https://doi.org/10.2352/ISSN.2169-4451.2020.36.75

3D Surface Structures and 3D Halftoning

Sasan Gooran and Fereshteh Abedini; Media and Information Technology Division, Department of Science and Technology, Linköping University; Norrköping, Sweden

Abstract

As 3D printing is becoming increasingly popular, the demand for high quality surface reproduction is also increasing. Like in 2D printing, halftoning plays an important role in the quality of the surface reproduction. Developing advanced 3D halftoning methods for 3D printing and adapting them to the structure of the surface is therefore essential for improving surface reproduction quality. In this paper, an extension of an iterative 2D halftoning method to 3D is used to apply different halftone structures on 3D surfaces. The results show that using different halftones based on the 3D geometrical structure of the surface and/or the viewing angle in combination with the structure of the texture being mapped on the surface can potentially improve the quality of the appearance of 3D surfaces.

Introduction

Two-dimensional halftoning is a well-established topic in image reproduction and many 2D digital halftoning methods have been developed over the past half a century. 2D halftoning methods are basically divided into a number of categories, from point-by-point ordered dithering [1] to error-diffusion [2] to advanced iterative halftoning methods such as DBS halftoning algorithm [3]. As 3D printing is becoming more and more popular, the demand for high quality surface reproduction is also increasing. Therefore, development of advanced 3D halftoning algorithms, which directly affect the appearance of 3D surfaces, has been a topical subject over the past few years. Many of the proposed 3D halftoning algorithms are an extension of well-known 2D halftoning algorithms. In [4], Brunton et al. propose an error-diffusion halftoning algorithm to produce full color with multi-jet 3D printer. In order to diffuse the error as proposed in the original 2D error diffusion algorithm, they introduce a novel traversal algorithm for surface voxels. In [5], Michals et al. use the 3D traversal algorithm proposed in [4] and develop a 3D tone-dependent error diffusion method. Their proposed algorithm is a fast 3D halftoning method, which, according to the authors, produces results of quality close to iterative methods [5]. An extension of the 2D DBS halftoning algorithm has also been proposed in [6], which generates high quality surface reproduction. In [7], an iterative 3D halftoning method, called 3D IMCDP (Iterative Method Controlling the Dot Placement) is introduced, which is an extension of the 2D IMCDP halftoning method [8].

Many of the developed 2D halftoning algorithms, such as error diffusion, DBS and IMCDP, belong to the category of FM halftoning methods, which we refer to as the 1st generation FM methods in this paper. In this type of FM methods, the single dots are distributed “stochastically”. There is also another type of FM method, referred to as the 2nd generation FM halftoning in this paper, that “stochastically” distribute the clustered dots [9]. One of the advantages of the 2nd generation FM halftoning over the 1st generation FM is that the former one results in halftones that give less grainy impression in the areas of an image where the tones vary smoothly.

In this work, a 3D extension of the 2D 1st and 2nd generation IMCDP producing different halftone structures is applied to several 3D surfaces. First in this paper, the 1st and 2nd generation FM halftoning based on 2D IMCDP are briefly described, followed by their extension to 3D. In Section 3D structures and halftoning, the 3D IMCDP is used to generate different halftone structures on a test 3D surface to show how different halftones behave with regards to the geometrical surface structure. In the succeeding section, an approach to divide a 3D surface into several different structural areas is proposed and 1st and 2nd generation FM halftones are applied to different parts of the same 3D surface. Finally, the paper is summarized, where some discussions and suggestions for future work are also given.

2D IMCDP, 1st and 2nd Generation FM

The iterative halftoning method, referred to as Iterative Method Controlling the Dot Placement (IMCDP), has been proposed and thoroughly described in [8]. This algorithm, briefly described, starts with a blank image the same size as the original image and places the first dot at the position where the original image holds the maximum pixel value. A very small number is set at this position in the original image to make sure that this position will not be found as the maximum again. The effect of this dot placement is then fed-back into the halftoning process, by subtracting a neighborhood of the position of the found maximum by a filter. By doing that, the probability to find the next maximum in that neighborhood is reduced. This process proceeds and in each iteration one dot is placed at the position of the maximum pixel value and the effect is fed-back by using a filter, until a pre-determined number of dots are placed. The number of dots to be placed are determined by the average value of the original image in different tonal regions. The filter used in the feed-back process is to control the dot placement and plays an important role in shaping different halftone structures. In order to generate first-generation FM halftones, a Gaussian filter, as shown in Eq. 1, is used.

$$h_{1st}(m,n) = Ke^{\frac{-1}{2\sigma^2}\left(\frac{m^2}{k_1}+\frac{n^2}{k_2}\right)}, \quad (1)$$

where (m,n) and σ denote the position and the standard deviation, respectively. K is a normalization factor to make the sum of the filter elements equal to 1 and k_1 and k_2 decide the symmetry of the generated filter. To generate well-formed first-generation and symmetrical halftone structures with blue-noise characteristic, k_1 and k_2 should be equal. Figure 1a, b, and c show a grayscale ramp being halftoned by 2D IMCDP using the Gaussian filter in Eq. 1, with $k_1 = k_2 = 1$, $k_1 = 1\,\&\,k_2 = 3$ and $k_1 = 3\,\&\,k_2 = 1$, respectively. While equal k_1 and k_2 creates a symmetrical halftone structure, unequal k_1 and k_2 could generate horizontal or vertical line halftone patterns. It is also possible to generate line halftones in other directions by

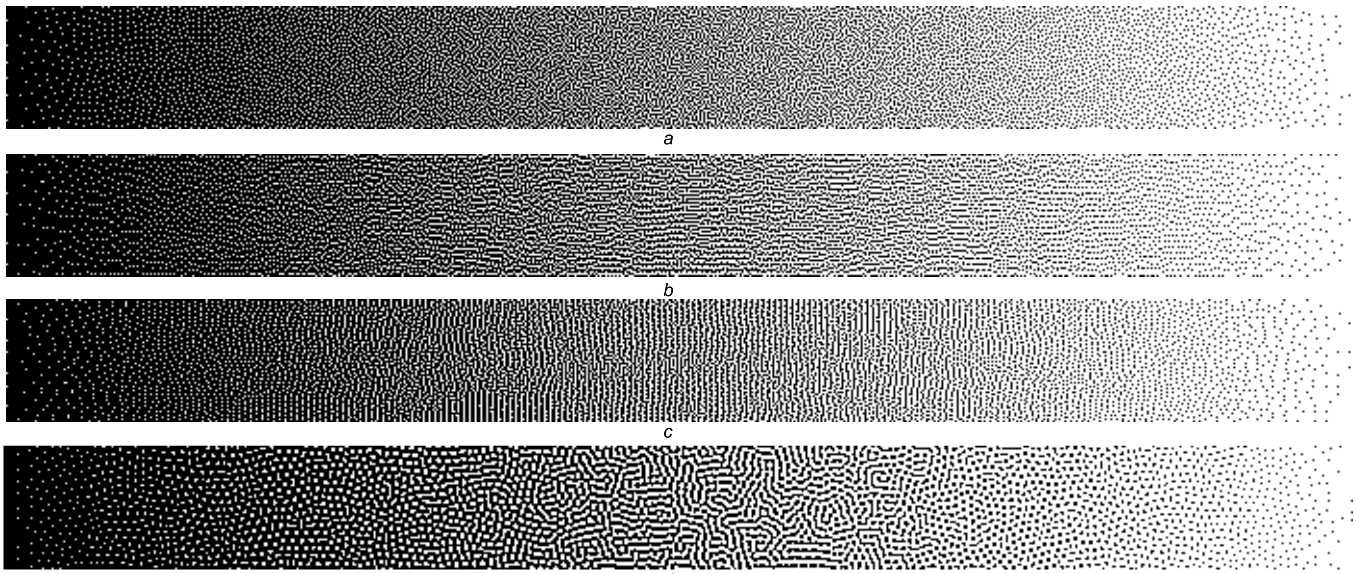


Figure 1 Grayscale ramp being halftoned by a), b), c) 1st generation FM using the filter in Eq. 1 with $k_1 = k_2 = 1$, $k_1 = 1$ & $k_2 = 3$ and $k_1 = 3$ & $k_2 = 1$, respectively. d) 2nd generation FM using the filter in Eq. 2.

rotating the filter in Eq. 1. Other halftone structures are also possible to generate by using other filters than the Gaussian filter in Eq. 1 [9].

Another important aspect of IMCDP is that, it can also generate second-generation FM, i.e. green-noise, halftone structures by using the following filter in the feed-back process.

$$h_{2nd}(m,n) = K\left(e^{\frac{-1}{2\sigma_1^2}(m^2+n^2)} - e^{\frac{-1}{2\sigma_2^2}\left(\frac{m^2}{k_1}+\frac{n^2}{k_2}\right)}\right). \quad (2)$$

The filter in Eq. 2 is a Gaussian function subtracted from another Gaussian function with larger standard deviation, i.e. $\sigma_1 > \sigma_2$. By this filter, the pixel values around the found maximum are decreased with a radius decided by σ_1. After the single dots have been distributed, then the dots start to cluster, and the maximum size of the clustered dots will depend on σ_2 [9]. k_1 and k_2 decide the symmetry of the generated halftones. Figure 1d shows a grayscale ramp being halftoned using the filter shown in Eq. 2 with $k_1 = k_2 = 1$. By appropriate choices of σ_1 and σ_2 it is possible to meet a specific demand for the size of the clustered dot at a certain gray level [9]. It is also possible to generate different halftone structures, dot shapes and alignments using a non-symmetrical or a non-Gaussian filter [9]. The flexibility of IMCDP also allows us to combine different halftone structures on the same image by using appropriate filter in each part of the image. An example could be to use 1st generation FM halftone in the details of an image and 2nd generation FM halftone in the areas where the tones vary slowly. Figure 2 shows an enlargement of a part of a halftoned image displayed at $dpi = 75$, where two different halftones are combined. As seen in this figure, the wall of the clock tower is halftoned mostly by 2nd generation FM while the details, i.e. the highpass regions, for example the small window to the left or the right side of the clock, are halftoned by 1st generation FM halftoning. This was achieved by using the filter in Eq. 1 in the highpass regions and the one in Eq. 2 in the rest of the image.

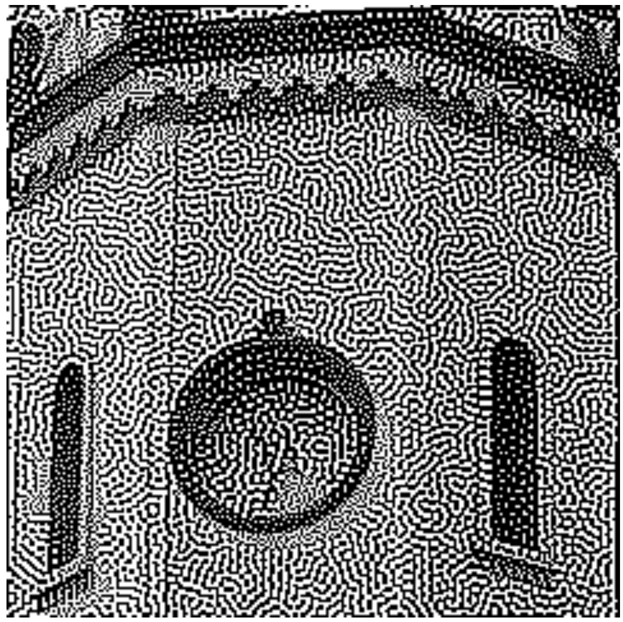


Figure 2 1st and 2nd generation FM halftones are combined.

3D IMCDP

In [7], the extension of the two-dimensional IMCDP to a 3D halftoning method, called 3D IMCDP, is thoroughly described. In this section, a brief description of 3D IMCDP is given. The 3D IMCDP starts by finding the position of the voxel holding the maximum value and assigning the same position in the halftoned 3D surface, a “dot”, i.e. black voxel. The effect of this placed black voxel is fed-back to the halftoning process, like in the 2D IMCDP, by subtracting a neighborhood around the found maximum by a filter. By the neighborhood, we mean all surface voxels within an $m \times m \times m$ box around the found maximum. The filter could then be a three-dimensional Gaussian function similar to that in Eq. 1. Unlike in 2D, the Euclidean distance between two voxels in 3D, doesn’t always give a good measure of the distance between the two voxels on a 3D surface. For example, there might be two voxels that are equally far from the central voxel on the surface but having different Euclidean distances to the central voxel. This will give one of them much more chance to be chosen as the maximum than the other one. This will cause undesirable halftone structure artifacts, as illustrated in [7].

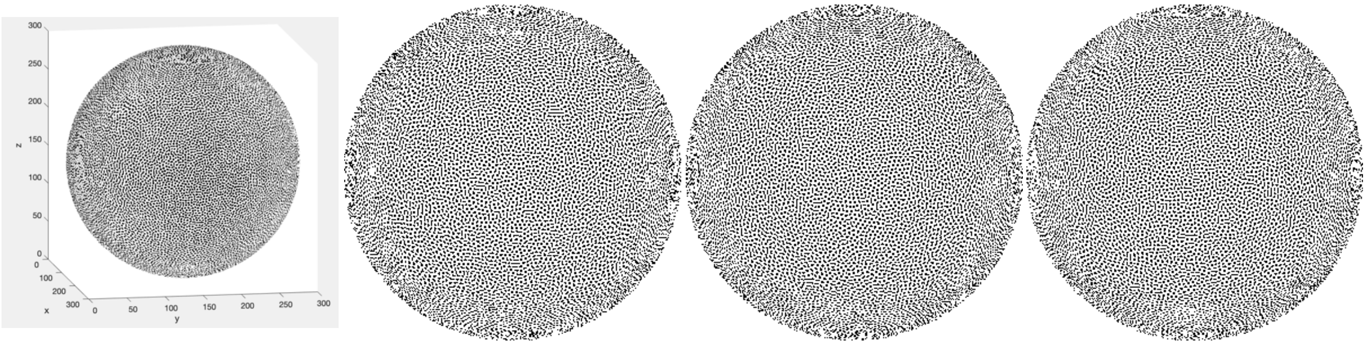


Figure 3 *Sphere of radius 150 with a constant absorptance of 0.3 being halftoned by 2nd generation FM halftoning. The 2D XY, XZ and YZ views are also shown.*

In order to reduce this effect, instead of using a 3D Gaussian function, an $m \times m$ 2D Gaussian function is designed and the weights are sorted in descending order. The surface voxels within an $m \times m \times m$ box around the found maximum are sorted by their 3D Euclidean distance to the central voxel in ascending order. The closest voxel is subtracted by the first weight in the sorted list, i.e. the largest weight, and the second closest voxel by the second weight in the sorted list and so on. If the number of surface voxels around the found maximum is higher than m^2, only the first m^2 surface voxels are affected. If the number of surface voxels around the found maximum, e.g. n, is less than m^2, all surface voxels are subtracted by weights in the sorted list from position 1 to n. Although the 3D Euclidean distance still decides the weight assigned to a voxel, the Euclidean distance is not directly used in the Gaussian function and the weights are taken from a 2D Gaussian filter. This means that two voxels having the same distance to the central voxel on the 3D surface might still be subtracted by two different weights, but the difference is not as large as using a 3D Gaussian function. Figure 3 shows a sphere of radius 150 with a constant absorptance of 0.3 being halftoned by 3D IMCDP using 2nd generation FM halftoning. Notice that an absorptance of 0 and 1 corresponds to white and black, respectively. Three 2D-views, namely XY, XZ and YZ views, of the halftoned sphere are also shown in Figure 3. All images show a well-formed 2nd generation FM halftone. Worth mentioning that in all 3D halftoned surfaces in this paper m equals 11.

3D structures and halftoning

When a 3D shape is made, there are different structures that might exist on its surface. One of them being undesirable structures caused by the voxelization or the printing process, which could be because of the resolution, the material being used, etc. The other one is the geometrical structure that exists in the 3D shape being created, for example forehead wrinkles of a 3D face being printed. We refer to these two types of structures as 3D structures. There might be other structures coming from the texture/image content being mapped on the 3D shapes, similar to structures in 2D images, for which several 2D halftoning algorithms have been developed [10, 11]. In the present paper, we mainly focus on the 3D structures on a three-dimensional surface and study how different halftone structures could diminish or emphasize the appearance of the surface structure. Figure 4 shows two different views of a slightly structured 3D surface with a constant input tone of 0.3 absorptance halftoned by 3D IMCDP using different feed-back filters. In (a), the filter in Eq. 1 with $k_1 = k_2 = 1$ has been used, creating symmetrical 1st generation FM halftones. In (b), the filter in Eq. 2 with $k_1 = k_2 = 1$ has been used, creating symmetrical 2nd generation FM halftones. Different choices of σ_1 and σ_2 in Eq. 2, control the clustered dot sizes, as discussed in [9]. In (c) and (d), the filter in Eq. 2 with $k_1 > k_2$ and $k_1 < k_2$, respectively, have been used. These two different filters resulted in non-symmetrical 2nd generation halftones with vertical line halftones on 2D planes parallel to the YZ and the XZ-plane, respectively. Comparing the images in Figure 4a and 4b reveals that the structure is slightly diminished using the 2nd generation FM halftone, as expected. Furthermore, it can be noticed that the 3D structure is emphasized in Figure 4c and diminished in Figure 4d, because of the halftone dot shape and alignment.

Recall from Section 3D IMCDP that the 3D Euclidean distance from surface voxels within an $m \times m \times m$ box to the central voxel was used to assign a weight to a voxel. The square of the Euclidean distance, however, should be modified according to Eq. 3 when non-symmetrical halftones are created.

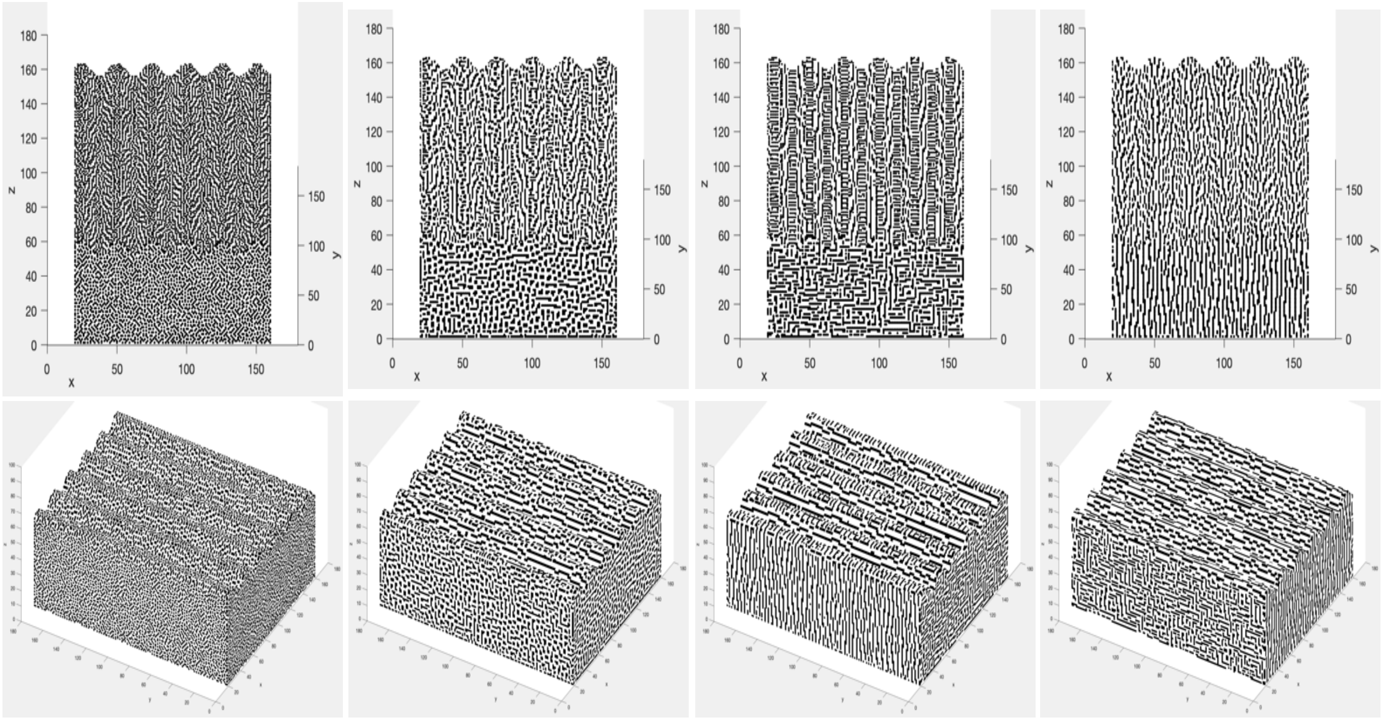
$$d^2 = \frac{\Delta x^2}{d_1} + \frac{\Delta y^2}{d_2} + \frac{\Delta z^2}{d_3}, \qquad (3)$$

where d_1, d_2, and d_3 not only decide the halftone dot shape and alignment, but also can create different halftone structures on different view planes. One example can already be seen in Figure 4c and 4d, while in (c) $(d_1 = d_3) > d_2$, in (d) $d_1 < (d_2 = d_3)$. For example, since $d_1 = d_3$ in the former example, the halftone structure should be symmetrical on the XZ-plane, which can also be noticed in Figure 4c. The same is valid for the halftone structure on the YZ-plane in Figure 4d.

Structure based 3D halftoning

In Section 2D IMCDP, 1st and 2nd Generation FM, we described the possibility to combine two or more halftone structures based on the content of the 2D image. This was illustrated in Figure 2, where the 1st generation FM halftone was applied to the highpass regions of the original image, and the 2nd generation FM to the rest of the image. This was achieved by the use of appropriate filters in different regions of the image. In the previous section, it was shown how different choices of halftone structures can diminish or emphasize 3D structures. In this section, we introduce the concept of combining different halftones based on the geometrical structure of 3D surfaces. The ability of the IMCDP method to create different halftones by using appropriate filters allows us to examine this concept. As mentioned before, in this paper we mainly focus on the 3D structure and illustrate how different halftones could be combined on a 3D surface.

The idea that is going to be explored in the present paper is to use different halftones based on how structured different parts of a 3D surface are. For example, in the parts where the 3D surface is heavily structured, one halftone structure, and in the areas that



a b c d

***Figure 4** Two different views of a slightly structured 3D surface halftoned by, (a) 1st generation FM, (b) symmetrical 2nd generation FM, (c) and (d) non-symmetrical 2nd generation FM with vertical line halftones on 2D planes parallel to the YZ and XZ planes, respectively.*

are less structured another halftone structure, and in slightly structured areas another halftone structure should be used, and so on.

The first task is now to decide how structural an area on a 3D surface is and the second task is to decide what halftone is more appropriate for different areas having different structures. Undertaking both of the aforementioned tasks greatly depend on the application, the 3D shape being printed, the material being used, the users' demand, etc. In the following, we give an example of assessing the structure of a 3D surface.

Consider first a 3D surface that is parallel to one of the coordinate planes as structureless, as it is actually a 2D surface. Therefore, there shouldn't be any 3D structures on such a surface, unless it is caused by the print process due to low resolution and/or print materials. Hence, it is appropriate to use halftones with larger dots in these areas, to cover or diminish the undesirable structures. Even if the surface is smooth enough, larger dots would still give a more homogeneous appearance in these areas. Thus, in our example, we use a 2nd generation FM with larger clustered dots in these regions. In such an area, the surface voxels within an $m \times m \times m$ box around a central voxel will include two-dimensional $m \times m$ surface voxels. The standard deviation of one of x, y or z coordinates of the voxels on this area is zero, and that of the other two is $\frac{m}{2\sqrt{3}}$. As $\frac{m}{2\sqrt{3}}$ is the largest and 0 is the smallest standard deviation of coordinates of a regular $m \times m$ area, we use the difference between the maximum and the minimum standard deviation of the coordinates of the surface voxels as a measure/threshold to identify different structures. Therefore, for an area parallel to one of the coordinate planes, this threshold would be $\frac{m}{2\sqrt{3}}$. Another surface worth considering is a 3D surface like ⊓ or ⊔, where the top (or bottom) of the area is one row of surface voxels and the two sides of it, which are of size $m \times \frac{m-1}{2}$ each, are parallel to one of the coordinate planes. The standard deviation of the coordinates of the voxels on such a surface are $\frac{m}{2\sqrt{3}}$, $\sqrt{\frac{m}{m+1}}$ and $\frac{\sqrt{m^2+3}}{4\sqrt{3}}$. The threshold for this surface, i.e. the difference between the largest and the smallest standard deviation, would be $\frac{m}{2\sqrt{3}} - \sqrt{\frac{m}{m+1}}$ for $m > 5$, which is always the case considering the fact that m is always an odd integer greater than or equal to 11 in IMCDP. The third interesting surface to investigate is when the central voxel is at the edge of a box and at least $\frac{m+1}{2}$ voxels away from the corner of the box. On such a surface, the standard deviation of one of the coordinates is $\frac{m}{2\sqrt{3}}$ and that of the other two is $\frac{\sqrt{5m^2+3}}{8\sqrt{3}}$. The threshold corresponding to this structure will therefore be $\frac{m}{2\sqrt{3}} - \frac{\sqrt{5m^2+3}}{8\sqrt{3}}$. Finally, it is noteworthy to know where this threshold is zero. The threshold is zero when all three standard deviations are equal, and this happens for example when the central voxel is located at the corner of a box. The area in this case will consist of $3(\frac{m-1}{2})^2 + \frac{3m-1}{2}$ surface voxels, on which all three coordinates will have the same standard deviation giving the threshold of zero. Another 3D surface on which the coordinates of the surface voxels will have the same standard deviation, is a plane that is tilted 45 degrees with regards to the coordinate planes. These three aforementioned thresholds could be used to divide 3D surfaces into four different regions, each being reproduced by a different halftone structure.

Figure 5 shows this partitioning using $m = 11$ for two different 3D surfaces, namely, a sphere of radius 100 and a box with additional structures on top of it. The green areas are those

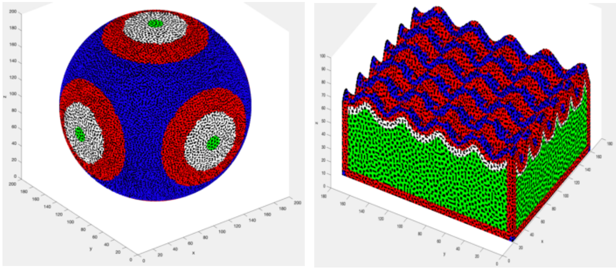


Figure 5 *Two 3D surfaces divided into four different structural regions.*

very close to 2D surfaces parallel to one of the coordinate planes, clearly seen on the box. In these areas, we use a 2nd generation FM halftone with reasonably large clustered dots. The white areas are those that are not 2D surfaces parallel to one of the coordinate planes, but quite close to that, best seen on the sphere. In these areas, a 2nd generation FM halftone with a bit smaller clustered dot is used. The red areas are those having similar structure as the edge of a box, clearly seen on both the box and the sphere. In these areas, we use a 2nd generation FM halftone with even smaller clustered dots. Finally, the blue areas are those that have small threshold values, for example surface voxels close to the corner of the box or close to planes being tilted 45 degrees on the sphere. In these areas, a 1st generation FM halftone is used.

Figure 6 shows the sphere and the box, both with the constant absorptance of 0.3, being partitioned as shown in Figure 5 and halftoned as explained in the previous paragraph. The XZ-view of both 3D surfaces are also shown. As seen in these images, especially in the XZ-views, the clustered dot size in the 2nd FM halftones gradually and smoothly decreases to end with the 1st FM halftone in the most structured areas, colored blue in Figure 5.

As stated before, defining structures and partitioning them as explained in this paper is just an example to illustrate how different halftones can be combined in one 3D surface. Using 1st generation FM halftone in the blue regions on the sphere could also be argued. These regions on the sphere are the most structured part of the sphere according to the measure being used in this paper. However, one might argue that, this structure is caused by the voxelization of the surface and should be diminished instead of being emphasized. If so, the order of using different halftones in the color-marked regions in Figure 5, could be reversed or a halftone structure diminishing the structures could be used in the blue regions of the sphere instead of 1st generation FM method.

Besides the 3D structures, a combination of the geometrical 3D structures of the surface and the structure of the texture/image being mapped on it is an interesting topic to be studied in more detail. Figure 7 illustrates an example to show the appearance of a 3D surface from different viewing angles with an image being mapped on it. The 3D surface has been reproduced by two different halftones, namely 1st and 2nd generation FM. The image has been mapped using planar texture mapping on the XY-plane. The 3D surface, which is the same 3D surface shown in Figure 5 and 6, is a box having some structures on top of it. The bottom face of this shape, on the other hand, is completely flat. Besides a 3D view, the XY-view from above (top face) and below (bottom face) are also shown in Figure 7. As seen in this figure, the details of the image on the bottom face of the 3D surface are better reproduced using 1st generation FM halftoning. The top view, on

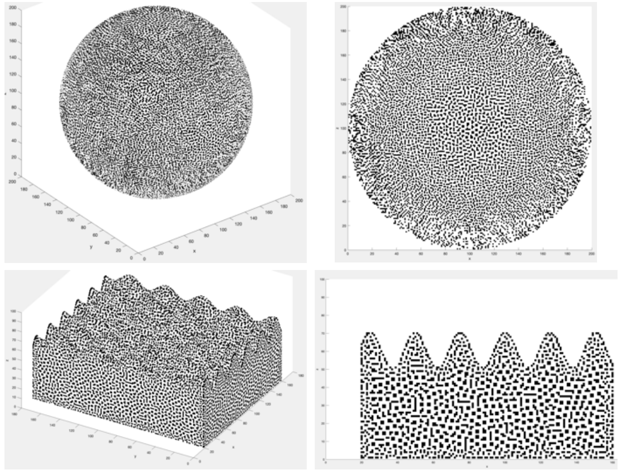


Figure 6 *A 3D and XZ-view of a halftoned sphere of radius 100 and a halftoned box with structures on top of it, both with a constant absorptance of 0.3. The 3D surfaces have been divided into four structural regions as shown in Figure 5. Second generation FM halftones with three different clustered dot sizes and 1st generation FM halftone have been used in these four structural regions.*

the other hand, gives a noisier impression using 1st generation FM halftone, whereas none of the halftones is superior when it comes to reproducing the image details on the top face. Therefore, the 2nd generation FM might be preferred for the top face of this 3D shape whereas the 1st generation FM for the bottom face.

Summary and Future Work

In this paper, the two-dimensional 1st and 2nd generation FM halftoning have been adapted to 3D. The main focus has been on the geometrical structures of 3D surface voxels to examine how different halftones reproduce different structures. For instance, while a type of halftone could diminish some 3D structures, another type of halftone might enhance the same structure. The possibility of combining different halftones on the same 3D shape based on the structure of the different parts of the shape has also been investigated. The results verify that the extension of the 2D IMCDP halftoning to 3D produces well-formed halftones on 3D surfaces. The ability of this method to combine different halftones by utilizing appropriate feed-back filters has also been extended and examined using 3D surfaces. An approach to divide a 3D surface into different structural regions has also been proposed and tested on two different 3D shapes. The results show that the transition between different halftones used in different areas is very smooth and does not create any artifacts.

The proposed halftoning method is flexible and can be used to combine halftones using other aspects than the 3D structures. For instance, one might be interested to create different appearances from different viewing angles. In this case, instead of the 3D structure, the normal vector of the surface voxels within an $m \times m \times m$ box around the central voxel can be used to decide the halftone structure. One example has already been illustrated in Figure 7 and the proposed 3D halftoning method is capable of using one halftone on the top face and another one on the bottom face. This is an interesting topic to be further studied as it might improve the appearance of some 3D surfaces. Another interesting topic to be studied in more detail is to combine different halftones based on the 3D structures of the surface and the structure of the

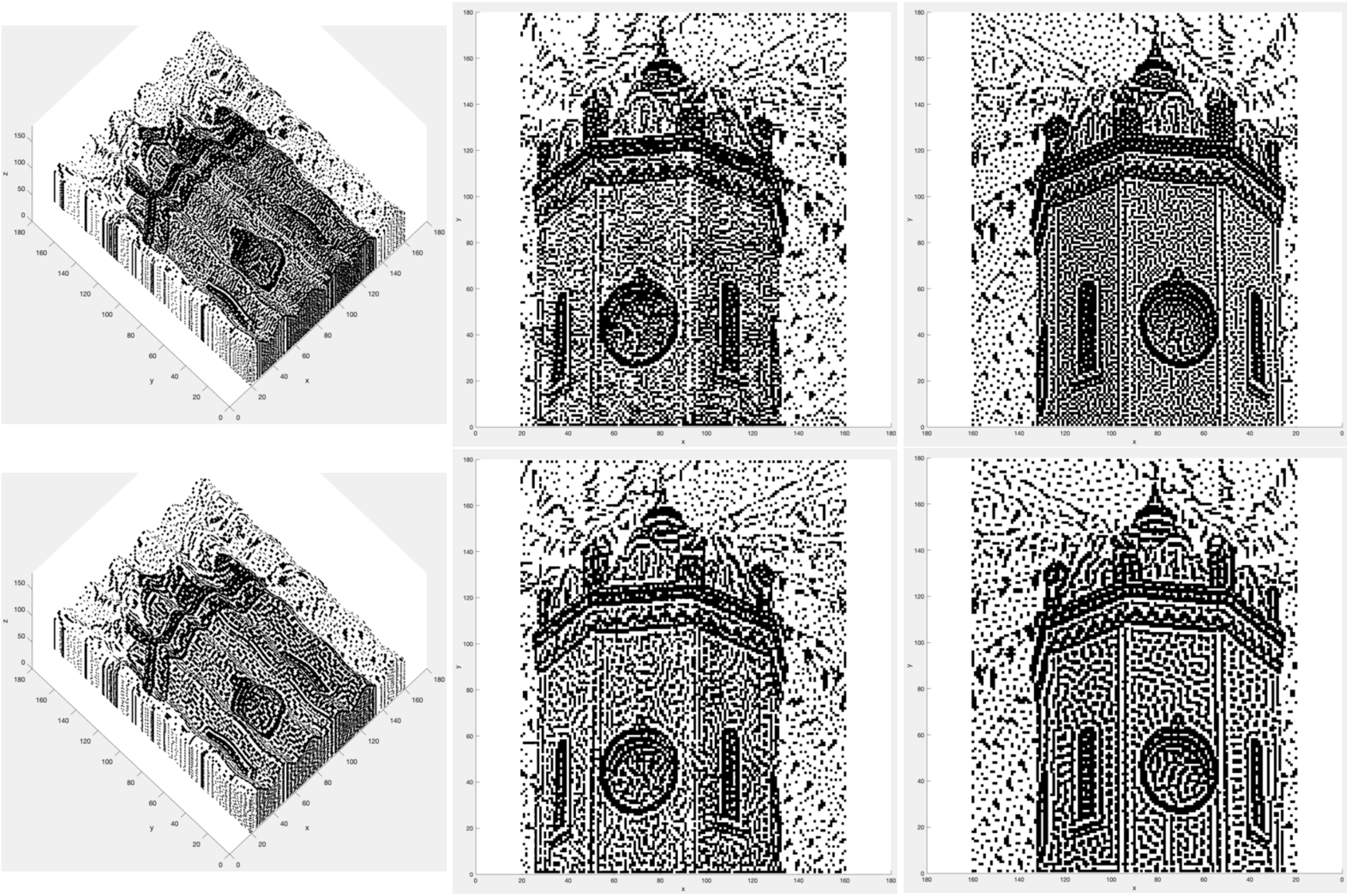


Figure 7 *A texture has been mapped on a 3D surface by planar mapping on XY-plane. The surface, whose top face has structures on it while its bottom face is completely flat, has been halftoned by, Top row) 1st generation FM. Bottom row) 2nd generation FM. Left) 3D view, Middle) XY-top face. Right) XY-bottom face.*

texture being mapped on it. We believe that adapting the halftones to 3D surfaces based on their geometrical structure and the structure of the texture being mapped on it will increase the quality of surface reproduction.

Acknowledgement

This work has received funding from the European Union's Horizon 2020 programme under the grant No. 814158.

References

[1] R. A. Ulichney, Digital Halftoning, (MIT Press, Cambridge, MA, 1987).

[2] Robert W. Floyd and L.S. Steinberg, "An adaptive algorithm for spatial gray-scale," vol. 17, pp. 75–77 (1976).

[3] M. Analoui and J. P. Allebach, Model-based halftoning using direct binary search, Proc. SPIE/IS&T, 1666, 96 (1992).

[4] A. Brunton, C. A. Arikan, and Ph. Urban, "Pushing the Limits of 3D Color Printing: Error Diffusion with Translucent Materials," ACM Trans. Graph., vol. 35, pp. 1–13 (2015).

[5] A. Michals, J. Liu, A. Jumabayeva, Zh. Li, and J. P. Allebech, "3D Tone-Dependent Fast Error Diffusion," Electronic Imaging, vol. 2019, pp. 101–1 (2019),

[6] R. Mao, U. Sarkar, R. Ulichney, and J. P. Allebach, 3d halftoning, IS & T International Symposium on Electronic Imaging Science and Technology, vol. 2017-January, pp. 147 – 155 (2017).

[7] F. Abedini, S. Gooran, and D. Nyström, 3D Halftoning based on Iterative Method Controlling Dot Placement, printing for fabrication 2020.

[8] S. Gooran, "Dependent color halftoning: Better quality with less ink.," Journal of imaging science and technology, vol. 48, no. 4, pp. 354–362 (2004).

[9] S. Gooran and B. Kruse, "High-speed first- and second-order frequency modulated halftoning," Journal of Electronic Imaging, vol. 24, no. 2, pp. 1–19, (2015).

[10] J. Chang, B. Alain, and V. Ostromoukhov, Structure-aware error diffusion. Proc. SIGGRAPH-ASIA. ACM Transactions on Graphics 28, 4 (2009).

[11] H. Li and D. Mould, Contrast-aware halftoning. Computer Graphics Forum, 29(2):273–280 (2010).

Author Biography

Sasan Gooran received his M.Sc. in Computer Science and Engineering (1994) and his Ph.D. in Media Technology (2001), both from Linköping University, Sweden. He is currently an associate professor at Media and Information Technology division, Linköping University. His research has mainly focused on digital imaging, digital halftoning, color and image reproduction, 3D halftoning and appearance printing. He has taught courses in, among others, Graphic technology, Computer graphics, Image processing, Numerical methods, Transform theory and Mathematics.

Fereshteh Abedini received her M.Sc. in Digital Electronics Engineering from Amirkabir University of Technology, Iran (2015). Currently, she is pursuing her Ph.D. studies at Media and Information Technology division, Linköping University, Sweden. Her research interest includes digital halftoning, digital image processing, image reproduction, 3D halftoning and appearance reproduction.