Artistic Screening

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Abstract

Artistic screening is a new image reproduction technique incorporating freely created artistic screen elements for generating halftones. Fixed predefined dot contours associated with given intensity levels determine the screen dot shape's growing behavior. Screen dot contours associated with each intensity level are obtained by interpolation between the fixed predefined dot contours. A user-defined mapping transforms screen elements from screen element definition space to screen element rendition space. This mapping can be tuned to produce various effects such as dilatations, contractions and nonlinear deformations of the screen element grid. Discrete screen elements associated with all desired intensity levels are obtained by rasterizing the interpolated screen dot shapes in the screen element rendition space. Since both the image to be reproduced and the screen shapes can be designed independently, the design freedom offered to artists is very great. The interaction between the image to be reproduced and the screen shapes enables the creation of graphic designs of high artistic quality. Artistic screening is particularly well suited for the reproduction of images on large posters. When looked at from a short distance, the poster's screening layer may deliver its own message. Furthermore, thanks to artistic screening, both full size and microscopic letters can be incorporated into the image reproduction process. In order to avoid counterfeiting, banknotes may comprise grayscale images with intensity levels produced by microletters of varying size and shape.

Keywords

Image reproduction, graphic design, halftoning, artistic screening, microlettering

1 Introduction

Halftoning and screening techniques are aimed at giving the impression of variable intensity levels by varying the respective surfaces of white and black within a small area. Traditional techniques use repetitive screen elements, which pave the plane and within which screen dot surfaces define either white or black parts [17]. As long as the screen element period is small, or equivalently, the screen frequency is high (for example 150 screen elements per inch), distinct screen elements cannot be perceived by the human eye from a normal viewing distance [11]. However, in order to achieve such high screen frequencies, resolutions above 2400 dpi are required. With office printers, respectively photocomposers, having resolutions between 240 and 800 dpi, respectively between 1200 and 2400 dpi, halftoning or screening effects cannot be completely hidden. This explains why so much effort has been invested in developing halftoning techniques which reduce the impact of halftoning artifacts as much as possible [7].

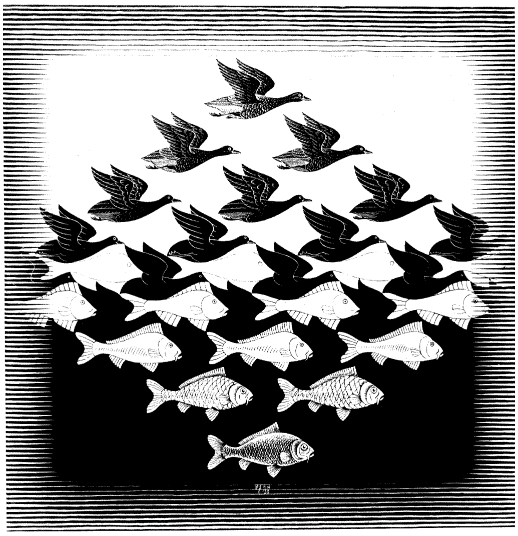

Figure 1: Escher's *Sky and Water* woodcut (reproduced with permission, ©1995 M.C. Escher, Cordon Art, Baarn, Holland).

We would like to take a different approach. Instead of looking at the halftoning layer as a pure functional layer producing undesired *artifacts*, we propose a new screening technique which enables the shape of screen dots to be tuned. By creating artistic screens which may take any desired shape, screening effects, which up to now were considered to be undesirable, are tuned to convey additional information for artistic purposes.

The approach we follow is somewhat related to the *pen and ink illustration techniques* where pen strokes are used for sketching illustrations, at the same time creating texture and intensities. While computer-aided pen and ink illustration systems [18] aim to offer the same flexibility as traditional pen-based stroking, artistic screening, as presented in this contribution, is a new computer-based image reproduction technique, which opens a new design space for artistic realizations.

For artistic screening, we extend the dynamics of screen dot

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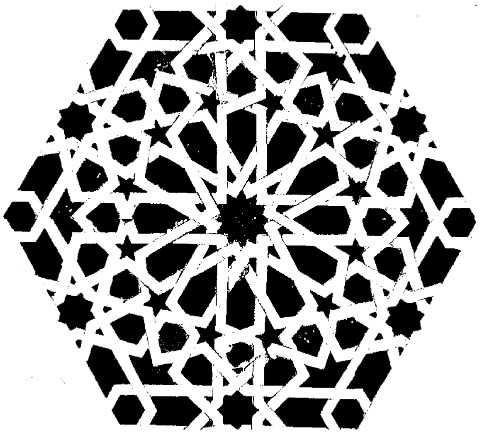

Figure 2: Mosaic tilework faces walls surrounding the courtyard of the Attarine Medeza, Fez (Courtesy of R. and S. Michaud, Rapho).

Figure 3: Thoulthi classical calligraphy by Majed Al Zouhdi (Courtesy of H. Massoudy, [8]).

shapes by using more sophisticated artistic shapes as screen dots. We would like to have full control over the evolution of the artistic screen dot shape and at the same time offer a halftoning method which is competitive with regard to conventional high-resolution clustered-dot screening. We have sought our inspiration in the work of medieval artists [1], who after having tiled the plane with repetitive polygonal patterns, created beautiful ornaments in each of the separate tiles (Fig. 2). Escher [12] further developed this technique by letting shapes circumscribed by a regular tile smoothly grow into one another (Fig. 1). The present work is also related to the decorative motives found in Islamic art which incorporate beautiful calligraphic work with letter shapes well-distributed over a given geometric surface (Fig. 3).

Previous attempts to develop screen dots having non-standard shapes were aimed at improving the tone reproduction behavior at mid-tones [9]. Elliptic screen dots for example, have an improved tone reproduction behavior due to the fact that at the transition between 45% and 55% intensity, at first only two neighbouring dots touch each other and only after a certain increase of intensity does the screen dot touch all its four neighbours (Fig. 4).

State of the art techniques for generating screen dot shapes are based on dither threshold arrays which determine the dot growing behavior. Since the dither threshold levels associated with the dither cells of a dither threshold array specify at which intensity the corresponding binary screen element pixels are to be turned on, the so generated screen dot shapes have the property of overlapping one another.

In order to generate screen dots of any shape, which need not overlap one another and which may have self-intersecting contours, we propose a new way of synthesizing screen dot shapes. We define the evolution of screen dot contours over the entire intensity range by interpolating over a set of predefined fixed dot contours which define the screen dot shape at a set of fixed intensity levels. Once the evolving shape of the halftone dot boundary is defined exactly for every discrete intensity level, the screen elements associated with each intensity level are rasterized by filling their associated screen dot contours (Section 3).

After having generated the screen elements, digital screening proceeds with the halftoning process described in more detail in Section 2. This halftoning process distinguishes itself from previous halftoning methods described in the literature [7] by the fact that the screen elements associated with every intensity level are precomputed and that no comparisons between original gray levels and dither threshold levels are necessary at image generation time. Furthermore, it ensures smooth transitions of the artistic halftone pattern in regions of high intensity gradients by applying bi-linear interpolation between source image pixels.

The results obtained with artistic screening (Section 5) demonstrate that contour-based generation of halftone screens effectively provides a new layer of information. We show how this layer of information can be used to convey artistic and cultural elements related to the content of the reproduced images. Since there is no limitation to the size of the halftone screen elements, they can be made as large as the image itself. The introduced mapping (Section 4) between screen element definition space and screen element rendition space enables the production of highly desirable, smooth deformations of screen dots, without affecting the image content. In addition to their nice visual properties, geometric transformations of screen element shapes are of high interest for creating microscopic letters for security purposes, for example on banknotes.

Since artistic screening relies on the evolution of dot shapes at continuous intensity levels and since it allows building large screens (superscreens) containing arrays of screen subshapes, it is also able to produce traditional halftone screen dots having those frequencies and orientations which are required for traditional colour reproduction. Artistic screening may therefore also be used at high resolution as an alternative to current exact-angle clustered-dot screening techniques [2].

2 The halftoning process

Classical clustered-dot halftoning techniques rely on ordered dither threshold arrays. A dither threshold array is conceived as a discrete tile paving the output pixel plane. A dither threshold level is associated with each elementary cell of the dither threshold array. The succession of dither threshold levels specifies the dot shape growing

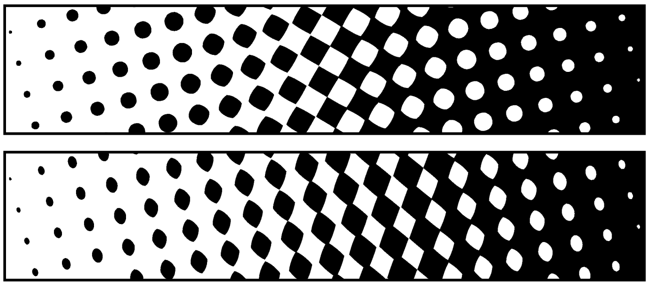

Figure 4: Traditional screen dot shapes, above with round and below with elliptic screen dots, produced by the artistic screening software package.

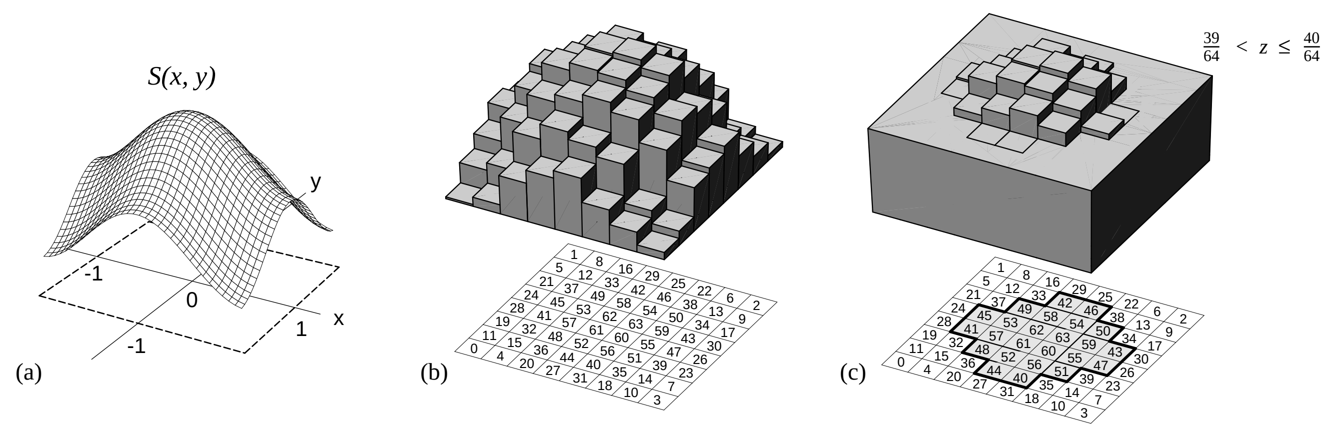

Figure 5: Spot function, dither matrix, and corresponding screen dot shapes.

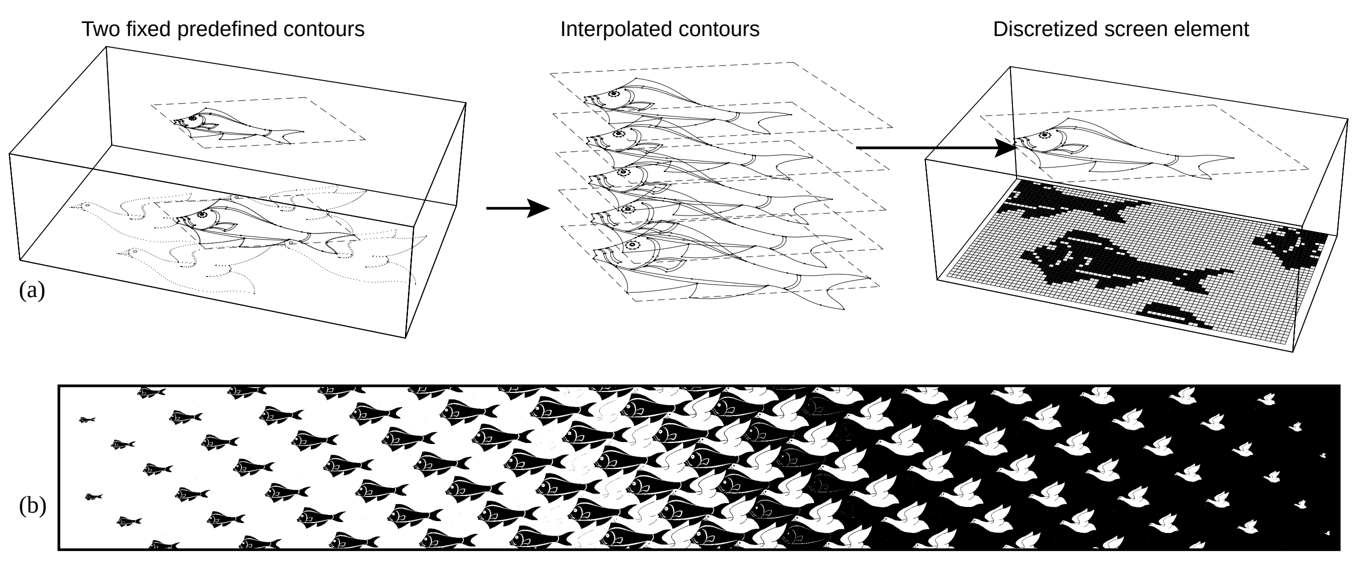

Figure 6: Artistic screening with a screen dot pattern inspired by Escher reproduced on an image representing a grayscale wedge.

behavior at increasing intensity levels (see Fig. 5). Dither threshold levels can either be specified manually or algorithmically [17]. Previous algorithmic approaches for generating discrete dither arrays are based on *spot functions* [2]. A spot function $z = S(x, y)$ defines the dither threshold levels for a dither element tile defined in a normalized coordinate space ($-1 \le x, y < 1$).

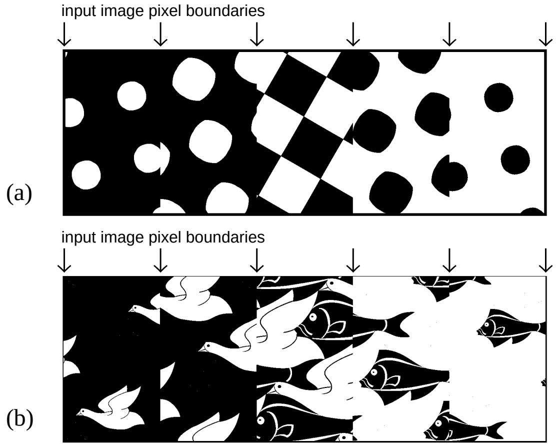

Figure 7: Effect of rapid intensity transitions on (a) standard clustered-dot screen elements and (b) artistic screen elements (enlarged).

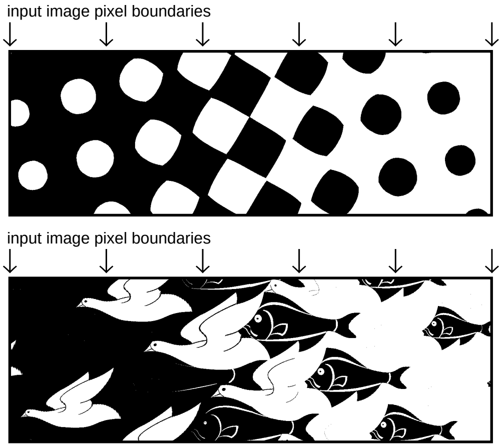

Figure 8: Rapid intensity transitions smoothed out by bi-linear interpolation of source image pixels at halftoning time on (a) standard clustered-dot screen elements and (b) artistic screen elements (enlarged).

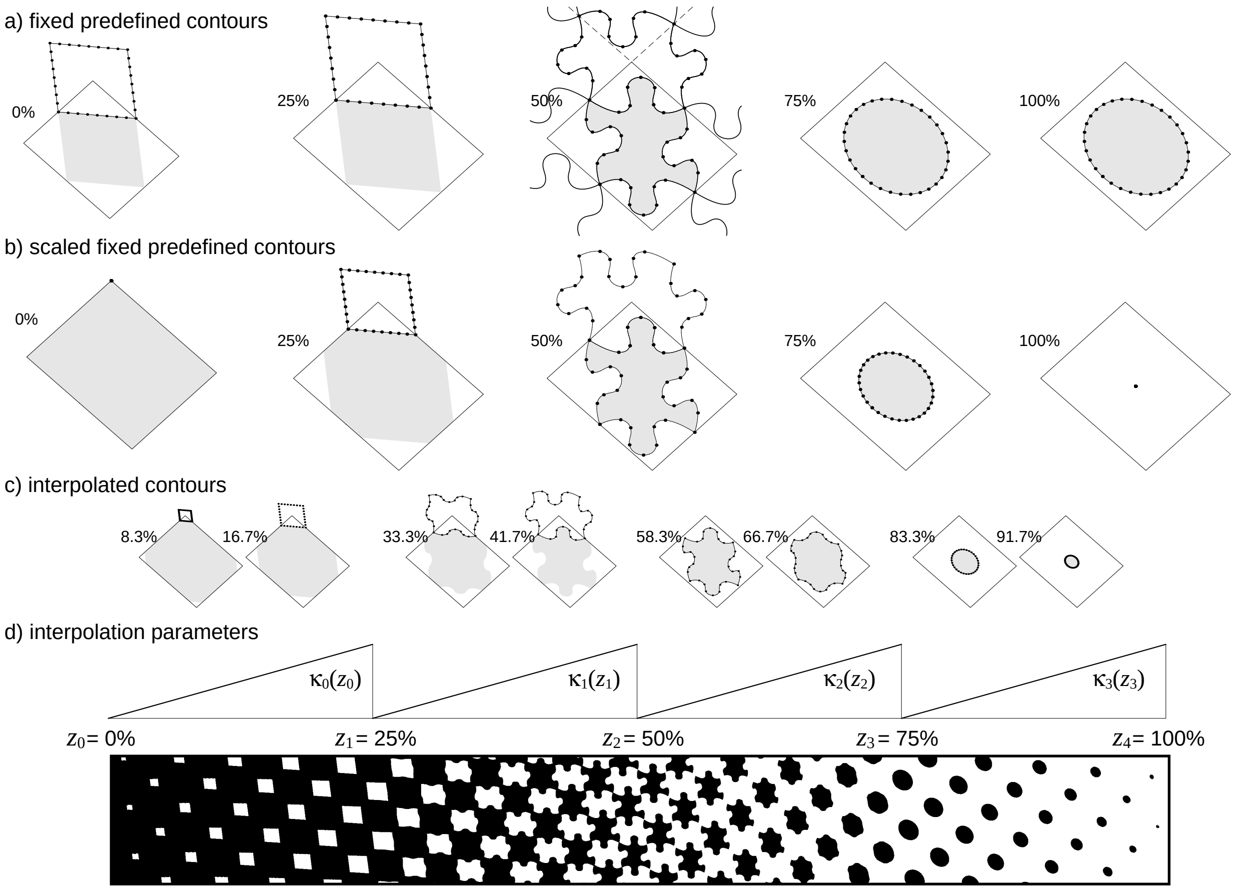

Figure 9: Simple dot shape obtained by blending between a set of fixed contours.

By discretizing this spot function, i.e, by computing its elevation at the coordinates of the centers of individual screen cells, and by numbering successive intersection points according to their elevations (Fig. 5b), one obtains the dither threshold array used for the halftoning process. The comparisons between given source image pixel intensity levels z and dither threshold levels determine the surface of a screen dot. For example, the dot shape associated with an input intensity level of 40/ 64 is obtained by activating all screen element pixels with threshold values 40 or greater (Fig. 5c).

With a given dither threshold array, the classical halftoning process consists of scanning the output bitmap, for each output pixel, finding its corresponding locations both in the dither array and in the grayscale input image, comparing corresponding input image pixel intensity values to dither array threshold levels and accordingly writing pixels of one of two possible ouput intensity levels to the output image bitmap.

Since artistic screening is not based on dither matrices, we precompute the screen elements (halftone patterns) representing each of the considered intensity levels. The halftoning process associated with artistic screening consists of scanning the output bitmap, and for each binary output pixel, finding its corresponding locations both in the grayscale input image and in the screen element tile. The input image intensity value determines which of the precomputed screen elements is to be accessed in order to copy its bit value into the current output bitmap location (Fig. 6a). This process may be accelerated by executing the same operations with several binary output pixels at a time [10].

In standard clustered-dot screening, due to the comparison between source pixel intensity values and dither threshold values, rapid transitions within a single halftone screen element are possible (Fig. 7a). They ensure that rapid intensity transitions occurring in the original image are preserved in the halftoned image. With artistic screen elements however, rapid transitions may introduce unacceptable distortions in the screen dot shape (Fig. 7b). Smoother transitions are obtained by computing for each output bitmap pixel the corresponding interpolated gray intensity value at the corresponding location in the source image pixmap (bi-linear interpolation). Smoother intensity variations will be associated with output bitmap neighbourhoods, which will in turn smooth out the transitions within single artistic screen elements (Fig. 8). If the original image is scanned at high resolution (300 dpi and higher), undesired sharp intensity transitions may be avoided by applying to it a low-pass filter. There is a trade-off between the continuity of the halftone dot shapes and the faithful reproduction of sharp transitions.

3 Contour-based generation of discrete screen elements

Spot functions $S(x, y)$ generating simple screen dot shapes can be described easily. More complicated spot functions for generating shapes such as the dot shapes described in Fig. 6 are impossible to generate, since they cannot be described as single valued functions.

In order to generate complicated dot shapes capable of representing known subjects (birds, fishes) or objects (letter shapes), we define the evolving screen dot shape by a description of its contours. For this purpose, we introduce fixed predefined screen dot contours which are associated with specific intensity levels. Shape blending techniques [15] are used to interpolate between those predefined screen dot contours at all other intensity levels.

The fixed predefined contours, defined in a screen element def-

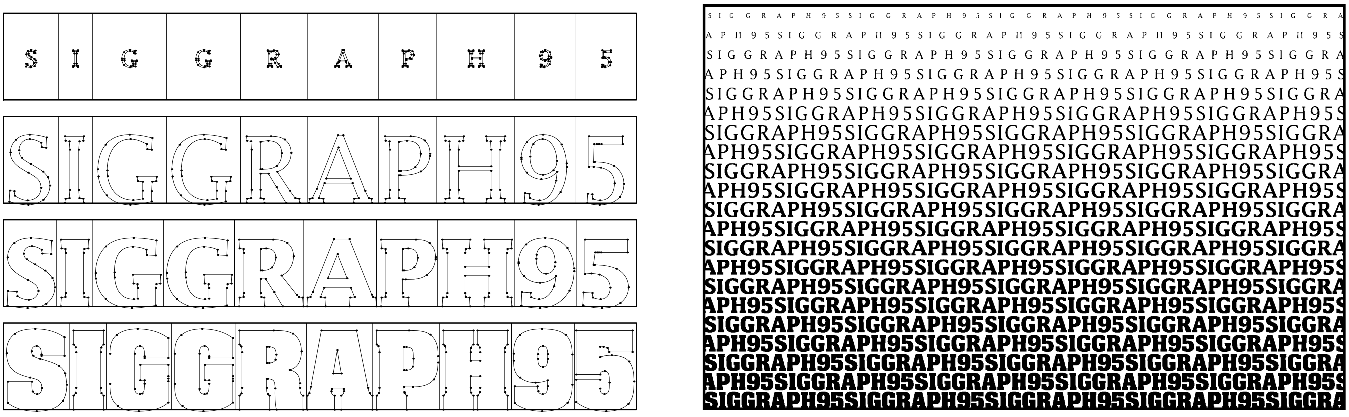

Figure 11: Screen tile containing subscreen shapes made of individual characters, at different intensity levels.

inition space, are designed by a graphist using a shape drafting software package such as Adobe Illustrator. The graphist defines his contours in the screen element definition coordinate space of his preference. Figure 9a shows a set of fixed predefined contours defining the evolution of a screen dot shape.

For ease of implementation, we assume that each fixed contour has the same number of distinct contour parts and that the contour parts of the interpolated contours are obtained by blending between corresponding fixed contour parts. Curved contour parts may be described by polynomial splines. For convenience, we use a cubic Bézier spline given by its control polygon to define each curved contour part. In order to simplify the interpolation process, we also assume that each straight line contour part is also defined by Bézier control polygon having its vertices aligned on the given straight line segment. The arrangement of contour parts in each of the fixed predefined contours governs the interpolation process (Fig. 9).

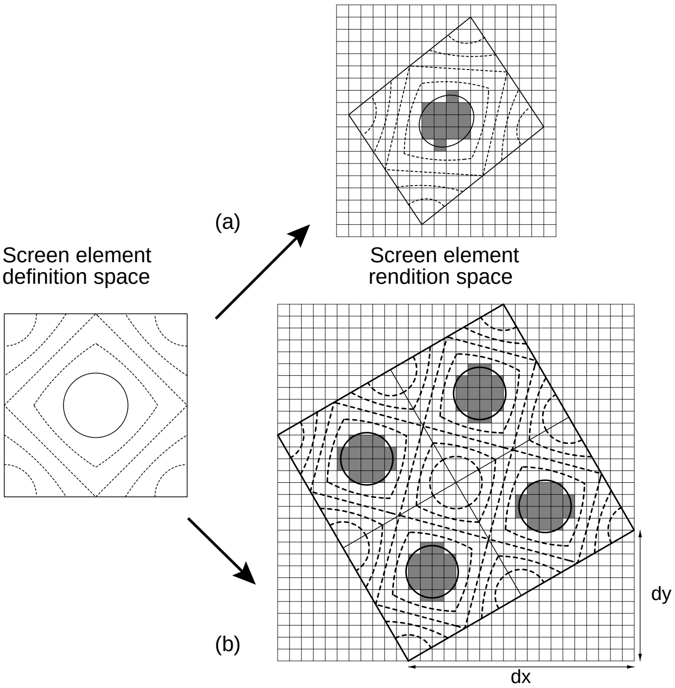

Figure 10: Transformation between screen element definition and rendition space (a) applied to a small screen tile and (b) applied to a large screen tile (super screen) made of repetitive subscreen elements.

In order to control the speed at which the interpolated contour parts move from one fixed contour to the next, we introduce interpolation parameters $\kappa_i(z)$ varying between 0 and 1 (Fig. 9d). The coordinates of a control point $\vec{P}$ at intensity z interpolated between two fixed contour control points $\vec{P}_i$ and $\vec{P}_{i+1}$ associated with the extremities of intensity range $[z_i, z_{i+1}]$ is given by

$$\vec{P}(z) - \vec{P}_0 = (1 - \kappa_i(z))\,(\vec{P}_i - \vec{P}_0) + \kappa_i(z)\,(\vec{P}_{i+1} - \vec{P}_0) \qquad (1)$$

where $\vec{P}_0$ represents the screen element origin.

Parameters $\kappa_i(z)$ are mapped to the range of intensity levels $[z_i, z_{i+1}]$ by interactively defining the curves $\kappa_i(z)$ in the same way as gamma correction curves are defined in well known grayscale halftoning packages (Adobe Photoshop for example). Figure 9 shows the full intensity range, fixed predefined and intermediate contours as well as their associated interpolation parameters.

In the range between intensity level $z_0 = 0$ and intensity level z_1 associated with the first fixed contour, the only operation which takes place is scaling. We therefore assume that the contour at level z_0 is a fixed contour of infinitely small size and that it has the same number of control points as the one at level z_1.

The tone reproduction behavior of a given printing process depends heavily on the dot gain, i.e. to what extent the printed dot has a larger surface than expected due to printer toner or ink spread properties. For a given printing process, the tone reproduction behavior depends on the shape of the printed dot. When increasing the darkness (or, equivalently, decreasing the intensity) at light and mid-tones, the relative printed surface increase is larger for dots having a higher contour to surface ratio. Since the fixed contours defining the artistic screen dot shape may have any contour to surface ratio, the surface growth of the printed dot for a given intensity difference may vary considerably at different intensity levels. We can therefore use interpolation parameters $\kappa_i(z)$ as local gamma correction factors [4].

If the created screen element is required to have a similar shape growing behavior in the light and in the dark tones, one may first design the fixed screen dot contours in the light tones and then in the dark tones. Taking into account the plane tiling behavior of a single screen element, the fixed contours associated with intensity levels, $z \leq 0.5$ are drawn at a location whose center is translated by half a period in each direction from the original screen element center. The fixed contour parts located on the three quadrants outside the original screen element boundary are copied back into the original screen element (see Fig. 9a, 50% intensity).

A single fixed contour associated with an intensity level equal to or close to $z = 0.5$ delimits the white growing region and the black growing region.

Once all fixed contours have been designed in the screen element definition space, and the table of blending parameters is initalized

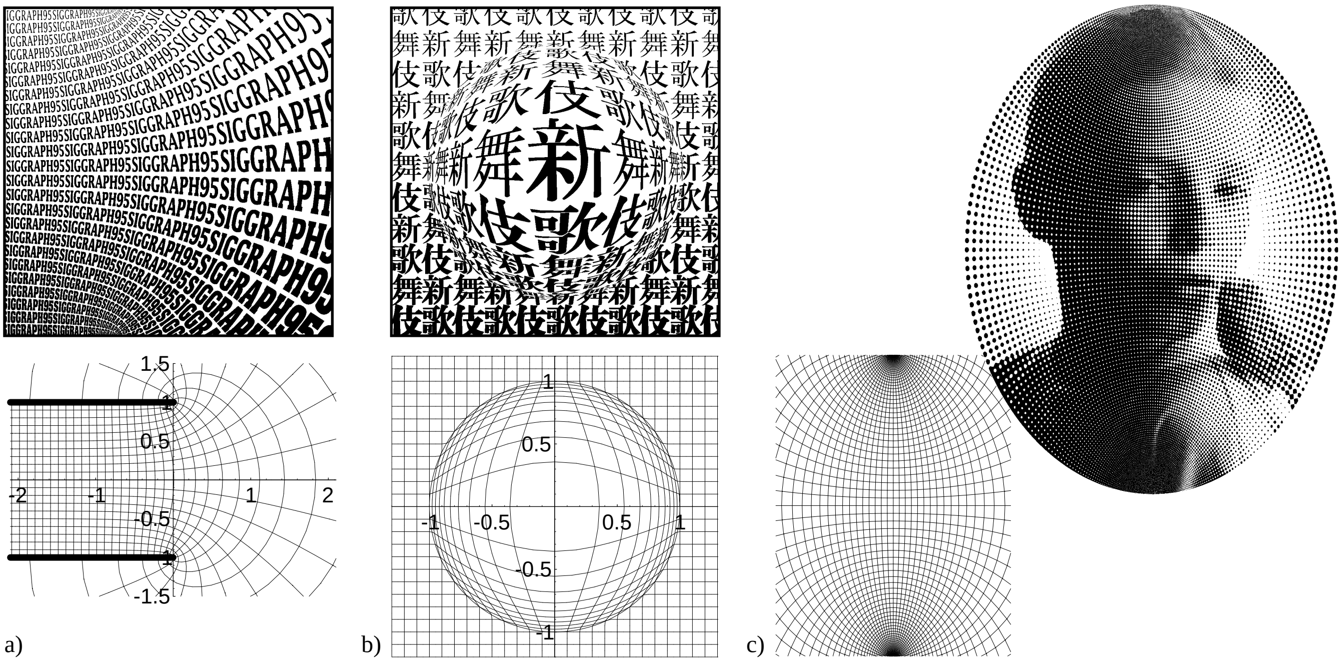

Figure 12: Non-linear mapping between screen definition and screen rendition plane.

with values $\kappa_i(z)$, one merely needs to define the corresponding screen element boundaries in the screen element rendition space, e.g. in the space associated with the output bitmap. The transformation between screen element definition space and screen element rendition space enables the fixed predefined screen dot contours to be defined independently of the orientation and size of the final screen elements (Fig. 10). This transformation provides the basis both for screen element morphing (see Section 4) and for the generation of screen elements having exact screen angles, as required by traditional colour reproduction techniques [19].

A square screen element defined by its supporting cathets and (Fig. 10b) whose desired orientation is given by angle can be approximated by an angle $\alpha' = \arctan\left(\frac{dy}{dx}\right)$ as closely as required by increasing integer values dx and dy. The screen element's subdivision into a certain number of replicated subscreen dot shapes defines its screen frequency. In the screen element definition space, all subscreen dot shapes are identical. In the screen element rendition space however, rasterized discrete subscreen elements differ slightly one from another due to the different phase locations of their respective continuous contours (Fig. 10b). At high resolution, the so obtained exact angle screen elements are equivalent to the super-screening methods known in the field of colour reproduction [2], [13]. They have the advantage of offering the potential for colour reproduction with specifically designed screen shapes.

Once the fixed predefined contour parts have been transformed from screen element definition to rendition space, the discrete screen elements may be generated for each discrete intensity level. For reproducing 256 intensity levels, the intensity interval between $z = 0$ and $z = 1$ is divided by 255 and intermediate screen dot contours are successively generated at intensity levels $z = 0, z = 1/255, \ldots, z = 255/255$. At each discrete intensity, the screen dot contours are rasterized by applying well known shape rasterization techniques [4]. In the case of self-intersecting dot contours or dot contours having at a single intensity level multiple intersecting contours, care must be taken to use a scan-conversion and filling algorithm supporting the non-zero winding number rule and generating non-overlapping complementary discrete shapes [5]. Furthermore, the filling algorithm must be able to fill shapes becoming smaller and smaller until they disappear [6]. Figure 6 shows the result with an artistic screen dot shape inspired by Escher's drawing (Fig. 1a), reproduced on a grayscale wedge. Small details, such as the wings of the bird, progressively fade out as the bird's shape size decreases.

4 Screen Morphing

Since screen tiles can be as large as desired, they can be conceived so as to cover either the whole or a significant part of the surface of the destination halftoned image. Such large screen tiles are divided into elementary subscreen shapes which may contain either identical or different shapes. For microlettering applications, each elementary subscreen shape may contain a different letter shape (Fig. 11).

By defining the mapping from screen element definition space to screen element rendition space as a non-linear transformation, smooth, highly esthetic spatial variations of the subscreen shapes can be attained. For example, conformal mappings [14] [3] transform a rectangular grid of screen element sub-shapes into the sub-shapes of a deformed grid following electro-magnetic field lines (Fig. 12a). In that example, the conformal mapping is $w = k(1 + z + e^z)$, where k is a real scaling factor, z represents complex points $z = x + iy$ lying in the original (x, y) plane and $w = u + iv$ the corresponding complex points lying in the destination (u, v) plane.

Alternatively, if one would like to enlarge a few screen subshapes at the expense of their surrounding subshapes, one may define a circle of unit radius within which a geometric transformation maps the original rectangular grid into a highly deformed grid (Fig. 12b). A possible transformation is one that keeps the angle and modifies the distance of points from the center of the circle (fisheye transformation). With the center of the circle as the origin of the coordinate system, the mapping expressed in polar coordinates is the following:

$$\theta' = \theta; \quad r' = \begin{cases} \dfrac{m * \frac{r}{1-r}}{1 + m * \frac{r}{1-r}} & \text{if } r < 1 \\ r & \text{otherwise} \end{cases} \tag{2}$$

where m is a magnifying factor.

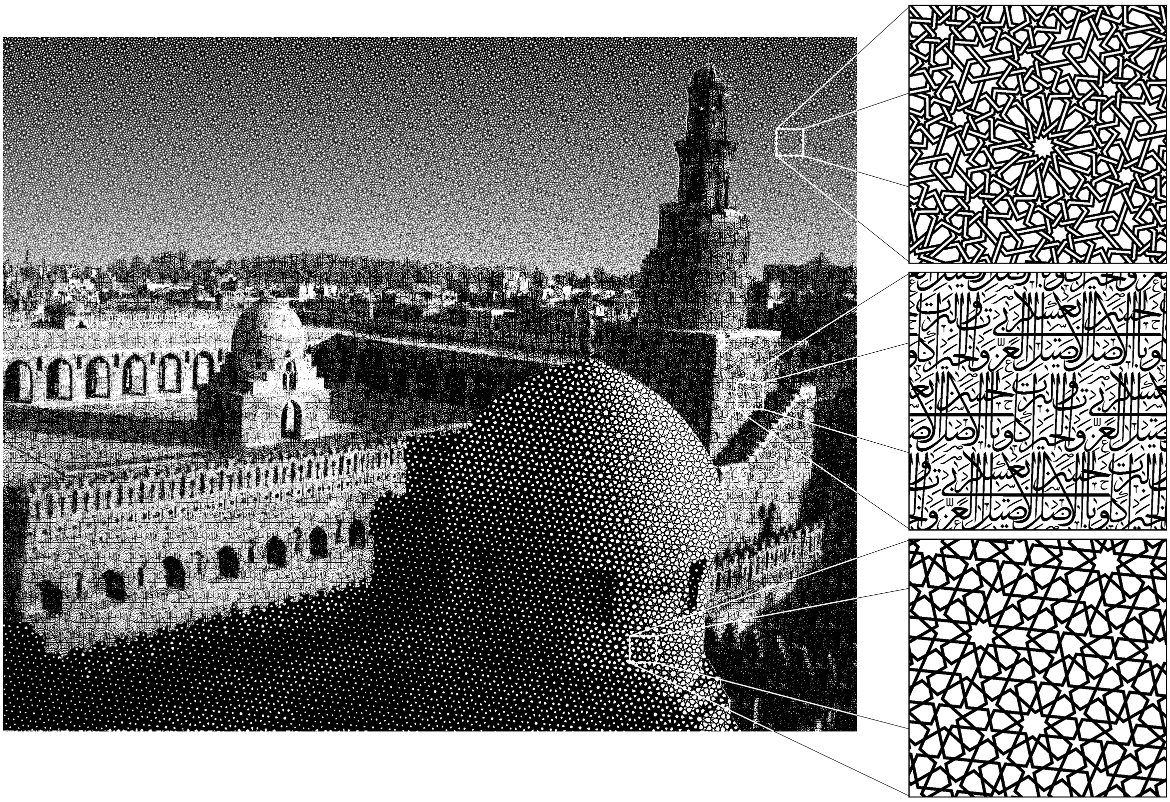

Figure 13: View of the Ibn Tulun Mosque, Cairo (Courtesy of R. and S. Michaud, Rapho).

5 High-quality artistic screening

In high-quality graphic applications, the shapes of artistic screen dots may be used as a vector for conveying additional information. This new layer of information may incorporate shapes which are related to the image. When reproduced in poster form, the screen elements of the screening layer will become sufficiently large to produce the desired visual effect.

In Figure 13, we show an example of a mosque rendered by screen dots made of calligraphic arabic letter shapes and oriental polygonal patterns. This screening layer adds a touch of islamic culture to the reproduced image.

The next example (Fig. 14) shows a poster displaying a scene inspired from the well-known Kabuki theater shows. Such a poster could be used for example to advertise a Kabuki theatre performance. The beautiful Kanji letter shapes can be seen close up whereas the full poster can only be perceived from a certain viewing distance. These two different views complement one another and each contributes towards transmitting the message to the public.

In the last example, we show that artistic screening can bring new solutions for avoiding desktop counterfeiting [16]. Since 1990, the US treasury protects banknotes by using microprinting techniques for generating letters having a size of approximatively 150 µm in order to avoid reproduction by photocopy or scanners (Fig. 15). In Figure 16, we show that by using artistic screening techniques, microletters of the type shown in Figure 11 can be incorporated into the grayscale image. Furthermore, due to the conformal mapping function $w = tg(z)$ between screen element definition and rendition spaces (Fig. 12c), a non-repetitive screen is created which cannot be scanned easily without producing Moiré effects.

6 Conclusions

We have presented a new halftoning technique, where screen elements are composed of artistic screen dot shapes, themselves created by skilled graphists. Fixed predefined dot contours associated with given intensity levels determine the screen dot shape's growing behavior. Screen dot contours associated with each intensity level are obtained by interpolation between the fixed predefined dot contours. User-defined mappings transform screen elements from screen element definition space to screen element rendition space. These mappings can be tuned to produce various effects such as dilations, contractions and non-linear deformations of the subscreen element grid. By choosing an appropriate mapping, images can be rendered while ensuring a highly esthetic behavior of their screening layer.

Since artistic screening uses precomputed screen elements, its performance at image halftoning time is similar to that of other dithering algorithms. The time required for precomputing the screen elements associated with every intensity level depends on the size of the screen element tile. Limited size repetitive screen elements such as those used in Figures 13 and 14 can be generated quickly (few minutes). On the other hand, very large screen elements morphed over the output image may require considerable computing power and time. Therefore, libraries of precomputed screen elements should be created. With such libraries, artistic screening can be made nearly as efficient as conventional halftoning.

Artistic screening can be seen as a new image reproduction technique incorporating freely created artistic screen elements used for generating halftones. Since both the image to be reproduced and the screen shapes can be designed independently, the design freedom offered to artists is very great. In the examples of sections 4 and 5, we have shown that one may reproduce simple images with complicated screen elements morphed over the destination halftone image, real images with beautiful but repetitive screen shapes or

Figure 14: *Kabuki actor*, by Toshusai Sharaku. Scene inspired from the Japanese Kabuki theater. The word Kabuki, 新歌舞伎 *shin-ka-bu-ki*, is used for creating the Kanji screen dot shape (Courtesy of the British Museum).

real images with complicated and morphed screen shapes.

Artistic screening enables both full size and microscopic letters to be incorporated into the image reproduction process. For example, next-generation banknotes may incorporate grayscale images with intensity levels produced by microletters of varying size and shape.

Currently, artistic screening is made possible by creating screen shapes with existing shape outlining tools and feeding them as input to the artistic screening software package. In the near future, we intend to add specific screen shape creation and morphing tools in order to simplify the design of the fixed predefined screen dot contours and the specification of the transformation between screen element definition and screen element rendition space.

Thanks to these novel computer-based screening techniques, artistic screening may become an important graphic design tool. It may have a considerable impact on future graphic designs.

Figure 15: Microletters on current ten dollar notes.

Figure 16: Design of a banknote incorporating microletters as screen dot shapes.

7 Acknowledgements

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REFERENCES

[1] K. Critchlow, *Islamic Patterns,* Thames & Hudson, 1989.

[2] P. Fink, *PostScript Screening: Adobe Accurate Screens,* Mountain View, Ca., Adobe Press, 1992.

[3] E. Fiume, A. Fournier, V. Canale, "Conformal Texture Mapping", *Eurographics'87,* North-Holland, 1987, 53-64

[4] J. Foley, A. van Dam, S. Feiner, J. Hughes, *Computer Graphics: Principles and Practice,* Addison-Wesley, Reading, Mass., 1990.

[5] R.D. Hersch, "Fill and Clip of Arbitrary Shapes", in *New Trends in Animation and Visualization,* (D. Thalmann, N. Magnenat-Thalmann, Eds.), J. Wiley & Sons, 1991, 3-12.

[6] R.D. Hersch, "Font Rasterization: the State of the Art", in *Visual and Technical Aspects of Type,* (R.D. Hersch, Ed.), Cambridge University Press, 1993, 78-109.

[7] Peter R. Jones, "Evolution of halftoning technology in the United States patent literature", *Journal of Electronic Imaging,* Vol. 3, No. 3, 1994, 257-275.

[8] H. Massoudi, *Calligraphie arabe vivante,* Flammarion, Paris, 1981.

[9] R.K. Molla, *Electronic Color Separation,* Montgomery, W.V., R.K. Printing and Publishing, 1988.

[10] M. Morgan, R.D. Hersch, V. Ostromoukhov, "Hardware Acceleration of Halftoning", Proceedings SID International Symposium, Anaheim, May 1993, published in SID 93 Digest, Vol XXIV, 151-154.

[11] L.A. Olzak, J.P. Thomas, "Seeing Spatial Patterns", in *Handbook of Perception and Human Performance,* (K.R. Boff, L. Kaufman, J.P. Thomas, Eds.), John Wiley & Sons, Vol. 1, 1986, 7.1-7.57.

[12] D. Schattschneider, *Visions of Symmetry, Note, Books, Periodic Drawings and Related Works of M.S. Escher,* W.H. Freeman and Company, New York, 1990.

[13] S.N. Schiller, D.E. Knuth, Method of controlling dot size in digital halftoning with multi-cell threshold arrays, US Patent 5305118, issued on April 19, 1994.

[14] R. Schinziger, P.A.A. Laura, *Conformal Mappings: Methods and Applications,* Elsevier, 1991.

[15] T.W. Sederberg, E. Greenwood, "A Physically Based Approach to 2-D Shape Blending", SIGGRAPH'92,*ACM Computer Graphics,* 26(2), 1992, 25-34.

[16] G. Stix,"Making money, desktop counterfeiting may keep the feds hopping", *Scientific American,* March 1994, 81-83.

[17] R. Ulichney, *Digital Halftoning,* MIT Press, 1987.

[18] G. Winkenbach, D.H. Salesin, "Computer-Generated Pen-and-Ink Illustration" Proceedings SIGGRAPH'94, *Computer Graphics, Annual Conference Series,* 1994, 91-100.

[19] J.A.C. Yule, *Principles of Color Reproduction,* John Wiley & Sons, New York, 1967.

Figure 17: The vignette shown in Fig. 16, enlarged 4 times.