Digital Halftone Database (DHD): A Comprehensive Analysis on Halftone Types

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Abstract— **Digital halftoning is a technique to represent the binary approximation of continuous tone image meant for printing. There are wide variety of halftone methods available based on ordered dithering, error distribution, dot diffusion and iterative approaches. This paper emphasizes on the development of a digital halftone database (DHD) consisting of 23 varieties of halftone methods. Moreover, the detailed elaboration on implementation of each technique and its comparison study is carried out. The critical halftone characteristics such as homogeneity, isotropy, directional artifacts and its impact to the pattern quality are comprehensively analyzed using the stochastic halftone statistics. Finally, a complete performance comparison based on rendered image quality, spatial and spectral statistics of stochastic process parameters are analyzed. The DHD database consisting of more than 4500 halftone images along with some of its source code is made free access for scientific study and purposes.**

I. INTRODUCTION

Digital halftoning is a critical technique to obtain appropriate binary patterns meant for printing devices. The method involves converting the color- or gray-scale image into its approximate binary version. When the binary patterns are viewed from the specific distance, due to the low pass nature of the human visual system it is perceived as a continuous tone image. This technique is extensively utilized in printing productions units such as newspapers, magazines, books and others periodicals. Various halftone strategies are proposed considering two important aspects such as visual fidelity and computational complexity.

The technique is broadly classified into two categories such as blue- and green-noise halftoning based on the spatial and spectral characteristics. The blue noise patterns correspond to the high spectral components and is constructed by distributing the minority pixels as homogeneously as possible. This technique results in dispersed dot patterns and is optimal for printing mechanisms like inkjet printers. As the spacing of the dots varies according to the tones, this method is also termed as frequency modulated or FM halftoning.

On the other hand, the green noise pertains to the mid frequency spectral components and is composed of clusters of minority pixels in the blue-noise centers. This results in homogeneous clustered dot patterns and is suitable for laser printer machines. As the pattern generate dither patterns with different cluster size it is termed as amplitude modulated or AM digital halftoning.

Digital halftoning is not limited to printing but the technique also has wide-spread research domain ranging from halftone restoration, classification, authentication, water-marking, image compression and so on.

- Image restoration: It deals with converting the halftone version to the original gray scale image and is termed as inverse halftoning. It is very useful for the digital publishing, printed image processing and to restore tampered manuscripts.

- Classification: There are plenty of halftone varieties and its classification is critical for its perfect reconstruction, halftone authentication and to study pattern anomalies.

- Authentication & watermarking: For confidential and legal documents, a secret way of embedding data is important to prevent forgery. For instance, in currencies lot of random patterns are either hidden or made partly visible, makes them very difficult to duplicate. As each halftone methods yields different results, it can be adopted for secret authentication.

- Image compression and retrieval: Block truncation coding image is one of the simplest yet effective image compression technique. Due to its inherent similarity with halftoning, many halftone techniques are extended to BTC for its improvisations. In subsequent developments, halftone based features are used to perform effective image retrieval.

II. DIGITAL HALFTONING TYPES

As introduced, the digital halftoning is broadly classified as clustered dot (amplitude modulated) and dispersed dot (frequency modulated) halftoning. Four varieties of halftoning techniques such as ordered dithering, error diffusion, dot diffusion and error minimization methods are proposed to generate both the halftone patterns. TABLE I provides the halftone pattern and its corresponding methods

TABLE I: HALFTONE PATTERN AND ITS METHODS

S. No	Halftone Pattern	Methods
1	Clustered Dot	a) Ordered dithering b) Iterative approach
2	Dispersed Dot	a) Ordered Dithering b) Error diffusion c) Dot diffusion d) Iterative approach

A. *Ordered Dithering*

This method is the simplest approach and involves thresholding using a specific screen and depends on the screen specification both dispersed and clustered dot patterns can be generated. Let us assume that the $in(x, y)$ corresponds to the original gray scale image. As shown in Eq. 1, the halftone image $H(x, y)$ can be obtained by thresholding with some specific screen $S(x, y)$. x, y refers to the image pixel location.

$$H(x,y) = \begin{cases} 1 & in(x,y) \geq S(x,y) \\ 0 & otherwise \end{cases} \quad (1)$$

Depends on the thresholding screen specification, different halftone patterns can be obtained and typical screen size is of 8x8 and 16x16 pixels. The foremost approach is proposed by Bayers, et. al. [1] to obtain both clustered and dispersed dot patterns. From the results, it is concluded that clustered dot results in poor detail rendition and dispersed dot yielded fine amplitude quantization over large area and detail rendition within small area. Further, Bryngdahl [2] proposed a different screen which can produce concentric ring in halftone patterns and it is proven to have a better visual quality.

Ulichney, et. al [3] published a comprehensive book on digital halftoning in which majority portion is dedicated to AM halftoning techniques. This paper considers two types of Ulichney ordered dithering work meant to obtain clustered and dithered dot patterns. Finally, Kacker, et. al [4] proposed a dispersed dot screen based on the direct binary search (DBS) algorithm.

B. *Error Diffusion*

Error diffusion (ED) is a superior approach which involves thresholding a pixel with a constant threshold value, and subsequently distributing the difference of error to the neighborhood pixels. Depends on the error distribution kernels, various methods are proposed and each has its own advantages and disadvantages. The foremost and most revolutionary error diffusion technique is proposed by Floyd et. al [5], and due to its dispersed dot nature it is widely used in printers which can print small and isolated dots. To begin with, the input image is thresholding using a constant value of 128, and then the output image is assigned with 0 or 255 accordingly. In the next step, the error value is computed between the assigned and the actual value as provided in Eq. 2-4 and Fig. 1. Finally the computed error is distributed to the neighbourhood pixels according to the error filter kernel. Some of the error diffusion kernels considered under this study are listed in Fig. 2.

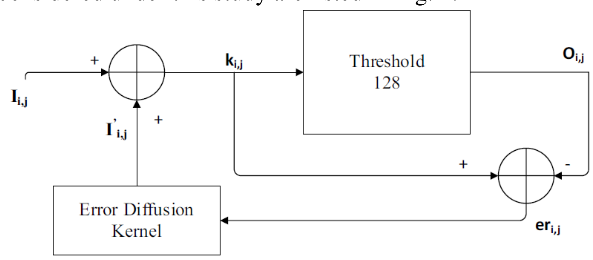


Fig. 1. Error diffusion

$$k_{i,j} = I_{i,j} + I'_{i,j} \quad (2)$$

$$I'_{i,j} = \sum_{m=0}^{2} \sum_{n=-2}^{2} er_{i+m,j+n} * h_{m,n} \quad (3)$$

$$e_{i,j} = k_{i,j} - O_{i,j} \quad (4)$$

$$O_{i,j} = \begin{cases} 0 & if\ k_{i,j} < 128 \\ 255 & if\ k_{i,j} \geq 128 \end{cases} \quad (5)$$

where $e_{i,j}$ refers to the difference between actual input $k_{i,j}$ and output $O_{i,j}$. $h_{m,n}$ refers to the error diffusion filter. $I'_{i,j}$ contains the difference of error that need to be added with the neighborhood pixels.

	.	7/12
1/12	3/12	5/12

(a) Floyd

		.	7/48	5/48
3/48	5/48	7/48	5/48	3/48
1/48	3/48	5/48	3/48	5/48

(b) Jarvis

		.	8/42	4/42
2/42	4/42	8/42	4/42	2/42
1/42	2/42	4/42	2/42	2/42

(c) Stucki

Fig. 2. Error diffusion kernels

Apart from this, the paper also considers some of its derived versions and totally includes nine ED methods. The major shortcomings of the error diffusion method are that, unlike ordered dithering which can be operated in parallel whereas in error diffusion the process is sequential and time consuming.

C. *Dot Diffusion*

This technique is similar to error diffusion but instead of sequential processing, the method can support parallel implementation. In comparison with error diffusion which relies on error kernels, the dot diffusion has class and diffusion matrix. The class matrix dictates the order of processing and diffusion matrix defines the weightage of error to the neighborhood pixels. The most popular dot diffusion methods are proposed by Knuth, et. al [6] and Mese, et. al [7]. As shown in Fig. 3, the process comprises of class matrix as provided above and it counts from 0 to 63.

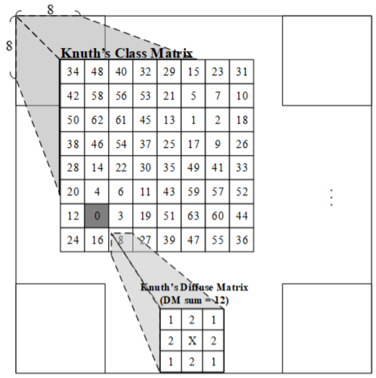


Fig. 3. Knuth Class and Diffusion Matrix

D. *Iterative Approaches*

The iterative approaches [8] involve minimizing the perceptual error between the halftone image and original image. Due to this process, the halftone patterns will be distributed as homogeneously as possible.

As it is a perceptual error measurement (E) both the original and halftone image undergo convolution with a point spread function (PSF). In general, PSF is a low pass filter which reflects the human visual system, and mixed gaussian models are widely used for this purpose. Let us assume that, $\tilde{f}(x)$ and $\tilde{g}(x)$ corresponds to perceived continuous tone original and halftone image.

$$E = \left\| \tilde{f}(x) - \tilde{g}(x) \right\|^2 \tag{6}$$

Direct binary approach is a heuristic optimization method and is proven to be very powerful to optimize binary patterns. The approach achieves the least minimum square error though swap and toggle operation. The swap operation consists of switching the current pixel with eight of its neighborhood pixels. Toggle operation is about switching the values between 0 to 255 or vice versa (as shown in Fig. 4)

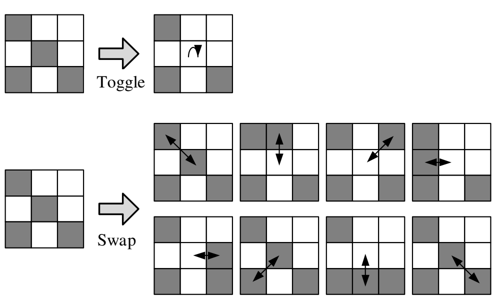


Fig. 4. Toggle and swap operation

With each iteration, the perceived error starts to reduce and in finally a superior halftone quality is achieved. The method is computationally very expensive and difficult to implement in hardware.

III. Digital halftone database

A digital halftone database comprising of 23 types of halftone class is developed (as shown in Table II). The database comprises of 196 reference images taken from CVG-UGR-Image database and Genreal-100 dataset. The database contains around 4508 images and some of the source code are also provided. Table III provides an image example from the dataset for the considered 23 classes.

TABLE II: HALFTONE METHODS

Halftone Method	Types
Ordered Dithering	(1) Bayer's CD (BCD) [1] (2) Bayer's DD (BDD) [1] (3) Ulichney CD (UCD) [3] (4) Ulichney DD (UDD) [3] (5) Bryngdahl DD (BLDD) [2] (6) Ulichney void and cluster DD (UVCDD) [9] (7) Kacker DD (KDD) [4]
Error Diffusion	(8) Atkinson DD (ADD) [10] (9) Burkes DD (BKDD) [11] (10) Fan DD (FDD) [12] (11) Floyd Steinberg DD (FSDD) [5] (12) Frankie Sieraa DD (FSIDD) [12] (13) Filter Lite DD (FLDD) [12] (14) Jarvis, Judice and Ninke DD (JJNDD) [13] (15) Jarvis DD (JDD) [14] (16) Stucki DD (SDD) [12] (17) Shio Fan DD (SFDD) [12]
Dot Diffusion	(18) Knuth DD (KDD) [6] (19) Messe Vaidhayanathan (8x8) DD (MSDD8) [7] (20) Messe Vaidhayanathan (16x16) DD (MSDD16) [7]
Iterative	(22) Direct Binary Search [8]
Digital Multi-tone	(23) Dispersed Dot Multi-tone (MTDD) [15] (24) Clustered Dot Multi-tone (MTCD) [16]

IV. Experimental Analysis

The experiment analysis consists of image quality analysis and various pattern analysis based on its spectral and spatial statistics. Under the quality assessment, the widely adopted structural similarity index [17] is used for the study.

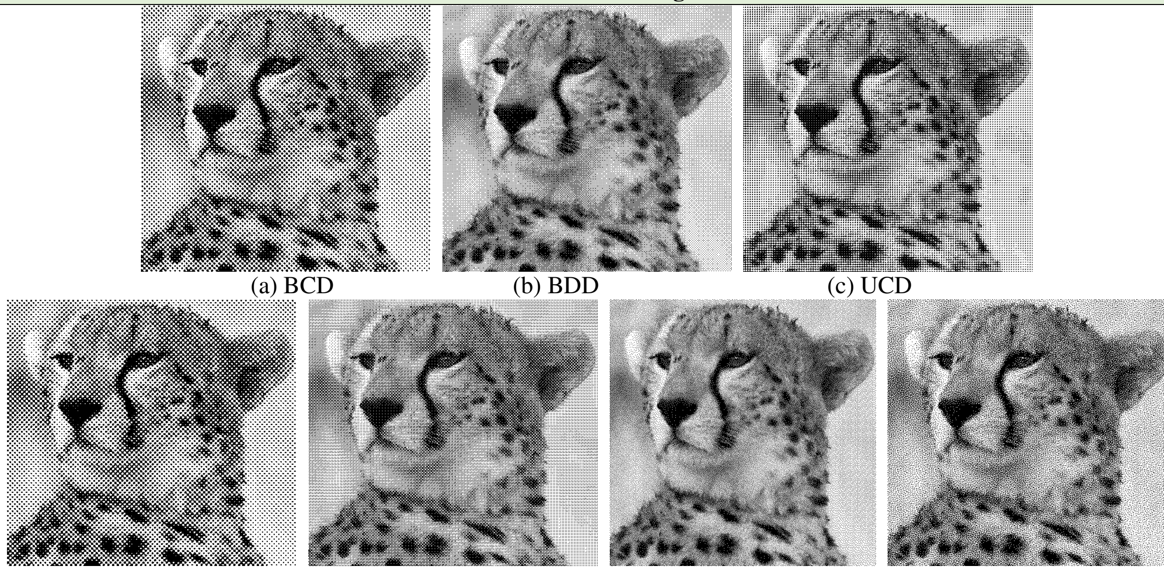
$$SSIM = \left(\frac{2\mu_x\mu_y + C1}{\mu_x^2 + \mu_y^2 + C1}\right)\left(\frac{2\,\sigma_{xy} + C2}{\sigma_x^2 + \sigma_y^2 + C2}\right) \tag{7}$$

where μ_x and μ_y refers to the mean of the test and reference image; σ_x and σ_y are the variance of test and reference image; σ_{xy} is the correlation coefficient.

For pattern analysis, the paper exploits the process of the stochastic halftone analysis and its statistical parameters [18]. To begin with, the stochastic geometry commonly deals with mathematical definition of complex patterns. For instance, the spatial point process deals with characterizing random distribution of points in space. The similar phenomenon can be observed with halftones, which also deals with distributing minority pixels (black dots) as homogeneous as possible.

TABLE III: DIGITAL HALFTONE DATABASE

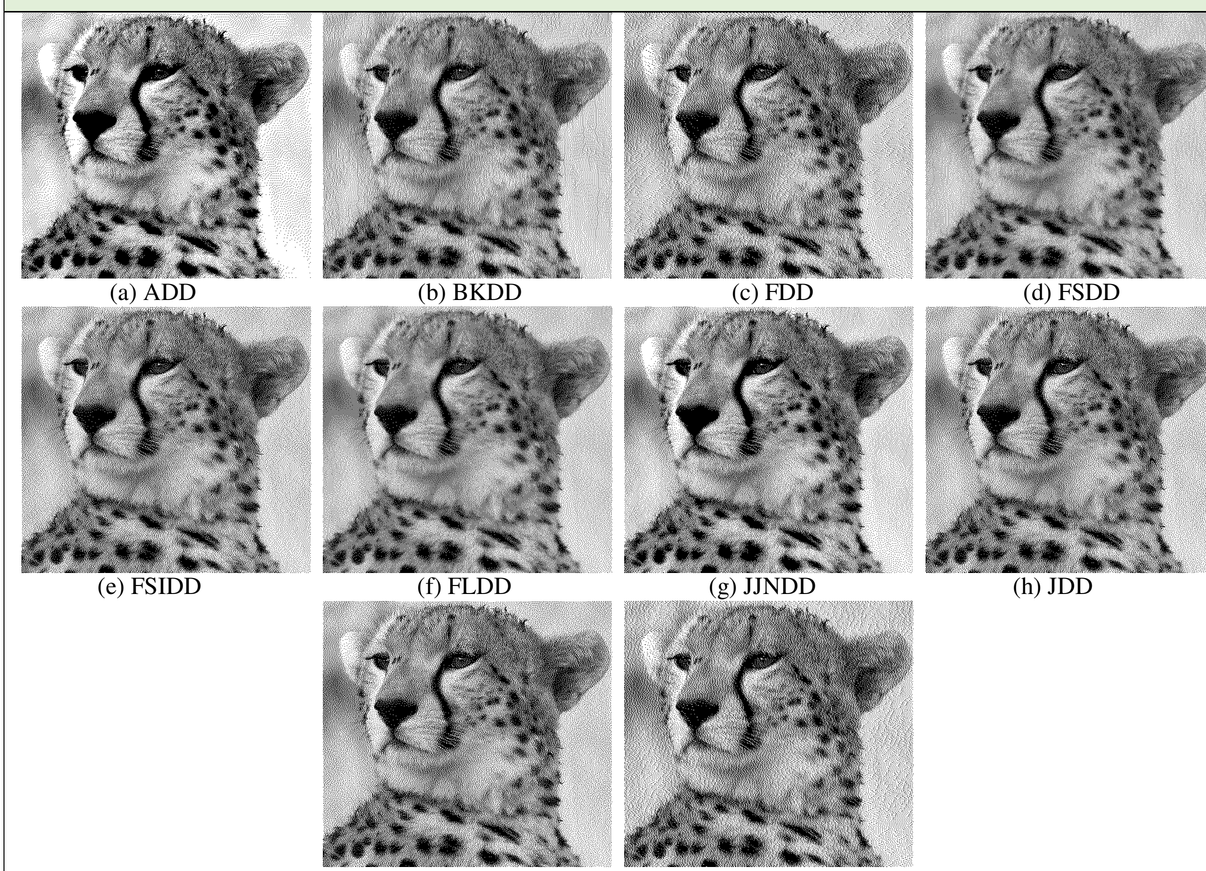
Ordered Dithering



(a) BCD (b) BDD (c) UCD

(d) UDD (e) BLDD (f) UVDDD (g) KDD

Error Diffusion

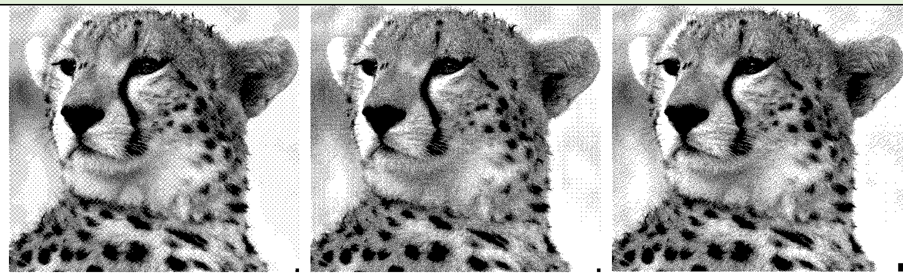


(a) ADD (b) BKDD (c) FDD (d) FSDD

(e) FSIDD (f) FLDD (g) JJNDD (h) JDD

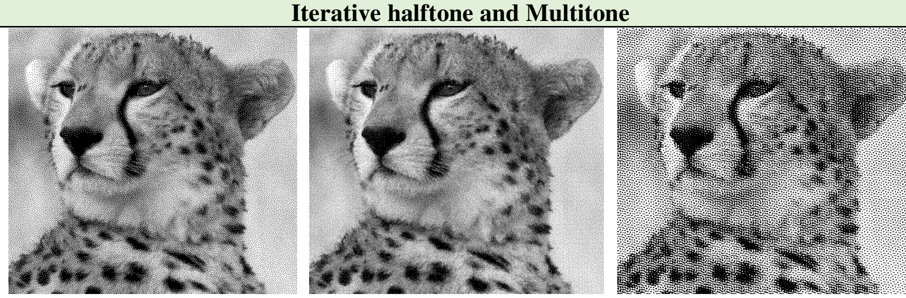
(i) SDD (j) SFDD

Dot Diffusion



(a) KDD (b) MSDD8 (c) MSDD16

Iterative halftone and Multitone



(a) DBS (b) MTDD (c) MTCD

As each halftone methods possess certain level of homogeneity, texture and artifacts, it requires complex mathematical process to accurately characterize the pattern geometry. Under stochastic halftone analysis, the basic parameter is reduced second order moment measure (RSOMM) , which basically determines the likelihood of point or it occurrence at point y given with a minority pixel at x. Based on this statistics, two parameters are constructed by partitioning the spatial and spectral domain of RSOMM into a set of annular rings $A_y(r)$ with certain radius r and width Δ_r, centered around the pixel x.

In spatial statistics two parameters are considered such as pair correlation and directional distribution function [18]. The pair correlation corresponds to the unconditional expected number of points in the ring r,

$$P(r) = \frac{E\{\,\phi(A_y(r))|y \in \phi\,\}}{E\{\phi A_y(r)\}} \tag{8}$$

where ϕ is the point process, and $A_y(r)$ refers to the average value of SOMM, and it indicate the inter-point distance relationships i.e. maxima refers to frequent occurrence and minima corresponds to the inhibition of points. Further, the direction distribution function (DDF) compute the expected number of minority pixels per unit area.

$$DDF_a(r1, r2) = \frac{E\{\Gamma_m^a|y \in \Phi\,\}/N(\Gamma_m^a)}{E\{\Gamma_m|y \in \Phi\,\}/N(\Gamma_m)} \tag{9}$$

where $r1$ and $r2$ are the inner and outer radius of the considered portion. Γ_m^a refers to the expected number of points in the section. It is important to mention that, the pair correlation is not widely used as it assumes the pattern to be isotropic and in general halftone patterns are allowed to be anisotropic. Hence, in spatial domain, the DDF is found to be an effective way to characterize expected number of points under a particular section.

In spectral statistics, radially averaged power spectral density (RAPSD) and anisotropy (ANIS) are considered. Primarily, Ulichney, et. al [3], used this technique to characterize error diffused halftones. To begin with, the spectral power is computed as

$$\hat{P}(f) = \frac{1}{K}\sum_{i=1}^{K} \frac{|DFT_{2D}(\varphi_i)|^2}{N(\varphi_i)} \tag{10}$$

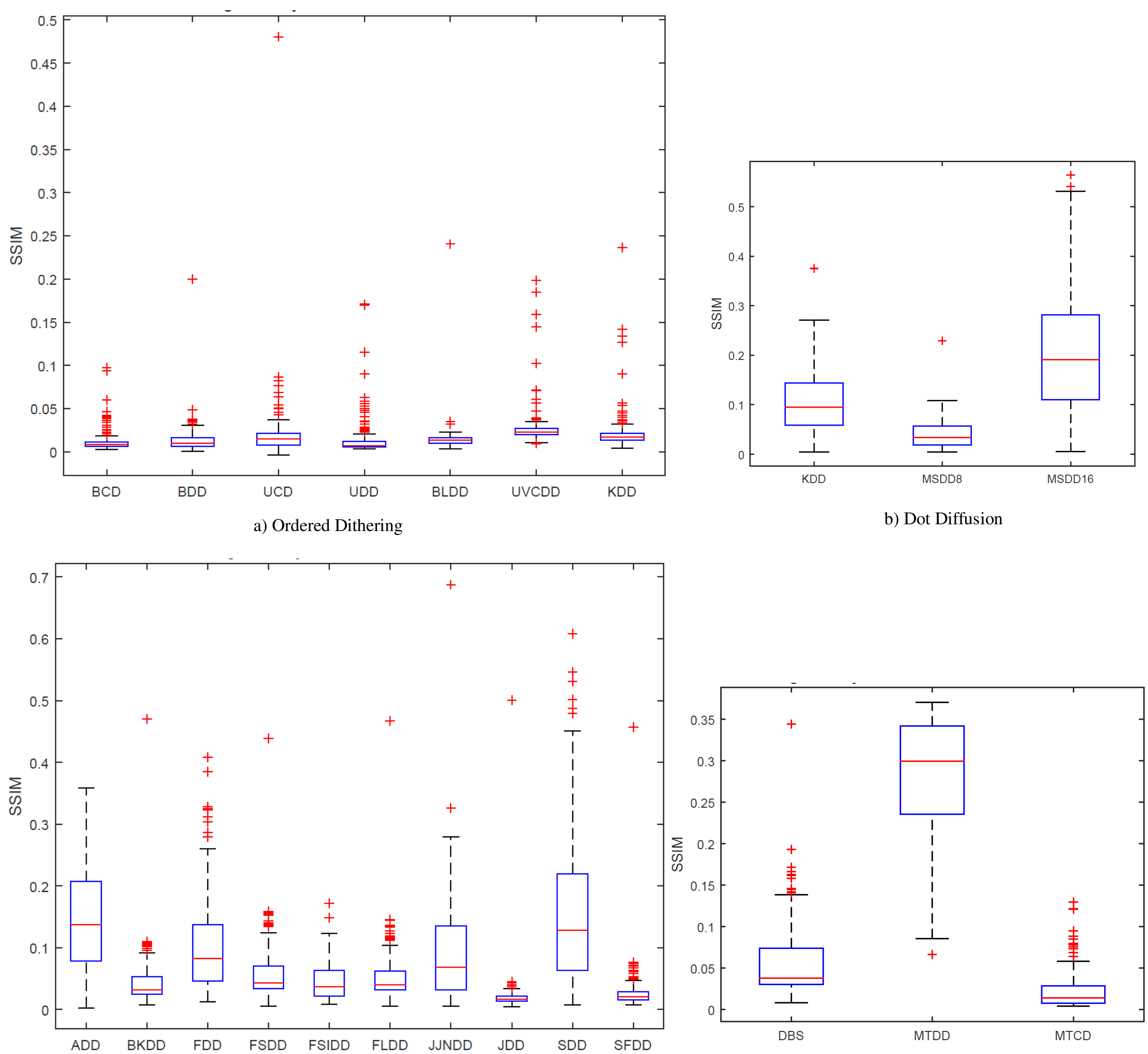
where DFT_{2D} is the two dimensional fourier transform of the considered sample φ; N(φ) refers to the number of pixels; K refers to the averaged periodograms. Subsequently, RAPSD is defined by partitioning the spectral domain into various annular rings R(f_p) of width Δ_ρ.

$$RAPSD(f_\rho) = \frac{1}{N\big(R(f_\rho)\big)} \sum_{f \epsilon R(f_p)} \hat{P}(f) \tag{11}$$

where $N\left(R(f_\rho)\right)$ is the number of frequency samples.

Then the second parameter termed ANIS is measured by computing the noise to signal ratio of the frequency samples in the annular rings. It basically measures the isotropic nature of pattern, and based on the fact that aperiodic patterns in the uniform area correspond to more pleasant patterns, less value of ANIS corresponds to high quality pattern.

$$ANIS(f_\rho) = \frac{1}{N\big(R(f_p)\big)^{-1}} \sum_{f \epsilon R(f_p)} \frac{\big(\hat{P}(f) - P(f_\rho)\big)^2}{P^2(f_\rho)} \tag{12}$$



a) Ordered Dithering

b) Dot Diffusion

b) Error Dithering

d) DBS and Multi-tone method

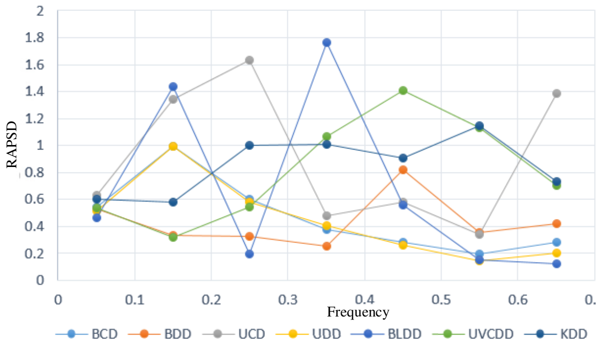
Fig. 5. Image quality assessment of different halftones

Further, the results of the mentioned image quality and halftone characteristic parameters for all the considered halftones are presented.

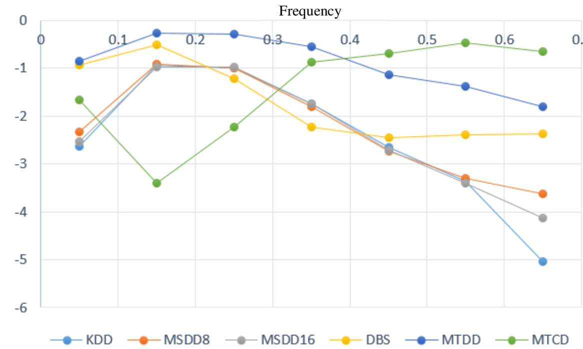
Box and whisker plots are used as it can illustrate in detailed way as follow, the middle line in the box indicate the median, the box corners indicate the upper and lower quartile and the whiskers indicate the highest and lowest observation.

Fig. 5, shows the image quality assessment of various halftone varieties. From Fig. 5.a, it can be inferred that UVCDD methods has high image quality and BCD score low. This is because of the fact, that UVCDD is developed based on the blue noise, which pertains to more homogeneously distributed patterns, whereas BCD comprise of highly clustered dot patterns and hence in low quality region.

Among the dispersed dot patterns considering, Fig. 5a, 5b and 5c, SDD and ADD are found to have better image quality in error diffusion halftones. In dot diffusion halftone, MSDD16 is found to have better image quality, as it involves big class matrix which results in more disperse patterns. It is important to mention, among all the existing techniques, DBS halftone possess highest visual quality because of the usage of iterative procedures and human visual system filters. Considering the multitoning it is evident that the dispersed patterns MTDD have better visual quality among all the halftone methods.

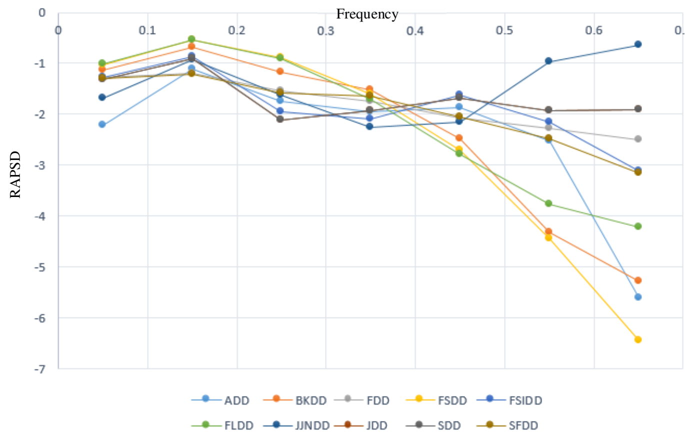


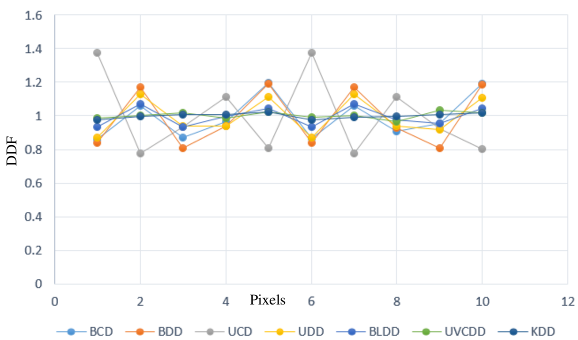
(a) RAPSD for ordered dithering



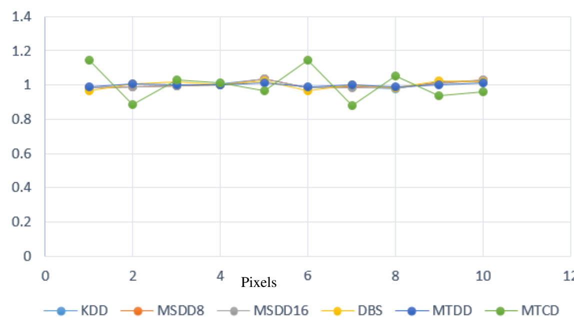
(b) RAPSD for dot diffusion, iterative and multitone

(c) Test image

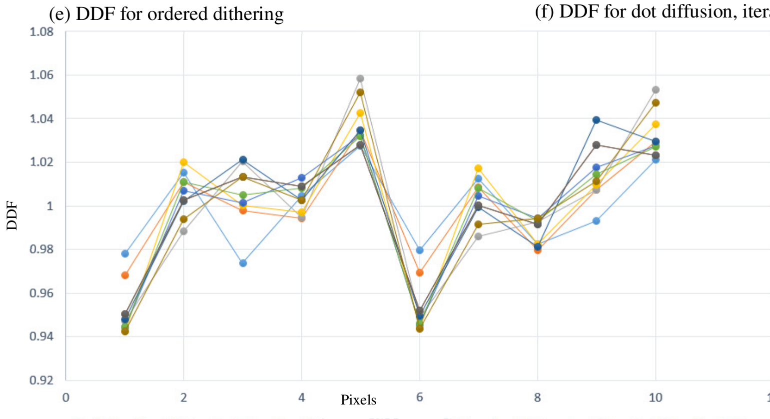




(e) DDF for ordered dithering

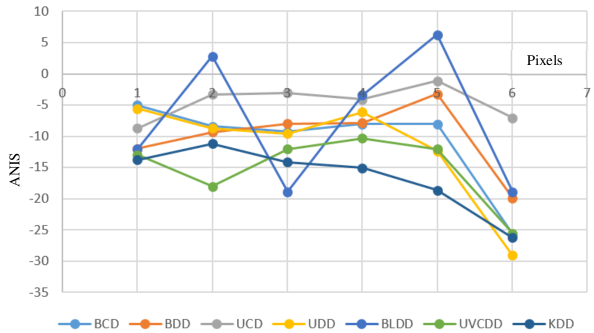


(f) DDF for dot diffusion, iterative and multitone

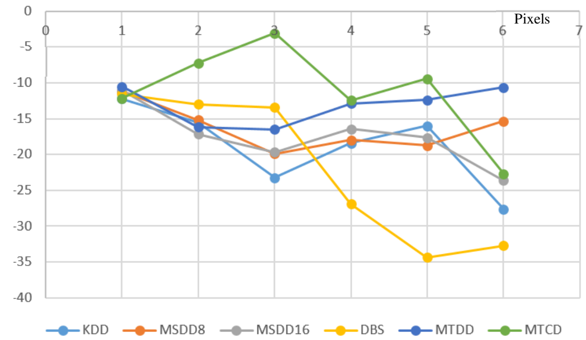


(g) DDF for error diffusion

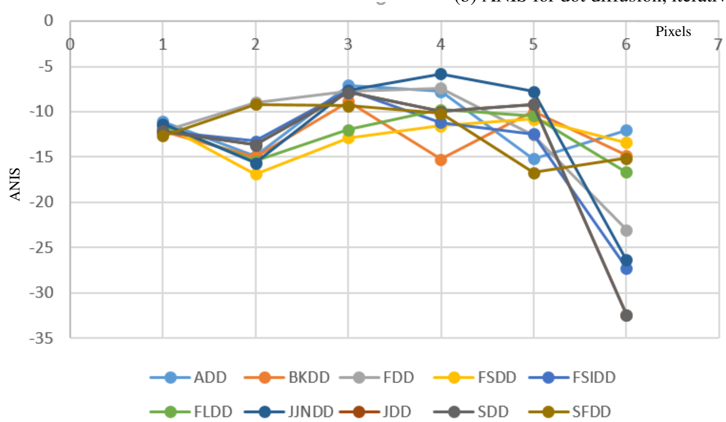
Fig. 6. Spatial and spectral statistics of various halftones



(a) ANIS for ordered dithering



(b) ANIS for dot diffusion, iterative and multitone



(c) ANIS for error diffusion

Fig. 7. Anisotropy of various halftones

Fig. 6, shows the RAPSD and DDF statistics for a test image from the database. For both these parameters, a flat line plot indicates the homogeneous distribution of points in all the directions. For instance, clustered dot patterns such as BCD, UCD and MTCD shows up and down plots which clearly describes its nature as non-homogenous (green noise) in comparison to dispersed dot. Among dispersed dot, DBS and MTDD is found to have ideal flat profile and followed by MSDD16, SDD and ADD. From this analysis, it can be inferred that the RAPSD and DDF has a good correlation with the image quality assessment. Thus, it can be concluded that the homogeneity of the patterns directly corresponds to the better visual quality. Similar phenomenon can also be observed with ANIS parameter, in which pattern with less value corresponds to the good visual quality as shown in Fig. 7. To summarize, it can be inferred that these stochastic parameters can characterize many aspects of halftone patters.

V. Conclusion

A digital halftone database comprising of 4508 images for the 23 varieties of halftones is developed. The paper considers all the methods of halftones such as ordered dithering, error diffusion, dot diffusion, iterative approach and the latest multitone techniques. In further, the study analysis some critical parameters of halftone such as its quality and pattern characteristics. From the experimental analysis, the relationship between the stochastic spatial and spectral parameters towards the visual quality is realized. The database is made open source and it will be useful to perform other halftone analysis such as classification, restoration, retrieval and other printed image processing tasks.

Link: https://sites.google.com/view/sankarasrinivasan-s/research-publication/DHD-Database

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