THE HUMAN VISUAL RESPONSE OF STOCHASTIC SCREENS

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Abstract: The finite resolution of the human visual system should be taken into account when assessing the performance of different printing technologies. In binary image printing the result should be evaluated with respect to the characteristics of the observer and the viewing conditions. So far, much of the interest in this area has been focused on low-end printers with a resolution of typically 300 dpi. In this resolution range artefacts are still a serious problem. This paper aims at establishing the printing resolution range that balances the problem of artefacts and the requirement of printing small dots. The results are based on a model for the modulation transition function of the visual system and the notion of just noticeable colour difference.

Introduction

The rendering of grey levels with a binary printing process relies mainly on an emulation of the characteristics of conventional optical screens. The illusion of grey is created by fragmenting the image into dots whose area is modulated in accordance with the desired grey level. Contrary to this, the emerging technology of stochastic screening does not use a regular tessellation of modulated dots. Instead the screen is made up by uniformly sized small dots whose frequency of occurrence is modulated according to the grey level of the image, (Floyd,1976). Hence the techniques are, somewhat inappropriately, often referred to as AM- and FM-modulation respectively. An intermediate method using a threshold matrix approach was early studied for low-end printing or display purposes and Bayer (1973) showed how to disperse dots optimally. Kruse (1993) suggests a classification of the various forms of halftoning methods.

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The problems of rendering images are very apparent in dealing with low resolution printing processes. The ability to reproduce a wide range of grey levels with conventional digital methods requires the dots to be large in the sense that they have to be formed by a large number of elementary dots. With N dots, N+1 linearly spaced levels of grey can be reproduced. To be able to produce, say one hundred levels, the size of the halftoning cell has to be on the order of 10 by 10 elementary dots. With a resolution of 300 dpi this corresponds to a screen ruling on the order of 1 cycle per mm and a rather coarse reproduction results. It is evident that there exists a trade-off between the requirements of the basic dot size and the number of reproducible tone values.

The inherent ability to print with better edge rendition favours stochastic screening in this trade-off. The pseudo randomised distribution of elementary dots can easily be tuned to make reproduction of details better. From this argument it is also clear that the human visual system sets a limit on dot size, beyond which there is no apparent quality improvement.

The formulation of the screening problem may be put in several different ways. A basic requirement, common to all solutions, is that the local deviation of the reproduction from the original should be kept at a minimum. One parameter can immediately be identified as the "locality". Since the reproduction technique employs a small discrete set of colours, 2 in case of monochrome, the locality cannot be made too small. Usually the different techniques employ some form of "error diffusion" or "error propagation" method to spread the errors over a substantially larger area than the individual dot itself (Floyd,1976, Jarvis, 1976b and Knuth, 1987). The properties of the human visual system can be taken advantage of in several ways to relax the requirements on local agreement. The edges, for example, can be made to appear better by rearranging the basic dots close to the edge, since the sensitivity of the eye to variations in grey levels is much lower in highly textured areas than it is in uniform areas. One approach to this has been demonstrated by Hammerin and Kruse (1994). In mathematical terms the integral

$$\int_{x \subseteq A} (p(x) - S(p(x)))dx \qquad (1)$$

where $p(x)$ is the original image and $S(p(x))$ is its digital halftoned counterpart, should be kept as small as possible for all A. With the point spread function $h(x)$ of the human visual system the actual form of the integral becomes

$$\int_{x \subseteq A} h(x) * (p(x) - S(p(x)))dx \qquad (2)$$

At macroscopic scales the simple methods produce artefacts in the form of "worm like" patterns that can be very disturbing to the eye. The higher the resolution is the less of a problem these artefacts become, however. Normally the specific colour plays an important role in this context. The black channel may produce very disturbing artefacts while the same type of patterns are barely visible in yellow.

Efforts to reduce the artefacts have been made by many authors, for example (Sullivan, 1991, Ulichney, 1987 and 1993, Flohr, 1993, Scheermesser, 1993, Mitsa, 1993). The problem has also been analysed theoretically by for example by Knox (1993). Several authors have approached the problem of quality using a model for the human visual system, (Flohr, 1993 and Lin, 1993).

Due to the low pass filtering characteristics of the human visual system - the convolution kernel in (2) is essentially of low pass character - the artefacts are of no importance beyond a certain resolution. To find that resolution limit is the issue of this paper.

The modulation transfer function of the human visual system

In this paper we adopt a model of the human visual system based on Mannos (1974). This model characterises the spatial frequency response of the human eye. It has also been used by Mitsa (1992) and a slight modification of it has been suggested by Sullivan (1993). For this paper we will use the model of Sullivan.

The actual model describes the response of the eye to sinusoidal patterns in terms of cycles per degree. The response is equal to one, up to approximately 8 cycles/degree after which it decreases rapidly as the wavelength of the ondulating patterns diminishes. The model also takes into account the varying sensitivity to the angular orientation of the sinusoidals. For a given wavelength the sensitivity is maximum for horizontally and vertically oriented patterns whereas it is smallest for the diagonal orientations.

In order to use the model the distance to the observer has to be set. We will adopt the same conditions that have been used in Sullivan (1993) with a viewing distance of approximately 250 mm (ten inches).

Colorimetric variation

The difference between the original and the halftoned image also manifests itself as colour variations. The rendition is very sensitive to the resolution and the viewing distance. The farther away the observer is the less variation is noticed since the impression of the actual colour dots is integrated optically in the eye.

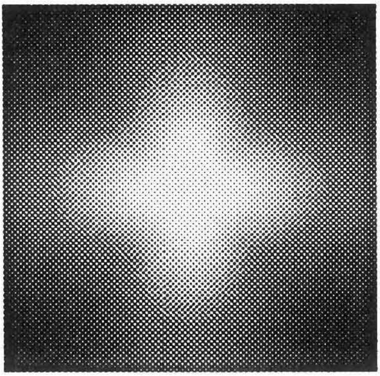

Figure 1. The modulation transfer function of the human eye. The transfer is equal to unity (white) for low frequencies in the centre of the spectrum image. It decreases continuously towards zero (black) for higher frequencies. The approach to zero is more rapid in the diagonal directions

Colour difference is measured by the difference in physical reflectance. This is usually computed as the Euclidean distance between the colour co-ordinates in some colour space. In this context we will use the CIELAB colour space from 1976, (Hunt, 1991). The colour difference is expressed as:

$$\Delta E_{ab} = \sqrt{\left(\Delta L^*\right)^2 + \left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2} \qquad (3)$$

where L^*, a^* and b^* are the co-ordinates of the space. The colour space is a non-linear derivation of the original CIEXYZ colour space from the 1930's.

The measure of colour difference has been modified to account for variations in sensitivity of the human eye depending on the position in the space. The CMC colour difference formula in Hunt (1991) gives a measure of difference in the CIELAB space for small colour differences that has been shown to give better correlation to the appearance than the simple formula (3).

All colour difference formulae are valid for small differences in colour only. Moreover they have been established under the assumption that fairly large colour patches are available for comparison. The standard observers in the CIE-standard refer to situations where the size of the matching colour samples extends over 2 and 10 degrees respectively. Under normal viewing conditions this corresponds to a coloured patch of between approximately 3 to 20 square cm respectively. Despite these drawbacks we will use the formulae in lack of something better.

The point where the colorimetric variance between the difference of the original continuous tone image and its stochastic representation falls below the level of one ΔE unit there is definitely no point in increasing the resolution further. Actually the difference may be much larger than that because of the afore-mentioned conditions that the unit colour difference applies. In the majority of cases the reproduced images are real and therefore we may not anticipate large homogeneous areas without structure. Since structure in the image reduces the possibilities for us as humans to discriminate between different colours, the limit that we will find using the variance of CMC colour difference as a measure is too conservative. We should bear in mind that under normal conditions with structure in the image the allowable size of the colour variation may extend to several ΔE.

Experiment

In the experiment two images have been used, one monochrome and one colour image. We have calculated the transfer function of the human eye with respect to the viewing conditions and applied it to the original and its stochastic representation according to the following notation:

$$\begin{aligned} \overline{T_O} &\xleftarrow{RGB-Lab} \overline{F^{-1}(mtf \cdot F(P))} \\ \overline{T_S} &\xleftarrow{RGB-Lab} \overline{F^{-1}(mtf \cdot F(S))} \end{aligned} \qquad (4)$$

$$\overline{\Delta L^* a^* b^*} = \overline{T_O} - \overline{T_S} \qquad (5)$$

where P and S are the original and the stochastic images in RGB-space respectively, T_O and T_S are the filtered results of P and S respectively in LAB-space and F is the Fourier transform and *mtf* the modulation transfer function. The co-ordinates of the original and the difference are both converted into L*a*b* space where its CMC(1:1)-value is computed for each pixel position.

This has been repeated varying the basic dot resolution so that a series of measurements that describe the difference under different printing resolutions have been acquired. In the measurements we have included both the standard deviation and the difference between the maximum and minimum of the CMC colour difference respectively. Figures 4 and 5 show the colour difference as a function of the resolution. The large CMC-values should not be taken too seriously since it is questionable if the conditions for using the CMC-formula are valid. However, for the range of values that we are interested in, close to one unit, they certainly are valid.

Figure 2. The original image and its stochastic representation as viewed from a distance 254 mm using a resolution of 12 dots/mm.

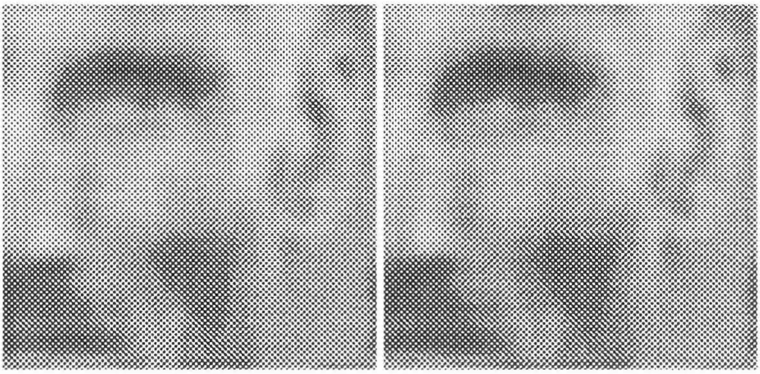

Figure 3. The original image and its stochastic representation as viewed from a distance 254 mm using a resolution of 95 dots/mm

Conclusions

From the experiments one can conclude that the resolution of the basic dot in stochastic screens need not be higher than around 40 to 50 dots/mm which corresponds to about 1000 dpi. If it is kept above that threshold the standard deviation of the colour difference is around one unit.

$$CMC \approx 1 \qquad (6)$$

This means that the colour difference is just noticeable under proper viewing conditions. Since the CMC colour difference formula is valid only for fairly large

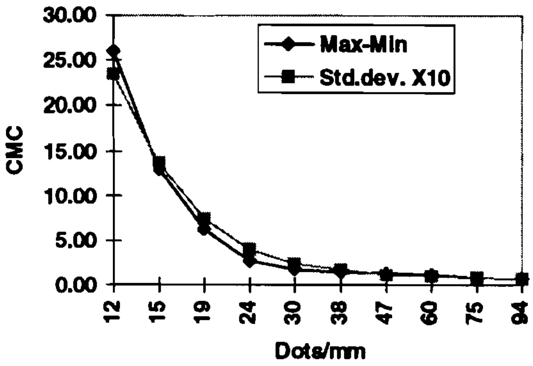

Figure 4. The standard deviation and max-min CMC colour difference for the monochrome image in Figure 2 displayed as a function of the resolution

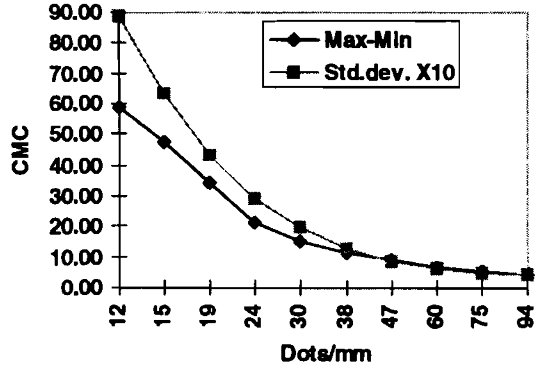

Figure 5 The standard deviation and max-min CMC colour difference for a colour image (part of the musicians image) displayed as a function of the resolution

colour patches and not for small scale structure it is also probable that the limit we have computed from the known models is too conservative. The resolution limit could very well be somewhat lower still. The resolution levels used in high quality printing may therefore not be needed using stochastic screening. In practice the results may be somewhat different due to other factors but from the point of view of the human perception the resolutions used to-day seems to be unnecessarily high. Needless to say this can have a great impact on both processing time and disk storage volume.

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