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Optimal image encoding for hard copy production and method of its efficiency estimation

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Abstract

Unlike in a soft copy generating, the multilevel pictorial data are, after capturing by camera or scanner, once again encoded in prepress to get the output signal governing the halftone printing in bi-level, "ink – no ink" fashion. Criteria of such encoding optimization are comprised in the transfer through physical plate making and press communication channel onto a print with as much as possible of original image data perceivable for a viewer. It undermines the providing of mutual conformity for parameters of a source image and channel, as well as for properties of an output print and vision. On the background of the screening developments overview for the last half a century, the paper presents: discussion of tone spatial dispersion in halftoning and accompanying contour and fine detail distortion; such distortion corrections and the method of quantitative estimation of their efficiency; principles of an image optimal encoding in prepress and their implementation in the High Definition Halftone Printing (HDHP); including results of testing and promotion issues of its practical application; and disclosed approach potential with the spatial dispersion adaptive to an arbitrary contour. Samples of test images and fragmentary photographs from illustrative print trails and jobs using HDHP are also presented. On this basis, the paper pretends to disclose some mainstream aspects bypassed in the most of other publications on halftoning.

Keywords: image data encoding, halftone dot, printing, adaptive halftoning, image sharpness, print definition

1. Background

1.1 Fifty years of electronic screening developments

In the sixties and early seventies of last century, the halftone transparencies were used to be exposed in electronic scanners through contact screens. Instead of being strongly connected just with the tone value signal, the halftone dot area was very dependent on collateral factors of the film chemical treatment due to the use of photomechanical screening effect in super contrast, lith-type photosensitive layers (Zernov, 1969). So, besides of contact screens eliminating, the halftone dot formation somewhere in the optical channel of a recorder, i.e. prior to or during the exposure onto conventional film or the, so-called, "electronic screening" providing the robust connection between the signal and resulting tone value was rather urgent. Putting aside some previous patent publications, the fifty years of electronic screening developments can be counted from October 1968 when the first remarkable technical report named "Electronic Halftones" authored by researchers from RCA Graphic Laboratory has appeared in IEEE Spectrum (Hallows and Klensch, 1968). They have generated the halftone on the faceplate of high-resolution CRT, with 110 lpi image being applicable for exposing on a photo plate. The dots of variable area were drawn by means of the electron beam spiral sub-movement under control of a tone signal. In spite of the actual use of a pulse-width modulation, they named this kind of halftones generating as amplitude modulated (AM) to disclose in the same paper the alternative method of such an image formation by the variable placement of fixed size dots and to call it frequency modulated (FM).

The first electronically halftoned color prints were next year distributed in ten thousand copies at the Moscow "Inpoligraphmash'69" exhibition by the Graphic Laboratory of Leningrad Bonch-Bruevich Institute of Electric Communication (Exhibition pamphlet, 1969).

Sharp image of variable area dot was formed on a faceplate of the special CRT by an electron beam cross section modulation (Kuznetsov and Uzilevskey, 1976). Such dot was then exposed onto a film fixed on rotated drum of a scanner. Photograph of one of those pictures with the dots random displacement avoiding moiré is given in Figure 1. Dots of variable area were also electronically formed in PDI scanners of the seventies with the use of galvanic mirrors or diaphragms (Moe, et al., 1973).

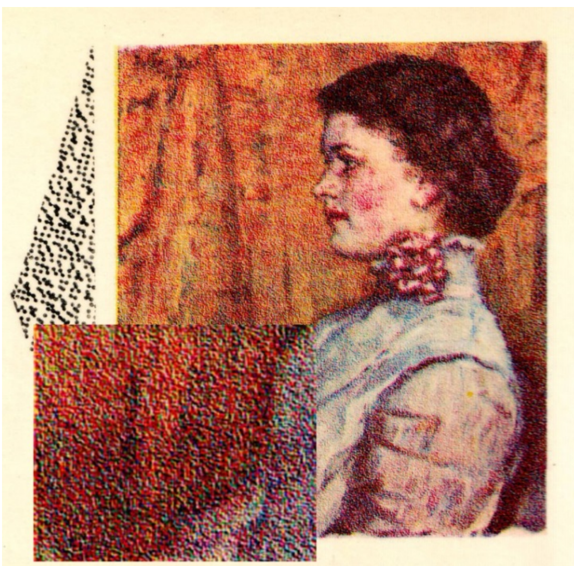


Figure 1: Copy of one of the first color prints produced with electronic screening the halftone transparencies and with avoiding moiré by using non-periodic dots placement (Exhibition pamphlet, 1969)

In spite of their use along with the digital color processing and image scaling, all these dot formation methods, as well as electromechanical engraving of that time, have provided the continuous dot area variation and relate to the analog electronic screening techniques.

“Digital” halftoning was at a full scale commercially implemented with the laser parallel exposing of six microdots onto a film in Chromograph 300 ER of Dr. Ing. R. Hell company in 1972 (Gast, 1973). The halftone dots were formed there from discrete elements within the matrix, which in the simplest case could comprise a screen period. So, in addition to an analog to digital conversion at an image capturing stage, the pictorial data were once again spatially sampled, at least, with a screen frequency while its tone range was a second time quantized according to a finite amount of dots in an “alphabet” defined by said matrix dimensions. As result of this new encoding, the output bit map was produced to control the film exposure in “on–off” fashion.

Figure 2 illustrates the mutual location of four discrete spatial periods within such a matrix (36 × 36 microdots unit area) for the screen with an angle of about 71.6 degrees with rational tangent of 3/1. The abbreviations commonly used nowadays (lpi, spi, ppi, dpi) of spatial frequencies, inverse to three of these periods, are also marked on this picture. The spot function period includes here ten halftone dots. In some further developments such period was extended to a “supercell” with many hundred dots thereby allowing for approximation of rational tangents, which with sufficient accuracy correspond to the “conventional” screen angles of 15° and 30° having irrational tangents.

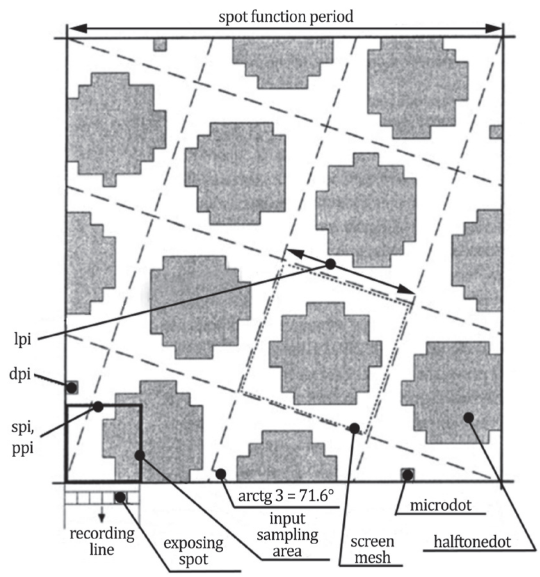
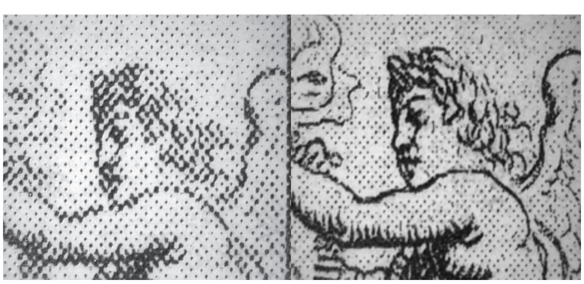


Figure 2: Mutual location of discrete spatial periods within the 36 × 36 microdots unit area for a screen angle of about 71.6 degrees at tangent 3 in Chromograph 300 ER, adopted from Gast (1972)

Due to the limited digital facilities of that time, the tone signal was presented in this machine by the six digits, i.e. by the halftone “alphabet” comprising just $2^6 = 64$ symbols. So, the visible steps could appear instead of continuous tone (CT) variation. That’s why the halftone symbols of adjacent levels were stochastically mixed at transitions to get rid of such quantization noise (Koll, 1972). This principle of error diffusion was later on expanded from 1/64 to 1/2 part of tone range with the use of just two symbols from the halftone “alphabet” comprising the fixed sized dot and blank (Floyd and Steinberg, 1976). Following this mathematically elegant error diffusion approach, the screening developments have then declined to stochastic or FM halftones generating. The great number of publications was devoted to make their irregular structure homogenous with applying of the, so-called, “blue”, “green” masks and other means (Ulichney, 1987; Lau and Arce, 2001). Nevertheless, they were lacking printability due to ignoring the basic physical issues of a plate–ink–substrate interaction (Kouznetsov and Alexandrov, 1999).

Use of a dot with a minimal available area within a whole tone range makes the resulting tone value very sensitive to printing tolerances. (It is easily evidenced by the attempt to print a 50 % tint comprising the chessboard location of minimal dots and blanks.) As result, they were just partially implemented in the ink jet and, so-called, hybrid halftoning. Effective tone range of the latter is expanded by modulating the amount of a fixed minimal size dots/blanks in the highlights or the darkest areas while using the usual dot area variation for the most part of the said range. Such kind of screen frequency auxiliary variation was earlier also met in photomechanical Respi screens of the '60s and in digital screening of K-separation in Chromograph 300 ER.

As far as it is concerned of conventional, AM digital screening, the certain improvements there were also done. Reduction of the dot gain and ink waste was achieved, for example, by the use of perforated or “concentric” dots providing lower adhesion in their inner area. However, all these developments were mostly related to the replacement of an optical, photomechanical screening by its electronic version, to some extent bypassing the drastic print image deterioration followed at the end of 19th century with introducing the screening itself instead of the previous manual engraving (Figure 3). Improvement of print image quality can be achieved using the so-called, adaptive screening methods, like high definition halftone printing (HDHP), directed to engraver skills restoration in the modern electronic prepress (detailed in Chapters 4.3–4.5).



a) b)

Figure 3: Enlarged fragments of halftones produced with the use of: conventional ABC screening (a); HDHP technique imitating the manual engraver skills (b), Kuznetsov (2017)

1.2 Overview of image reproduction process

In the light of communication theory, the prepress processing of a picture comprises its optimal encoding by the criteria of a picture data transmitting onto a print through the physical plate making and press communication channels, keeping as much as possible of a source image data which can be perceived by a viewer. Such encoding undermines the mutual conformity for parameters of original image, as well as for properties of output print and human visual system (HVS).

Representative example of such conformity providing is in the empirically found and traditionally used non-orthogonal, 45 degrees screen orientation on a black and white (b/w) print and that for the black ink on a multicolor one. It takes into account the angular anisotropies inherent in these three basic components. The first of them is in the statistics of contours orientation distribution on images, replicas of a visually perceived world where, due to gravitation, the vertical and horizontal contours prevail over the inclined ones. The other one relates to transmitting channel and is comprised in 1.41 greater spatial frequency response of its orthogonal screen grid for diagonal lines as compared with that for vertical and horizontal directions. The third anisotropy is, at last, in about the same degree less vision frequency response in diagonal direction (Grudzinsky, Tsukkerman and Shostatsky, 1976; Kuznetsov, 1998a).

However, unlike TV and pictorial data compression solutions, the printing technology doesn’t completely satisfy such principle in some other important relations. For example, it uses the same quantization scale or dynamic range per color separation without taking into account the specifics both of an image local area content and vision.

Such a fact is schematically illustrated (Figure 4). Three basic components (source, channel, user/receiver) are shown there streamed by the image data flow with the first of these components being of the greatest width while that of the channel, with inherent hindrances and band pass limit, the narrowest.

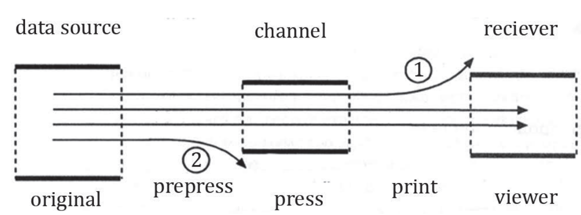


Figure 4: Data flow in halftone print production

Arrow 1 in Figure 4 indicates the image data which, in spite of being, in fact, present on a print copy, can’t be visually perceived by a viewer. In digital prepress of today it is formally pretended to reproduce (to transmit through the printing channel) any detail of an image and, for example, the quarter of millimeter thick line in as much as 16 million colors (256^3). The fact is that the eye can scarcely tell if such a line is somewhat darker or lighter, and whether it is green, cyan or gray is ignored. Such luxury of color interpretation isn’t available for the most of other, such as color TV, imaging techniques making them possible just by providing the necessary conformity between the properties of an output data and facilities of an end user. Arrow 2 designates, on the other hand, the data of original image which would be perceived on a print but were lost at the prepress stage. It is related to the contour and fine detail distortion accompanying the tone measure spatial dispersion inherent in the CT original transform to the bi-level (ink / no ink) output signal.

Such losses are illustrated by the enlarged fragment of a halftone print in Figure 3a. The same reproduction of manually engraved picture in Figure 3b is free of them. The original (not shown in Figure 3) consists of engravings and shades of print dots variations (mezzotint) at a stationary image area. Meanwhile, instead of the scattered halftone dots, the engraver uses exclusively the solid lines for contours and fine details imitating the average brightness of a local area by varying just the width of these lines. That allows him to reproduce the image content with as much as possible geometric accuracy.

So, the fundamental objective of image encoding in screening is comprised in more effective use of the imaging system resources by shortening the gap between printing process resolution and halftone image definition with exploring the elements of artificial intellect taken, by analogy, from the work of engraver.

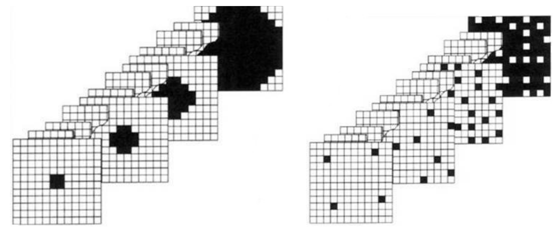
Practically approved, disclosed in several our patents and herein below described the HDHP technique is adaptive to local tone value gradient. It imitates the mentioned engraver skills to increase the halftone definition. Moreover, the reproduction system recourses are there completely used for standalone thin stripes with their accuracy inherent just in the line work (LW) kind of printing.

2. Introduction

2.1 Determination of tone spatial dispersion

Unlike some other imaging applications such as, for example, soft copy creating, the image data are at least twice encoded in printing. Its initial presentation by multilevel, predominantly 8-bit samples (256 levels) per color separation is quite sufficient for computer or TV display.

However, the set of such samples should be transformed into a bitmap to control the print output in a bi-level fashion. This new encoding is performed with the spatial image sampling at a screen ruling frequency and the use of sampled values quantization by an “alphabet” of finite size halftone symbols available in a raster image processor (RIP) or printer driver (Figure 5).



a) *b)*

Figure 5: Symbols of halftone dot “alphabets” with clustered (a) and diffused (b) distribution of microdots within a screen period, adopted from Kuznetsov (2016b)

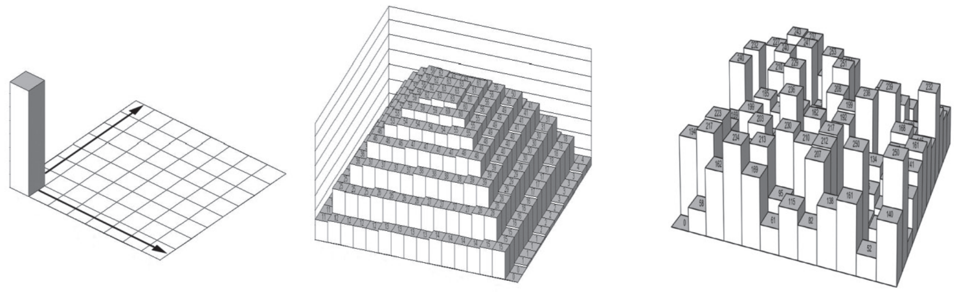
Such “halftoning procedure” is accompanied by the multilevel tone measure dispersion over screen mesh period as illustrated in Figure 6. The area of 16 × 16 microdots is formally required at the output for ascertain inking each of them according to one of 256 input levels. Such selective marking is provided by the so called “spot” function using a “screen hill” (Figure 6b), diffused (Figure 6c) or directional microdots weights distribution. Their horizontal threshold slices produce the symbols of halftone dot “alphabets” shown in Figure 5. Tile geometries are further discussed in Chapter 4.3.

As shown in Table 1, the dispersion parameters, such as margins of its spatial bounds, continuity, linearity, discreteness, and direction (geometry), strongly correlate to related properties of a halftone structure or an image itself. Bounds of dispersion define, for example, the print screen period (ruling) finally affecting an image sharpness and definition.

Table 1: Parameters of tone scale spatial dispersion and properties of a thereby produced halftone structure

Dispersion parameter	Halftone structure property
spatial bounds	screen period (definition)
continuity	AM, FM (stochastic)
linearity	tone response curve
discreteness	number of gray levels
direction	form of print element, screen geometry

The illustrative examples of Figure 5 relate to the beforehand defined dispersion by the use of corresponding weight or spot functions. However, in error diffusion and in some of the locally adaptive techniques, which provide the dispersion “on-fly”, such spatial period does, nevertheless, exist being defined by the input pixel code length. Eight-bit length requires, for example, the margins of, at least, 16 × 16 microdots for adequate presentation of one of $2^8 = 256$ quantization levels on a copy. Moreover, the input image file metric mostly relates to visually uniform optical densities or CIELAB values, which are in logarithmic or cubic degree relationship to the absorbance (tone value) on



a) b) c)

Figure 6: Spatial dispersion of the multiple values of an input image sample (a) between the screen mesh microdots with the use of a clustered (b) and random (c) distribution of their weights, adopted from Kuznetsov (2016b)

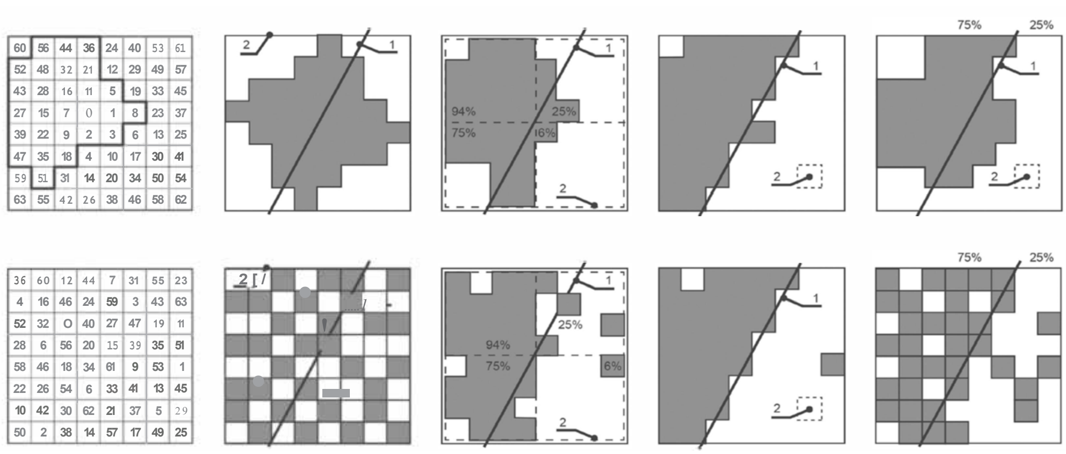
a print. That's why the dispersed quantization scale should be in rather strong non-linear connection to that of the input file, requiring, once again, the excess of dispersion discreteness. So, the print output resolution has to significantly exceed the scan frequency of an image input.

2.2 Image detail distortion in screening and its correction

Figure 7 shows the reproduction variants for border **1** sharply separating on CT original the dark (from the left) and light (from the right) areas altogether corresponding to a single screen mesh of a print copy. The greatest distortion happens when the original sampling area **2** is equal to such a mesh (period of halftone), i.e. at the so-called screening factor (SF) of 1.0. Because of this area, half division on black and white the tone value comprises 50 % for the whole screen period and the border sharpness is greatly lost as shown in Figure 7b.

In more realistic scale this effect is demonstrated in Figure 8b for letters **Q** and **n** as fragments of a CT original (Figure 8a).

The upper parts of Figure 7c and Figure 8d relate to the twice higher image capture resolution when SF = 2.0. Within each quarter of a screen mesh, the microdots are assembled here under control of four different input values, i.e. with the use of just parts of halftone symbols. The form of such "partial" dots somewhat better matches the contour geometry. The same degree of contour accuracy improvement, but with the use of a quarterly fewer amount of input samples at SF = 1.0, is demonstrated by Figure 8e. As indicated on the upper part of Figure 7a the dots are here shifted toward the darker side of a contour at a distance dependent on its contrast (Moe, et al., 1978; Ershov, et al., 1990). Joint effect of SF = 2.0 and such displacement is illustrated in Figure 8f where just the part of a dot is displaced on a border. It is interesting to notice that, instead of contour destroying (Figure 8b), these dots are them-



a) b) c) d) e)

*Figure 7: Print copies of sharp transition, with border **1** dividing dark (left) and light (right) areas on a CT original with the use of monotonous (upper) and random (lower) microdot weights distribution within a screen mesh (a) at: SF = 1.0 (b) and SF = 2.0 (c); SF = 8.0 for full (d) and intermediate (e) contrast (75 % to 25 %) values*

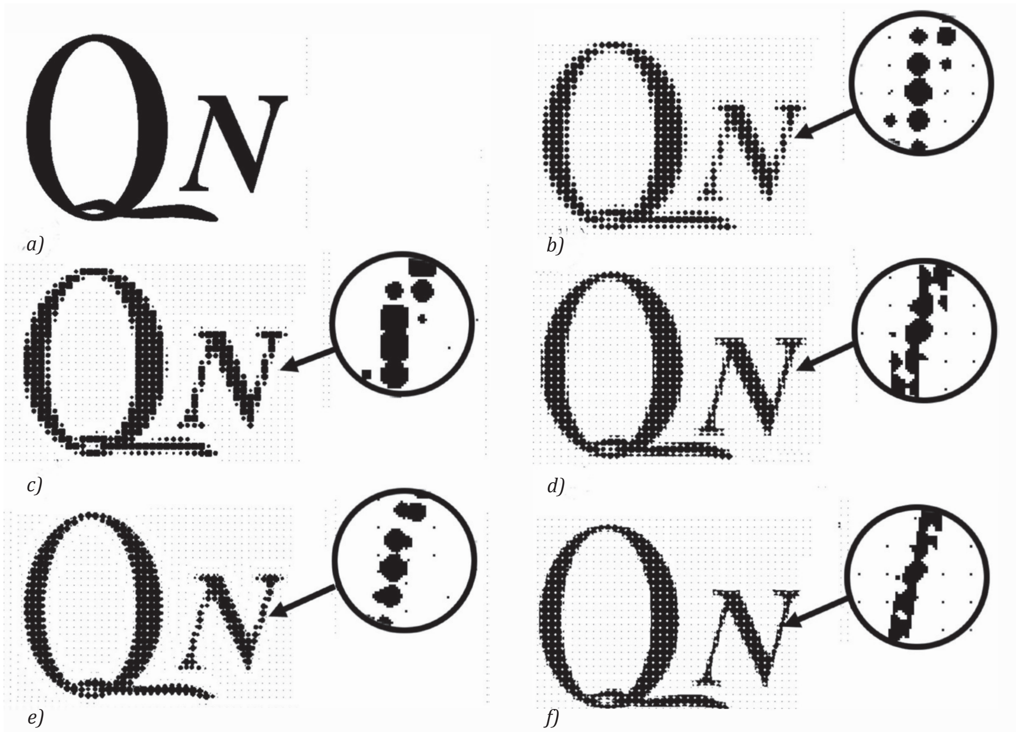


Figure 8: The distortion variants of a continuous tone original detail (a); on a print: at SF = 1.0 (b); with the use of unsharp masking at SF = 1.0 (c); at SF = 2.0 (d); with dots displacement at SF = 1.0 (e); with displacement and SF = 2.0 (f)

selves divided into parts each of them made to adjoin the nearest side of a border. Such effect is seen within the smaller opening of letter **Q** in Figure 8f.

Further increase of SF up to 8.0 improves the geometric accuracy on a print for the b/w border of full contrast to the level of LW as shown in Figure 7d. As far as the LW image doesn't need halftoning at all, the printer deals with it as a Boolean repeater in a "fine scan/fine print" mode. However, the most of the CT original contours are of some lower contrast. Figure 7e demonstrates that the eight times increase of a scan frequency, i.e. the ultimate SF value of 8.0 doesn't help so much. In spite of sharpness on original the scattered dots and blanks of reproduced transition tone values (in this example of 75 % and 25 %) are, nevertheless, formed at each side. Moreover, it was shown that the use of SF values greater of 2.0 results in specific losses of textures (Schadenko and Kuznetsov, 2009).

According to one of "halftoning myths" (Kuznetsov, 2016; 2017), the above kind of distortion can be corrected not in screening procedure itself but by the previous high-frequency filtration of an input multi-level data. However, as demonstrated by an example in Figure 8c, the unsharp masking (USM), except of increasing the local contrast, doesn't at all improve geometric accuracy of a detail.

3. Halftone definition and sharpness estimation

3.1 Investigation of the halftoning effect on image quality

Resulting amount of ink transferred to a print and, hence, the basic quality aspects of the latter such as color, tone rendition, definition, sharpness, etc. are fundamentally dependent on halftone dots area, form and geometry of placement. That's why the screening comprises the actual, cornerstone R&D issue of illustrative printing and a lot of currently available, announced or upcoming, patented and trademarked screening techniques focus on their practical use. In such situation the demand arises for correct, quantitative comparison of their efficiency (Kuznetsov, 1999).

The generalized approach to the halftone print quality evaluation was formulated on the basis of comparing not the original and its halftone copy themselves but the image metaphors of the both produced with the use of HVS model (Nilsson and Kruse, 1999). Such approach embraces the whole set of a halftone print quality parameters. In our research, it was, however, purposeful to divide this set into two groups with the first of them including parameters characterizing: color, contrast, tone range, number and distribution of gray levels, etc. Along with the visual estimation, such quality indices can be quantitatively and separately measured on a test wedges by a colorimeter and densitometer with plotting the tone reproduction curve, color gamut, tone deviation, etc.

Our research was focused on estimation of the second group of parameters, such as definition and sharpness. They are responsible for the high spatial frequency content of an image and thereby for the accuracy of its fine details. The definition is commonly estimated by the overall amount of smallest details which can be potentially reproduced on a print. Sharpness characterizes, on the other hand, the border quality independent on detail dimensions. The ISO standard 12647-1 (International Organization for Standardization, 2013) recommends, for example, to measure dot sharpness on a halftone transparency by the inverse of its edge fringe width. Such a fringe is schematically illustrated on a "photograph" (Figure 9b) of an "ideal" original b/w transition of Figure 9a.

a) b) c)

Figure 9: The "ideal" stripe (a) and its copies on a photograph (b) and on a halftone print (c)

More adequately the sharpness evaluation is provided when, beside the width, the gradient of optical density within a fringe is also taken into account. It explains, for example, in today obsolete process, the practical use of dots optical density up to 5.0, in spite of about 1.0 being sufficient to protect the sensitive layer in offset plate making (Kuznetsov, 1998b).

Modulation Transfer Function (MTF) is commonly used in modeling the frequency response of an imaging system. Micro photometric measuring across the variable spatial frequency bar pattern is applied, for example, in photography, to verify the modeled MTF and experimental data correlation. However, such measurement isn't applicable for halftone print of such a pattern (Figure 9c) because of its bi-level nature being formally similar to that on an original in Figure 9a. The only difference is that, instead of straight lines, the structure of print version comprises the scattered halftone dots or just parts thereof filling both the pattern stripes and blanks in a different, illustrated, for an example, in Figures 7 and 8, being dependent on specific screening algorithm or of its settings. Therefore, the facility of certain halftoning to preserve the sharpness is mostly judged visually. The objective visual comparison meets, meanwhile, the difficulty of keeping non-changed the multiple of other imaging conditions. The slightest parameters variation in color, gradation and the like may affect the expert judgment of sharpness and vice versa. So, there is the need for a quantitative method allowing for evaluation the influence of various imaging parameters (volume of a scanned/input image data, printer resolution, type of printing, etc.) and settings (screen and dot geometry, screen ruling and angle, screening algorithm, etc.) on a halftone quality. It is also desirable to get such estimation at the different spatial frequencies and contrasts of details, as well as, along the whole chain of reproduction stages. Such an attempt was undertaken by Kitakubo and Hoshino (1997) with analysis of frequency spectra calculated for the differences between the input multilevel samples and averaged sums of bits on a print copy.

3.2 The method of a detail distortion quantitative evaluation

We have proposed to directly measure the norm of error for quantitative estimation of the fine detail distortion involved by screening (Kuznetsov and Zheludev, 2008). This value is found by superimposing the bitmaps of an original test pattern and its halftone copy with calculating the normalized sum of bits (microdots) changing their polarity (from black to white and from white to black) as result of halftoning. That allows for defining the screening efficiency factor (SEF) as

$$\mathrm{SEF} = 1 - 0.5\left(\frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\left|A_{ij} - B_{ij}\right|}{\sum_{i=1}^{M}\sum_{j=1}^{N}A_{ij}}\right) \qquad [1]$$

where A_{ij} and B_{ij} are the bi-level values in original **A** and screened **B** pattern bitmaps (Figure 10), while M and N denote the numbers of their lines and columns.

In this approach, the initial test with resolution pattern of full or intermediate contrast is concerned as a detail of a CT original. With high-resolution bitmap **A** of a test pattern (Figure 10a) being formed this method emulates the following prepress procedures:

- coarsely scanning and encoding the test at prescribed resolution (SF) to provide the input gray level ("byte-map") file (Figure 10b);
- creating the metaphor of a PostScript file at predetermined tone value percent for white and black on a print (Figure 10c);
- screening the PS file by the investigated method to get the bitmap **B** of a halftone (Figure 10d).

Superposition of initial **A** and final **B** bitmaps shows in Figure 10e the bits, which have changed their polarity as result of screening, and allows for calculation the SEF according to Equation 1.

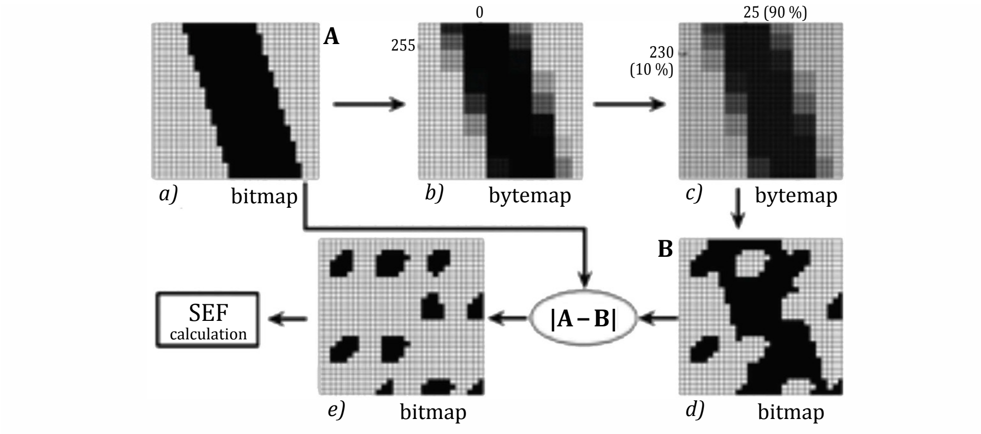


Figure 10: Steps sequence of resolution test pattern processing for the SEF calculation

It should be noticed that, even if the extreme input values of 0 and 255 are prescribed for "black" and "white" in a test pattern file, the intermediate, gray ones indicated in Figure 10b nevertheless appear at boundaries due to aperture distortion of scanning or, in other words, because of tone value averaging over a sampling area. When the picture is further prepared for printing the new meanings should be assigned to its black and white. They relate, in this example, to 10 % and 90 % ultimate areas of halftone dots available for a certain given kind of print job (Figure 10c).

For testing this method the MATLAB functions were used to create the resolution test patterns at 3600 dpi, to screen them with analytically defined spot functions, to calculate and plot the SEF curves. Test image formation, scanning, and encoding were emulated in Photoshop. When plotted along pattern periodicity the graphs of such a factor (Figure 11) comprise some equivalent of MTFs and allow for comparing the various screening methods efficiency in the relation to high frequency image content reproduction.

Presence of peaks on curves of Figure 11a is explained by the interference of a pattern and screen frequencies. These peaks almost disappear due to integral nature of SEF calculation when the concentric test stripes are used instead of the vertical ones (Figure 11b).

The SEF value is normalized in such a way that its zero meaning corresponds to some virtual, negative presentation of a test (Figure 12c) when all the input bits are reversed. The 0.5 SEF value takes place when half of an input test pattern bits has changed their sign thus producing, instead of stripes, the uniform tint as, for example, shown in Figure 12b. So, all the SEF meanings lower than 0.5 are non-representative. The SEF = 1.0 relates, on the other hand, to facsimile reproduction

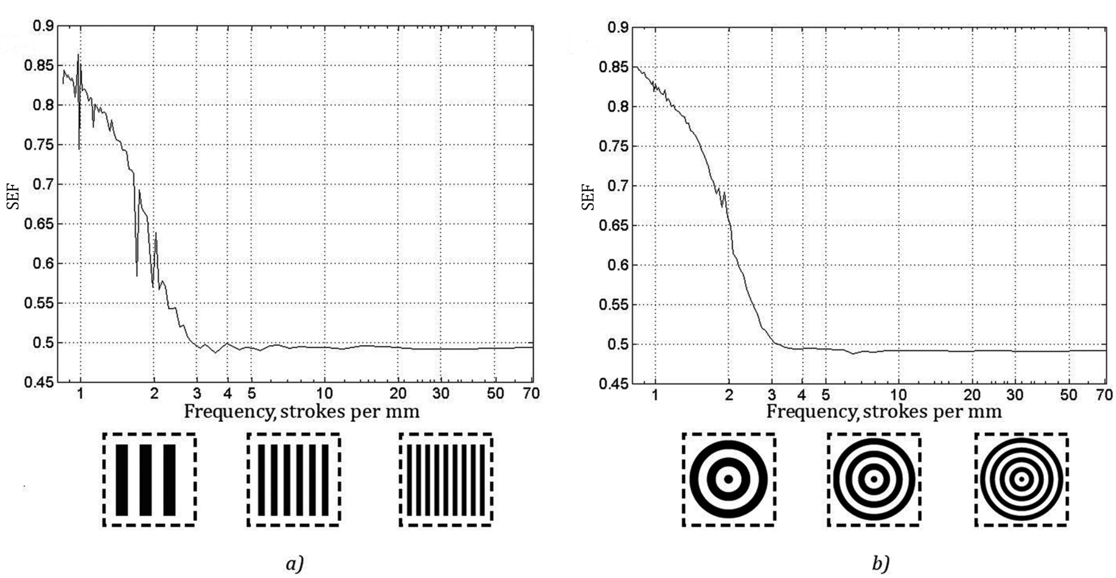


Figure 11: The SEF plotted along the resolution test pattern frequencies for two of its geometries: parallel (a) and concentric (b)

of a pattern with all input pixels remaining unchanged (Figure 12a). It takes place for the test of full contrast scanned at maximal SF, i.e. at as high resolution as that of the printer (fine-scan/fine-print mode) and assigning to its white and black levels correspondingly the halftone dot of 0 % and ink solid (100 %) tone values. With no screening in such case, the dot generator works as a repeater and the upper SEF curve in Figure 13 comes parallel to the abscissa.

a) b) c)

Figure 12: Halftone copies of the input test pattern at SEF: 1.0 (a); 0.5 (b); and 0.0 (c)

3.3 Efficiency of screening with its settings variation

The curves in Figures 13 to 15 adequately show the different effect of SF, screen ruling, and stripes contrast on the test pattern distortion. Figure 16 demonstrates the rather strong reciprocity effect for SF and screen ruling when reduction of the former is compensated by the increase of the latter and vice versa. The curve plotted for SF = 2.0 and screen ruling of 20 lines/cm comes very close to that calculated for half SF (SF = 1.0) but doubled (40 lines/cm) ruling.

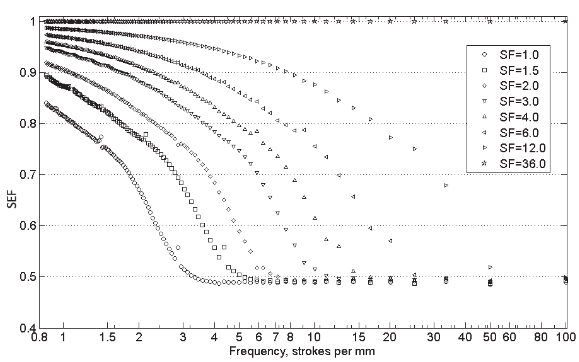


Figure 13: SEF at different SF values for test of a full contrast and screen ruling of 40 lines/cm

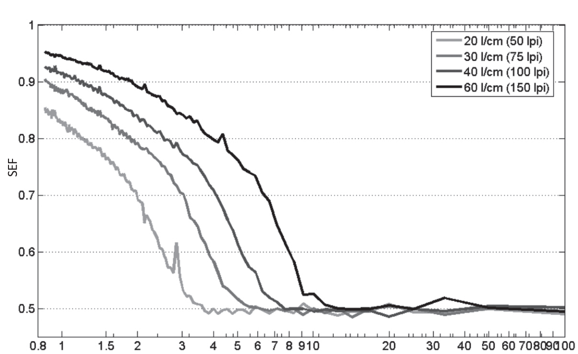


Figure 14: SEF for different screen rulings at SF of 2.0

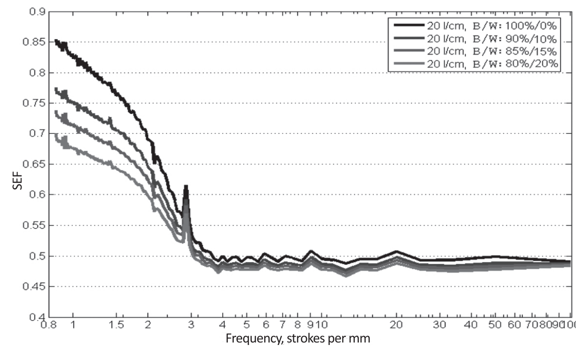


Figure 15: SEF for different contrasts of the input test at screen ruling of 20 lines/cm and SF = 2.0

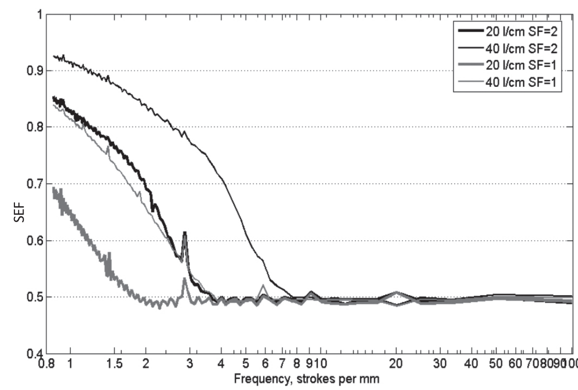


Figure 16: Proximity of two middle SEF curves illustrates the reciprocity effect of screen ruling and SF

In spite of the use at the last step of some idealistic image copy, the method allows, nevertheless, for objective, quantitative estimation of frequency response for various screening techniques unlike the visual comparing the realistic halftones or their enlarged fragments in Figures 7 and 8. Moreover, the use of high resolution scanned test of a halftone transparency, plate or print may help to estimate the share of distortion involved by the additional low pass filtration inherent in the further technology stages. For screen printing, it makes, for example, possible to detect the effect of a mesh and stencil parameters on an image sharpness and definition. Similarly, the effects of anilox roller parameters can be estimated in flexography. At last, the method should be helpful for evaluation of the halftoning facilities of a digital printer whose screening algorithm is concealed in its closed architecture.

4. Adaptive screening research

4.1 Tone value dependent processing

As it was already mentioned, the issues of tone (color) rendition and of contour accuracy are mostly independently concerned in the imaging science. Screening comprises, however, the unique kind of an image transform with inherent conflict of providing both tonal and spatial resolution. The tradeoff is solved in reproduction practice on behalf of the first of these requirements, i.e. by preserving the tone value range between 3–5 % and 95–97 % for all the variety of practically used screen frequencies (International Organization for Standardization, 2013; Kouznetsov, 1999; Kuznetsov, 2016).

At such a condition, the screen ruling depends on the absolute minimal size of a dot steadily available for given type of job, i.e. for the particular kind of print stock, ink, plate, equipment, etc. Providing such dot over a print sheet within a run is therefore fundamental for the optimal adjustment of substrate-plate-ink system. Altogether it is worthwhile to notice, that the ink solid densities, used in wide practice to indicate the match to some standard conditions, are just the secondary factors of a proper press setting.

To provide both as much as possible amount of steps within the gray range and uniformity of vast stationary areas the optimal geometry of a dot form transformation was empirically found in over a century of halftone printing use. However, some of the lately suggested digital screening techniques, being aimed to achieve a certain novel image quality, failed to be practical because of ignoring said long term experience. The non-periodic, “screenless” photomechanic halftones, provided, for example, in collotype printing of the past, were renewed by digital techniques of last decades under the names of FM, dither, stochastic, error diffusion, etc. In spite of providing the greater spatial frequency response than regular, periodic ones, they have found limited application because of putting aside the practically approved priority of tone rendition and printability requirements. As result, the concept was just partially implemented, for example, in the already mentioned hybrid halftones. In terms of adaptive screening approach such a way of modifying the algorithm over an image area can be referred to *tone value* dependent ones. Similarly, the printing element form variation along a gray scale from, for example, round in highlights to elliptical in middle tones, etc., is also *tone* dependent.

4.2 Tone gradient dependent screening

In early period of electronic screening developments, the other, *tone value gradient* dependent approach was suggested for screening distortions correction. Local image nature is evaluated in the closest vicinity of a processed pixel by a differential operator to form the parameter for dynamic, over a picture area, algorithm readjustment. The first examples of such control were comprised in the halftone dots or their parts displacement toward the darker side of a contour eliminating its stepwise serration in analogue electronic halftones of P.D.I. scanner of the '70s (Moe, et al., 1978; Hunt, 2004) and in its digital version (Ershov, et al., 1990). Modifying the form of dots (their elongation matching the contour direction) was also suggested (Hammerin and Kruse, 1994).

However, the eternal conflict of providing both tonal and spatial resolution to a greater extent withdrawn by the increase of a screen ruling on detail borders with taking into account the acceptability of accompanying gray scale reduction.

Screens sequence of the stepwise square root of two higher rulings was used for this purpose at the first step of our developments (Kuznetsov, et al., 1978). Such kind of solution is similar in its approach to adaptive differential pulse code modulation where the dynamic mutual exchange of a sampling rate and quantization scale is explored. With a signal gradient increase the samples of shorter bits length and, hence, of a fewer quantization scale are used to get the higher frequency response. However, the effects of data compression are limited there by spending extra bits to indicate the actual bit length of a current sample for decoder. This is no problem for halftoning where the results of both spatial sampling and value quantization are finally presented by a single bitmap.

Our first experiments have shown that the abrupt changing of frequency, as well as of any other screen parameter, along the contour of gradually fading contrast is distinct for a viewer. To get rid of the stepwise, noisy change of an image structure we proposed to seamlessly blend the screens of different ruling in each other (Kuznetsov and Nishnianidze, 1982; Kuznetsov, Kogan and Nishnianidze, 1982). It is performed by dividing the current tone value S in two parts S_1 and S_2 in proportion depending on the local image area content estimated as its busyness q:

$$S = (1 - q)\, S_1 + q\, S_2 \qquad [2]$$

The first part S_1 may control any kind of a basic, practically approved algorithm providing the appropriate printability and tone rendition for the stationary, low spatial frequency image area. The S_2 part relates to fine detail and governs the screen functions of higher ruling but of shorter quantization scale (symbols “alphabet”).

Busyness parameter q characterizes, in general, the share of high frequencies within the local image area comprised of a processed pixel and its neighboring ones. It can be estimated, for example, with the use of Fast Fourier Transfrom (FFT) or by the sum of difference modules in all pixels pairs of such area. As our experience has shown, the maximal tone value difference module among these pairs does also quite satisfactorily present *q*. Later versions of disclosing this method in HP patents name the same parameter as activity index (Bradburn, Hoffman and Lin, 1999).

In this approach the contour geometry improvement was, however, dependent on the excess of an input data captured from original, i.e. at SF much greater than commonly used 2.0 and, hence, at many times larger image file volumes.

4.3 High definition halftone printing (HDHP)

In our further development there was proposed to use the set of auxiliary functions having constant, about twice higher frequency than a basic screen (Kuznetsov, 1998b). Relying on typical "coarse-scan/fine-print" mode (SF = 2.0) it can formally just double the halftone print definition. However, the variety of about a thousand dots (tiles) in their "alphabet" (Figure 17) allows for much greater geometric accuracy of contours and fine details as shown in Figure 18.

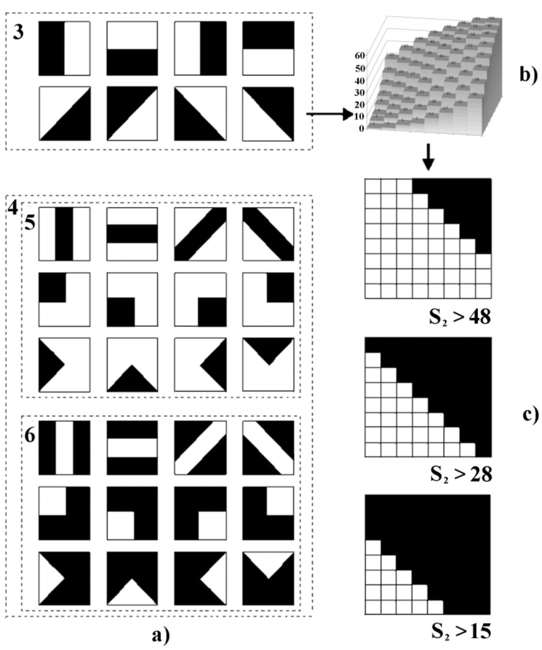


Figure 17: Tile geometries (a) with their first (3) and second (4) pluralities, the latter subdivided into the subsets (5) and (6); auxiliary spot function (b) for one of geometries; tiles (c) produced by this function for three tone values S_2 (Kuznetsov, 2017)

To properly identify the auxiliary function within a set and extract the tile closely matching a reproduced detail or contour geometry the pattern recognition technique is used in the vicinity of a processed input pixel. Each input sample of non-stationary image area is jointly presented within the screen mesh by such a tile and conventional dot or its part in proportion defined by the busyness factor *q*. This mixture is illustrated by Figure 19 for the contour of intermediate contrast sharply separating the original areas of 75 % and 25 % tone value, i.e. having *q* = 0.5.

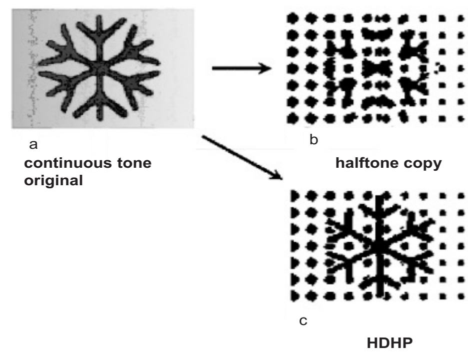


Figure 18: The fine detail (a) of CT original and its halftone copies in conventional (b) and adaptive screening (c) at SF = 2.0, adopted from Kuznetsov (2016b)

Share of tiles use increases with *q* growth up to 1.0 resulting in precise matching the geometry of a detail as was shown in Figure 18c. Such a mixture is, on the other hand, gradually replaced by the conventional dots of 50 % tone value when the contrast is fading along a contour with its complete dissolving in uniform background of 50 % value where *q* = 0.

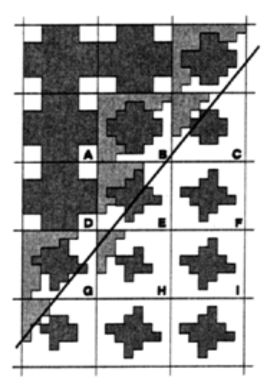


Figure 19: The mixture of tiles (lighter) and halftone dots (darker) for contour of intermediate contrast sharply separating on an original the areas of 75 % and 25 % value (SF = 1), adopted from Kuznetsov (2016b)

As it became clear from further experiments, the issues of seamless blending of different dot structures can be also concerned in different way for the boundary and standalone thin line, i.e. for the double tone jump within an input sample area **E** indicated in Figure 20. The constrained use of tiles instead of dots isn't visually caught here. That allows for reproducing such line by the ink solid (Figure 20d) instead of the mixture of tiles and dots (Figure 20c). On the other hand, the gradual contrast fading along such a line can be quite satisfactorily compensated simply by the line width reduction.

As follows from engraver practice, the 0.1 mm thick gray line (Figure 20b) doesn’t need screening at all and can be printed by solid, for example, with half of its initial width to preserve the average grayness of an area (Figure 20d).

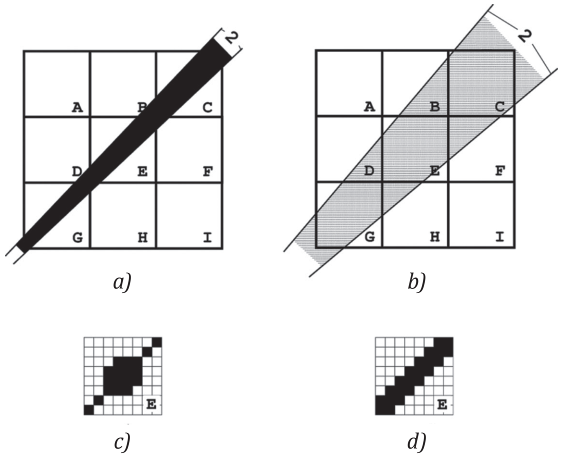


*Figure 20: Thin black (a) and wider gray (b) lines producing the same tone value for each of **A–I** sampling areas due to reflectance averaging at the CT original input; halftone copies of these lines for the processed **E** area in previous (c) and current (d) HDHP versions, adopted from Kuznetsov (2016b)*

The set of auxiliary screen functions was for this purpose divided in two groups with subdividing the second of them in two subsets (shown in Figure 17a) allowing for the selective use of tiles of different geometry and polarity (Kuznetsov and Volneikin, 2011). As result, the standalone thin lines are reproduced by the latest HDHP version with the complete use of a printer resolution.

4.4 Discussion on HDHP testing in traditional and digital printing

Selective distribution of the imaging system resources over a picture, taking into account its local area content as described above allows for the mutual exchange of printing system facilities in relation of tone/color rendition and contour/fine detail graphic accuracy, i.e. with tonal and spatial resolutions adaptively replacing each other. This new way to form and place the print elements was realized as the computer program. Meanwhile, the absence of iterative procedures in algorithm facilitates to implement it in a RIP or in a hardware halftone dot generator. The technology was named HDHP and tested in lithography, flexography, screen printing, toner based and ink jet digital printing.

The results of experimental printing of the tests and realistic images as well as of the commercial jobs with the use of adaptively halftoned image files have vividly shown the following advantages:

- twice higher definition at any screen ruling used for the stationary image area;
- reproduction of black or white thin lines by the ink solid or clean paper instead of the scattered or partial dots in any other kind of halftoning;
- higher appearance of contrast and color gamut accompanying the increase of image sharpness and definition;
- these quality improvements at a standard volume of input data and without any special requirements to ink, plate, paper or their interaction in printing.

Figure 21 illustrates the higher frequency response, as compared to halftoning in Harlequin RIP, by the SEF curves produced with the use of the above described method of screening efficiency estimation. Two lower curves for Harlequin regular and diffused screening almost coincide. It may indicate the use of the latter for a random spot function of the same size as for the former with the both of them similar to those shown in Figures 5 and 6.

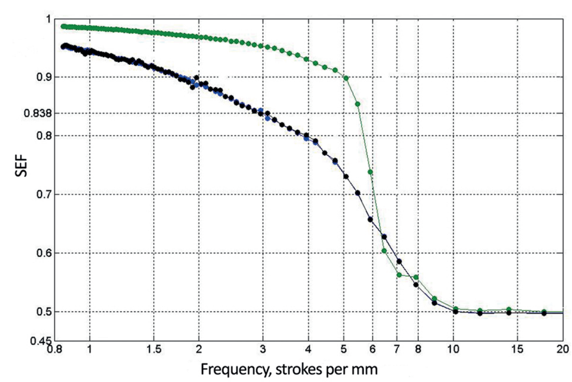


Figure 21: Frequency curves for SEF: HDHP at SF = 2.0 and 150 lpi (upper); two lower (almost coinciding) for Harlequin regular (150 lpi) and for diffused screening

Over a dozen pictures of different content were printed on same sheet in about 1000 copies at standard printing conditions on offset press KBA Rapida 130. The pictures were positioned in pairs allowing for quality comparison of Scitex Class Screening 175 lpi and HDHP. The latter has used as its basic the screen of the former. So, the stationary image area in each pair has had exactly the same tone and color thereby providing the correct conditions for visual comparison of sharpness and definition (Figure 22).

Quality improvement is more evident for pictures containing the greater amount of fine detail and textures and, as well, for gravure in Figure 23. The same periodic screen was also used for whole stationary area but HDHP just for the left part of an image.

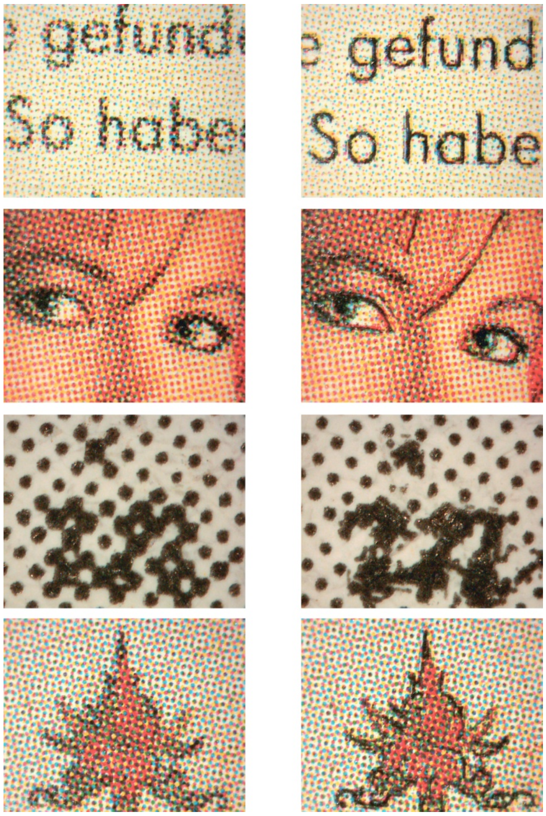


Figure 22: Fragmentary microphotographs of 4-color halftone prints produced at 175 lpi and SF of 2.0 with the use of Scitex Class Screening (left) and HDHP (right), Kuznetsov (2016b)

As it is seen on the enlarged fragment of Figure 23, its HDHP processed left part contains, to the contrary to its right part, the print elements (dots, lines and blanks) much smaller of minimal printable ones conventionally used in the halftone range settings (from 3–5 % to 95–97 %). Being present in output HDHP signal, such elements, nevertheless, doesn't have effect on resulting printability due to such dots/lines loss and blanks filling just once again increasing the contour fidelity.

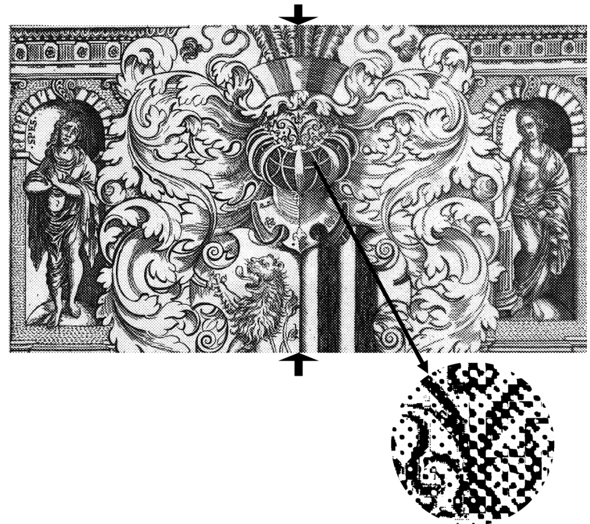


Figure 23: Halftone image of gravure with the use of HDHP (left part) and just of the same basic, conventional spot function (right part), Kuznetsov (2016b)

The rate of improvement increases when the image spatial frequencies are predominantly located in the wave band positioned between the frequencies of a screen and of twice higher input sampling. It is also dependent on the reproduction scale for its effect on the degree and distribution of auxiliary functions use. The special software option was developed to display this use by a histogram in our research (Figure 24). Such kind of visualization can also be useful for the semantic analysis of high frequency image content or to characterize the specific of creating some piece of art, e.g. gravure.

Another print trial has allowed for comparing the HDHP of 175 lpi with the Agfa ABS (175 lpi) and hybrid Agfa Sublima (210 lpi, 240 lpi) technologies. Microphotographs in Figure 25 vividly illustrate the higher sharpness and definition with HDHP at 175 lpi than that of, intended for the same purpose, hybrid screening at as much as 240 lpi.

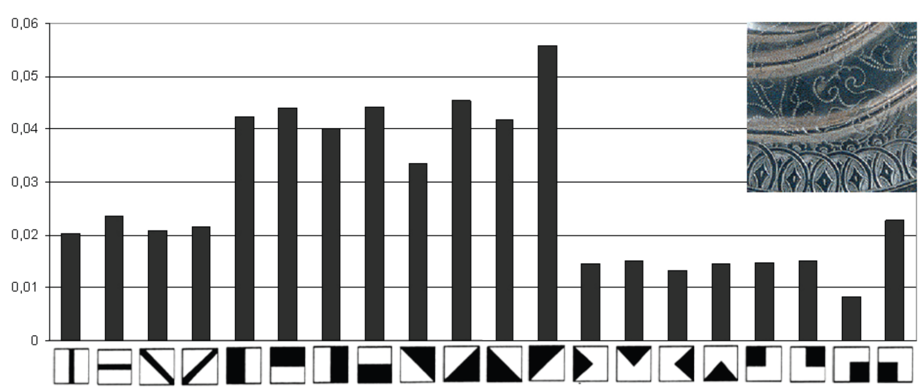
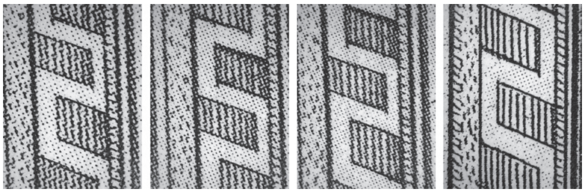


Figure 24: Distribution of various geometry tiles use in adaptive halftoning of the image fragment



a) b) c) d)

Figure 25: Photographs of halftones produced at SF of 2.0 with the use of (a) Agfa ABS (175 lpi), (b) hybrid Agfa Sublima (210 lpi), (c) hybrid Agfa Sublima (240 lpi) and (d) HDHP (175 lpi), Kuznetsov (2016b)

Advantages were especially evident for the screen printing in various combinations of its relatively low rulings (85 lpi and 100 lpi) with the meshes of 240 and 300 threads/inch on different substrates. The flexography tests have shown rather excessive increase of sharpness which, however, can be easily compensated by the HDHP settings control.

For testing in digital printing the special file was prepared with resolution grids and realistic images. One of its parts is the EPS file produced according the scheme in Figure 27 while the other one is the source TIFF to be halftoned in a printer default mode. The both parts were output on the same sheet.

The lack of resolution is inherent in digital printing (600 dpi against 2 400–5 400 dpi of filmsetters, platesetters). So, a lot of effort was spent and solutions patented for the screening techniques enhancement providing the appropriate screen ruling of digitally printed halftones. Shortage of quantization scale at high rulings was compensated there by the increase of addressability (Kishida, 1991), use of multi clustered screen functions (Kang, 1995), multilevel screening (Jin, et al., 2015) and other means of expanding the halftone dots “alphabet”. With such solutions concealed within a printer driver the results we have got for the most of over a dozen tested machines were looking surprisingly good. Some examples are shown in Figure 26.

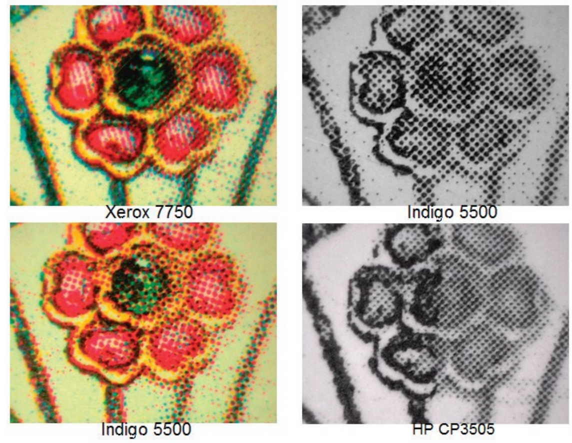


Figure 26: Seamlessly divided fragment of the test file outputs: in a printer default mode (right parts of each image); with use of HDHP (left parts), Kuznetsov (2016b)

4.5 HDHP use in prepress environment and further developments

The latest version of HDHP program creates the according to Equation 2 modified CT file for a stationary image area and the LW mask (bitmap) of tiles for contours and thin lines, the both being then combined in EPS or TIFF file. After EPS file interpretation, the RIP creates a halftone bitmap for CT component and combines it in overprint mode with the LW mask (Figure 27).

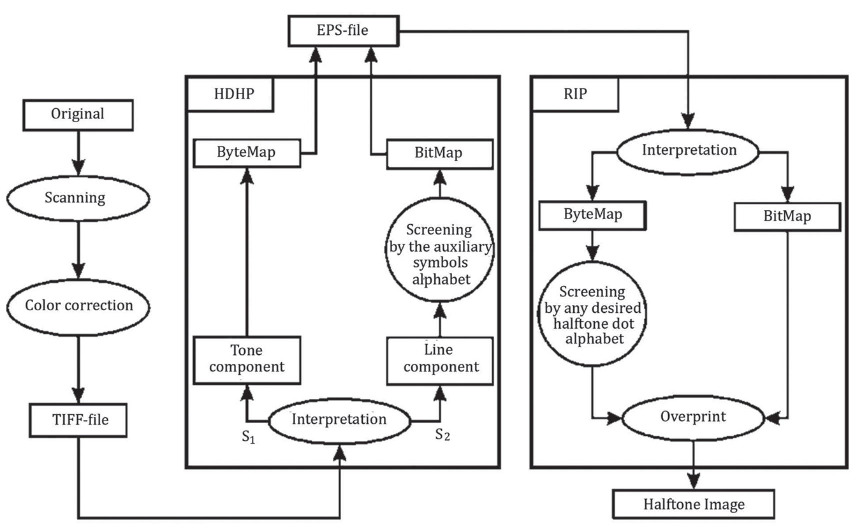


Figure 27: HDHP within the prepress workflow

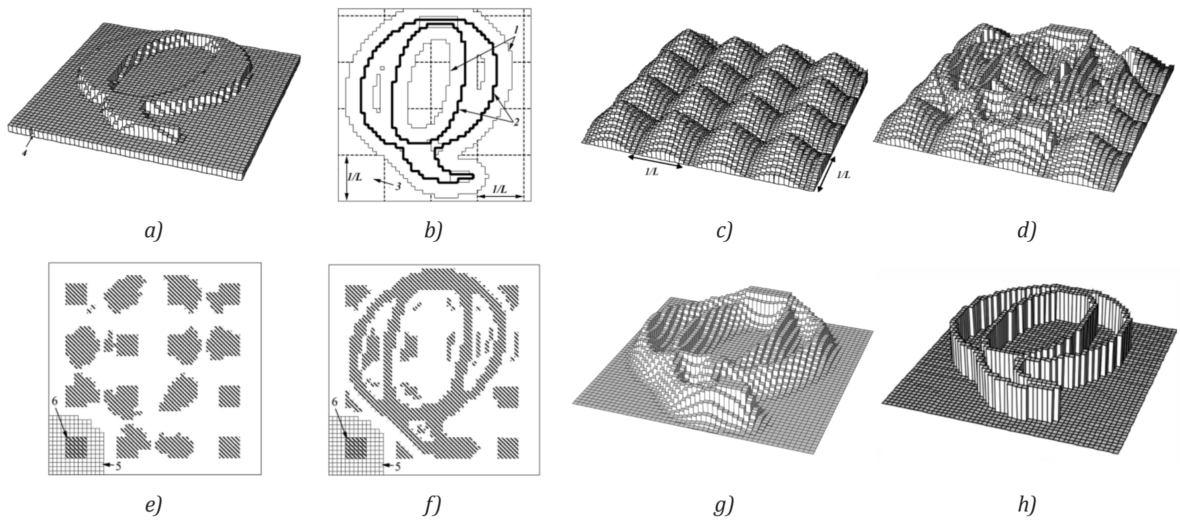


*Figure 28: Halftoning adaptive to arbitrary contour: multilevel fine scan of a dark detail on gray background (a); its scheme (b) designating the margins **1** of tone value dispersion, "trace of contour" **2** and period **3** of a basic screen function shown on (c); resulting screen function (d); halftones (e) and (f) produced correspondingly with the use of functions (c) and (d); auxiliary function (g) generated adaptively to arbitrary contour with the use of its "trace" signal (h) within margins **1** of (b), Kuznetsov and Shadenko (2005)*

This way of operating allows for exactly the same tone and color rendition as provided by a RIP or customer profiles for the stationary area. Moreover, the parts processed in the HDHP mode and in some conventional manner can be seamlessly divided in any area of an image thereby providing the facility of absolutely correct visual comparison of a reproduction quality.

With the on-line use of this HDHP version, the films were output and the number of art books was produced in four color production runs without any additional adjustments of printing conditions or requirements to printing consumables. Some color images seamlessly combining two screening techniques were also published in graphic technical magazines.

Relying on the standard volume of an input image data at SF = 2.0, i.e. in coarse-scan/fine-print mode the HDHP twice increases the halftone definition and improves the quality of standalone lines. However, the printing process resolution still stays about five times higher. For more completely use of this reserve, the fine-scan/fine-print mode with about hundred times larger input image file is required. With taking into account the constant increase of data storage facilities, computation/transmitting speeds and in view of permanently growing requirements to print image quality the processing of such files doesn't nowadays look as problematic as at times of beginning the adaptive screening research.

Instead of operating with the predominantly given set of finite size weight matrices, we have proposed the quantization scale spatial dispersion adaptive to an arbitrary contour as the way to more effective use of the "excessive" volume of an input image data as shown in Figure 28 (Kuznetsov and Shadenko, 2005).

Auxiliary screen function (Figure 28g) can be "on-fly" produced on the basis of the contour "trace or path" signal (Figure 28h) within the margins **1** designated in Figure 28b. This signal is created by the differential operator dealing with the high-resolution input data and that's why it is completely representative for the image high spatial frequency content. With such a signal being formed the input data can be downsampled at over a 100 times compression ratio. So, the combination of downsampled "byte map" and of contour trace signal bitmap may comprise the basis for the file format to be effectively used in fine-scan/fine-print way of a hardcopy production.

5. Conclusions

Basic quality parameters of a graphic arts product are fundamentally dependent on printing element area, form and geometry of placement. So, the screening stays among the most actual issues of illustrative printing. Conflict of tonal and spatial resolution, inherent in this procedure, is solved on behalf of keeping the first of them constant for all the variety of screen frequencies. Their choice depends, in its turn, on the available minimal size of a halftone dot. Providing it over the print sheet within a run is the basic criteria of halftone printing optimal adjustment.

Spatial dispersion of tone measure requires the great excess of a printer resolution over screen ruling which comprises, at the same time, the reserve for print quality improvement. The specific of an HVS should be exploited for more effective use of such resource.

The optimal geometry of a screen and halftone dot, as well as, the way of a dot form variation was empirically found in over a century of halftone printing. The number of later suggested solutions failed to be practical because of the ignoring long-term industry experiences. The need exists in a quantitative method allowing for objective evaluation of screening effect on a print quality. Traditional methods of its estimation incompletely satisfy these purposes due to bi-level nature of halftones. Proposed SEF criteria allow for comparing various screening techniques with the use of its frequency response curves.

Imaging system resources are effectively explored within the tone gradient dependent approach, where the stationary area is presented by some traditional, basic screen, while the set of auxiliary functions of higher frequency provides the dots (tiles) matching the form of detail boundaries.

It is useful to differentiate the way of processing the single and double sharp tone transitions in tone gradient dependent screening.

Relying on the “coarse-scan/fine-print” mode the current HDHP version provides the accuracy of standalone narrow stripes at the level of a printer resolution. However, the further halftone definition increase is limited there due to the lack of a higher frequency input image data.

Instead of operating by predominantly given set of spot functions the better use of an input data excess in “fine-scan/fine-print” system can be provided by the “on-fly” dispersion of tone measure adaptive to the arbitrary contour.

Down-sampled byte map for image stationary part and bitmap for contour trace signal can be combined in the compact file format of such a system.

Results of research and industrial approbation allow foreseeing the adaptive techniques of HDHP kind as “by default” prepress image processing procedures, i.e. as the widespread norm of graphic arts technology.

Acknowlegement

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