QUALITY IN DIGITAL PRINTING REPRODUCTION

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ABSTRACT

The paper is concerned with image quality measures which have applications in digital reproduction. These include the bandwidth of the image signal, called the gamut, and measures based on linear systems theory and information theory. The sensitivity of the quality parameters to variation in imaging performance is documented. This, taken together with the types of parameters, allows the assessment of the applicability of the different measures as criteria in restoration and enhancement, in digitalization and screening and in the prediction of process performance.

INTRODUCTION

Image quality is, generally speaking, determined by the suitability of an image to its purpose. In the case of printed images it is thus the visual quality which represents the ultimate criterion. The control of reproduction processes is, however, increasingly based on physically measured image properties. This is a consequence of the digitalization of the processes and the concurrent automation of the quality control operations. These trends make it important to know how visual quality and physically measured properties of images are correlated. Understanding of the relationships is still deficient.

The changing reproduction processes also set new demands on the physically measured image properties - the subject matter of this paper. Both the character of the image signal and the methods by which it is processed are completely different for digital and photomechanical reproduction. In addition to representing the density variations of the image signal, a digital image signal also has the character of data. Process efficiency requires that the information content of the signal be transferred to the print with minimal losses.

Although digital image processing has been studied extensively for a quarter of a century, the algorithms used in digital printing reproduction have not often been discussed with consideration of the extended possibilities which digital processing offers; the freedom in the choice of the type of the algorithms and their criteria is virtually limitless.

In the case of image restoration and enhancement, image formation mechanisms in the analog steps of the process (e.g. photography and printing) provide a basis for the algorithms. In other words, the algorithms utilize models of image distortions as they arise in analog imaging and carry out reverse operations to compensate for the distortions /1/. The compensation becomes reproduced in the output image within the performance bandwidth. This implies that the bandwidth should be taken into account in algorithm development.

In a posteriori restoration and enhancement, as for instance of photographs, noise in the image acts as a constraining factor to the strength of the operations. The role of noise in a priori restoration and enhancement is the opposite; with an increase in the level of noise, the needs of restoration and enhancement go up.

Digitalization and screening limit the bandwidth of the image signal. The choice of the digitalization and screening parameters is made according to the target level of image quality. Yet it is the bandwidth of the output image which ultimately determines what the level of quality becomes.

Summarizing, the demands which image quality measures used in digital reproduction should meet can be stated as follows:

— the measure should define the magnitude of information in the image signal and
— the measure should make it possible to predict mathematically the input-output relationship in an imaging process.

IMAGE MEASURES

An image can be considered to be a two-dimensional realization of the image signal. It can be defined in terms of the darkness D which is a function of the spatial coordinates x and y:

$$D = f(x,y) \tag{1}$$

The reproduction of the image in different process steps is defined by the transfer operator S( ):

$$g(x,y) = S(f(x,y)) \tag{2}$$

where f( ) and g( ) are the system input and output.

Images can be characterized in two ways which differ in principle: the quality parameters can be extracted from the image signal, or they are determined by comparing two images. Practical measures of the former type include the bandwidth, while fidelity and information measures belong to the second category.

Gamut

The bandwidth of an image signal is defined by the amplitude response and noise, both of which are functions of the spatial frequency. The bandwidth of an image signal, determined as the extreme values from the representation given by Formula 1, is called the gamut. By common definition, the concept of gamut additionally includes the term called dynamic range which expresses the amplitude response at zero frequency. The performance of an image system thus becomes defined by the following three properties:

- dynamic range,
- amplitude response and
- noise.

Each of these parameters has the units of optical density. For purposes of digital reproduction, the gamut of an analog image can be transformed to bits by computing the signal-to-noise ratio /Appendix/ from the amplitude response and noise. The gamut given in bits expresses the magnitude of data needed to digitalize the signal without a loss of information.

Fidelity

Fidelity-type measures compare two image signals by computation of the difference between the two. The two signals can be the input and the output, or any arbitrarily defined reference and the output. The term "difference" can have various interpretations.

In most cases, the same measures can be applied to express the properties of an imaging system and the gamut of the output image. Figures 1a, 1b and 1c illustrate this in the case of the gamut parameters, the dynamic range, the amplitude response and the signal-to-noise ratio.

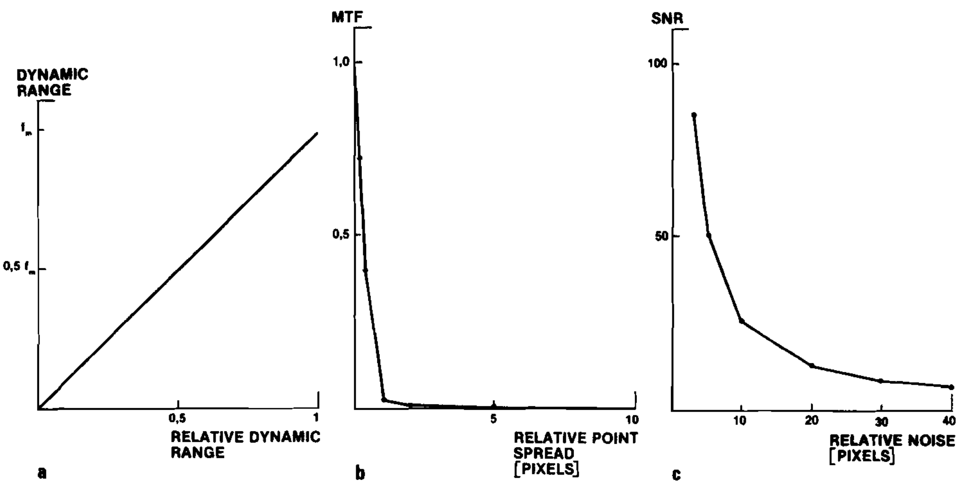

Figure 1a The dependence of output dynamic range on dynamic range transfer in the imaging process.

Figure 1b The dependence of the output MTF on point spread in the imaging process. An exponential point spread function is assumed.

Figure 1c The dependence of the output SNR on relative noise in the imaging system. A Gaussian noise distribution is assumed.

Most widely used fidelity measures are based on linear systems theory /2/. The parameters based on the theory measure the difference of two images as the ratio in the frequency plane. In a linear transfer system, output is obtained as a convolution product of input and the point spread function. This allows the input-output relationship to be given as the modulation transfer function (MTF) which can be computed from the point spread function by the Fourier transform. An analogous measure which characterizes the structure of an image signal in the frequency plane is the power spectrum.

Average pixel distortion (APD), which is mathematically defined as the root mean square difference of two images /Appendix/ expresses the difference of two images in density units. Figures 2a, 2b and 2c present average pixel distortion as a function of dynamic range, point spread and noise. Figure 4a illustrates how the pixel distortion varies from point to point with variation in the gamut parameters when the input is sinusoidal wave.

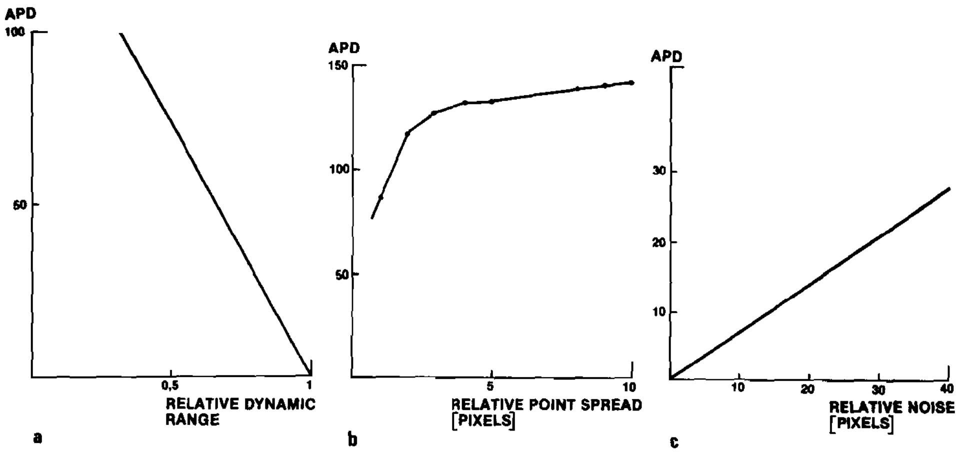

Figure 2a Average pixel distortion (APD) in an process, as a function of variation in the dynamic range.

Figure 2b Average pixel distortion (APD) in an imaging process, as a function of point spread. An exponential point spread function is assumed.

Figure 2c Average pixel distortion (APD) in an imaging process, as a function of noise. A Gaussian noise distribution is assumed.

Information

The information content of an image is determined by the distribution of darkness in the image, called density histogram (for the input p_f). It can be calculated in the units of bits/pixel from the expression for statistical entropy:

$$H_f = -\sum p_f \log_2 p_f$$

The corresponding gamut measure is obtained by maximizing over the histogram and becomes:

$$H_f \max = C = \log_2 m$$

in which m is the number of the quantization levels.

In reproduction, however, it is not only the information carried by an image which is of interest, but also - and more importantly - the information transferred from an original to the print. The gamut measure of information in the output is an indication of the number of correctly distinguished tones /6/. It can be computed from the SNR ratio.

Consistent with Shannon's /9/ information theory, average mutual information (AMI) is a measure of the transfer of information from the input to the output in bits/pixel:

$$AMI = \sum_g \sum_f p_f \, p_{g/f} \, \log_2(p_{g/f}/p_g)$$

The authors /5/ have recently made an extension and defined AMI to be a function of the spatial frequency. This extension allows computation of the transfer in the units of bits per unit area.

Figures 3a, 3b and 3c show how the information transfer is influenced by a change in the gamut parameters between the input and the output. The distribution of the mutual information is illustrated in Fig. 4b when the input is sinusoidal.

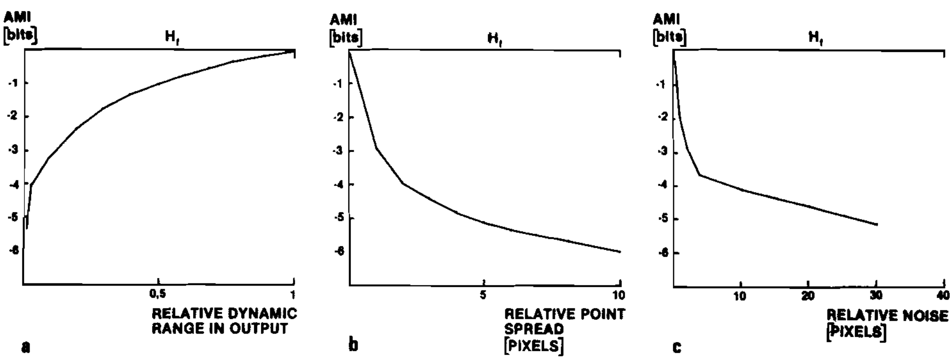

Figure 3a The dependence of average mutual information (AMI) in an imaging process with variation in dynamic range.

Figure 3b The dependence of average mutual information (AMI) on point spread in an imaging process. An exponential point spread function is assumed.

Figure 3c The dependence of average mutual information (AMI) on noise in an imaging process. A Gaussian noise distribution is assumed.

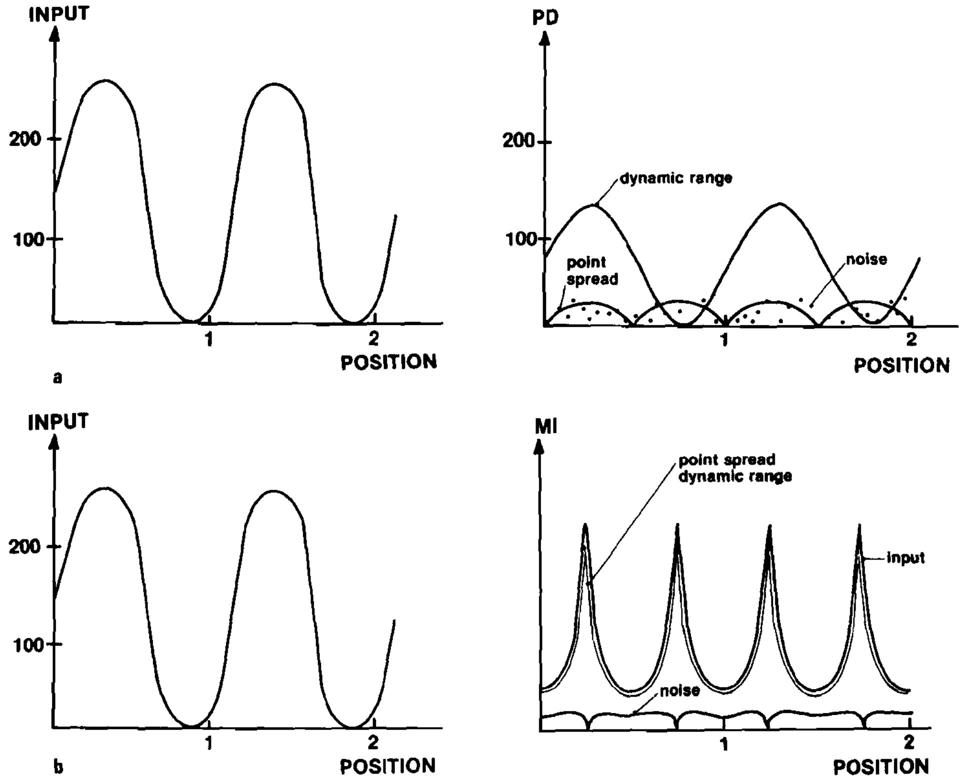

Figure 4a The influence of gamut parameters on pixel distortion. The input is sinusoidal.

Figure 4b The influence of gamut parameters on mutual information. The input is sinusoidal.

DISCUSSION

In digital image reproduction, knowledge of the quality measures is required for different purposes: for the prediction of process performance, for restoration and enhancement algorithms and for the choice of the digitalization and screening parameters. These uses require different behaviour from the quality measures. Application of the different quality parameters will be outlined below.

Performance of an imaging process

The performance of an imaging process is predicted by the bandwidth which is measureable from the output image. This implies that dynamic range, point spread and noise provide a characterization of the quality potential of a process.

In current printing reproduction, the original image is still most often a photograph. A considerable loss of gamut takes place between originals and prints, as is illustrated in Figure 5. The gamut parameters of the print provide criteria for the choice of the digitalization parameters, viz. the sampling frequency and the quntization levels. If the digitalization parameters are selected in an optimum way with respect to the output, eventual differences in the gamut will be compensated.

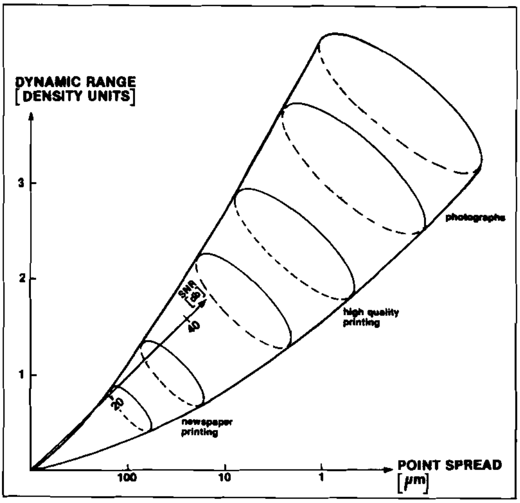

Figure 5 Examples of gamut parameters expressed as the dynamic range, the point spread and the signal-to-noise ratio /7, 8/.

Digitalization and screening

Digitalization and screening act in the spatial domain as low-pass filters. The filtering effect is depicted by the frequency-dependent transfer functions. The transfer functions express how the detail reproduction is attenuated at high frequencies, as a result of sampling. They also predict the aliasing effect close to the pixel frequency.

Along with detail reproduction, the rendering of the discrete density levels generated at quantization and at screening is also of interest. The distinguishability of the tones can be predicted by the signal-to-noise ratio /cf. Table 1/ as mentioned previously.

Average mutual information is a quality parameter which deals with the image signal as data. It is thus especially suited to uses which resemble coding. Such uses include digitalization and screening. AMI appears to be a useful measure for the quantification of the total influence on the quality of digitalization and screening. Information transfer is very sensitive to aliasing and noise. This suggests that it provides a useful criterion for the comparison of different screening methods /5/.

Figure 6 illustrates how digitalization and screening influence the image gamut. As for visual quality, digitalization and screening have no deteriorating influence if they cut out less of the gamut than the low-pass filtering properties of the human visual system do.

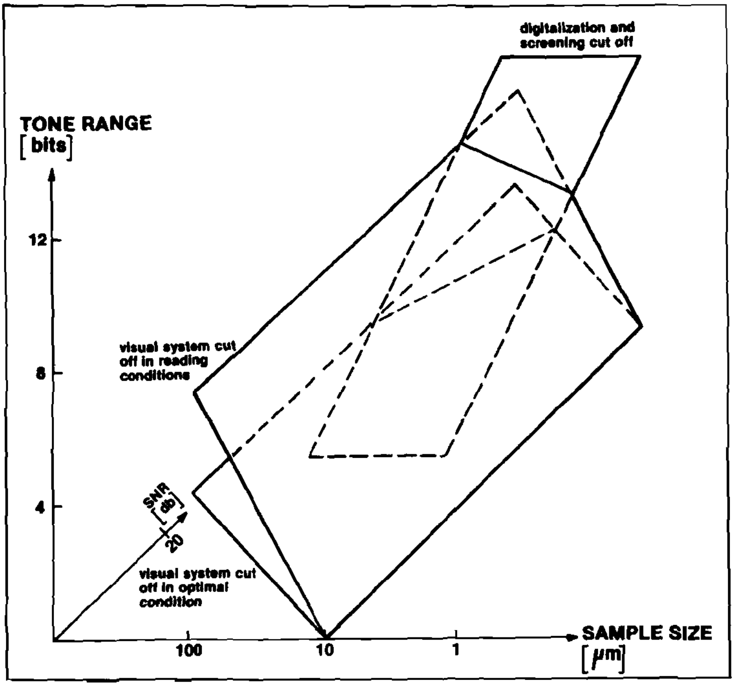

Figure 6 The influence of samling, quantization, screening and the visual system on gamut parameters /3, 4/.

Restoration and enhancement

The objective in restoration is to operate on an image so that it becomes equal to the input image. By methods of enhancement, on the other hand, the image quality is improved irrespective of the input image but with consideration of subsequent use. Once the aim of image processing has been defined, both restoration and enhancement can be carried out using the same algorithms. The image is processed to be similar to the target image or given image properties are adjusted to reach some level defined at will.
The properties which can be adjusted include:

— tone reproduction at zero frequency, as expressed by the tone rendering curve,
— detail reproduction measured as a frequency-dependent transfer function; usually expressed as the point spread function or the MTF,
— the mutual information of the two images or
— the average pixel distortion of the two images.

The input-output relationship expressed in terms of a transfer function, i.e. ratio of the two images, predicts the tone and detail reproduction. Both the darkness and the spatial information are maintained, which is why one of the three functions, the

Table 1 Quality criteria in reproduction control.

CRITERION	TYPE OF OPERATION	TARGET OF CONTROL	VARIABLES IN ALGORITHMS
$MTF\|_{u=0}$	r & e	tone reproduction	$i \& o\|_{u=0}$
MTF	r & e	deteil reproduction	$i \& o\|_u$ input spectrum
SNR	d & s	tone levels pixel size	$i \& o\|_u$
APD	r & e	i & o difference signal	i & o input histogram input spectrum
AMI	r & e d & s	tone reproduction detail reproduction tone levels pixel size	$i \& o\|_u$ input histogram input spectrum noise statistics

r & e restoration and enhancement
d & s digitalization and screening
i & o input-output relationship
u spatial frequency

input image, the transfer function or the output image can be computed when the two others are known.

Image processing which is based on the use of transfer functions, however, does not take into consideration the statistical properties of the original image signal. This is obviously one of the reasons why optimum reproduction from the standpoint of maximum visual image quality is not reached if the transfer function of the enhancement is fixed. Still transfer functions are, as is well known, widely used as criteria both in restoration and enhancement.

Mutual information is computed on the basis of the probability statistics of the transfer of an input to an output image. Complete information transfer guarantees that the signal statistics are the same for both of the images, which a constant transfer function does not. The computation of the mutual information does not utilize the spatial coordinates of the density information which are lost. This is the reason why mutual information cannot be used for the prediction of the input-output relationship. Yet it can be used as a criterion in modification of the input-output relationship as optimized in enhancement algorithms which use histogram modification.

When defined to be a function of the frequency, mutual information offers a possibility for the enhancement of the transferred information at different frequencies. As such, it is a promising but still not thoroughly proved criterion for image enhancement.

Pixel distortion /cf. Table 1/ gives expression to the absolute difference between two images. Minimizing the pixel distortion gives without doubt the best restoration result, provided the gamuts of the two images compared are equal. If the gamut is altered in the process, the computed distortion includes both the influence of the difference in the gamut and that of the signal distortion. This complicates its use.

CONCLUSIONS

The quality of images can be measured either as signal properties or as transfer properties of the imaging process. The former provide a characterization of the gamut of an image while the latter characterize the properties of the image transfer system.

The transfer-type quality measures can be relative, such as based on systems theory, probabilistic, such as based on information theory, or express the absolute difference of the two images, as distortion type measures do. All of these measures proved to be sensitive enough to changes in imaging conditions expressed in terms of the gamut parameters, the dynamic range, the impulse response and noise.

Transfer system measures, as well as information based measures, can be applied as criteria for restoration and enhancement algorithms in digital printing reproduction. Moreover, the transfer system measures allow the prediction of the input-output relationship. Quality parameters based on information theory are inherently suited to the characterization of coding type process steps such as digitalization and screening. Absolute difference measures are less applicable when the gamuts of the input and the output are different.

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Definition of quality criteria.

SYSTEMS THEORETICAL CRITERIA

dynamic range

$f_m = (f_{max} - f_{min})|_u$ — f_{max} max density at given frequency u; f_{min} min density at given frequency u

impulse response MTF

$MTF = F[h_{ij}]$ — F Fourier transform; h_{ij} point spread function

signal-to-noise ratio SNR

$SNR = (g_m/\sigma)|_u$ — σ rms noise

INFORMATION CRITERIA

average mutual information AMI

$$AMI = \sum_g \sum_f p_f \, p_{g/f} \log_2 \frac{p_{g/f}}{p_g}$$

p_f input histogram
$p_{g/f}$ probability of transfer of f (input) to g (output)
p_g output histogram

entropy at input H_f

$$H_f = -\sum p_f \log p_f$$

— **influence of dynamic range on AMI**

$$AMI = H_f + \log_2(g_m/f_m)$$

g_m dynamic range at output

— **influence of point spread on AMI**

$$AMI \geqq H_f + \sum_i h_i \log_2 h_i$$

(one dimensional)

— influece of noise on AMI

$$AMI \leq H_f + \sum_g \sum_f \frac{1}{f_m} p_n(g \cdot f) \log_2 p_n(g \cdot f)$$

p_n noise histogram

FIDELITY CRITERIA

average pixel distortion APD

$$APD = \left[\sum_g \sum_f p_f \, p_{g/f} (g \cdot f)^2 \right]^{1/2}$$

— influence of dynamic range on APD

$$APD = \frac{f_m}{\sqrt{3}} (1 \cdot g_m / f_m)$$

— influence of point spread

$$APD = f_m \left[\sum_i h_i^2/3 + \sum_k \sum_i h_i \, h_k/2 \right]^{1/2}$$

— influence of noise

$$APD = \sigma / \sqrt{2}$$