Objective Quality Measures of Halftoned Images

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Abstract

A variety of methods for halftoning images has been developed throughout the years. Some produce better results than others, and some works fine for certain kind of images but produce results of low quality for other images. However, quality of halftoned images is a rather vague concept, and has mainly been synonym to making the halftoned image look as good as possible, or as similar as possible to the original. This is of course still valid, but very subjective and hard to quantify. Without a proper objective quality measure, it is a difficult task to quantify the difference in quality of different halftoning methods or to optimize a certain method. We believe that one measure is not sufficient to reveal the quality of an image but that it is necessary to include several aspects of quality in a composite objective quality measure. This paper discusses what kind of measures that should be a part of a total objective quality measure and what requirements such measures should meet. Models for the simulation of print and the eye of an observer is also discussed.

Introduction

Defining image quality is not an easy task, and high image quality may in fact have very different meaning depending on the context in which it is discussed. The first thing to note is that the issue here is quality in *printed* images. This means that the factors that affects the image quality includes the printing method, the choice of printing media and, as we will concentrate on, the halftoning method. However, since images are meant for humans to observe, it is questionable to totally leave out the perception of images when discussing quality, and thus, this factor should also be regarded. In our opinion, image quality in this context is defined by the *perceived* difference between an original and the printed image. The problem is how to measure this difference and how to relate the measurements to a robust quality measure. The most obvious solution is to carry out a subjective experiment with a group of people. However, apart from the cost of doing such experiments, it may also be vary hard to quantify these results; what factors in the printing process did really affect the result and how should one change that factor to improve the image quality? Furthermore, there are so many parameters to change in the printing process and the combination of these are in practice too many to evaluate with subjective experiments. Therefore, we claim that objective quality measurements are of outermost importance without discarding the importance of subjective measurements; the ultimate goal is to find objective measurements that correlates well to subjective ones. Given such measures, we intend to use them to improve the halftoning methods previously developed by our group[3,12].

It is not likely to find one measure that reveals all aspects of quality, on the contrary, in the same manner as humans tend to use several scales when deciding the quality (the 'nesses', i.e. sharpness, graininess, brightness etc.), several properties of the image should be regarded and measured. It would be desirable to find what features in an image that correlates to these scales and to find robust ways to measure these. However, it is possible that measures that do not correlate well to such scales still reveals the quality of an image as long as they are consistent and rank images in the same way as humans would do. The problem of objectively measure quality have been considered by many authors[4,7,9-11]. However, the proposed solutions only reveal one, or a few, aspects of quality which in many cases are far from sufficient.

As mentioned above, we will concentrate on how the halftoning procedure affects the image quality. To isolate this factor from the others and to be able to apply the objective measurements without having to actually print anything, we intend to build a model that includes the printing media, the transfer of ink or dye to the media, the viewing distance and the eye. This will facilitate evaluation of different halftoning principles and adjustments within each principle. The idea is to use the model on both the halftoned original and on the original it self, but in the latter case, the parts of the model that relates to the printing process are omitted. The quality properties are measured on both resulting images using the different quality measurements, and the difference is used to put a value on how well the printed and perceived halftoned image describes the perceived original. At this initial stage, we consider gray scale originals only. Still, even if more complex, we believe that much of what is valid for such images is also valid for colour images.

The Model

The model for how a digital halftone is perceived when printed is a composite model which includes the printing media, the transfer of dye or ink to the media, and the eye of an observer. Since the transfer of ink also is dependent on the media, the first two parts are not independent. However, the two parts may be described with the optical effects in the media and the mechanical effects, the interaction between the media and the ink, which can be handled separately. Below, the variables that affects each part and the simplifications we have assumed are discussed. As stated above, the initial model only deals with gray scale images. If colour were to be considered, a lot of the principles of the model would still be valid but extra parts dealing with dye-on-dye phenomena, colour blending and colour perception would have to be added.

The mechanical effects in the transfer of ink

Since paper is the outermost common printing media, our initial model will not deal with anything else but paper. Still, some of the assumptions are valid for other media as well. When a halftone dot is transferred to the paper, it does not stay entirely within its bounds but spreads physically on the surface of the paper. Thus, the halftone dot becomes slightly larger than intended. The extent of this effect depends on both the properties of the ink and of the paper. The characteristics of how the halftone dot is spread on the surface is dependent on the structure of the surface, if the ink will penetrate the surface or not and so forth. This means that two halftone dots of the same size may appear very differently when printed on different positions on the same paper. Furthermore, on a microscopic scale, the edges of a dot will become very rugged and sometimes sprinkles of ink can appear around it. However, on a macroscopic scale these phenomena are hardly noticeable and the mechanical dot gain can be simulated by a filtering process without introducing significant errors. In Figure 1 a microscope image of halftone dots printed on paper is shown.

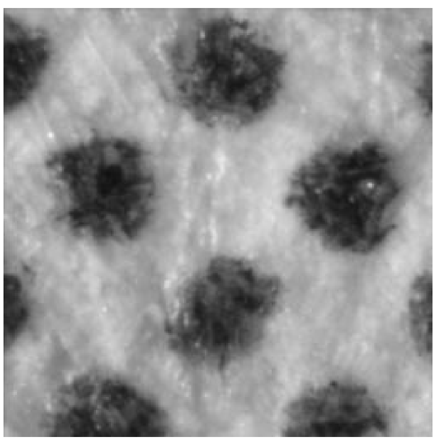

Figure 1. A microscope image of halftone dots printed on paper. The dots have rugged edges and have been spread outside their intended borders

In digital images the pixels (the smallest constituents of the image) have the shape of a square. However, for some printing methods, ink-jet for instance, the shape of the smallest producable dot is more or less circular. This is not a problem when using clustered dot techniques in the halftoning process, but for the frequency modulated halftoning this might be a problem. However, the effect of this artifact is considered to be small and we will not take this into account in our model.

The optical effects in the paper

In a microscopic scale, paper has a very complex structure. This can sometimes lead to unpredictable phenomena where light can follow the fibres and end up far from its place of incidence. Still, on a macroscopic scale, it is possible, without introducing too large errors, to model the normal scattering effects in the paper with a point spread function that describes the optical dot gain. Given the areas where the ink has been transferred to the paper, the simulation of optical dot gain is done with a convolution followed by a pixelwise multiplication with the image of the transferred ink, including the mechanical dot gain. The kernel used in the convolution is dependent on the paper and has to be measured for each type of paper.

The model that simulates the appearance when a halftoned image is printed, including both the optical and mechanical dot gain, has been published by our group at several occasions. The model is summarized in equations (1) and (2), where R(x,y) is the reflected image. For details, see for instance[5,6,14].

$$R(x, y) = I[T(x, y) * P(x, y)]T(x, y) \quad (1)$$

$$T(x, y) = 10^{-D_{max}[H(x, y) * B(x, y)]} \quad (2)$$

where H(x,y) is the halftone image, B(x,y) the kernel to simulate mechanical dot gain, D_{max} the full-tone transmissive density, I the intensity of the incident light, and P(x,y) the point spread function that simulates the scattering effects in the paper.

The digital original is assumed to have intensity values in the range from 0 to 1, where 0 is equivalent to black and 1 to white. In the model for the paper, the same notation is used. However, normal paper is often slightly coloured and seldom totally white, and even if we will not yet introduce colour into the model, the white-point of the paper could be set to something less than 1 to compensate for this.

Another effect that should be considered and modeled is gloss. Gloss can, under certain viewing conditions, totally change the impression of a printed image. For the time being, there is no adequate model for this effect but ongoing research will hopefully enable us to include this effect in to our model.

The visual system

It is well known that the eye has low-pass properties that are not uniform in all directions. The bandwidth in the vertical and horizontal directions are larger that in the diagonals. For this reason, a line in the horizontal direction is seen as sharper than the very same line in a diagonal direction. In our model we adopt the basics of the model of the human visual system based on Mannos[8] and Sullivan[13] which characterizes the spatial frequency response of the human eye. It has been proven that a modulation-transfer function (MTF) of a linear, shift-invariant system well approximates the visual response[2]. In one dimension and in the horizontal or vertical direction, this is given by[1]

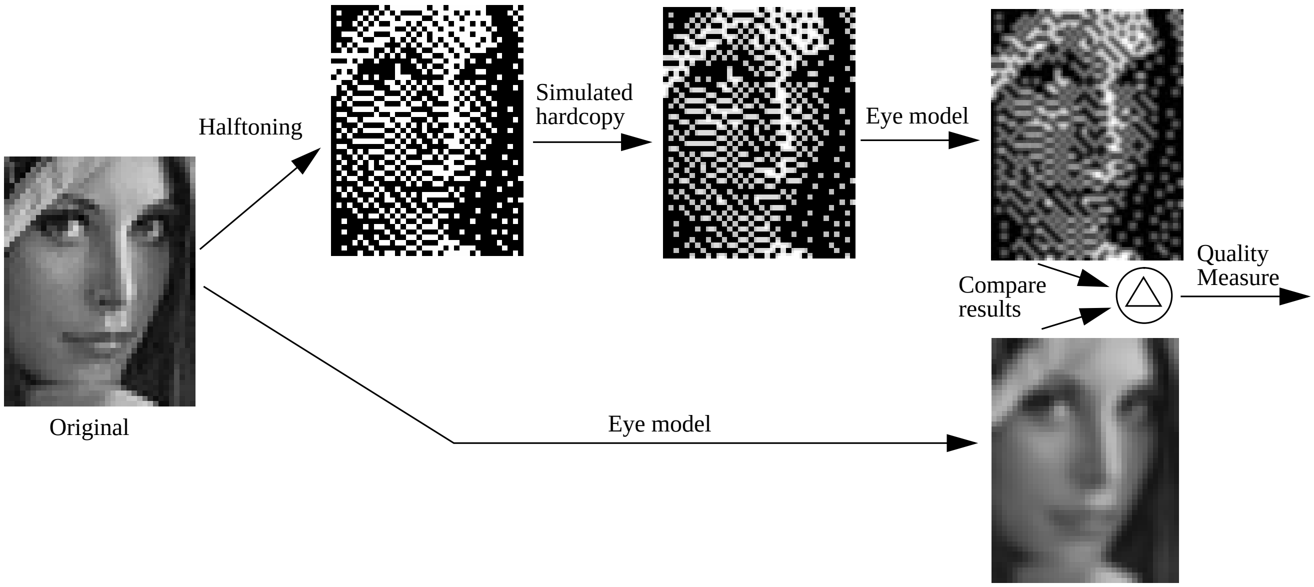

Figure 2. The principle of the model. The original is halftoned and the mechanical and optical effects when printed is added. The eye model is applied both on the original and the 'printed' image. The two results are to be evaluated by the quality measures.

$$MTF(f_v) = \begin{cases} a(b + f_v)\exp[-(cf_v)^d] & f_v \geq f_{max} \\ 1.0 & else \end{cases} \quad (3)$$

where f_v is in cycles/(visually subtended angle in degrees) and the constants a, b, c, and d are the same as used by Sullivan[13]. In two dimensions one has to compensate for the angular dependence of the eye, discussed above. The spatial frequency of the MTF is therefore scaled with an angular dependent function such that $f_v \to f_v / s(\theta)$ where

$$s(\theta) = \left(\frac{1-w}{2}\right)\cos(4\theta) + \left(\frac{1+w}{2}\right) \quad (4)$$

and the constant w is derived from experiments and set to 0.7.

The frequencies above are all given in cycles/visual degree. To be able to construct the low-pass kernel to use to simulate what an observer will be aware of, the frequency must be given in terms of image frequency, i.e. cycles/millimeter (or similar) on the document. This operation is dependent on the viewing distance and is accomplished with the geometrical-optics transformation

$$f_v = (\pi/180)\frac{1}{\operatorname{asin}[1/(1+dis^2)^{1/2}]}f_i, i = 1, \ldots N \quad (5)$$

where f_i are discrete document frequencies in cycles per millimeter given by $f_i = (i-1)/(N\Delta)$, dis is the viewing distance in millimeters, and Δ is the sample spacing on the document. A normal viewing distance is about 250 mm, however, we keep the distance as a variable for experimental reasons. Note that an increase in resolution (i.e. each halftone dot becomes smaller), is not the same thing as increasing the viewing distance since the dot gain effects, both mechanical and optical, are relatively larger in higher resolutions. When verifying the experiments with hard copies, it is possible to, by decreasing the resolution and increasing the viewing distance, simulate the effect of printing without any noticeable dot gain and without a change in percepted resolution. An illustration of the principle of the model is shown in Figure 2.

The Quality Measures

Basic requirements on the measures

It is not obvious which properties of a halftoned image are the most important from a quality aspect. Furthermore, even if we know what properties we would like to measure, it is even less obvious how to measure them. What measurable features in the halftoned image correspond to these properties and how should a measurement of such a feature be treated to give a robust judgement of the quality in the aspect of a certain property? Currently, there are no obvious or unambiguous solutions to these problems but as an initial approach we have stated two criteria that a objective quality measure should obey. Note that in the following, when referring to the original and to the halftoned original, this could also refer to the results after the visual and printing models have been applied.

- A quality measure should take both the original and the halftoned original into account and relate to the difference (distance) between them. We believe that one can not

make a judgement of the quality of the halftone without knowledge of the original. This criterion is just a reformulation of our definition of image quality in printed images.
- A quality measure should be based on the same measurements on *both* the original and the halftoned original, furthermore, the quality measure should relate these measurements in such a way that if the results are identical, the measure should indicate maximum image quality. This means that we have excluded all measuring methods that operates on binary images only.

When evaluating halftoning methods with quality measures, it is common to use simple, artificial images. In such an image, consisting only of a certain image property, it is possible to try out how well the halftone describes that property without having to introduce locality into the quality measure. However, since most of the images printed are real, more complex images, halftoning methods should also be tried out on such. This increases the demand for a quality measure that is capable of not only giving a judgement of the over all quality but also where in the halftone a good or poor resemblance to the original has been achieved. Our goal is to have quality measures that are capable of judging all kinds of images, therefore, we will require that the quality measures give locality information.

It would be desirable to have quality measures that works for both conventional, clustered dot, halftoning and for frequency modulated halftoning (FM). However, since they are fundamentally different and produce completely different artifacts, it is questionable if such a measure is realistic. The possibilities to increase the image quality when using a clustered dot principle are rather few. The shape of the dot can be changed, but mainly, an increase in quality is synonymous to increasing the resolution and compensating for the increase in dot gain. FM, on the other hand, offers a great number of possibilities. Of course, the increase in resolution is still an alternative. However, the possibility of placing the micro dots in any imaginable formation makes it possible to totally change the characteristics, the micro structure, of the halftoned image and thereby the quality, without altering the resolution. The possibility of designing halftoning structures can be used to produce images of very high quality. However, some kinds of structures, or sudden changes in structures, can be experiences as very unpleasant and drastically lower the perceived quality. It is therefore necessary to have a quality measure that is capable of evaluating the micro structures, something that is not necessary for conventional halftones. All quality measures discussed from here on will consider FM halftones only, even if it is possible that some of the measures is applicable on conventional halftones as well.

What to measure

There are a few properties that we believe affects the percepted quality more than others. Since these properties, listed below, are not too vague, there should exist one or more measurable features in a halftoned images that could be used to evaluate these properties:

- The *perceived* gray value. Note that this not necessarily means the that measured gray value at a corresponding position in the halftone and the original must be the same, but that it in its particular surrounding *appears* to be the same.
- Changes in structures. Some structural changes in the halftone should actually be there, for instance when crossing a distinct border a change in structure will emphasize the border. However, a structural change in wedges or slowly varying shades are very disturbing and must be detected and judged. An illustration of such can be seen in Figure 3.

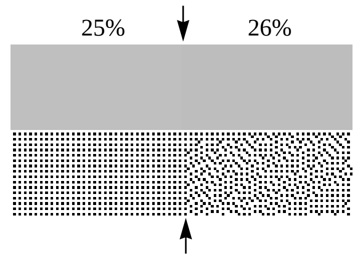

Figure 3. An enlargement of an undesired structural change in the halftone. The border between the two gray levels in the original is hardly noticeable but has been emphasized in the reproduction.

- Structure properties. Periodic patters in a larger scale often catches the interest of the eye and is often considered disturbing. However, periodical patterns in microscopic scale are preferable to totally stochastic patterns which gives a very grainy impression. Properties as periodicity, local frequency and direction characterize the structure and should therefore be considered in a quality measure. An example of halftones representing the same gray level but with different structure properties are shown in Figure 4.

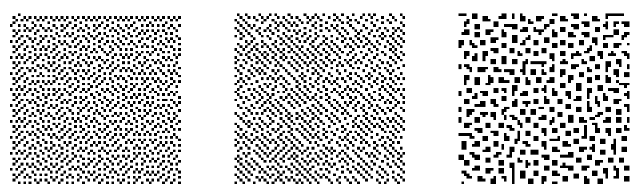

Figure 4. Three different halftones representing the very same gray level. The amounts of micro dots are the same but due to different structure properties, their appearances are totally different.

- Sharpness and detail reproduction. The halftoning method's capability of reproducing details (reproduce high frequencies present in the original) should be measured.
- Halftoning noise. Some part of the signal energy in the halftone does not add any useful information to the reproduction of the original. The energy of this part of this part should be measures and evaluated.

Conclusion

The presentation in this paper summarizes some of the effects that influence the image quality in printed images and especially those introduced in the halftoning procedure. It suggests some basic requirements that an objective quality measure should obey and some image properties that should be evaluated and judged by such measures. Furthermore, it discusses the special properties of the paper surface and the optical bulk properties of the paper that should be considered when building models for the printing process. The models suggested are, apart from the models for the optical and mechanical dot gain, rather premature.

Acknowledgment

The work presented here has been performed within the Swedish national research program, PFT. The financial support and the fruitful collaboration within PFT is gratefully acknowledged.

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