Design of a Multispectral System based on Transverse Field Detectors

Miguel Ángel MARTÍNEZ-DOMINGO,[1] Eva VALERO,[1]
Ville HEIKKINEN,[2] Giacomo LANGFELDER[3]
[1] Color Lab, Department of Optics, Faculty of Sciences, University of Granada (Spain).
[2] University of Eastern Finland (Finland).
[3] Polytechnic University of Milano (Italy).

ABSTRACT

Transverse Field Detector (TFD) sensors are tunable, full spatial resolution, color sensors, currently still under development (Langfelder 2009). One of their main advantages over common imaging systems is that their spectral sensitivities can be modulated by applied voltage and also that they can achieve full spatial resolution by exploiting the wavelength-dependency of the penetration depth of photons in silicon (Langfelder 2012). Some previous works have studied their properties, functionality, and some limitations arising when they are used as part of a multispectral imaging system (Langfelder 2011). This work aims to improve TFD performance beyond its initial 'raw' capabilities by narrowing down their spectral sensitivities with additional color filters added to the sensor matrix, and so achieving better quality of estimated spectra trading off full spatial resolution to some extent. Results show that decreasing spatial resolution by 1/6 using a Color Filter Array (Murakami 2012) (CFA) with 6 different transmittances and tuning alternate pixels to two different biasing conditions, we can get 18 channels in one shot, significantly outperforming existing traditional imaging capture devices both spectrally and colorimetrically.

1. INTRODUCTION

In previous work (Martínez 2012), TFD sensors were already proposed as part of multi-shot multispectral imaging systems. Additional channels were obtained via a tuning procedure. Previous results have shown that their spectrally broad sensitivities have a negative influence in the quality of the estimated spectral reflectances from TFD sensor responses. In this work we have studied whether including some band-pass color filters as part of a CFA-TFD system could increase the device performance, making the loss of spatial resolution be worthy. We have demonstrated that, unlike in the previous works, now including the CFA in the TFD-based system, it can outperform a scientific RGB camera with a double shot configuration using a cut-off filter. Since TFDs are still only a prototype, simulations were done to get the noisy sensor responses of all compared systems. With these sensor responses, a kernel-based regression method was applied to recover the spectral reflectances of 1700 color samples belonging to the NCS color atlas. The assessment of the performance of each system was done by calculating ΔE00 color difference, RMSE and GFC metrics. In Section 2 we explain the methods used in the simulations and calculus of results. In Section 3 we show the results and discuss about them, and finally in section 4 we deduce some conclusions.

2. METHOD

This section is divided in three subsections. First we explain how we selected the filters and the biasing conditions of the TFD out of all the available ones to do the simulations. Secondly we describe the simulation of the noisy sensor's responses, and finally we explain the spectral estimation procedure.

2.1 Channel selection

In this work we define channel as the combination of one sensor sensitivity and a filter transmittance. We selected a set of 13 band-pass color filters covering the visible spectrum and with some overlapping between them, out of a database of real existing filters that belongs to Andover Corp. USA. (Andover). We can see in figure 1(a) the 13 normalized transmittances of these filters, and in figure 1(b) the relative responsivities of 8 different biasing voltage conditions provided by TFD developers (Langfelder 2012).

Figure 1: a (left) 13 candidate filter transmittances. b (right) 24 TFD sensitivities.

Combining the 13 transmittances and the 24 sensitivities we get a total of 312 channels. Our aim is to find the optimal combination of them using only a maximum of 2 different biasing conditions, since TFD does not allow for more than 2 different biasing voltages applied in single shot configurations. Increasing the number of shots on the other hand would increase the capturing time, complicating the real time capture applications. Then we apply the voting PFA method explained in (Lu 2007) and (Chatzis 2007) and chose the 6 channels corresponding to the two most voted biasing conditions. Therefore tuning half of the total pixels with each biasing condition, and taking into account that we have selected 6 filters to be placed in front of 3 sensitivities each, we get up to 18 channels in just one shot. The other compared systems were: 2-shots and 8-shots TFD configurations without any color filter (6 and 24 channels respectively with full resolution), a 2-shots system composed by scientific RGB camera (model Retiga 1300) using an IR-UV-cut-off filter (one shot with the filter in front and one without it, yielding 6 channels and 1/3 resolution), and a common monochrome silicon sensor with the CFA placed in front of it (one shot, 6 channels and 1/6 resolution).

2.2 Sensor's responses simulation

Since there is still no imaging system that includes the prototype TFD sensor in it, we have computed the sensor responses including additive noise. We assumed standard D65 illumination, then we calculated the photocurrent and checked for saturation in order to set an optimal integration time for the 1700 NCS samples. Finally we add the thermal noise, dark current noise and quantization noise. This approach was used in the simulation of all systems examined in this study.

2.3 Spectral reflectance recovery

As shown in (Martínez 2012), a suitable candidate algorithm for spectral estimation from TFD sensor responses is kernel-based regularized regression. In this work we used an inhomogeneous polynomial kernel (Heikkinen 2007). We assessed the performance of the different systems by a 10-fold cross validation method. We divided the data set of samples in ten parts of equal size. Then in each iteration we separated one of these parts for evaluation and optimized the kernel parameters with the remaining 9 parts. The optimization was also done using 10-fold cross validation. For each optimization iteration we calculated the ΔE00 error surface for the parameter grid range (for imaging systems colorimetric accuracy is very important), and found its minimum to get the kernel parameters (polynomial degree σ and regularization term λ). See Figure 2.

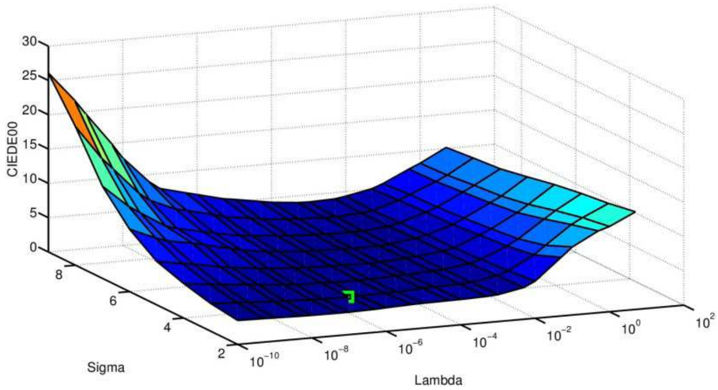

Figure 2: Error surface for an optimization iteration and its minimum found (green dot).

3. RESULTS AND DISCUSSION

In Table 1 we can see the summary of the results for the experiment. Configuration 1 combines half sensor polarized in one way and other half differently with the CFA. Takes one shot and uses all 3 channels under each filter of the CFA. Configurations 2 and 3 use 2 and 8 shots respectively, with the whole sensor polarized differently for each shot. Configuration 4 uses two shots of an RGB camera, one of them placing a IR-UV-cut-off filter in front of it (proposed in (Martínez 2012)). Configuration 5 uses a normal monochrome silicon sensor together with the same CFA used in configuration 1.

Table 1. Summary of the results from the experiment.

Config #	System	# shots	# channels	Resolution	ΔE00	RMSE	GFC
1	*TFD + CFA*	1	18	1/6	0.336	0.009	0.999
2	*TFD double shot*	2	6	1	3.149	0.017	0.998
3	*TFD multi shot*	8	24	1	1.892	0.014	0.998
4	*RGB + Cut-off*	2	6	1/3	0.662	0.010	0.999
5	*Monochrome + CFA*	1	6	1/6	2.870	0.032	0.993

As we can see, the best colorimetric and spectral results are found for the first configuration. Adding the CFA we are reducing the spatial resolution in 1/6, but the 18 narrow channels we get improved color metric results in 89.3% compared with a full resolution system that takes 2 shots (conf. 2) and 82.2% from a system that takes 8 shots (conf. 3), increasing significantly the exposure time required for a capture. We also see how configuration 1 outperforms the effect of the CFA itself together with a silicon monochrome sensor in a 88.3% (conf. 5). The closest result we could achieve was using the RGB camera with the cut-off filter (conf. 4). We would need to take 2 shots and the spatial resolution would still be 1/3, and also the TFD+CFA would be better by a factor of almost 2 in colorimetric quality. Regarding spectral metrics, the GFC is also best for first configuration (together with the fourth one), and the RMSE improves a minimum of 10% respect to the fourth configuration and a maximum of 72.9% respect to the fifth one.

4. CONCLUSIONS

We have proposed a new CFA-based configuration which improves the colorimetric and spectral performance of TFD multispectral imaging systems, outperforming previous full spatial resolution TFD-based approaches and also other common systems like RGB cameras or monochrome sensors with CFAs. The improvement was achieved by trading off spatial resolution down to 1/6 compared to full spatial resolution systems (1/2 compared with common RGB systems). The new approach will provide an elegant single-sensor, one-shot, 18-channels, portable size multispectral imaging system.

ACKNOWLEDGEMENTS

This work has been done under the framework of Erasmus Mundus master CIMET. It has been possible thanks to University of Granada, Polytechnic University of Milan and University of Eastern Finland. This work was supported by the Ministry of Economy and Competitiveness, Spain, under research grant DPI2011-23202.

REFERENCES

Langfelder, G., F. Zaraga, and A. Longoni, 2009. Tunable spectral responses in a color-sensitive CMOS pixel for imaging applications. *Electron Devices, IEEE Transactions on*, IEEE, 56, 2563-2569.

Langfelder, G., A. Longoni, and F. Zaraga, 2011. Implementation of a multi-spectral color imaging device without color filter array. *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, 7876, 7.

Murakami, Y., M. Yamaguchi, and N. Ohyama, 2012. Hybrid-resolution multispectral imaging using color filter array. *Optics Express*, Optical Society of America, 20, 7173-7183.

Martínez-Domingo, M., E. Valero; J. Hernández-Andrés, and G. Langfelder, 2012. Spectral reflectance estimation from transverse field detectors responses *CGIV, Sixth European Conference on Colour in Graphics, Imaging, and Vision. 12th International Symposium on Multispectral Colour Science*.

Andover Corp. (USA), http://www.andovercorp.com.

Langfelder, G,. 2012. Spectrally reconfigurable pixels for dual-color-mode imaging sensors *Applied Optics*, Optical Society of America, 51, A91-A98.

Lu, Y., I. Cohen; X. Zhou and Q. Tian, 2007. Feature selection using principal feature analysis. *Proceedings of the 15th international conference on Multimedia*, 301-304.

Chatzis, I., V. Kappatos, and E. Dermatas, 2007. Filter selection for multi-spectral image acquisition using the feature vector analysis methods. *Intelligent production machines and systems: 2nd I* PROMS Virtual Conference*, 283.

Heikkinen, V., T. Jetsu, J. Parkkinen, M. Hauta-Kasari, T. Jaaskelainen and S. Lee, 2007. Regularized learning framework in the estimation of reflectance spectra from camera responses. *JOSA A*, Optical Society of America, 24, 2673-2683.

Address: MSc. Miguel Ángel Martínez-Domingo, Department of Optics,
Faculty of sciences, University of Granada,
Campus Fuentenueva, Granada, 18071, Spain.
E-mails: m.martinez.domingo@gmx.com, valerob@ugr.es,
ville.heikkinen@uef.fi, langfelder@elet.polimi.it