Definition of Optical Density of Digital Images for Print Equipment Control Systems

Bohdan Durnyak [1], Mykhailo Nakonechnyi [1], Mikola Lutskiv [1], Volodymyr Polishchuk [2] and Petro Shepita [1]

[1]*Ukrainian Academy of Printing, Pid Goloskom str., 19, Lviv, 79020, Ukraine*
[2]*Uzhhorod National University, Narodna Square, 3, Uzhhorod, 88000, Ukraine*

Abstract

A mathematical model of optical density of digital images has been developed for print equipment management systems. The model accounts for variations in tone ranging from black to white, including intermediate shades of gray with a range of gray levels from 0 to 255. A logarithmic expression has been proposed to determine the reflection optical density, allowing for the calculation and construction of optical density characteristics for different levels of gray and various brightness gradation distributions within the tonal range. This enhances the efficiency of operators (designers) using computer publishing systems when preparing images for printing. A structural scheme has been developed for a simulator of optical density of digital images using MATLAB: Simulink. The simulator, based on the number of gray levels in an image, calculates and constructs the optical density characteristic achievable in offset printing within the range of [0≤D≤3.0]. To quantitatively evaluate technological influences on digitization results, a deviation of optical density from linearity is proposed, with a maximum allowable deviation of +30%. The results of simulation modeling are presented in the form of a gradation characteristic of the image in gray levels and the optical density characteristic of the image, depending on the number of gray levels. These results enhance the informativeness of digital images in the traditional context of the printing industry. The findings of analytical research and simulation modeling of optical density of digital images can be used by operators of computer publishing systems to select optimal gradation characteristics for reproduction at various stages of image preparation for printing.

Keywords

Modeling, digital image, control system, decision-making system, transformation, gray levels, optical density, simulator, gradation characteristics, printing tools.

1. Introduction

Optical density of digital images is a crucial parameter in the field of printing, as it indicates the concentration of ink or dye on a printing medium, such as paper or film. It is measured using a spectrophotometer or densitometer. The optical density of an image can be defined as the logarithm of the ratio between the light intensity passing through the printed material and the light intensity on a white background. It is measured on a scale of 0 to 5, where 0 represents a completely transparent material (no ink present), and 5 represents a fully opaque material (maximum ink concentration). In print management systems for graphic equipment, optical density is utilized for monitoring and calibrating the printing process. It enables the establishment of the desired printing intensity to achieve the desired levels of tone and color. Optical density can be measured separately for each color, such as process colors like cyan, magenta, yellow, and black, or as the overall density of the image. Precise measurement of optical density requires calibrated equipment and standardized

International Scientific Symposium «Intelligent Solutions» IntSol-2023, September 27–28, 2023, Kyiv-Uzhhorod, Ukraine
EMAIL: durnyak@uad.lviv.ua (Bohdan Durnyak); reboot1804@ukr.net (Mykhailo Nakonechnyi); lutolen@i.ua (Mikola Lutskiv); volodymyr.polishchuk@uzhnu.edu.ua (Volodymyr Polishchuk); pshepita@gmail.com (Petro Shepita);
ORCID: 0000-0003-1526-9005 (Bohdan Durnyak); 0009-0002-2617-8125 (Mykhailo Nakonechnyi); 0000-0002-2921-3662 (Mikola Lutskiv); 0000-0003-4586-1333 (Volodymyr Polishchuk); 0000-0001-8134-8014 (Petro Shepita)

measurement methods. It's important to note that optical density is one of several factors influencing print quality. Other factors, such as dot accuracy, dot size, halftone frequency, and the type of printing material, also play a significant role in achieving the desired outcome.

1.1. Problem Statement

To ensure high-quality reproduction of digital images in the field of printing, various adjustments are often required due to the imperfect conditions under which the images obtained. This includes imperfections in scanners, digital cameras, and non-professional equipment, as well as the presence of various artifacts and distortions. Therefore, most digital images require different corrections, including tonal adjustments [1, 3, 6, 7, 17-22]. When images are scanned in batches, they can be too light or too dark, with variations in the minimum and maximum values of optical density, which deteriorates the quality of the scanned images. As a result, nearly every scanned image needs digital processing in computer graphics software such as Photoshop [7, 8, 11]. It should be noted that optical density is not a measurement unit and is not applied in computer graphics software.

Proper quality of the final product achieved when the images and textual information reproduced in the print without significant losses, which is achieved through thorough control using step wedges, reference scales, standards, and measuring instruments. The primary instrument used is a densitometer, which employed to control printed reproductions, including the range of optical density, image contrast, relative area of halftone dots, and their spread [3, 9, 12-16]. The operator (designer) of the computer publishing system responsible for preparing images for printing often does not have a physical original and computer graphics software does not provide a means to determine optical density. Therefore, the operator has limited quantitative information about the image, and verbal descriptions such as "highlights" or "shadows" are insufficient for determining the gradation characteristics of the reproduction.

Hence, the determination of the optical density of digital images is a relevant task that allows for constructing the characteristics of optical density for the initial digital image after its adjustment.

1.2. Analysis of recent research and publications

Modern prepress processes are based on the digital representation of images, which involves converting continuous images into discrete (digital) representations using gray levels that can vary from zero (black) to 255 (white), with 127 representing a 50% gray level [2, 3, 11, 26]. Professional flatbed, drum, and drum scanners with resolutions ranging from 2000 to 2400 dpi are used in computer publishing systems. There are scanners available specifically for scanning black and white (monochrome) and line art images [3, 11, 23]. In most cases, images are scanned in batches, containing images with different tones and optical densities, making it impossible to account for the specific characteristics of individual originals. In such cases, various computer graphics software programs, such as Photoshop, are used to adjust the images.

If a digital image is reproduced on a monitor screen, laser printer, plotter, or in a printed reproduction, its tone will appear differently. This is because the image on the monitor is displayed using emitted light, while in printing it is reproduced using toner or ink, which needs to be taken into account when controlling the image at different stages of preparation for printing. To enhance the efficiency of digital image processing, it is necessary to have information about the optical density that can be used to predict image contrast, the area of halftone dots, and their spread. This contributes to improving the quality of image preparation for printing. The goal of the article is to develop a mathematical model of optical density for digital images, determine and construct reflection optical density characteristics for different levels of grayscale, and analyze their properties.

2. Presentation of the main research material

To construct a mathematical model of optical density for digital images, we assume that the digital images are obtained through scanning originals, which is based on the phenomenon of light reflection from the image. The main physical parameter involved is the reflectance coefficient R, which is determined by the relationship [5, 9, 11, 24].

$$R = \frac{\Phi_0}{\Phi_1}, \tag{1}$$

The equation you mentioned describes the relationship between the intensity of the incident light (Φ_0) and the intensity of the reflected light (Φ_1). If the scanned original reflects 10% of the light, then the reflectance coefficient of the analyzed image would be 0.1. The main parameter for scanning is optical density, which is measured in logarithmic units [5, 9, 11].

$$D = \frac{lg1}{R}, \tag{2}$$

After substituting the reflection coefficient in (1) optical density.

$$D = lg\frac{\Phi_1}{\Phi_0}, \tag{3}$$

In scanners, the intensity of reflected light is measured by photosensitive elements (e.g., CCD), and their output electrical signal corresponds to the brightness L of the image. Through analog-to-digital conversion (ADC), it is transformed into a corresponding number of gray levels within the range of 0 to 255 (an 8-bit representation of black pixels). The optical density of scanned digitized originals (digital image) is then determined by the number of gray levels that correspond to light intensity.

$$D = lg\frac{L_0}{L}, if\ 0 \le L \le 255, \tag{4}$$

where L_0 represents the nominal number of gray levels of the ADC and L corresponds to the brightness level of the image

The optical density of a digital image is determined by the expression:

$$D = lg\frac{255}{L+1}, \tag{5}$$

The unit is introduced to account for the first level of black.

If we linearly change the amount of gray in the range of $0 \le L \le 255$ in equation (5), we can calculate and construct the optical density characteristic of the digital image on a linear scale. In most cases, digital images have low quality and require adjustments, which can be done using computer graphics software such as Photoshop [6, 7, 8, 18, 25] in a dialog window. Various standard functions are used for adjustments. Let's consider an example of a popular gamma correction defined by the formula [4, 7, 19, 18, 26].

$$L_{out} = (\frac{L_{out}}{L_0})^r * L_0, \tag{6}$$

Where L_{out} – is the output brightness value, L_0 = 255 – is the number of gray levels, and r is the exponent that determines the desired correction of the digital image. Then, using equation (5), we can determine the optical density of the corrected image.

$$D_1 = Lg\frac{255}{L_{out}+1}, \tag{7}$$

To simplify the task of determining the optical density of a digital image, an imitation modeling approach was applied using the MATLAB Simulink package. Based on the available blocks from the Simulink library, a structural diagram of the simulator model for optical density of digital images was constructed, as shown in Figure 1.

The structural diagram of the simulator model for the optical density of digital images includes the following blocks:

1. Ramp Block: This block generates a linear scale of gray levels (L0) ranging from 0 to 255. The output of this block is connected to the input of the Mathematical Functions (Fcn) block.

2. Mathematical Functions (Fcn) Block: This block contains the program (equation 5) for calculating the optical density. It takes the gray levels from the Ramp block as input and performs the necessary calculations.

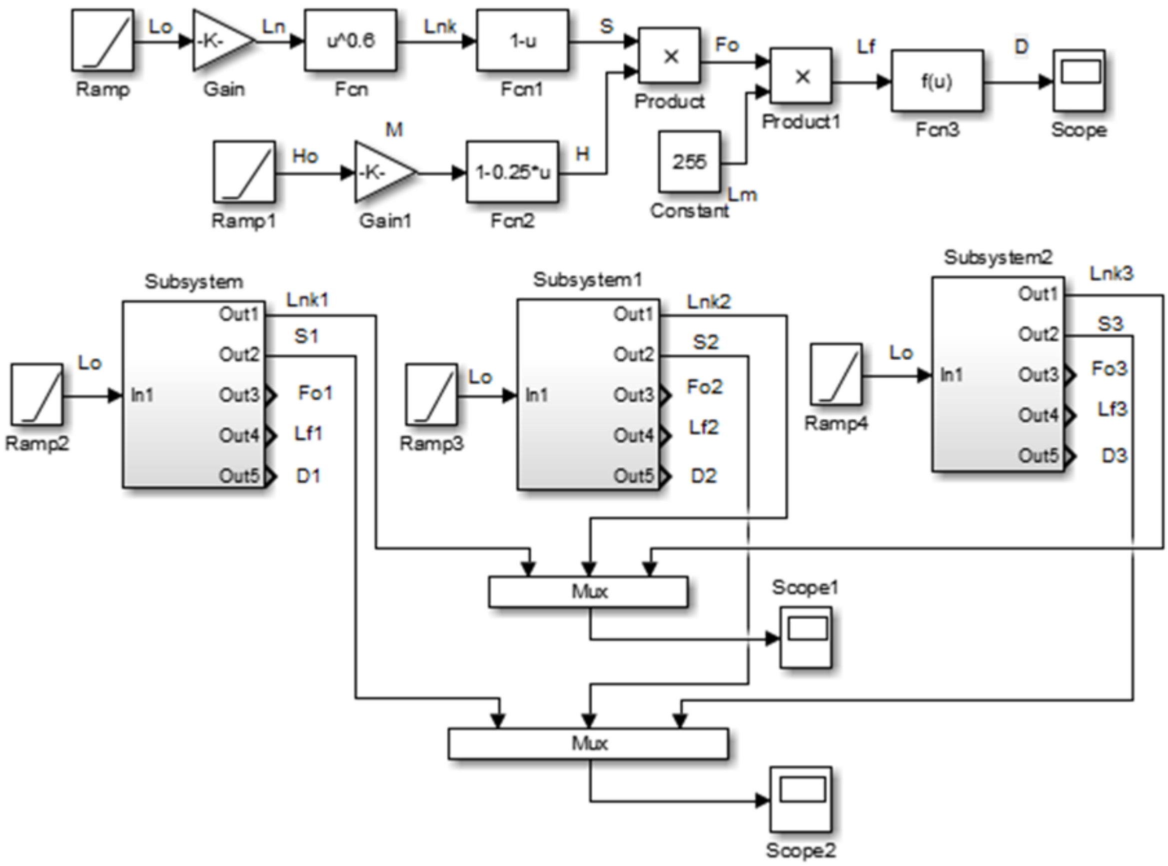

Figure 1: The structural diagram of the simulator model for the optical density of digital images

3. Gain Block (Gajn): This block receives the gray levels in parallel and applies scaling to them. The scaled gray levels are then passed to the next Mathematical Functions (Fcn4) block.

4. Mathematical Functions (Fcn4) Block: This block contains the program (equation 6) for determining the corrected number of levels based on the scaled gray levels. The result is then fed into the Mathematical Functions (Fcn1) block.

5. Mathematical Functions (Fcn1) Block: This block contains the program (equation 7) for calculating the optical density of the corrected digital image. It takes the corrected number of levels as input and performs the necessary calculations.

6. Scope Block: This block is used for visualization and displays the intermediate results or variables during the simulation.

7. Display Block: This block is used to visualize and display the final results of the simulation.

The results of the simulation, depicting the gradient characteristics of the digital images, are presented in Figure 2. The second characteristic is a straight line and corresponds to a linear digital scale with 256 levels of gray. The image exhibits more or less uniform information content and has a constant contrast value of 1. The first gradient characteristic of the corrected image is a convex curve. Shifting the characteristic curve upwards increases the brightness of the image, enhances contrast, and improves the visibility of details in darker areas of the image, but may lead to the loss of details in brighter areas. Shifting the characteristic curve downwards results in image darkening, increased color saturation, better visibility of details in brighter areas of the image, but at the expense of losing details in the shadows. The results of the simulated modeling of the optical density of digital images are presented in Figure 3.

Maximum optical density value, Dm = 2.5, corresponds to the achievable level in offset printing. The optical density of the linear digital scale changes according to the logarithmic law (equation 5), gradually approaching zero in the gray tones. The characteristic curve of the optical density of the corrected digital image (equation 2) is positioned below the previous one. Shifting the curve downwards results in a decrease in optical density and lightening of the image.

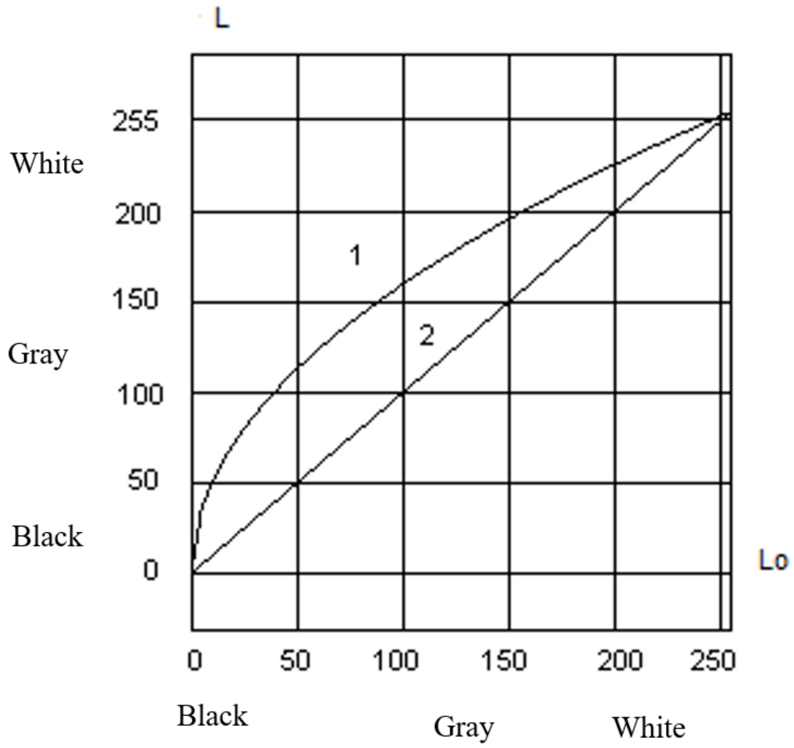

Figure 2: Gradient characteristics of digital images.

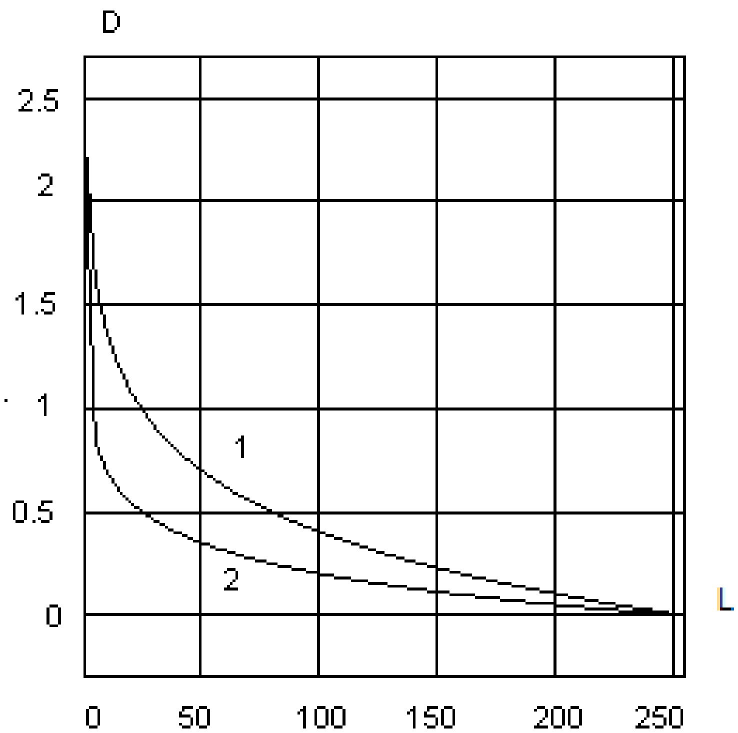

Figure 3: Characteristics of the optical density of digital images.

Comparing Figures 2 and 3, we can conclude that the optical density of digital images is inversely related to the grayscale characteristic provided by the gray levels, which is due to the logarithmic algorithm for calculating the optical density (equation 7). Therefore, optical density and brightness of digital images describe different aspects of the image. It should be noted that the characteristics of optical density more fully describe the black tone of digital images compared to the grayscale characteristic. To assess the impact of image correction, it is proposed to determine the deviation of the optical density in percentage.The maximum deviation of optical density occurs at the beginning of the range and amounts to -27.5%. It gradually decreases and crosses zero at a coefficient of R_0 = 0.12, becoming positive with a maximum deviation of +10% and gradually approaching zero. Therefore, the main deviation of optical densities occurs only at the beginning of the range with the maximum density value.

As mentioned earlier, there are problems in determining individual parameters using densitometric methods, and significant errors in their determination exist. One of the reasons for these errors is the sensitivity of the algorithms to the reflection coefficient R0, especially at low values. It is proposed to determine the sensitivity of the algorithms to changes in optical density using derivatives.

$$E = \frac{D_0 - D}{D_m}, \qquad (8)$$

where D_m is the maximum value of optical density of the digital image.

The results of the simulated modeling of the optical density deviation are presented in Figure 4.

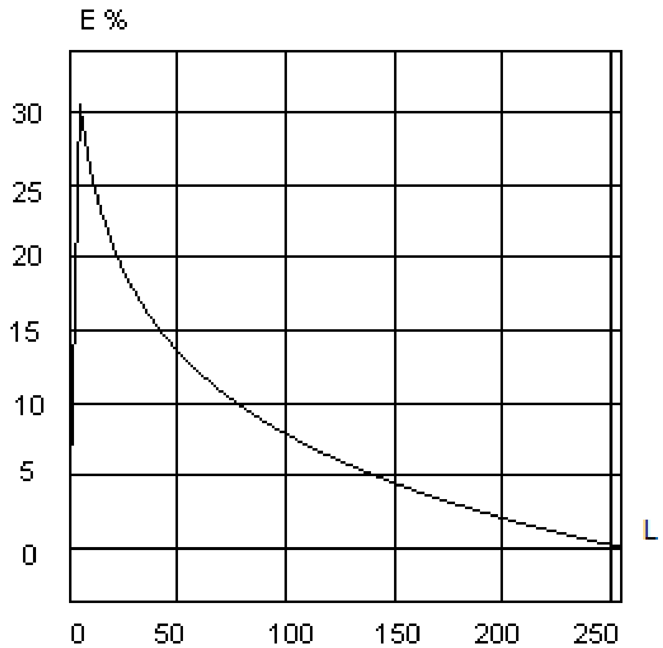

Figure 4: The deviation of optical density for the corrected digital image.

The maximum deviation of optical density occurs at low gray levels, with a maximum value of 30%. It gradually decreases and approaches zero at the end of the interval.

Let's examine the influence of the number of gray levels on the optical density. As an example, we set the number of gray levels to 128. The simulator was adjusted accordingly to have 128 levels (see equation 7). The results of the simulated modeling of optical density for different numbers of gray levels are shown in Figure 5.

The initial value of the first characteristic of optical density is 2.5 and decreases logarithmically, approaching zero at 255 gray levels. On the other hand, the second characteristic has an initial value of D = 2.4, positioned below the previous one, and approaches zero at 128 gray levels. Decreasing the number of gray levels compresses the optical density characteristic, reduces tonality, and brightens the image. Adjusting the image in this way will result in fewer details in the dark areas of the image, which should be taken into account when preparing the image for printing.

3. Conclusions

A mathematical model of optical density for digital images has been developed, expressed logarithmically as the ratio of the nominal number of gray levels (255) to the given digital image. A structural scheme of the accumulator model for optical density of digital images in the MATLAB package Simulink has been constructed, which allows for computing and generating characteristics of optical density for specified digital images and analyzing their properties.

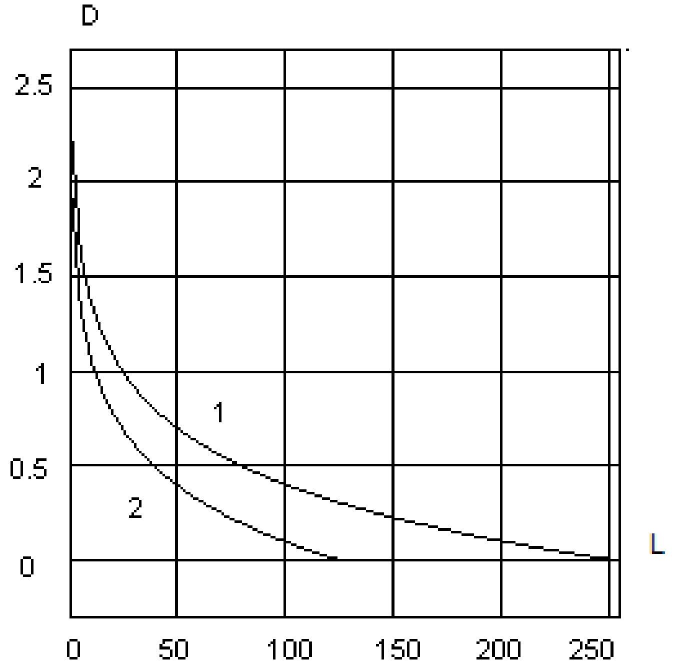

Figure 5: Characteristics of the optical density of images for different numbers of gray levels.

The presented results of simulation modeling are in the form of optical density characteristics for typical digital images with linear scales and convex gradation characteristics. It has been established that the optical density characteristic for a linear digital scale has a maximum value of Dm=2.5 and gradually approaches zero for gray tones. The characteristic for the adjusted image is positioned below the previous one, resulting in a decrease in optical density and image brightening. The deviation of optical densities has been determined, with the maximum value occurring at low gray levels and reaching 30%. The influence of the number of gray levels on optical density has been examined. It has been found that with 128 gray levels, there is compression of the optical density characteristic, a reduction in tonality, and image brightening. Consequently, the adjusted image will have fewer details in the dark areas.

It has been established that the optical density characteristic of a digital image is inversely related to the gradation characteristic provided by gray levels, which is due to the logarithmic algorithm for calculating optical density. Optical density and brightness describe images in different planes. The optical density characteristics more fully describe the black tone of digital images compared to gradation characteristics. The results of this work enhance the informativeness of digital images and can be used in computer publishing systems to select optimal gradation characteristics for reproduction at different stages of image preparation for printing.

4. References

[1] "33rd International Conference on Digital Printing Technologies (NIP)", NIP & Digit. Fabr. Conf., v. 33, № 1, c. i—xliv, 2017. doi.org/10.2352/issn.2169-4451.2017.33.1.

[2] "Metrology, Standardization, Quality: Theory and Practice (MSQ-2017)", *J. Physics: Conf. Ser.*, v. 998, p. 011001, 2018. doi.org/10.1088/1742-6596/998/1/011001

[3] “Complex fuzzy sets and complex fuzzy logic. an overview of theory and applications” (2018) Fuzzy Logic Theory and Applications, pp. 309–325. Available at: https://doi.org/10.1142/9789813238183_0011.

[4] “Fuzzy relations” (2018) A First Course in Fuzzy Logic, pp. 225–252. Available at: https://doi.org/10.1201/9780429505546-12.

[5] Durnyak, B., Lutskiv, M., Shepita, P., Hunko, D., & Savina, N. (2021). Formation of linear characteristic of normalized raster transformation for rhombic elements. Paper presented at the *CEUR Workshop Proceedings, , 2853* 127-133
[6] Durnyak, B., Lutskiv, M., Shepita, P., Hunko, D., & Savina, N. (2021). Formation of linear characteristic of normalized raster transformation for rhombic elements. Paper presented at the CEUR Workshop Proceedings, 2853, 127-133.
[7] Durnyak, B., Lutskiv, M., Shepita, P., Karpyn, R., Sheketa, V., & Pasieka, M. (2022). *Modelling of tone reproduction with round raster elements in a short printing system of parallel structure* doi:10.1007/978-3-031-04812-8_4
[8] Durnyak, B., Lutskiv, M., Shepita, P., Sheketa, V., Karpyn, R., & Pasyeka, N. (2022). *Analysis of transfer of modulated ink flows in a short printing system of parallel structure* doi:10.1007/978-3-031-04812-8_2
[9] E. Alzaghoul, M. B. Al-Zoubi, R. Obiedat, and F. Alzaghoul, “Applying machine learning to DEM raster images,” Technologies, vol. 9, no. 4, p. 87, 2021.
[10] E. Ontiveros-Robles, P. Melin, and O. Castillo, “Comparative analysis of noise robustness of type 2 fuzzy logic controllers,” Kybernetika, pp. 175–201, 2018.
[11] Friedrich, L., Begley, M. Printing direction dependent microstructures in direct ink writing. Additive Manufacturing, Vol. 34, P. 2020101192.
[12] Imamović, B., Halilčević, S.S. and Georgilakis, P.S. (2022) “Comprehensive fuzzy logic coefficient of performance of absorption cooling system,” Expert Systems with Applications, 190, p. 116185. Available at: https://doi.org/10.1016/j.eswa.2021.116185.
[13] J. Felici, Complete Manual of Typography: A Guide to Setting Perfect Type. Pearson Education, Limited, 2018..
[14] J. Harder, “Looking at other Adobe applications for GIF Animation Creation and GIF alternatives,” Creating GIF Animations, 2022.
[15] J. Yoo, D. Lee, C. Son, S. Jung, B. I. Yoo, C. Choi, J.-J. Han, and B. Han, “Rascanet: Learning tiny models by raster-scanning images,” 2021 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), 2021.
[16] Japanese Journal of Applied Physics, Vol. 59(SG), 2020, P. SG0802.
[17] Jurečić, D., Žiljak, V., Gršić, J. Ž., Rajković, I. Near infrared spectrography of colorants for offset printing with individualized rasters on drug packaging. Acta Graphica, Vol. 29(4), 2020, PP. 7-12.
[18] Kusaka, Y., Fukuda, N., Ushijima, H. Recent advances in reverse offset printing: an emerging process for high-resolution printed electronics.
[19] Kusaka, Y., Kanazawa, S., & Ushijima, H. Design rules for vertical interconnections by reverse offset printing. Journal of Micromechanics and Microengineering, Vol. 28(3), 2018, P. 035003.
[20] L. Kakinada and K. Singh, “WCA optimized fuzzy PD controller for stabilizing the two wheel self-balancing robot,” 2021 Asian Conference on Innovation in Technology (ASIANCON), 2021., doi:10.1109/ASIANCON51346.2021.9544711
[21] L. Zweifel, M. Samarin, K. Meusburger, V. Roth, and C. Alewell, “Identification of soil erosion in alpine grasslands on high-resolution aerial images: Switching from object-based image analysis to deep learning,” 2020.
[22] L. Zweifel, M. Samarin, K. Meusburger, V. Roth, and C. Alewell, “Identification of soil erosion in alpine grasslands on high-resolution aerial images: Switching from object-based image analysis to deep learning,” 2020.
[23] Litunov, S. N., Gusak, E. N., Toshhakova, Y. D. Numerical study of printing ink structuring. In Journal of Physics: Conference Series. Vol.1050(1), 2018, P. 012045
[24] M. Azimipour, R. J. Zawadzki, I. Gorczynska, J. Migacz, J. S. Werner, and R. S. Jonnal, “Intraframe motion correction for Raster-scanned adaptive optics images using strip-based cross-correlation lag biases,” PLOS ONE, vol. 13, no. 10, 2018.
[25] Moreira, A., Silva, F. J. G., Correia, A. I., Pereira, T., Ferreira, L. P., De Almeida, F. Cost reduction and quality improvements in the printing industry. Procedia manufacturing, Vol. 17, 2018, PP. 623-630.
[26] N. Karmaker, "Digital Image Processing and Its Application for Medical Physics and Biomedical Engineering Area", Digital Image Processing Applications. IntechOpen, 2022. doi.org/10.5772/intechopen.100619.