Optimisation of Printer Calibration in the Case of Multi Density Inks

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Abstract

We introduce a framework for printer calibration. The calibration encompasses ink limitation and linearisation. The visual consistency needed in proofing can only be ensured when the calibration uses visual quantities.

We extend the framework to describe printing with multi density inks using ink mixing. We show that ink mixing needs to be incorporated into the calibration. As a further refinement, we propose a technique we call multiple linearisation. It allows to achieve a predefined response with respect to more than one quantity, by exploiting the additional degrees of freedom offered by similarly coloured inks.

The techniques are illustrated with an example of a two ink calibration for which it is shown that multiple linearisation significantly improves visual uniformity.

1. Introduction

Almost every printing system is prone to output variations caused by changes in system and environmental variables. Since these variables cannot always be controlled with the required precision, calibration as a software solution will be added in order to compensate for the changes.

The goal of calibration is to bring the printer into a standard condition. Only when a printer is kept in such a condition, it can achieve consistent output over time. To a certain extent, a well designed calibration procedure can also be used to bring different printers of the same make into a single common condition and thus enable consistent output at different locations.

We will further view calibration in the context of digital proofing systems based on inkjet technology. In contract proofing, the behaviour of one printing process is simulated on another process, in this case an inkjet printer. Colour management solutions exist that carefully model both processes and specify the desired output in a device independent manner. Crucial to the success of proofing is that the proofer produces reliable results. More precisely for a given input it should always produce exactly the same, well defined output.

As the rendition of precise colours is pursued, the demands for consistent and predictable colour quality are very high. This makes proofing much more colour-critical than other printing applications where the main concern is to produce pleasing images. The fact that proofing quality is generally judged by the worst match encountered also stresses the importance of a tight control on the printed output.

We will describe calibration in a framework that includes ink limitation and linearisation. We will study ink mixing as the practical approach to using multi density inks and introduce the concept of calibrated ink mixing. By doing so, ink mixing is integrated into the calibration and visually optimal ink mixing can be conserved. In a further refinement, we will introduce multiple linearisation as a method to improve the visual uniformity.

2. Calibration Framework

2.1. Objective

The variables that influence the printed output cannot always be controlled with the required precision. In order to compensate for the changes, a calibration is needed. The goal of the calibration is to bring the printer into a standard condition. A calibration typically includes printing out an optimised set of colour patches. The resulting measurements precisely describe the ink behaviour on paper. By comparing this to the desired reference tonal behaviour, calibration tables can be calculated.

2.2. Printing Process

A printer starts from image data i and outputs prints that can be described in percentages of ink p. We consider the printing of a single ink colour only. In order to make sure that the ink percentages are as intended, the translation from i to p is governed by a calibration function C:

$$i \overset{C}{\rightarrow} p = C(i) \tag{1}$$

Both i and p are assumed in the range $[0, 100]$. The printed output is measured and a value m is obtained:

$$p \overset{M}{\rightarrow} m = M(p) \tag{2}$$

The measurement function M describes the combined effects of both the printing and the measurement processes. Both are physical processes and thus subject to variability.

2.3. Quantities

Calibration necessarily builds on measurable quantities. The question arises of what quantity should be used. Foremost, it should relate directly to the characteristic one intends to control. In proofing applications, visual resemblance between proof and print is envisaged, so a quantity closely related to visual perception is preferred.

The quantity needs to be measurable in a convenient way. Densitometers have the advantage of being commonly available. In present days, lower priced spectrophotometers are also becoming more widespread. This opens new possibilities, especially since they allow measuring CIELab quantities.

Additionally, it can be advantageous to have the quantity relate to the physical characteristics of the printing process. For printing presses, this justifies the use of quantities such as dot gain. In inkjet proofing, the situation is different. The spectral properties of inkjet inks are not the same as those in the final print. Since pure colours in print are not pure colours on the proof, comparing densities across processes makes no sense.

When multi density inks are involved, dot area comparisons between proof and print become meaningless. Moreover, there is no longer a simple one-to-one correspondence between the visual quantities and densities. E.g. a patch of light ink compared to a patch of heavy ink can yield the same density value but a significantly different lightness (and vice versa). The visual correspondence is to be found more important than the densitometric one.

We summarise that the traditional practice of using densitometric measurements makes sense on the press, but should not be transferred to proofing on inkjet printers. Here the most important aspect is the *visual* matching, so visual quantities are the best choices. We use CIELab lightness for cyan, magenta and black ink. Chroma is used for yellow ink because the lightness range between paper white and solid yellow is too small.

2.4. Ink Limitation

The term *ink limitation* can refer to two different concepts. Total ink limitations, governing the amount of all inks together, belong to colour profile making. Ink limitations on individual inks are part of calibration and can serve a double goal. The first goal is that of calibration: ensuring that the printer is in a standard condition. Printing a solid at the maximum level of ink should yield a fixed result. This can be obtained by adjusting the maximal percentage of ink. Apart from this, the maximum useful or wanted ink percentage is often less than 100%. Reducing the percentage as such becomes the second goal of ink limitation, as it is convenient to incorporate this into the calibration.

The calibration function C can map the input range to the full ink range $[0, 100]$. It is however often preferred to map to a smaller range. The starting point is kept at zero ink percentage $p_0 = C(0) = 0$. This point is also visually stable as long as the paper does not change. If the end point is held to a fixed percentage $p_{100} = C(100)$, the measured quantity will vary as:

$$m(p_{100}) = M(p_{100}) + \mu(p_{100}) \tag{3}$$

The variability of the printing and measuring processes is described by $\mu(p_{100})$. If we want to achieve a fixed measured (visual) endpoint m_{100} we have to replace the fixed p_{100} by a calibrated p_{100}^C:

$$p_{100}^C = M^{-1}(m_{100}) = p_{100} + \pi(m_{100}) \tag{4}$$

Since the maximum amount of ink is limited:

$$p_{100} + \pi(m_{100}) = p_{100}^C \leq 100\% \tag{5}$$

m_{100} should be chosen in such a way that p_{100}^C is always sufficiently smaller than 100%.

2.5. Regularisation and Linearisation

While the printed output for the maximum amount of ink is already fixed by the ink limitation, the tonal behaviour for all intermediate values can still vary. This can be resolved by regularisation. This is the construction of a calibration function C that establishes a fixed correspondence F between the image data i and the measured quantity m:

$$m = F(i) \tag{6}$$

Because $m = M(p) = M(C(i))$, we can write:

$$F(i) = M(C(i)) \tag{7}$$

For a given F, C has to satisfy the condition:

$$C = M^{-1}F \tag{8}$$

because then:

$$m = M(C(i)) = M(M^{-1}F(i)) = F(i) \tag{9}$$

This can only be achieved if M is invertible which in turn requires M to be strictly monotone. since M contains the variability of the printing and measurement processes. C is recalculated with every calibration.

The correspondence F can be freely chosen. A typical example is to regularise a printing process so that it emulates the dot gain behaviour of a printing standard, which is generally different from that of the process itself.

In most cases F is chosen as the identical function, so that the correspondence $i = m$ results. For this case, regularisation reduces to linearisation. There are distinct advantages to having a linear correspondence, e.g. regarding stability and optimal use of available levels. Because this special case is so widely used, the term linearisation has become the common term for the more general regularisation process.

In practice, calibration is performed by printing out and measuring a set of ink percentage values, while using an identity transform for C. The relationship $m = M(p)$ is then established by constructing an interpolating or fitting fuction through the measured data.

3. Multi Density Inks

3.1. Objective

Many modern inkjet printers extend their ink set beyond CMYK and include extra inks. These can be different coloured inks e.g. a green or orange ink, which result in a wider gamut. In most cases however an additional light cyan and light magenta ink are used. The main purpose is then to improve the apparent resolution. The light ink is used in the highlights, creating less visible dots. Heavy ink is used in the shadows, keeping total ink use low.

3.2. Methodology: Ink Mixing

A traditional separation into CMYK does not suffice for printing with multi density inks [2]. The most general solution would be to make a separation to the colours of all inks. There are however important disadvantages to this method. The complexity of the separation technique grows enormously with an increasing number of colour planes. Moreover, current separation techniques do not always work well when planes with very similar colours are used together. Compatibility issues with existing standards and software also hinder the use of solutions that radically break with CMYK separations.

There exists however a much simpler practical solution for using multidensity inks: *ink mixing*. It exploits the presence of pairs of very similarly coloured inks and does not suffer from the forementioned problems. It introduces multidensity inks in a postprocessing stage to a normal CMYK separation [3]. In this stage ink percentages of cyan or magenta are mapped to percentages of light and heavy ink by a mapping function $\vec{S}$.

We extend the calibration model to accomodate for the use of multiple inks per colour. Eq. 1 is replaced by:

$$i \overset{\vec{C}}{\to} \vec{p} = \vec{C}(i) \tag{10}$$

Now $\vec{p}$ is the vector with as components the percentages of the different inks. $\vec{C}$ necessarily becomes a vector valued function with the same dimension as $\vec{p}$. We can decompose $\vec{C}$ into a scalar calibration function C, followed by the vector valued mapping function $\vec{S}$:

$$\vec{C} = \vec{S}C \tag{11}$$

$\vec{S}$ needs to fulfill some basic requirements. The objective of increasing the apparent resolution is the first concern. Therefore the highlights will always be mapped onto light ink only. The light dots contrast less with the background, resulting in a smoother appearance. On the other hand, the shadows must be mapped to heavy ink as this allows a darker, more saturated appearance with less ink use.

It still needs to be determined how to make the transition between the inks. Several criteria for this have been identified in [1]. The key concern is to avoid creating artefacts. Foremost, smooth transitions must be pursued so that colour gradations in vignettes appear impeccable.

Other artefacts are caused by too large amounts of ink. Using less light ink is the solution to this, so inevitably a trade-off needs to be made. At least it should be avoided to have the sum of light and heavy ink exceed 100 %. This is very undesirable since then heavy and light dots inevitably are placed on top of each other, creating extra dark dots that increase the local contrast and noisiness. It could be considered only when 100% of heavy ink still yields a too light colour. This situation would however preferrably be solved by using a different (heavier) ink.

3.3. Calibrated Ink Mixing

A key characteristic of existing ink mixing solutions is that they define the mapping in a fixed way, independent of the calibration. This means $\vec{S}$ is is kept fixed and only C is adapted during calibration. Various proprietary solutions are used for determining $\vec{S}$. The ink mixing is most often transparant to the user, or at most a global control of the amount of light ink is offered.

The mapping is usually empirically optimised for a certain condition of the printer. However, the behaviour of the printer can vary over time and the variations can be different for light and heavy inks. A calibration acting only on CMYK inks cannot compensate for this in an accurate way. The incomplete compensation results in an ink mixing that is no longer optimal.

This effect can be easily appreciated from following example. Assume that for a particular printer, the best ink mixing trade-off is obtained when the heavy ink starts at 50% (corresponding to a lightness $L = 60$). This *optimal* inksplit is fixed. Later on the printer (now printing somewhat lighter) is calibrated again. Now the $L = 60$ is translated to 58% ink. Still, the heavy ink will start at 50%, which now corresponds to $L = 65$. The calibration procedure results in a correctly linearised printer, but now the heavy ink starts at a lighter tone. This appearance of the first heavy dots at different points can have a very obvious effect on the appearance of printed output.

We propose to replace the fixed ink mixing by a *calibrated ink mixing* in which $\vec{S}$ is adapted by the calibration. For this the ink mixing characteristics (when and how to start and end with the different inks) are defined in measured quantities. Calibrated ink mixing allows to maintain a visually optimal ink mixing, also when the conditions of the printer vary. It requires different combinations of light and heavy ink to be included in the calibration target.

In the example, the heavy ink is set to start at $L = 60$. In the later calibration, this is conserved and yields an unchanged visual effect (using a different ink percentage).

3.4. Multiple Linearisation

In the extended calibration model the condition for the calibration function becomes:

$$m = M(\vec{p}) = M(\vec{C}(i)) = M(\vec{S}(C(i))) \tag{12}$$

For a fixed $\vec{S}$ the ink mixing can be regarded as being part of the internal printing process, the combined scalar function $M\vec{S}$ then acts as measurement function. Starting from eq. 6, the calibration function is still uniquely defined:

$$C = (M\vec{S})^{-1}F \tag{13}$$

In general, both $\vec{S}$ and C parts are variable and must be adapted during calibration. The calibration is then no longer uniquely defined by a single scalar measurement m because different $\vec{p}$ (combinations of the different inks) can yield the same m.

To resolve this, extra conditions can be put by replacing M by a vector valued measurement function $\vec{M}$, containing several measurable quantities. If the dimensions of $\vec{C}$ and $\vec{M}$ match and the components of $\vec{M}$ are independent, C is again completely determined.

A serious practical problem still remains. For linearisation with with respect to more than one variable the measured values $\vec{m}$ cannot be ordered in a 1D series. Without this, it is not straightforward how the linearisation should be performed.

We propose a solution in which a hierarchy of linearisation variables is chosen. The main advantage of this method is that the linearisation can be perfect with respect to the primary variable, exactly as for single density inks.

Alternative solutions could be constructed for which the variables could be a priori equally important. We did not pursue this option because it cannot garantuee any exact linearisation. This shortcoming could cause quality issues far greater than the expected advantages over simple 1D linearisation.

The proposed multiple linearisation method works as follows: Linearisation is carried out in the usual manner for the primary variable: ink increments are computed that correspond to equal increments or decrements in the measured variable. The difference with single density linearisation is that for a measured value, there now generally exist a set of different solutions, corresponding with various ratios of light and heavy ink. From the set of solutions, that one is chosen that best approximates linearity with respect to the secondary variable. The result will be exactly linear for the primary variable, and linear to the extent possible for the secondary variable.

Of course the secondary variable is only used for that part of the range where both ink types are used simultaneously, which is normally not the case for the whole range (there are no heavy dots in the highlights).

3.5. Choosing multiple linearisation quantities

The primary linearisation variable can be chosen with entirely the same reasoning as for single density inks. For inkjet proofing, CIELab quantities are still preferred. The choice of a secondary linearisation variable is more subtle. It needs to be carefully considered in order to be able to realise a distinct advantage, given the often limited freedom coming from the multi density inks.

A promising approach is to try constructing a calibration that results in more uniform CIELab ΔE steps. For a pair of magenta inks (light and heavy), the range of b is much smaller than that of L and a. This indicates that the b component contributes much less to the ΔE. By choosing the linearisation variable pair: $\vec{M} = (L, a)$, the linearisation remains exact for L, but the more linear behaviour for a yields more evenly spaced visual steps at the same time. For cyan inks, the pair $\vec{M} = (L, b)$ has similar properties.

A different approach could establish a closer link between densitometric and colorimetric calibration by choosing density as a secondary variable, complementing lightness as primary variable.

4. Experimental Data

4.1. Introduction

Experimental results on the properties of multi density inks are scarse. In [2] spectral reflectance curves are studied for light and heavy inks. It was observed that while significant changes occur with varying the amount of ink, the curves for light and heavy ink are comparable at the same lightness level. This can be expected if the inks only differ by the concentration of dye or pigment. True ink mixing, the simultaneous use of light and heavy ink, was not considered.

We now present new experimental data that complements the previous sections. We concentrate on the common case of pairs of light and heavy ink. For this we can easily illustrate some of the colour effects associated with the use of multi density inks. It also allows to give an instructive geometrical description of the calibration and to clarify the method of multiple linearisation.

We present results for magenta, those for cyan are similar and are omitted for brevity. We printed a series of patches on an Agfa Sherpa 43 printer, using high quality proofing paper. The Sherpa 43 uses (CcMmYK) inks so light and heavy cyan and magenta are present. All possible combinations of ink (in 6.67% increments) were used.

4.2. Geometrical interpretation for single density inks

With a single ink a 1D trajectory is described in the 3D colour space by varying the ink percentage. Two typical ink trajectories are shown in fig. 1 and 4.

Linearisation means dividing the trajectory into steps that correspond to an equal increment (decrement) in a measured variable v. For a constant value v_1, we have to look for the intersection of the plane $v = v_1$ with the trajectory. Within the achievable range, the intersection contains a single point if v is monotone. If there are multiple points, the variable v is either poorly chosen (not monotone), or measurement noise is dominating the results. Besides a careful choice for v, it is often useful or even necessary to set ink limitations in order to cut off areas that cause problems in linearisation.

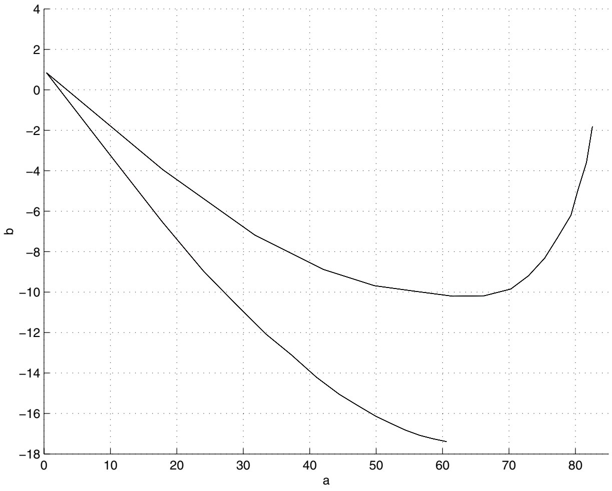

Figure 1: Trajectory of two inks: projection on the (a,b) plane.

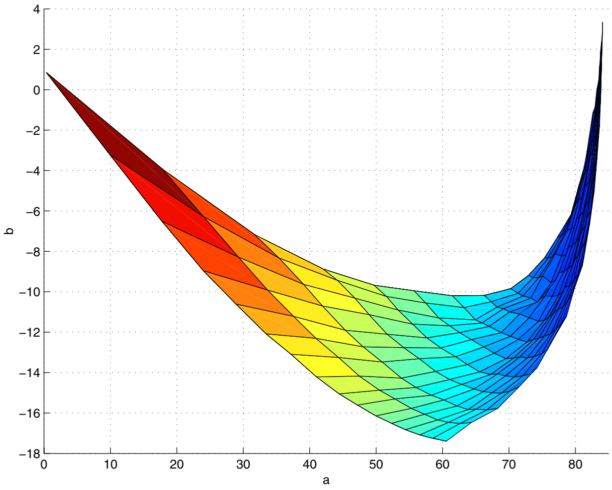

Figure 2: Surface spanned by light and heavy magenta ink: projection on the (a,b) plane.

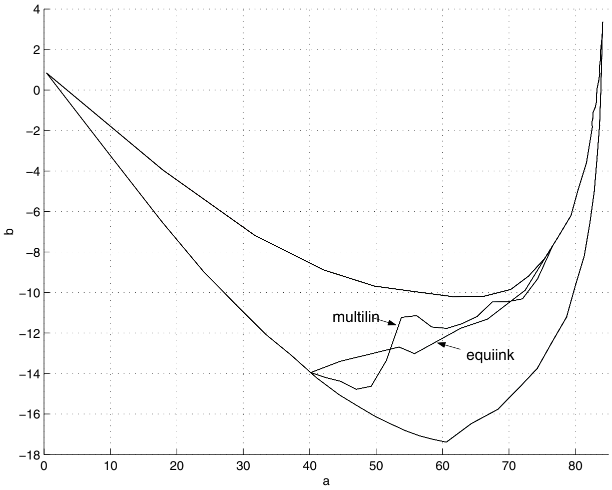

Figure 3: Ink mixing paths: equiink vs. multilin with (L, a).

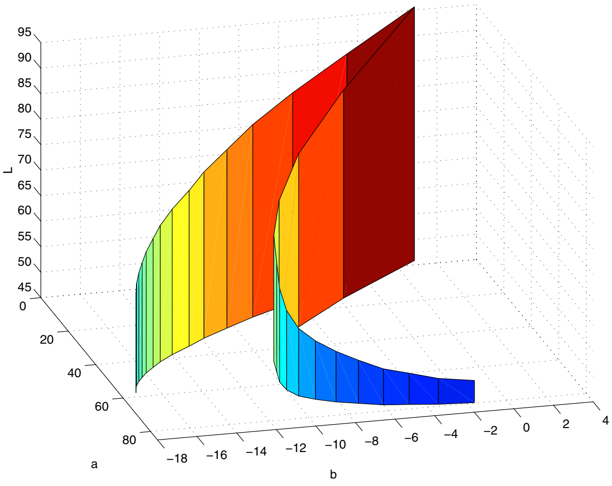

Figure 4: 3D view of fig. 1.

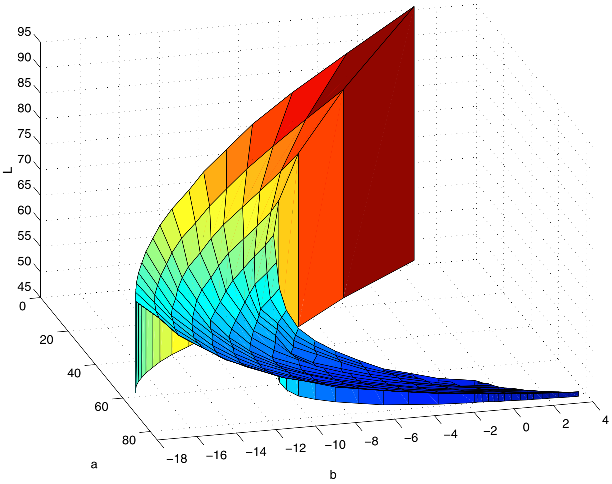

Figure 5: 3D view of fig. 2.

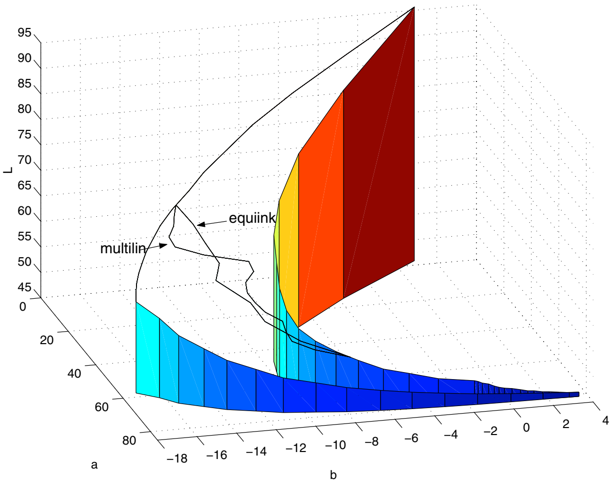

Figure 6: 3D view of fig. 3.

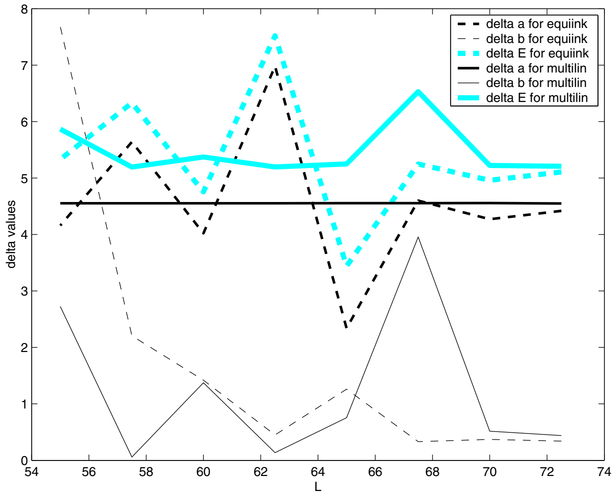

Figure 7: *Steps in Δa, Δb and ΔE corresponding with equal ΔL steps. Solid lines for equiink, dashed lines for multilin.*

In fig. 1 it is clear that for the lower trajectory, both a or b would make a good choice as linearisation variable. For the upper trajectory, b would be unsuitable unless ink limitations would make the curve end somewhere halfway.

4.3. Geometrical interpretation for multi density inks

The upper and lower curves on fig. 1 are in fact the trajectories of heavy and light magenta ink respectively. They describe distinct trajectories in the colour space, differing not only in lightness but also in colour. By taking both inks in all mixtures, a surface is spanned within the colour space. We plot the complete surface in figs. 2 and 5.

With a single linearisation variable, the intersection of the plane $v = v_1$ with the surface generally is a line segment. Within the line segment, the position (mixture of light and heavy ink) can be freely chosen. The underdetermination can be resolved by choosing a secondary linearisation variable. This is the key point of multiple linearisation.

4.4. Calibrated ink mixing for magenta

We now show paths generated by calibrated ink mixing. We start from paper white using only light ink until $L = 75$ is reached. Then both light and heavy ink can be used until the end point of $L = 55$, which is realised with only heavy ink. The points $L = 75$ and $L = 55$, created with a single ink, are calibrated.

The path inbetween is generated using two different methods. In the first method, a transition with equal ink percentage steps between begin and endpoints is imposed (equiink). The second method is multiple linearisation (multilin). The pair (L, a) is used as linearisation variables since it was found advantageous in sect. 3.5.

In figs. 3 and 6 paths are shown for the two methods. The path of the first method seems more regular. It must be noted that the scale on the b axis is different, so the irregularities in b appear comparatively larger.

We now study the results in a different way, by investigating the visual differences caused by equal steps in lightness. The results for steps of $2.5L$ units are shown in fig. 7. For the first method, the variation of a drastically changes, while it is constant in the second method. The b differences are irregular but small and as a result the second method yields much more uniform ΔE steps.

We quantify this by calculating the variance of the ΔE steps. For the first method, the variance is 1.18, for the second it is 0.48. The variance is reduced with more than a factor of two. This proves the capability of the method in producing more visually uniform calibrations. This can be important for printing smoother and more stable vignettes with less visual artefacts.

5. Conclusion

A framework for printer calibration was introduced. Ink limitation and linearisation are the main components needed to ensure a consistent tonal behaviour. The calibration is done with respect to measured visual quantities.

We elaborated on calibration for multi density inks. We first proposed to move away from fixed ink mixing in favour of a calibrated ink mixing that is part of the calibration. The advantage is that visual consistency is improved since the effects related to the use of different ink densities are also controlled.

Secondly, we extended the framework to make it possible to linearise with respect to more than one variable. We introduced the method of multiple linearisation, which allows to make the output linear with respect to more than one variable. The potential of the method was shown in an experiment, where the secondary linearisation significantly improved the visual uniformity of the output.

The general conclusion is that for multi density inks it is important to take special care in the calibration in order to precisely control ink mixing behaviour.

References

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