filters to the space spanned by the color matching functions. Other measures which have attempted to measure the entire set, such as using the average of the Neugebauer Q-factor [1], [2], need additional information to be effective. For example, it is obvious that the peak transmissions of the scanning filters should be well separated to produce effective filters. However, using the average value of the Q-factors forces this constraint to be enforced by the designer. The measure developed in [3] and [5] can be used without such intervention. This allows easy implementation of optimization programs, either by commercial packages, such as MATLAB, or programmed by the designer.

We will consider the measure to see how easy it is to use. First, let us write the mathematical model for the color scanning device. The desired tristimulus values are obtained by

$$\mathbf{t} = \mathbf{A}_L^T \mathbf{r} \approx \mathbf{B} \mathbf{M}^T \mathbf{O} \mathbf{D} \mathbf{L}_0 \mathbf{r} \quad (1)$$

where $\mathbf{A} = [a_j(\lambda_i)]$ is an $N \times 3$ matrix of the CIE color matching functions sampled at N wavelengths, \mathbf{L} is an $N \times N$ diagonal matrix representing the spectrum of the illuminant under which the sample is viewed (called the viewing illuminant), $\mathbf{A}_L = \mathbf{L}\mathbf{A}$ combines the color matching functions and the viewing illuminant, \mathbf{t} is a 3×1 vector of the tristimulus values; \mathbf{M} is the filter set, \mathbf{L}_0 is the diagonal matrix whose elements define the instrument illumination, \mathbf{D} is the diagonal matrix whose elements define the detector sensitivity, \mathbf{O} is the diagonal matrix whose elements represent the transmission of the optical path and \mathbf{B} is the 3×3 transformation to obtain the estimate of the CIE tristimulus values under illuminant \mathbf{L} .

The approximation is a result of the fact that the scanning filters, together with the other instrument responses, may not span the space defined by the color matching functions and the viewing illuminant. The measure is an indication of how well the vector space defined by $\mathbf{M}^T \mathbf{O} \mathbf{D} \mathbf{L}_0$ spans the space defined by \mathbf{A}_L^T . Mathematically, the measure is defined by

$$\nu(\mathbf{A}_L, \mathbf{M}_H) = \frac{\text{trace}(\mathbf{H} \mathbf{M} (\mathbf{M}^T \mathbf{H}^T \mathbf{H} \mathbf{M})^{-1} \mathbf{M}^T \mathbf{H}^T \mathbf{L} \mathbf{A} (\mathbf{A}^T \mathbf{L}^T \mathbf{L} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{L}^T)}{\alpha} \quad (2)$$

where α is the dimensionality of \mathbf{A}_L (usually three) and we have written $\mathbf{H} = \mathbf{O} \mathbf{D} \mathbf{L}_0$ for simplicity [3]. Notice that all matrices except the matrix \mathbf{M} are known. Without any other restrictions, the measure is a function of $3N$ parameters, each parameter being the transmissivity of a filter at a particular wavelength. The filter design problem may be interpreted as an optimization problem where the goal is maximization of the measure with respect to each of the $3N$ parameters. It is noted that the assumption of three filters is only for current convention. The measure has been applied to problems where more filters are required.

2 OPTIMIZATION OF FILTER MEASURE

In general, the optimization of $3N$ parameters is impractical because of excessive computation time. Furthermore, if the value of the filters at each wavelength are independent parameters, the resulting optimal filters might have discontinuities which would make them impossible to fabricate accurately. For most simulations the vectors have at least 31 elements. In order to make the problem tractable and the resulting filters manufacturable, the filters are described by parametric forms that require many fewer parameters. In [4], a sum of Gaussian curves was used effectively. This allows sufficient freedom to obtain a high measure of goodness while keeping the number of parameters within a reasonable range (15 in this case).

The optimization was done using the FMINS function of the commercial MATLAB package. This multidimensional optimization routine uses the Nelder-Meade simplex search method which does not require the computation of gradients. The measure of goodness function is multimodal and has local maxima which can cause problems. The multimodal property can be seen from the fact that the order of the three filters can be interchanged in the parameter space to produce exactly the same measure. To alleviate some of the uncertainty about the optimal values, the optimization program was run several times with different initial estimates. The results were usually quite similar.

After obtaining parametrized estimates for the optimal filters, a final trimming step can be done to further improve filter performance. The trimming, using all $3N$ parameters, is feasible since we assume the parameterized solution is in the neighborhood of the true optimal solution. The examination of gradients in the region of the parametrized solution provides information to improve the measure of goodness. The trimming can be used directly on the ΔE_{ab} error which allows minimization of the error that is most often used to measure the visual color quality of the data obtained by the filters.

A second advantage of the examination of the gradients around the optimum filters is the ability to measure the sensitivity of the filter design to perturbations. A quantitative measure of sensitivity can be used by the filter manufacturer to indicate the regions of the spectrum where the filter must have very close agreement with the design values; conversely, it allows the manufacturer to know where he is permitted to deviate from the design

values without causing large degradations in performance. The trimming and sensitivity issues are discussed in detail in [6].

3 DESIGN RESULTS

The design of the filters for an actual scanner at the Eastman Kodak Company were described in [4]. The scanner is a flat bed device with an easily accessible filter wheel. The matrix \mathbf{H} was obtained by measuring the transmission of 14 narrow band filters and interpolating the data to the N values required by Eq.(2). This interpolation is probably the source of some of the degradation in the performance of the fabricated filters. The spectrum of \mathbf{H} is shown in Figure 1.

The fabrication of the filter designs were done using thin film technology at Eastman Kodak. The transmissions of the designed filters and the fabricated filters is shown in Figures 2-4. It was found that the placement of the spectral edge around 590nm in the "red" filter was critical as predicted by the sensitivity analysis [6]. It was also predicted that the slope around 580nm in the "green" filter was not a critical point.

The measure of goodness of the designed filters was 0.9832. This was significantly higher than the best combination of Wratten filters which was reported in [4] as 0.912. The measure was also slightly lower than the best filter set we obtained of 0.9928. We choose the suboptimal set because the green filter was easier to fabricate. The fabricated set had a measure of 0.9583.

The filters were tested on a set of 64 Munsell chips. The predicted ΔE_{ab} performance for the designed set was 1.25, for the fabricated set was 1.99 and 2.04 for the Wratten set. The optimal filter set with measure 0.9928 gave a predicted ΔE_{ab} of 0.46. We did not measure the transmission of the Wratten filters but used the tabulated values for the predicted computation. Had these values deviated from the tabulated values, the predicted performance may have been worse. The actual ΔE_{ab} performance was 2.66 for the set fabricated from the design and 3.02 for the Wratten set.

4 CONCLUSIONS

It was shown that the measure of goodness that was developed earlier can be used to design filters for color scanners which can be fabricated within reasonable tolerances by thin film technology. The performance of the fabricated filters, while not as good as the predictions, exceeded the performance of filters obtained in any other way. The deviation of the performance of the actual filters from the prediction is most likely caused by the estimation of the optical properties of the scanner. Work on determining the amount of improvement that can be obtained by better estimates is not planned.

5 ACKNOWLEDGEMENTS

The authors would like to thank Eastman Kodak for their support and cooperation in this research. In particular, we thank Anna Hrycin for her work in fabricating the filters and Brian Pridham for his help in making the measurements with those filters.

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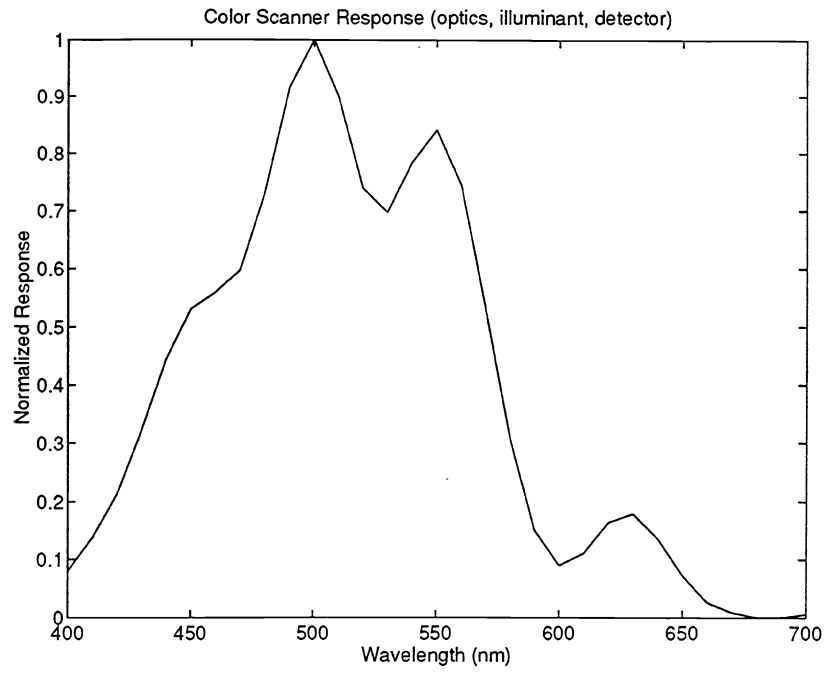


Figure 1: Spectral Response Function for Color Scanner

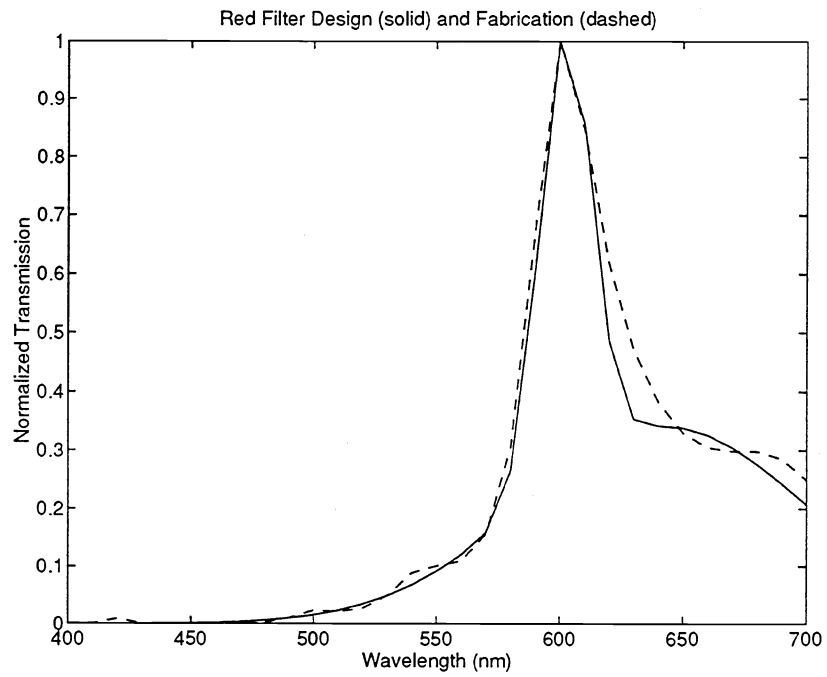


Figure 2: Comparison of Designed and Fabricated Red Filter

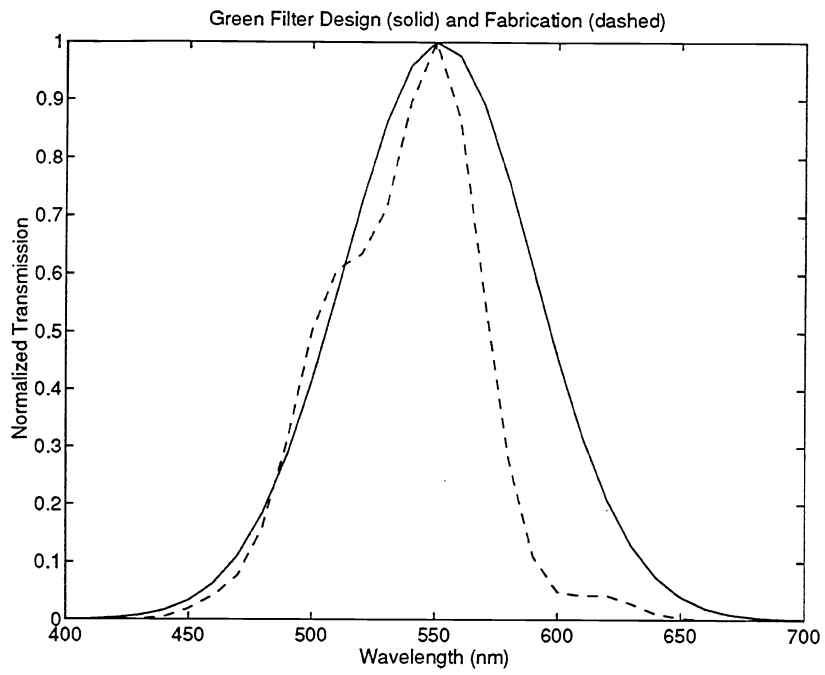


Figure 3: Comparison of Designed and Fabricated Green Filter

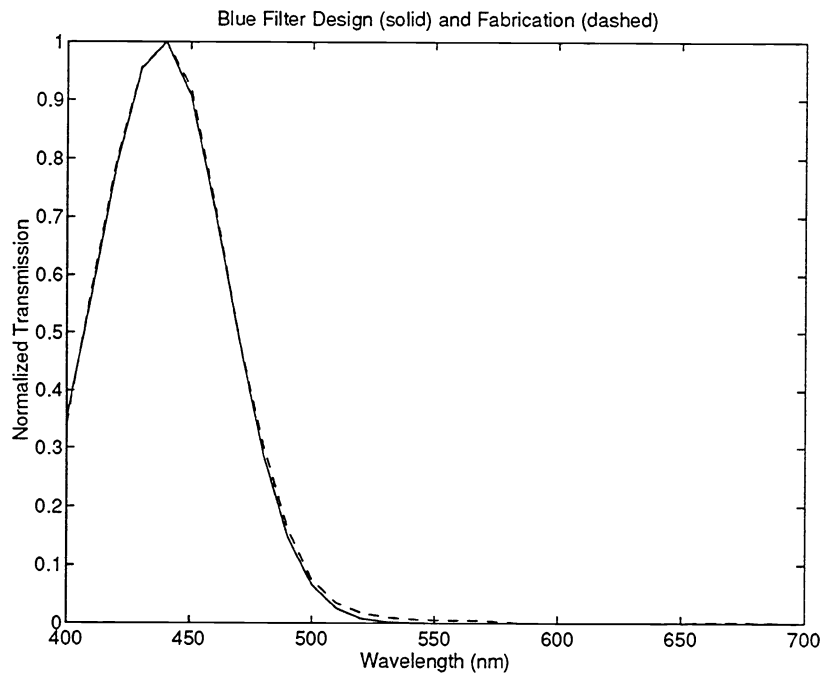


Figure 4: Comparison of Designed and Fabricated Blue Filter