

## Determining the absorption tolerance of single chromophore photodiodes for machine vision

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Color information is much less useful to machine vision systems than to people because the spectrum of light illuminating a scene is unknown. For scenes illuminated by daylight, color information can be made significantly more useful to machine vision systems if the scene is imaged using sensors with a specifically chosen combination of spectral responses. In this paper we show that detectors with a full width at half maximum of up to 100 nm can give good color discrimination, and that conjugated dendrimer chromophores have the spectral properties required to allow machine vision systems to confidently use color information. © 2010 American Institute of Physics. [doi:10.1063/1.3456374]

Machine vision is a rapidly growing topic important for automated systems, robots, and remote vehicles. Unlike humans, machine vision systems have a poor ability to use color<sup>1,2</sup> because they are unable to cope with changes in the spectrum of the light illuminating the scene, placing demands on detector materials and system design. Current systems can only utilize color information if the illuminant is either known or unchanging. It is therefore necessary to develop a method of describing the color of a surface that is illuminant independent and compatible with the spectral properties of detector materials. Photodetectors based on organic semiconductors have shown high detectivity and linear dynamic response over a wide spectral range rivaling photodetectors made with inorganic semiconductors.<sup>3</sup> In general, organic semiconductors offer key advantages such as the scope to tune the spectral response through selection of suitable chromophores. In this paper, we report steps toward improving color machine vision using organic photodiodes with narrow absorbing chromophores that are compatible with integrated silicon circuitry. This prevents color crosstalk between pixels, releases space on the silicon for processing circuitry, and increases the resolution ultimately achievable. Up to four different chromophores are selected as candidates for sensing the entire visible region. The combined spectral response of these organic materials (designed to absorb specific wavelengths) can then provide robust color information without using color filters.

In recent work we have proposed a method of obtaining illuminant independent descriptors of a surface over a wide range of illumination conditions.<sup>4</sup> This method starts from a model for the response,  $SR_n$ , of a sensor with a spectral response  $S_n(\lambda)$

$$SR_n = \int S_n(\lambda)L(\lambda)R(\lambda)d\lambda, \quad (1)$$

where  $R(\lambda)$  is the reflectance of the surface being imaged and  $L(\lambda)$  is the light falling on the surface. In the analysis we assumed that objects illuminated by daylight can be modeled using the spectrum of a blackbody. In particular, by assuming that the spectrum of the illuminating light can be approximated using Wien's approximation to the spectrum of a blackbody and that each of four sensors responds to a different single wavelength ( $\lambda_1$ ,  $\lambda_2$ ,  $\lambda_3$ , and  $\lambda_4$ )<sup>4</sup> then the two features,  $F_1$  and  $F_2$  as follows:

$$F_1 = \log(SR_2) - [\alpha \log(SR_1) + (1 - \alpha)\log(SR_3)],$$

$$F_2 = \log(SR_3) - [\gamma \log(SR_2) + (1 - \gamma)\log(SR_4)],$$

are independent of the spectrum of illuminating light if

$$\alpha = \left( \frac{1}{\lambda_2} - \frac{1}{\lambda_3} \right) / \left( \frac{1}{\lambda_1} - \frac{1}{\lambda_3} \right)$$

$$\text{and } \gamma = \left( \frac{1}{\lambda_3} - \frac{1}{\lambda_4} \right) / \left( \frac{1}{\lambda_2} - \frac{1}{\lambda_4} \right).$$

Sensors that respond to a single wavelength will receive a very small signal and are therefore impractical. To study the effect of using sensors that respond to a range of wavelengths, we represented the spectral responses of the sensors using Gaussians and used the reflectances of the Munsell colors.<sup>5</sup> The responses of the sensors were then modeled for different Munsell reflectances and twenty CIE standard daylight spectra,<sup>6</sup> with correlated color temperature (CCT) varying between 4000 and 25000 K (see Ref. 13). The two features  $F_1$  and  $F_2$  were then obtained from the calculated responses (including noise) of four sensors using the wavelengths of the peak absorptions as the values of  $\lambda_1$ ,  $\lambda_2$ ,  $\lambda_3$ , and  $\lambda_4$  needed to calculate  $\alpha$  and  $\gamma$ . As expected,  $F_1$  and  $F_2$

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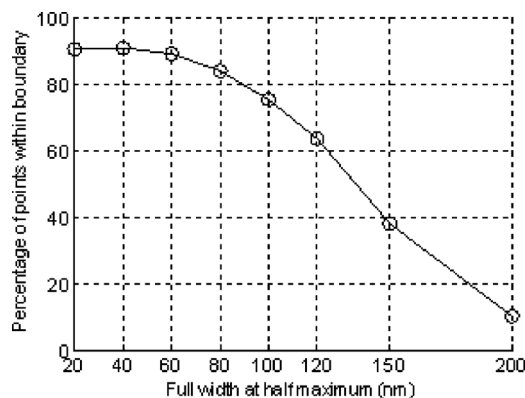


FIG. 1. Simulation results showing the effectiveness of color discrimination obtained using Gaussians with different full width at half maximum.

form a two dimensional space in which different colors are widely separated and similar colors are neighbors (see Ref. 13). However, the combination of noise and sensors that respond to a range of wavelengths mean that  $F_1$  and  $F_2$  have a residual dependence upon CCT. This means that each reflectance creates a cluster of points in the two dimensional space ( $F_1, F_2$ ) rather than a single point. The effect of this residual dependence has been determined using 100 pairs of Munsell reflectances separated by six units in CIELab space. This color space was chosen because it is a perceptually uniform space and the distance was chosen because colors that differ by this amount have been described as good matches to each other.<sup>7</sup> For each pair the potential usefulness of  $F_1$  and  $F_2$  in machine vision was assessed by placing an elliptical boundary around the cluster of points associated with each reflectance so that the two elliptic boundaries just touch (see Ref. 13). The number of points within the correct boundary was then counted. Once this process had been repeated on each of the 100 pairs of reflectances, the percentage of points within the correct boundary was calculated. The results obtained for Gaussian sensors with different values of full width at half maximum (FWHM) are shown in Fig. 1. For sensors whose spectral responses were represented using Gaussians with FWHM of less than 100 nm and peak absorptions at 437.5, 512.5, 587.5, and 662.5 nm, more than 75% of the responses fell within the correct boundary. This shows that useful features can be obtained using four sensors each with FWHM of 100 nm. However, there is a marked deterioration in performance for larger spectral widths, which makes the broad spectra of conjugated polymers and unfiltered inorganic semiconductors unsuitable for this application.

The modeling results offer a significant challenge to developing organic photodiodes with the required response due to the fact that it is difficult to precisely control the absorption maxima, width, or shape. In addition, organic chromophores often absorb to a significant extent across all wavelengths shorter than the onset of absorption and, particularly in small molecule absorbers, the absorption of the chromophores has been found to be broader in the solid-state than in solution due to aggregation effects.<sup>8,9</sup> In order to investigate the feasibility of implementing our scheme using real materials, we studied the solution and film spectra of four different chromophore types, namely, tetrathiophene **1**, neutral **2** and charged **3** cyanines, and squaraine **4** (Fig. 2) incorporated into a dendritic architecture (see Ref. 13). The reason for selecting dendrimers is that they have excellent

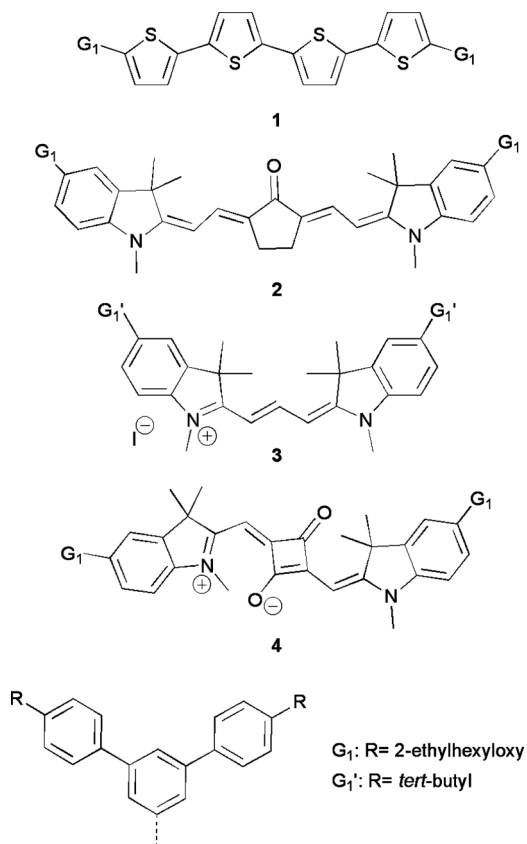


FIG. 2. Structures of the dendronized chromophores used in this study.

solubility—allowing simple processing,<sup>10</sup> and have the additional benefit that they could limit the interchromophore interactions that lead to spectral broadening.<sup>11,12</sup> The solution spectra of **1**, **2**, **3**, and **4** (Fig. 3) have  $\lambda_{\max}$  at 431 nm, 516 nm, 582 nm, and 659 nm, respectively, which are close to but not exactly the peak positions of the previously studied Gaussian absorbers. However, in the UV-visible absorption spectra it can be clearly seen that the absorptions are not symmetric and that the FWHM for each spectrum is around 100 nm and changes in going from solution to the solid-state.

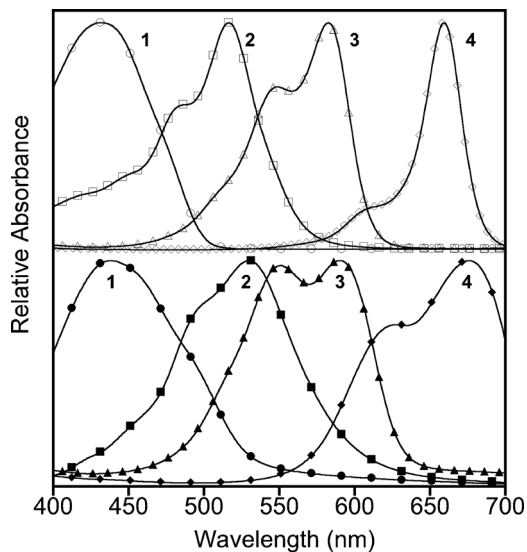


FIG. 3. Solution (top panel) and film (bottom panel) UV-visible absorption spectra of the four dendrimers.

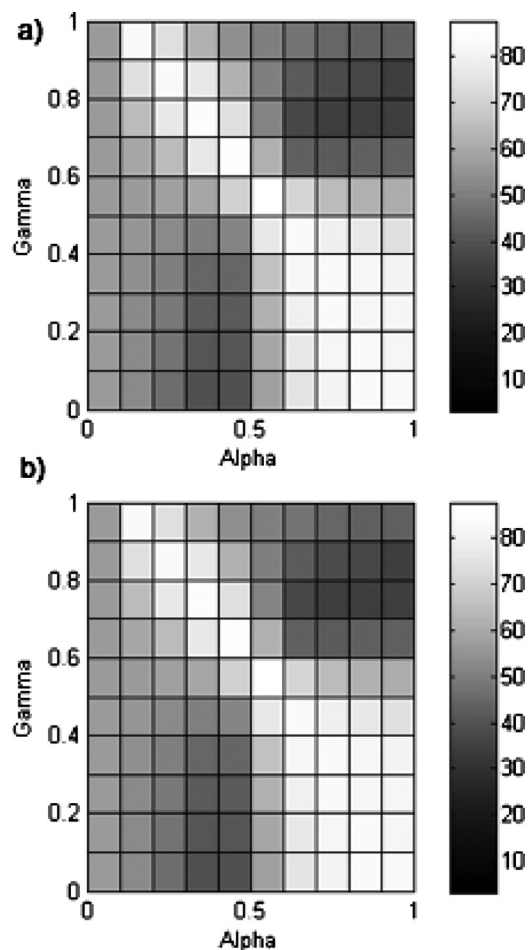


FIG. 4. Results showing the effectiveness of color discrimination as a function of the coefficients  $\alpha$  and  $\gamma$  for (a) solution and (b) film spectra. The effectiveness of color discrimination is represented using the greyscale shown to the right of each set of results.

In going from solution to the solid-state all the peaks and shoulders redshift and the relative optical density of the shoulders increases, resulting in broader spectra. The asymmetry in the absorption spectra mean that unlike the symmetric Gaussians it is not possible to calculate  $\alpha$  and  $\gamma$ . Instead the parameter space for  $\alpha$  and  $\gamma$  had to be searched by changing the values of these parameters and determining the percentage of responses that fell within the correct boundary. The results obtained for each  $\alpha$  and  $\gamma$  are shown in Fig. 4.

The first point to note in Fig. 4 is that for the better values of  $\alpha$  and  $\gamma$  the percentage of features that fall within the correct boundary are very similar. That is, in both cases for the reflectance pairs separated by six CIELab units significantly more than 75% (87.8% for solution and 77.4% for film) of the features would be recognized as a particular Munsell color correctly. Thus, despite the broadening and asymmetry of the absorption spectra the quality of the information obtained is not significantly degraded and would give useful color information to a machine vision system.

In conclusion, the results of the model indicate that selected organic chromophores can be used as the sensing elements for object recognition in spite of their broad and asymmetric absorption. In particular, the responses of sensing elements with spectral responses of four dendronized chromophores can be used to correctly recognize a Munsell color with a probability of 77.4%. A final interesting point from Fig. 4 is that the probability of correct recognition when  $\alpha=0.1$  and  $\gamma=1.0$ , which corresponds to a three sensor configuration, is 76.7%. This opens up the intriguing possibility that a system with only three sensors is required to obtain illuminant independent descriptors of a surface for machine vision applications.

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<sup>13</sup>See supplementary material at <http://dx.doi.org/10.1063/1.3456374> for simulation details and materials synthesis.