The why and the how of video-based on-line densitometry

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Abstract

This paper is a technical overview of the color measurement developments by Quad Tech International. This paper has two parts: the why and the how. The first part of the paper (the "why" section) examines the decision to measure optical density rather than colorimetric measurements, and also the decision to use a video camera rather than a point source sensor. The second part of the paper (the "how" section) discusses how a complete understanding of video camera technology can be utilized to compute densities that are accurate enough for use in the pressroom.

Why

Why measure density?

Density as a measure of ink

If yellow paint were to be applied over a wall which had previously been painted cyan, the color of the wall should be yellow. If the wall turns out to be green (that is, the cyan paint shows through), then the customer is likely to complain. We expect paint to be opaque. This opacity is not desirable, however, in printing ink. In order to achieve as wide a gamut as possible, ink needs to be transparent. In this way, yellow ink over cyan ink shows up as green.

One normally thinks of light reflecting from the surface of ink. A more accurate model is one of light traveling through the ink, and reflecting from the paper, as illustrated in figure 1. In this case, the yellow ink will absorb the blue portion of the light, and the cyan ink will absorb the red portion of the light, leaving green as the predominant light that passes through. In this way, ink can be modeled as a filter.

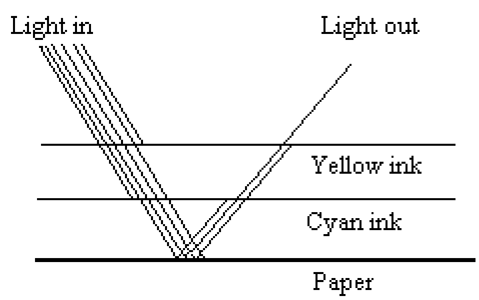

Figure 1. First order approximation of light reflecting from ink

With the model of filters, we can then make use of the Beer-Lambert law (also known as "Bouger law" and "Lambert law of absorption"). The law states that the transmitance of a filter is proportional to some

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constant raised to the power of the thickness of the filter*. To illustrate this law, consider the experiment illustrated in figures 2 and 3. In figure 2, a single thickness of a filter separates the light from the detector. The filter reduces the light that hits the detector to 90%.

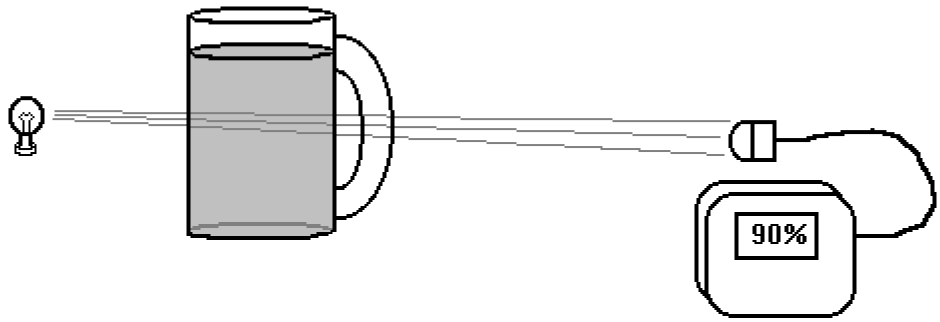

Figure 2. The Beer's law experiment

In figure 3, a second filter is added between the light and the detector. The second filter transmits 90% of the light incident on it, so that 90% X 90% = 81% of the light passes through the filter combination.

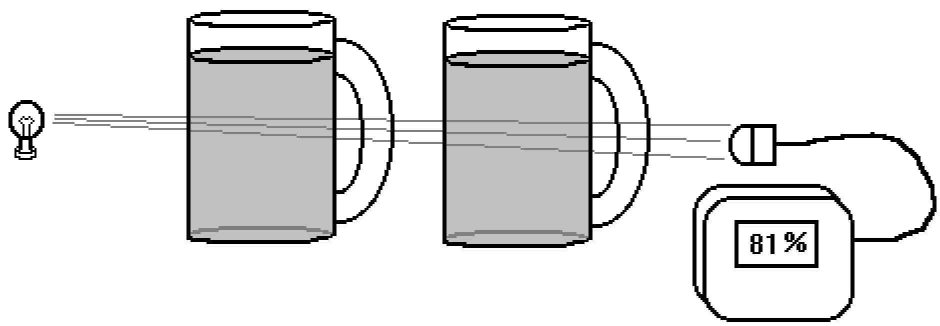

Figure 3. Phase two of the Beer's law experiment

From this we see that each additional filter (that is, each additional thickness of ink) will reduce the light by a multiplicative factor, so that

$$\frac{light\_out}{light\_in} = 0.9^{num\_filters}\ . \qquad (1)$$

If we convert the right-hand side to optical density by taking the logarithm of both sides and negating, we see that the optical density is proportional to the number of filters. This is to say the optical density is proportional to the thickness of the ink.

$$-\log_{10}\left(\frac{light\_out}{light\_in}\right) = -num\_filters \times \log_{10}(0.9) \qquad (2)$$

The fact that optical density is roughly proportional to ink film thickness makes it a useful tool to have in the pressroom.

* It should be noted that the Beer-Lambert law is a model which only *approximates* the behavior of light in ink. It does not take into account light which is reflected from the surface of the ink, nor does it consider light which is scattered within the ink.

Human perception

In 1858, Weber presented a model that roughly modeled all of our senses. The Weber law stated that our senses all have logarithmic response, that is, that the difference between 1 unit and 10 units is perceived as the same as the difference between 10 and 100 units. When applied to hearing, we use the decibel, which is logarithmic in nature. When applied to vision, we use optical density.

Many approximations to the transfer function of our visual system have since been proposed, including logarithm and cube root. Suffice it to say that optical density, being logarithmic comes closer to approximating our perception than does a linear scale. Thus, a 0.1 density unit change has roughly the same appearance whether it is from 0.5 to 0.6 or 1.5 to 1.6.

Press operator's view

From the view of the press operator, optical density is the measurement which is most readily understood. The controls on the press are for cyan, magenta, yellow, and black ink film thickness. Having measurements of each of these (or measurements which correlate directly to each of these) is of much benefit. When controlling a press, it is of little direct benefit for the pressman to have an instrument which reports a hue error or ΔE. There are no knobs to control L*, a*, or b*.

Thus, we see three reasons for measuring optical density in the pressroom: it is roughly proportional to ink film thickness, it corresponds roughly to our perception of ink darkness, and it corresponds well to the controls of an offset printing press. This does not mean that colorimetric measurements such as CIELAB are not useful for the printing process. Colorimetric measurements are important for tying the whole process together. Density measurements are the most applicable measurements on a printing press.

Why use a video camera?

Pro

With much experience putting sensors on web offset printing presses, we have an appreciation for the difficulty of timing and positioning a point sensor to measure the color of a patch from a color bar as it goes by. Long stretches of paper act like a rubber band. The web is constantly weaving laterally, changing its speed circumferentially, and fluttering up and down as the tension on the web changes.

In one experiment, we mounted a camera on press after the chill roll web guide. The web was held flat over a roller. Images were collected at roughly three per second, illuminated by a strobe light triggered by an encoder connected to the drive shaft of the press. Two dimensional cross correlation was used to measure the positional variation. Figure 4 shows the circumferential variation over a period of one minute. Similar results have been seen mounted on other parts of the press.

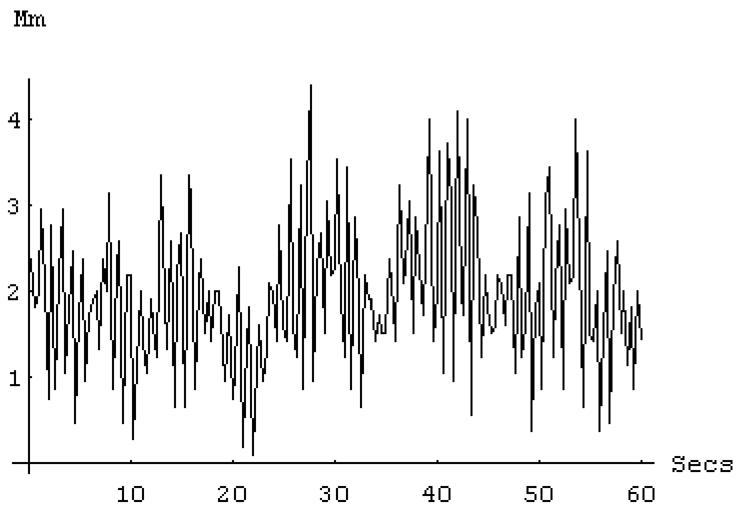

Figure 4 – Circumferential position of target in image

The demands for positioning a point source color sensor are great. It must reliably sample a color patch which is perhaps as narrow as 2 mm, and which is traveling at speeds of 15 meters per second. The plot in figure 4 shows a typical movement of several millimeters from one sample to the next. The movement is on the order of a color bar width three times every second. Unfortunately, even a tiny mistiming of the camera snap could cause the system to incorporate a small amount of the surrounding white paper or bleed into the density measurement. A positioning control system is needed in order to snap a picture at the right time.

For such a positioning control system to successfully track such a high frequency, the sampling rate must be many times faster than three times a second. Bearing in mind that the press may typically deliver 15 or 20 impressions a second to sample, this is a difficult problem.

On the other hand, if the color measurement systems were video based, image motion from shot to shot could be tolerated. Color patches can be located with software, rather than tracked with a positioning control system.

Con

On the down side, video cameras are not designed to be quantitative instruments. They are designed to deliver images that look good on a video monitor. Similarly, video digitizers (also called "frame grabbers") are also designed to capture images that look good, but are not necessarily accurate measurements of light levels. Furthermore, the science of quantitative imagery is not very well developed. People who use video cameras to measure light are few and far between.

Figure 5 shows the results of an early experiment that we performed to quantify how well a video camera could measure optical density. Patches of uniform gray with densities ranging from 0.0 to 1.9 were presented to a video camera for measurement. The camera data was corrected only for white level and absolute black level. In this particular experiment, the video camera was reporting almost 0.4D too low at the dark end. Of the six references to using CCD video cameras to measure optical density[2, 3, 5, 8, 10, 11] two of the references[3,5] came to the conclusion that CCD's are inadequate.

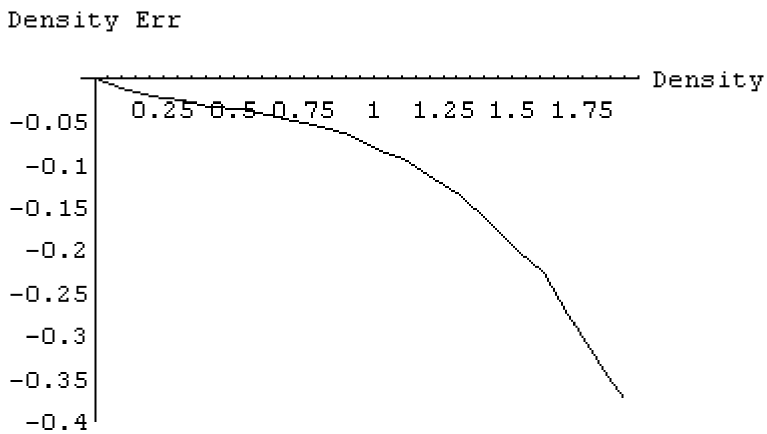

Figure 5 – Uncorrected density error of a video camera

We are faced with a dilemma. Simplistically speaking, the choices are between taking accurate measurements of the wrong location, and taking inaccurate measurements of the right location. This is an oversimplification, since either of these problems could be solved with enough effort. Our real choice is where to put our effort: into developing a control system for consistently positioning a point source sensor, or into building the science behind quantitative video. We chose the latter.

How

One approach to converting gray values from the digitizer into optical densities is to create a look-up table. A particular gray value (or triplet of red, green and blue values) is mapped into an optical density, as measured with a reliable densitometer. By presenting the system with a variety of color patches, the system can be "trained" to "recognize" a variety of densities. The system would apply some form of interpolation to recognize intermediate densities. This general approach could be implemented as a look-up table, as suggested, as interpolating polynomials, as least-square fit polynomials, or as a neural network.

Such an approach could undoubtedly be used to reliably measure the calibration set, provided there are no changes in the system. If other samples are presented, or if conditions are changed, the reliability of the measurements are in question. The approach lacks a systematic understanding of what conditions effect the measurement and how.

Our approach has been to understand the distortions that keep a video camera from producing accurate numbers, minimize the distortions where possible, and correct the remaining problems with software that models the distortions.

General system description

Our prototype system uses a standard three chip color video camera. The camera is fitted with a lens that enables it to see a field of view of about 50 mm by 44 mm. The camera is mounted perpendicular to the web.

Illumination for the camera is provided by a pair of low pressure xenon strobe lights. The strobe lights are designed to provide a bright pulse of light which is no more than several microseconds long. A pulse this short avoids smearing of the image at high web speeds. The illumination system must provide flat illumination over the field of view. To comply with various standards for densitometry, the illumination is at 45° to the web.

The video camera and illumination system are housed in a package that provides shielding from ambient light. The package is mounted on a transport mechanism that positions the camera laterally on the web. The camera images the web over a black roller to minimize showthrough from the other side of the web.

The signals from the video camera are fed into a frame grabber, which converts the video signals into numbers, which are stored in the computer's memory. The computer searches the image to locate the color patches, and computes the densities of each of the patches. In order to accurately compute the densities, several corrections must first be made to the image.

Corrections

PMZ

The first correction needed is the subtraction of a "photometric zero reference". This corrects for any offset added in camera electronics and in the digitizer. The reference image is taken with the camera shutter closed. The photometric zero will vary with temperature, so it needs to be taken frequently. Tests suggest every two minutes in a pressroom is acceptable. The PMZ correction is most critical for highest densities.

Nonlinearity correction

The electronics of the video camera and the digitizer are not generally linear enough for our purposes. Figure 6 shows the error in optical reflectance calculation due to the system nonlinearity. This departure from linearity of less than 1% is certainly acceptable if the images are only going to be viewed. Figure 7 shows the effect of this error on density calculation. Here it is seen that the errors are insignificant below 0.5D (that is, *above* 0.3 reflectance), but that the errors are as bad as 0.15D at densities near 2.0D. Similar nonlinearities have been reported[1].

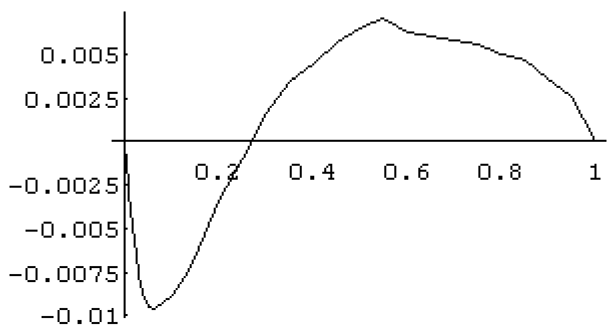

Figure 6. Reflectance error due to system nonlinearity

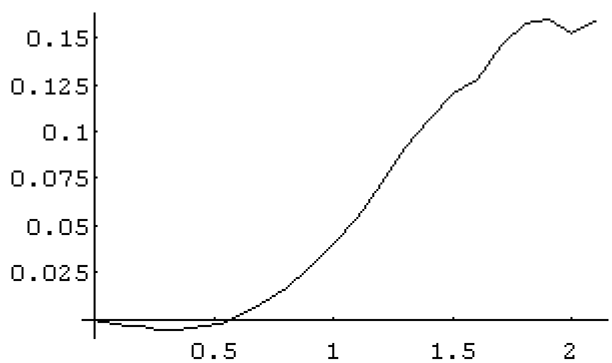

Figure 7. Density error due to system nonlinearity

This system nonlinearity has been modeled by analysis of the circuits to develop the transfer functions. The transfer functions have been verified by measuring a calibrated light source with our system. Implementation of the correction is most efficiently performed as a look-up table.

Scattered light correction

Some light will reflect from the surface of the CCD. Of this light, some will reflect off the CCD's glass cover plate and be imaged by the CCD. Light is also scattered by non-homogeneities in the lenses. In these ways, a black patch surrounded by white paper is corrupted by scattered light[4,8,12]. The video camera sees the black patch as having a lower density.

One approach to correcting for scattered light is to determine the point spread function[12], and deconvolve this from the image[13]. Unfortunately, point spread functions are generally difficult to determine. This point spread function is extremely difficult to determine since it has extremely small amplitude and very broad coverage. Furthermore, deconvolution is a relatively compute-intensive process. I have avoided these problems by using an approximation to the point spread function. The shape of this function is easier to determine, and the particular approximation lends itself to very efficient computation of the deconvolution.

Nonuniformity correction

If the sample presented to the camera has a perfectly uniform white reflectance, all the pixels in the camera will not report the same gray value[8]. There are three factors which influence this: 1) The illumination of the sample may not be uniform. 2) Vignetting may occur in the lens which causes the center of the image to be brighter than the edges. 3) The response of the pixels themselves is not uniform due to variation in the CCD manufacturing process.

These effects should first be minimized. Careful attention should be paid to the illumination profile, so that it is as uniform as possible. The lens and aperture size should be chosen so as to avoid severe vignetting. Uniformity within about 10% is achievable.

The residual nonuniformity is a multiplicative effect that can be corrected by dividing the image through, pixel by pixel, by a white reference image.

Color patch location

One of the key benefits of a video-based on-line densitometer is the ability to cope with movement of the web. This ability comes from algorithms that are capable of locating the color bar, and patches within the color bar.

In brief, the algorithm works by matching rows from the image against a template of the color bar. The matching is done by computing the correlation coefficient of the row against the template. Efficient computation of the correlation coefficient at all possible match locations is effected through fast Fourier transforms.

Because of the possibility of small deviations in registration between inks, the boundaries of each patch are determined by finding the edges between individual patches.

Averaging

Most commercially available digitizers offer only eight bits of precision. This is not nearly enough for accurate density measurements at 2.0D. To achieve precision of ±0.01D at 2.0D, roughly 12 bits of precision are required.

A naive approach would be to increase the bit depth of the digitizer (at great expense) to 10 or 12 bits. This is, however, unwarranted. The precision available in an individual pixel is inherently limited by the total number of photons that the pixel can capture. For a typical CCD, this number is 300,000, yielding a signal to noise ratio which is no better than 550:1, e.g., nine bits provided there is no other noise in the system[2,6,8].

Thus, since each individual pixel is too noisy, a large number of pixels must be averaged together to obtain precise measurements. It is imperative to image at a spatial resolution small enough so that each color patch has many pixels, and to average all the pixels in a patch to reduce the noise level.

I assert that averaging can increase the effective bit depth of the digitizer. This assertion has a firm mathematical and physical basis which is beyond the scope of this paper.

Color transformation

The spectral response of a commercially available video camera comes close to the specified responses for Status T densities, but there is some error introduced in the density. Figure 8 compares the spectral response of the red channel from a typical video camera, and the requirements for a Status T cyan density measurement. A typical plot of the reflectance of cyan ink is overlaid for convenience.

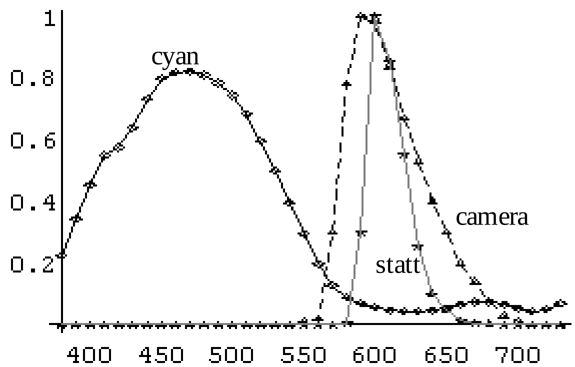

Figure 8. Comparison of spectra of cyan ink, spectral response of video camera's red channel, and Status T requirements.

From the plot, we see that the video camera and Status T peak at nearly the same wavelength, but that the Status T filter is narrower than the video camera. If cyan ink had completely flat response of the range of the video camera, this would not be a problem. The problem comes in that the reflectance of cyan is decreasing in the region of 560 to 580 nanometers, where the video camera is seeing it, but Status T does not. The result is that the video camera sees a slightly higher average reflectance (lower density) than does a Status T densitometer. In this particular case, the video camera's computed density reads about 0.1D low.

We have modeled the error introduced and collected significant data to validate the model. A simple parabolic equation has shown to provide adequate correction.

Results

Our goal was to develop an on-line densitometer with accuracy of ±0.05D and precision of ±0.01D at all densities up to 2.0D. The term "accuracy" is taken to mean the degree to which our instrument agrees with an industry standard. The goal was based on how well an informal sampling of instruments agreed. The term "precision" is taken to mean the repeatability of measurements of the same sample. The goal was based on a typical tolerance for a printing process of ±0.07D.

In one test of the accuracy of our system, we collected nine sample color bars from three runs. The samples were chosen to represent a variety of bleeds. A set of four color patches (solid black, 75% black, 50% black and 25% black) was selected from each of the sample sheets. Each of these 36 samples were measured in fifteen positions in the field of view of the camera. Thus, we had a total of 540 measurements, which ran from 0.1D to 1.8D. The data were compared with measurement of the patches by an Xscan scanning densitometer manufactured by Xrite. The RMS (root mean square) error for the data set is 0.031D. Figure 9 shows the error distribution versus density.

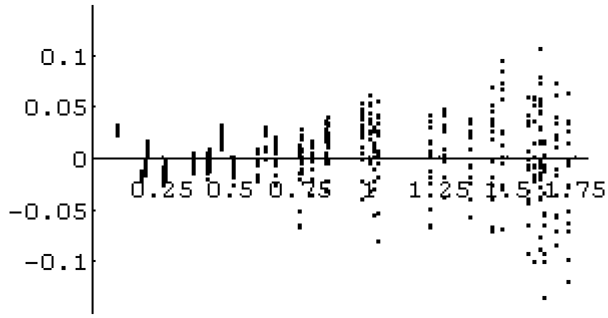

Figure 9 – Density error of the video densitometer

Work on the accuracy of the measurements is continuing at this time (July 20, 1995). It is expected that the error will be reduced, and that color density errors will be comparable.

Acknowledgments

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Patent protection has been filed for on this system.

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