Six Color Scanning

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Abstract

Scanner color accuracy is of growing importance as more and more people want to scan color photographs. Traditional three color scanners can suffer from color reproduction errors due to the significant mismatch between their spectral sensitivities and those of the human visual system. In this paper the authors describe some of the technology behind a novel six color scanner that combines data captured with two different light sources to produce an improved final scan. Specifically, they describe the selection of appropriate light sources and the tuning of the scan parameters for those lights. They also describe a color processing pipeline that avoids amplification of image noise, and data processing methods to overcome illumination problems with non-flat subjects and slightly misaligned scans.

Introduction

The spectral sensitivities of traditional three color scanners never perfectly match the sensitivities of the human visual system and as a result they often suffer significant color reproduction errors [1]. In this paper we describe aspects of the technology that we developed for a scanner that captures additional color channels to reduce the color errors. The novel scanner that is shown in figure 1 captures six color channels in total from two separate scans using two different cold cathode fluorescent lamps (CCFL).

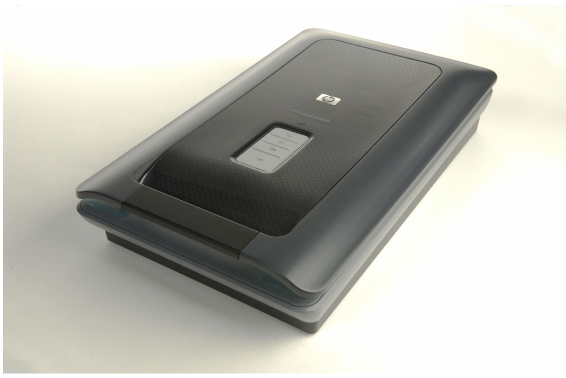


***Figure 1.** The HP Scanjet G4050 six color scanner based on the technology described in this paper.*

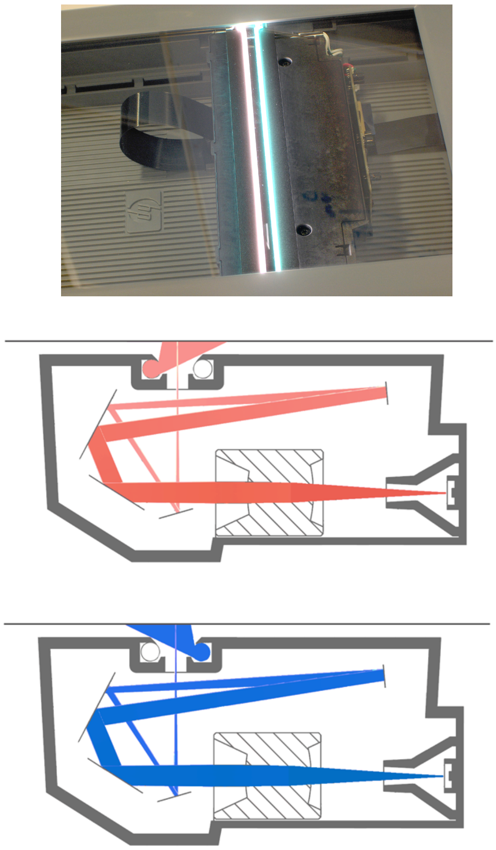
We describe three main technical challenges in developing the six color scanner. Firstly, we describe how we determined the appropriate mix of CCFL phosphors to yield a complementary pair of light sources. Secondly, we describe the image processing pipeline that combines the data from the scans in order to minimize the perceivable image noise and avoid false colors due to any inconsistencies in illumination or alignment. Finally we describe a regression scheme that allowed us to find the optimal parameters for the color pipeline to ensure that the scanner would deliver class leading color accuracy.

Phosphor Selection

In general, optical reduction (OR) scanners are faster and achieve higher image quality than the simpler contact image sensor (CIS) scanners. A typical optical reduction (OR) scanner employs a cold cathode fluorescent lamp and a linear charge coupled device (CCD) with integral red, green, and blue color filters.

The simplest technique to enable six-color OR scanning would be to increase the number of CCDs, or increase the number of linear arrays within a CCD, and use three additional color filters. This approach would be expensive and would give limited benefit using the existing CCFL since the spectral properties of the lamp would dominate the combined spectral profiles of the filter and lamp together. Instead, our goal was to enable six-color OR scanning using a single three color CCD by performing a second scan using a second CCFL with complementary spectral characteristics. The scanner carriage with two complementary lamps is shown in figure 2.

(a)



(b)

(c)

***Figure 2.** (a) the HP Scanjet G4050 scanner carriage has two lamps with different spectral properties, (b) section through the scanner carriage showing the light path from a first lamp, (c) illustration of the light path from a second lamp during a second scan of a subject.*

The spectral distribution of any CCFL is determined by a combination of the underlying Mercury gas discharge spikes and the spectral distribution of the lamp phosphor. The spectrum of the gas discharge is fixed but there is reasonable latitude in the choice of the phosphor mix of the lamp.

We have developed a simulator to select and optimize the set of phosphors that comprise the second CCFL. The simulator models the scanner pipeline using data relating to the standard CCFL spectral distribution, the proposed alternative CCFL spectral distribution, the scanner responsivity functions, and the spectral reflectances of color patches from typical scanned material. The simulator also models the expected noise properties of the scanner and the effects of the color correction matrix on image noise.

We have used the simulator to compute the expected color error and noise in output images for a range of different phosphor mixes. The phosphor mix that minimized the combined color error and noise was selected by the simulator as a candidate for the second CCFL.

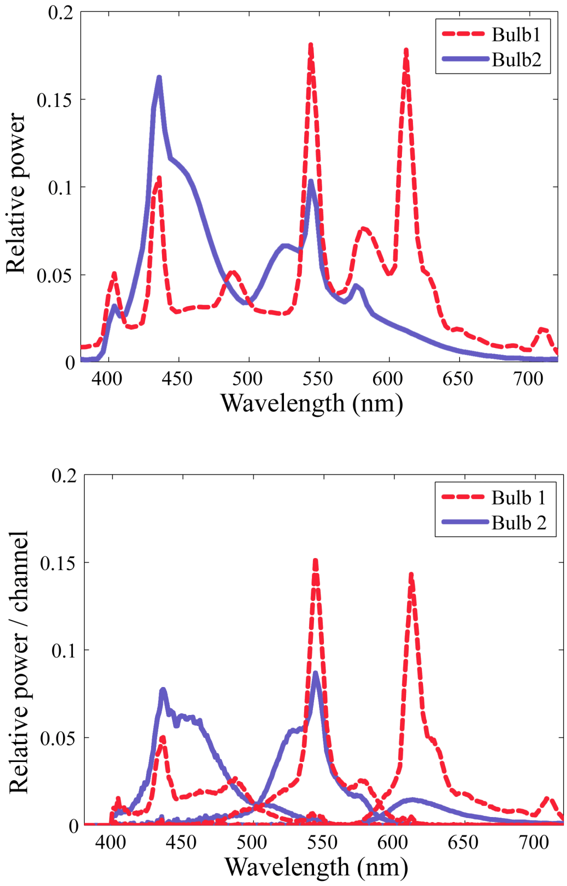


Figure 3. *Lamp spectra (top) for two candidate scanner lamps, and overall scanner responsivities (bottom) for scans captured using those lamps.*

In figure 3 (top), the dashed red line shows the spectral power distribution of a standard scanner CCFL. The solid blue line shows the different spectral power distribution of an optimized phosphor mix for the second CCFL. With two lamps, some wavelengths with low energy from one CCFL have higher energy from the other CCFL.

The differences in spectra for the first and second scans derive small but significant differences in the corresponding sets of RGB color samples as is illustrated in figure 3 (bottom).

The dashed red lines in the bottom figure show the blue, green and red responses for the standard CCFL, and the solid blue lines show the blue, green and red responses for the second CCFL. Although there is some similarity between the responses of the standard and second lamps, we get sufficient additional color information from the second CCFL to be able to derive higher color accuracy. We do this by processing the data channels using a novel scan combination pipeline that avoids compromising other aspects of image quality [2].

Scan Combination Pipeline

The scan combination pipeline has to overcome three main problems. The first is the problem of noise amplification when trying to derive improved color accuracy from two images with very similar color responses. The second is the problem of color fringes that can be caused by small misalignments of image features in the color channels (as a result of inevitable inconsistencies in scanner carriage motion during each of the two scans). The third problem is that since the two CCFLs are not co-located, any non-flat subject matter will introduce color errors due to differences in the patterns of illumination in each scan. We will begin by describing how we overcome the noise problem.

It is usually necessary to transform the color image data generated by a scanner to a standard trichromatic (three channel) color space based upon the CIE colorimetric observer [3]. For example sRGB [4] uses the color space defined by the CIE color matching functions for the primaries specified in ITU-R BT.709 (The HDTV Standard for the Studio and for International Programme Exchange). Given that the response curves of the individual channels of the scanner sensor arrays are linear (or suitable calibration can be used to make them linear), the transformation to the colorimetric space will also be linear and can be achieved using as a simple nx3 matrix (where n is the number of color channels in the scanner).

Depending upon the detailed spectral properties of the scanner, this transformation will closely approximate the correct colorimetric representation of the original scene. A perfect mapping is only possible if the spectral distributions of the color filter and lamp combinations span the space of the color matching functions [5]. In general, errors will occur in the mapping since ideal color filters and lamps are not available.

In addition to mapping as best it can to a standard color space, the color transform also affects the degree of noise amplification in the resulting image. Assuming statistical independence of noise in the color channels, the noise amplification of a linear transform is given by the root of the sum of the squares of the n elements along each row of the matrix. In general, a matrix that gives more accurate color correction will also give more noise amplification. When defining a color correction matrix, it is therefore necessary to balance color accuracy with the resulting amplification of image noise [6].

To reduce the potential effects of noise amplification, we have chosen to use a frequency controlled color transform (FCCT) when combining the six color channels from the two separate scans.

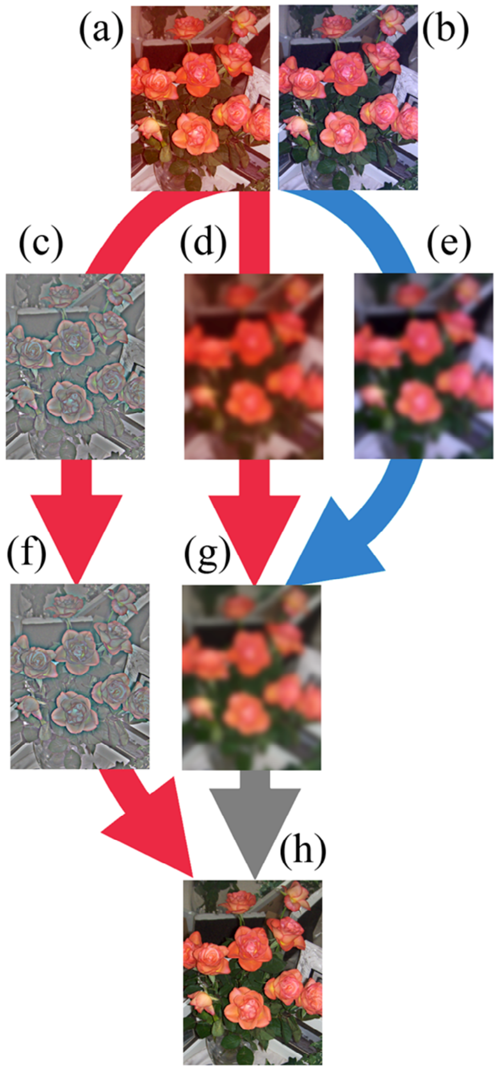


Figure 4. *Six-color scanning with FCCT: high frequencies from one scan and low frequencies from two scans are transformed separately to provide more accurate colors in a final recombined image: (a) first scan, (b) second scan, (c) first scan high frequencies, (d) first scan low frequencies, (e) second scan low frequencies, (f) transformed high frequencies, (g) combined low frequencies, and (h) recombined high and low frequencies.*

The FCCT approach to scan combination is illustrated in figure 4. This shows the splitting of scanned data into low and high frequency components and the application of different color processing to each.

We combine the low spatial frequency components of the two scans using a 6x3 color matrix that is designed primarily to give accurate color. The low frequencies naturally suppress image noise that would otherwise be amplified by the matrix transform. The high frequencies are taken from only one scan and are processed using a 3x3 color matrix that is designed primarily to avoid excessive noise amplification. The final image is a simple combination of the transformed low and high frequencies. The method allows greater color accuracy in areas of low spatial frequency than conventional methods without any greater noise penalties. FCCT has the additional advantage that one of the scans can be performed at lower resolution which can be a significant performance improvement, especially when scanning at resolutions exceeding 600ppi.

Frequency decomposition is achieved by smoothing the image using a low pass spatial filter such as the standard Gaussian [7]. This image is then subtracted from the original to obtain complementary high frequency components. As such the decomposition of the image can be thought of as a simple version of the Laplacian Pyramid, introduced by Burt and Adelson [8], but with just 2 layers.

The effect of the Gaussian filter on noise is computed analogously to that of the color transformation matrix and is given by the root of the sum of squares of the filter elements. The noise suppression provided by the filter is proportional to the sigma of the Gaussian. Thus with FCCT, a more aggressive than normal color matrix can be applied to achieve higher color accuracy, while any increase in noise from the matrix is compensated by the noise suppression Gaussian filter.

Furthermore, if the degree of smoothing is selected correctly for the range of expected viewing conditions, then it is not necessary to achieve the same degree of color accuracy for the high frequency components provided that luminance is appropriately corrected. This follows from the fact that the human visual system is insensitive to chromatic variations beyond 10 cycles per degree while variations in luminance are perceivable beyond 100 cycles per degree. In practice we have found that Gaussian filters with sigma of between 1 and 3 provide a good balance of noise reduction (3.5 and 10.5 times reduction in the standard deviation of the noise respectively) and visible artifacts (a sigma of 3 roughly corresponds to the limiting chromatic spatial frequency for a 200ppi target viewed at 12”). Since the color matrix for the high frequencies need not provide the same degree of color accuracy, it is possible to select a matrix that does not significantly amplify any noise present in the high frequencies.

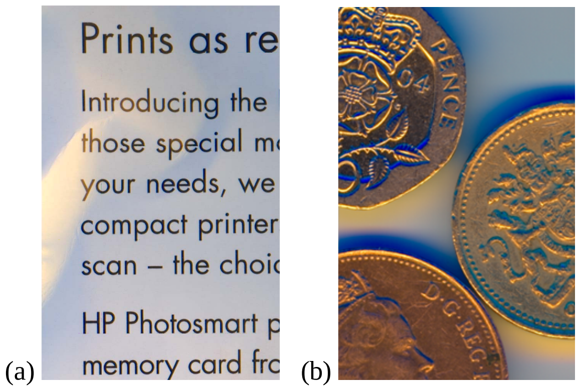


Figure 5. *(a) false coloration of a scanned white page due to small changes in the surface angle , (b) false coloration due to significant 3D structure in the subject.*

The scan combination method described above works well if the scan subject is perfectly flat. If the subject is not flat, even if it only has slight bends or creases, the signals from the two scans will vary according to the surface shape as well as the surface color. In practice, no scan subjects is perfectly flat and so the varying illumination levels from each lamp across the surface of the subject must be taken into account otherwise the derived final scan will exhibit false colors as can be seen in figure 5.

Since a conventional scanner captures all pixels with approximately the same spectrum and angle of illumination, it does not need to distinguish the surface tone and color of the subject from the effects of illumination and shading. Since our six color scanner derives improved color accuracy from two separate images of a surface captured using different illumination spectra and different illumination directions, we must estimate the subject shape and correct for shading effects.

Consider a set of coins being scanned with a 6-color scanner. The first scan captures an image of the coins illuminated by a first lamp as shown in figure 6(a). The second scan captures an image of the coins illuminated by a second lamp as shown in figure 6(b). Notice that the shadows extend in opposite directions in the two scans. Also notice that there are very subtle differences in the colors of the coins in the two scans. These differences are essential for any color accuracy improvement.

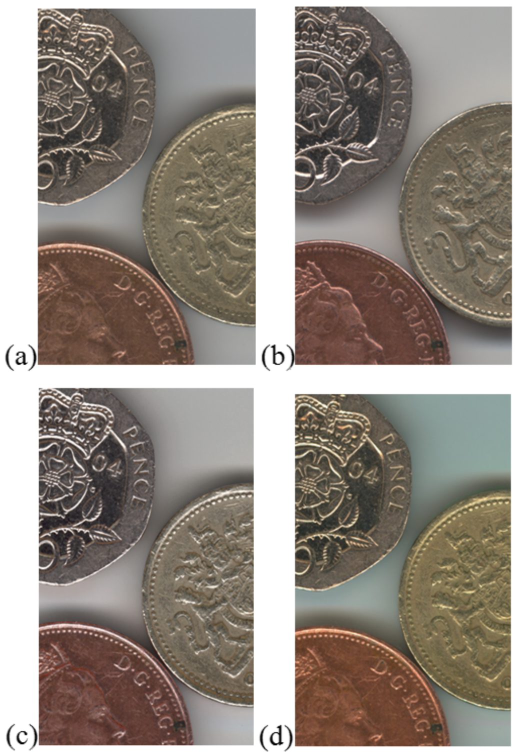


Figure 6. *(a) a first scan of a non-flat subject, (b) a second scan of the same subject using a different lamp, (c) a corrected version of the second scan, (d) a final image combining the first scan and corrected second scan.*

We leave the first scan as it is, and apply a correction to the second scan so that the corrected second scan seems to be lit by the spectrum of the second lamp but from the direction of the first lamp. The result of the correction can be seen in figure 6(c), where the subtle colors from the second scan have been preserved but the shading is consistent with the first scan. Thereafter, the six channels from the first and corrected second scan can be combined using the frequency controlled method we have already described to produce the final result shown in figure 6(d).

A scanner mechanism may provide sufficient positional accuracy to locate a scanned image feature to within a fraction of a pixel from one scan to another. The FCCT approach is reasonably robust to alignment errors since only the low frequencies from the three channels of the second scan are used for color correction. Even so, where image features are of sufficient tonal contrast, a misalignment of the second scan can give rise to visible color fringes around edges.

Consider a scan of black text on a green form as shown in figure 7. The first and second scans have subtle color differences due to the subtle differences in the two bulb spectra, but they exhibit considerable local differences due to scan alignment errors (exaggerated here for clarity). The displacement of image features in three of the six color channels can give rise to highly visible color fringes around the edges of the features.

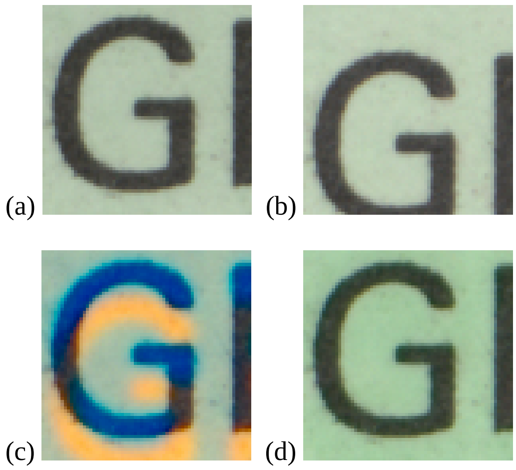


Figure 7. *(a) cropped region of a first scan of text on a green form, (b) a second scan of the same subject with a scan registration error, (c) false coloration of a combined scan due to the registration error, (d) a combined scan using tonal adaptation of the second scan and proportional weightings of the two scans.*

Since the main source of visible color errors is misalignment of high contrast tonal edges, we can reduce the errors by adapting the tones of the second scan according to the tones of the first scan (taking account of the two different lamp spectra). This still gives false colors in regions of misalignment but the color errors are more subtle than in the uncorrected case shown in figure 7(c). To reduce the color errors further, we can use the degree of tonal inconsistency between the scans to vary the relative weight of the two scans in the final result. Where the two scans have consistent tonal levels, both scans contribute equally. Where the tones are inconsistent, the color is computed almost entirely from the three channels of the first scan. The result of color correction after tonal adaptation and proportional weighting is shown in figure 7(d).

Pipeline Regression

Generally we measure the color accuracy of a scanner as root mean squared or maximum differences (delta E's) in CIELAB space over a set of accurately measured color tiles that form one or more scanner test subjects. Following Barnhofer et al [6] we consider the projection of measured/simulated image noise into CIELAB space, however in our case we also split the noise into its low and high frequency components and we transform those components using different matrices according to the frequencycontrolled color processing scheme we use.

To derive the final color correction parameters we perform non-linear optimization over all the parameters of the scanner pipeline which includes channel offsets, gains, gammas and color matrices for each of the low and high frequency components. The regression was the final step of our scanner pipeline development, since it required final product hardware.

Results

The suppression of noise and alignment artifacts by our scanner pipeline can be seen in figure 8.

Figure 8. *Cropped 200 ppi six color scans without FCCT (top), and with FCCT (bottom).*

The top image is a cropped region of a 200 ppi six color scan captured without using FCCT. The image has conspicuous noise and strong color fringes at the edges of the white fence. The bottom image is a cropped region of a six color scan using the method described in this paper. Our pipeline is able to avoid the noise amplification that would otherwise be inherent in the 3x6 color transform, while also avoiding the visible color fringes.

In extensive tests by HP and by an independent company, our six color scanning technology has been shown to give greater color accuracy than other scanners in the same product class [9]. This improvement, of up to 10 deltaE for some image formation modalities, was achieved without compromising other aspects of image quality.

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Author Biographies

Andrew Hunter joined HP Laboratories after receiving his BSc Hons in Computing Science from Glasgow University (1986). He worked on HP's CMOS image sensors and has developed image capture and image processing technologies for handheld PC products, scanners, cameras and mobile phones.

Stephen Pollard received his BSc in Computer Science from the University of Newcastle upon Tyne (1981) and his PhD in Computer Vision from the University of Sheffield (1985). He was awarded a 2-year Science and Engineering Research Council Information Technology Research Fellowship in 1985 to work on 3D machine vision. Since joining HP Laboratories in 1992 he has developed image and document processing algorithms for digital scanners, copiers and cameras.

Jeffrey DiCarlo received his BS in electrical engineering from Case Western Reserve University in 1994 and his MS and PhD in electrical engineering from Stanford University in 1996 and 2003. He joined HP Laboratories as a research scientist in 2003. His research work has focused on color reproduction, spectral imaging, and accurate device characterization.