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Analysis of color reproduction accuracy of digital printing systems

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In the last 10 years, the new generation of state of art digital printing technology has become a significant driver of technical development, and it has become increasingly important in all areas of imaging science, packaging, and printing industry. The new printing technologies offer better color reproduction accuracy, fewer color deviations in the printing run, higher speeds, reduced material and energy consumption, reduced machine preparation time. A large number of various indicators related to the quality of digitally printed output are considered in this study. In the experimental part of this research color difference ΔE, gray balance, color gamut evaluation, tone value, tone value increase, etc., were investigated. These indicators are directly related to the printing process and the possibility of its continuous optimization to achieve a high quality of printing output and the ability to meet international ISO printing standards and requirements. Quality of densitometric and colorimetric characteristics of different types of print media production was investigated. Digital printouts from different manufacturers were used in the media. ICC profiles were generated, and 2D and 3D visualizations were made for visual comparison with international ISO standards. Color quality and accuracy of Pantone colors reproduction was assessed. The Pantone color reproduction is very important for wider spreading out of digital printing processes in packaging, where the color accuracy demands are higher. From the results we can derive how important it is to keep as much as possible recommendations and ISO standards so that we can optimize and maintain print quality to meet the customer's high demands on the end product. This is especially important when printing packages, labels, and more.

Keywords: Printing Quality, Color Reproduction Accuracy, Digital Print, Color Difference, Tone Value Increase

INTRODUCTION

Digital print is a new generation technology in comparison to all known methods of printing information on paperback or any other type of carrier. With the development of information technologies, the application of this printing method also increases. It picks up style in the Graphic industry, as the tendency is for it to go into full industrial use for the production of packages and labels in small and medium circulations. [2]

This paper is the first part of a series of researches, which are focused on different classes of digital printing machines as the latter are used in a variety of applications, such as “Commercial Printing”, “Outdoors Advertisement”, “Packaging and Label” and so on.

EXPERIMENTAL

Reaching the set goals was aided by the use of different measurement tools – densitometer, spectrophotometer, which served to examine the accuracy and quality of tonal and color reproduction in digital printing machines. In order to maintain result reproducibility, a specialized test form was developed and used.

The test form consists of:

- ECI 2002 test chart with 1485 patches for colorimetric assessment and generating of ICC profiles [6];
- Test charts with 0, 5, 10, 20 to 100% for all process colors and their double overlays;
- Positive and negative lines of different width and number of colors for assessment in order to detect the thinnest lines, which could be reproduced from the given material by the examined printing systems;
- Test images for visual analyses;
- Small positive and negative texts of different size;

A multitude of colorimetric and densitometric methods were used [7-9].

The goal of this paper is to render examination results on the accuracy and quality of tonal and color reproduction in ink-jet and electrophoto-graphical digital print as a multitude of assessment methods related to tonal and color reproduction accuracy were selected regarding the Pantone coloring system, color characteristics of solid primary colors, tone value increase, assessment

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of 3D and 2D color gamut shape and values, visual analyses of images, reproduction of thin positive and negative line art and lines, as well as fonts with small size in one, two and more colors [3]. The following digital machines were used to carry out the experiment: Canon IPF 9400 – ink-jet printer with water-based inks; media used to perform the experimental analyses were: glossy photo paper – 190 g/m^2.

RESULTS AND DISCUSSION

Due to the large dataset obtained from the thorough research on the precision and quality of tonal and color reproduction for ink-jet and electrophotographical digital print, this paper will only include the results obtained during the experiments with Canon IPF 9400 loaded with photo paper. The examination included assessment of color characteristics of test prints, simulating specially selected Pantone colors. Also there was a measurement of the color coordinates as per the CIE Lab system with included calculation and comparison of ΔE_{76} and ΔE_{00} according to ISO 12647-2:2013 [4]. A dedicated software product was used to render the 2D and 3D visualization and a comparison between the color gamut of the examined media was made with a standard ICC profile FOGRA47 and FOGRA51 [6].

In order to compare the quality of tonal and color reproduction of catalogue and selected Pantone system colors, one must calculate the color difference ΔE for a set number of colors. In order to calculate ΔE, one must first obtain the color coordinates of all colors according to the CIE Lab system. The reference values are the color coordinates as per ISO 12647-2:2013 [4].

Process control for the production of half-tone color

Color differences were derived using the following formulas:

color difference ΔE_{76}:

$$\Delta E^*_{76} = \sqrt{(L^*_1 - L^*_2)^2 + (a^*_1 - a^*_2)^2 + (b^*_1 - b^*_2)^2} \quad (1)$$

color difference ΔE_{00}:

$$\Delta E^*_{00} = \sqrt{\left(\frac{\Delta L'}{K_L S_L}\right)^2 + \left(\frac{\Delta C'}{K_C S_C}\right)^2 + \left(\frac{\Delta H'}{K_H S_H}\right)^2 + R_T \frac{\Delta C'}{K_C S_C} \frac{\Delta H'}{K_H S_H}} \quad (2)$$

where: L – lightness/brightness; C – saturation; H – hue.

The measurements of color coordinates are made using a spectrophotometer under the following conditions:

- standard light illuminant - D50;
- 2° standard observer;
- no polarization filter;
- aperture – 4 mm;
- white backing.

Investigation of color reproduction accuracy of digital printing systems and calculation of ΔE for Pantone colors

In order to examine the reproduction precision of the fundamental Pantone colors, the color coordinates (Lab) for the media listed above were measured. Figure 1 represents the basic Pantone colors.

In order to examine the reproduction precision of the basic Pantone colors, the color coordinates (Lab) for the media listed above have been measured. Figure 1 represents a selection of Pantone colors.

Due to the extensiveness of the measurements and the multitude of obtained results, this paper presents only an excerpt there to concerning the stated printing machine and the printing media, used in conjunction with it. Tables 1 and 2 show all results derived from ΔE calculations.

Fig. 1. Selection of Pantone colors used in the experiment

Table 1. Experimental results for color reproduction accuracy obtained for selected Pantone colors

Selected Pantone colours			ΔE76			Count of colours corresponding to the average limitations (total of 13)			ΔE00			Count of colours corresponding to the average limitations (total of 13)		
№	Digital machine	Media	ΔE avg.	ΔEmin	ΔEmax	ΔE<3	ΔE<5	ΔE>5	ΔE avg.	ΔEmin	ΔEmax	ΔE<3	ΔE<5	ΔE>5
1	HP Latex 370	polypropylene	7,16	1,42	23,94	2	4	7	3,30	0,48	6,21	7	3	3
2	HP Latex 370	Self-adhesive PVC	7,21	2,31	24,17	2	3	8	3,36	1,25	6,40	8	2	2
3	Agfa Anapurna M2540	Vinil	7,34	2,31	22,03	3	3	7	3,44	1,43	8,47	8	2	3
4	HP Latex 370	Jetcoat paper	7,44	2,03	24,30	2	3	8	3,48	1,18	7,44	7	3	3
5	HP Indigo 5500	Matte coated paper	7,59	1,69	18,68	2	2	9	3,83	1,49	5,95	4	7	2
6	Canon IPF9400	Photo paper	8,28	3,72	21,07	0	3	10	4,18	1,99	7,15	5	3	5
7	HP Indigo 5500	Glossy coated paper	8,63	2,41	19,65	1	1	11	5,00	2,15	16,07	4	7	2
8	HP Indigo 5500	Offset uncoated paper	11,49	3,76	21,39	0	1	12	6,49	3,25	9,68	0	4	9

Table 2. Results obtained from measuring the color differences with ΔE_{76} and ΔE_{00} and comparing Pantone colors with ISO 12647-2: 2013 for photo paper printed on the Canon IPF 9400

Selected Pantone Colors									
Photo Paper Media		Canon IPF 9400			ISO (coated)			ΔE_{76}	ΔE_{00}
№	color	L	a	b	L	a	b		
1	Pantone 7420	32.92	48.29	7.9	36	51	15	8.20	4.45
2	Pantone 429	72.67	-1.18	-9.23	70	-2	-3	6.83	5.47
3	Pantone 431	39.36	-2.91	-10.79	44	-3	-6	6.67	5.45
4	Pantone 151	62.34	37.58	64.44	67	51	80	21.07	6
5	Pantone 314	46.39	-38.05	-38.13	46	-43	-37	5.09	2.1
6	Pantone 618	66.46	-3.64	55.29	67	-4	49	6.32	1.99
7	Pantone 659	63.89	-6.58	-36.35	62	-3	-35	4.27	3.2
8	Pantone 318	82.25	-14.63	-13.81	84	-25	-11	10.89	7.15
9	Pantone 7465	72.99	-26.26	-5.33	71	-42	-5	15.87	6.57
10	Pantone 680	68.97	30.63	-14.33	68	24	-8	9.22	4.28
11	Pantone 348	46.31	-53.01	26.06	47	-57	23	5.08	2.22
12	Pantone 876	46.89	16.37	18.83	48	17	23	4.36	2.61
13	Pantone 4685	84.92	6.3	9.41	84	6	13	3.72	2.81
					ΔEavg			8.28	4.18

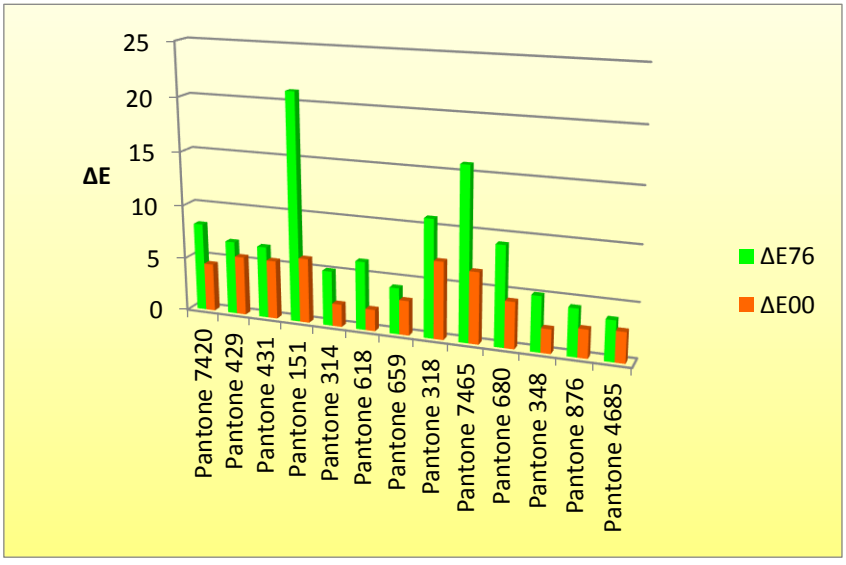

Fig. 2. Comparison of the color differences, according to CIE Lab, between the selected Pantone colors with ΔE_{76} and ΔE_{00} for glossy photo paper printed through Canon IPF 9400

Figure 2 shows the comparative graphs for comparison of the color differences according to CIE Lab, between the selected Pantone colors with ΔE_{76} and ΔE_{00} for glossy photo paper printed through Canon IPF 9400.

Investigation of tone value increase for digital printing systems on glossy photo paper

The tone value increase is an indicator which defines tone and color reproduction and under certain conditions it influences the image depth field. This is one of the most important measured values, serving to control the printing process and is directly linked to the quality of the printed image [1]. In order to define the tone value increase for the separate prints, one performs densitometric measurements of tonal fields in the interval between 5% and 100%.

Figure 3 depicts the relationship between the set and measured raster tone for photo paper, which is the gradation characteristic of reproduction in the four primary colors (CMYK). The figure shows that for all four colors (cyan, magenta, yellow and black) we have a substantially uniform increase. Only the black color from 0% to 15% has slightly higher measured values than the other colors.

Figure 4 shows the relationship between the reference tone value and the tone value increase of cyan, magenta, yellow and black printed on photo paper compared to standard curves according to ISO 12647-2: 2013. The graph shows that the experimental curves of the four primary colors have varying values, in light medium and dark tones. In cyan there is a slight decrease in the values from 20% to 35%, after which in the average tones from 40% to 70% we have approximately the same values compared to the reference (A-E) accepted in ISO 12647-2: 2013.

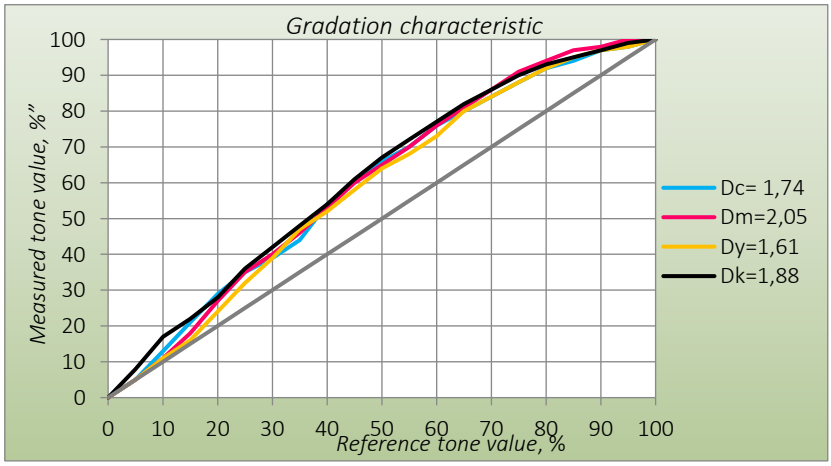

Fig. 3. Dependency between the reference and measured tone value (gradation characteristic) for glossy photo paper printed through digital printer Canon IPF 9400

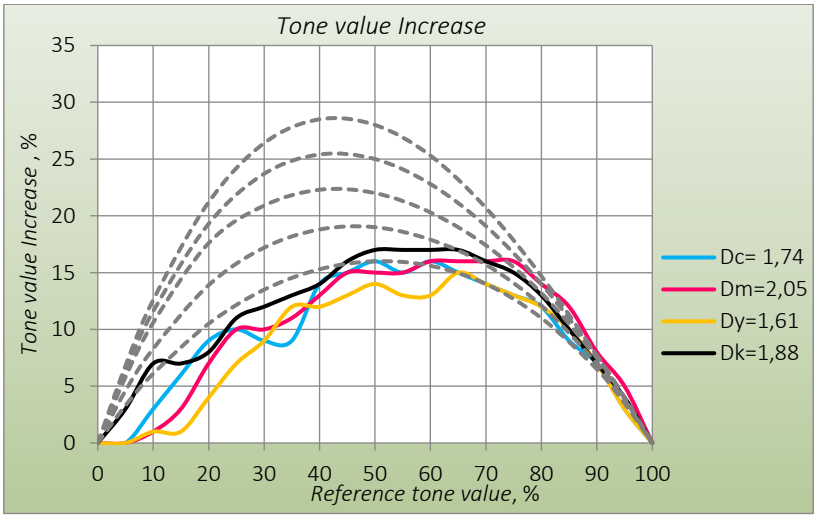

Fig. 4. Tone value increase for the four primary colors and standard curves as per ISO 12647-2:2013 for glossy photo paper printed through digital printer Canon IPF 9400

With magenta from 0% to 40%, the results obtained are lower than the standard values, at 50% and 60% the data obtained are closest to the standard values, and then in the dark tones we have slightly higher values. For the black color from 0% to 10%, the obtained data are approximately the same as the reference values, and then it can be seen that it has lower measured values than the standard values up to 45%. In the color yellow from 0% to 15%, significantly lower results are observed, followed by a smoother increase to medium tones, and between 50% and 60% a slight decrease occurs in the measured data. Yellow has the lowest values compared to the others. This graph shows no shift in the peak of growth, despite varying results in all four colors. These results can also lead to inaccuracies in tone and color reproduction.

Investigation of color gamut volumes and comparison of 2D and 3D color gamut of different digital printing systems

One important function which is used to visualise the colors, as reproduced by any given machine, is the 2D and 3D representation of the respective color gamut. This paper also uses 2D and 3D representations. The 2D representation of color gamut with different cross-sections along the L-axis of the CIE Lab color space allows for good visual comparison of colors in light, mid and dark tones, as well as comparison of a large number of color gamut at once [7]. The 3D representation of color gamut allows a complex visual assessment for the 3D body of the color gamut. It is appropriate for the visualization and comparison of one or two color gamuts.

In order to perform the comparison for the color gamut of the examined prints from the corresponding digital printing presses – HP Indigo 5500, Agfa Anapurna M2540, Canon IPF9400 and HP Latex 370 it is necessary to provide a 3D visualization with a standard ICC profile FOGRA 47 for uncoated papers and FOGRA 51 for coated papers with the ultimate goal to achieve visual representation for the color gamut. The 3D visualization of the ICC color profiles was performed using the software PROFILE MAKER 5.10. To compare the color gamut on offset uncoated paper, a standard ICC profile FOGRA 47 was used.

From Figure 5 it can be seen that the color range of FOGRA 51 is significantly larger than the color range of photo paper printed on the Canon IPF9400. It is observed that in certain areas the color range of the digital machine under study may produce colors that FOGRA 51 cannot.

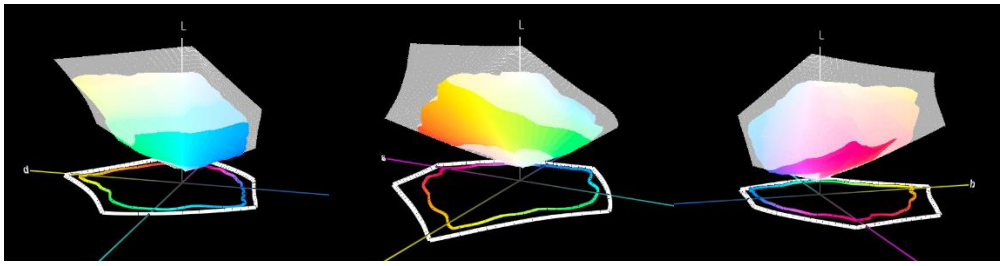

Fig. 5. 3D visualization (Lab system) of an ICC profile of glossy photo paper printed through Canon IPF 9400 and FOGRA 51

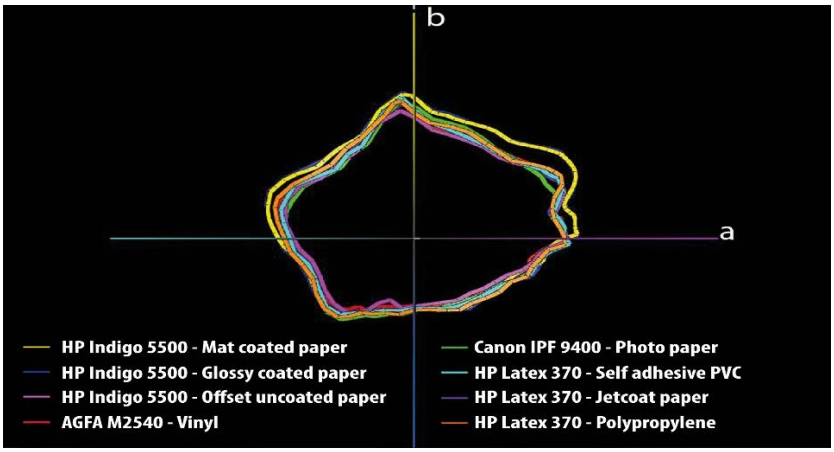

Fig. 6. 2D visualization of the color range of all types of media used within the scope of the experiment

It can be seen that with photo paper we have better color reproduction in the medium tones of the yellow-red area and in the light tones of the blue-green area. While with FOGRA 51 we have better color reproduction in dark tones and light tones in the yellow-green area.

Figure 6 depicts a 2D visualization of the color gamut of the tested media. The data shows that the most accurate tone and color reproduction occurs on matte and glossy papers printed through HP Indigo 5500, as they coincide in all areas. The smallest color gamut occurs with offset paper printed through the same machine. This phenomenon is due to the fact that offset paper is considered an uncoated print medium and has more porous structure, thus causing more ink intake in comparison to coated media.

Table 3. Volume of the color gamut.

№	Machines	Used media	Volume of the color gamut ΔE^3
1	HP Indigo 5500	Offset uncoated paper	202 479
2	HP Indigo 5500	Matte coated paper	293 021
3	HP Indigo 5500	Glossy coated paper	314 299
4	Agfa Anapurna M2540	Vinyl	244 498
5	Canon IPF 9400	Glossy photo paper	246 780
6	HP Latex 370	Paper “Jetcoat”	236 614
7	HP Latex 370	Polypropylene	254 321
8	HP Latex 370	Self-adhesive PVC	244 983

CONCLUSIONS

Based on the experimental results obtained in this paper, the following conclusions were drawn:

1. Color reproduction accuracy is an ever more important factor provided by the increasing usage of digital printing systems, especially in the production of packages, labels and other. In spite of the extended color gamut in most digital printing systems some of the fundamental problems originate from the insufficient color reproduction accuracy – especially with Pantone. After printing 240 Pantone colors, colorimetric measurement and appropriate analyses it was established that:

- The average color difference in ascending order between the set Pantone colors and the measured prints is:
  a. $\Delta E_{00\ avg.}$ HP Indigo 5500 varies between 3.83 and 7.06 ($\Delta E_{76\ avg.}$ from 7.59 to 23.33);
  b. $\Delta E_{00\ avg.}$ HP Latex 370 varies between 3.30 and 8.48 ($\Delta E_{76\ avg.}$ from 7.16 to 25.98);
  c. $\Delta E_{00\ avg.}$ Canon IPF9400 varies between 4.18 and 7.40($\Delta E_{76\ avg.}$ from 8.28 to 25.37);
  d. $\Delta E_{00\ avg.}$ Agfa Anapurna M2540 varies between 3.44 and 8.26 ($\Delta E_{76\ avg.}$ from 7.34 to 25.87).
- The minimal color difference in ascending order is ΔE_{00} = 0,48 (HP Latex 370) up to 4,10 (HP Indigo 5500)
- The maximal color difference in ascending order is ΔE_{00} = 5,95 (HP Indigo 5500) up to 26,06 (HP Latex 370)

From the obtained results one may conclude that the highest color reproduction accuracy of the Pantone colors is achieved while using the machine HP Indigo 5500 followed by all the other examined printing systems. Therefore, the present paper focuses mainly on its results as closest to ISO12647-2:2013. However, the average color difference ΔE is relatively high and could be the source of some inaccurate perception, especially with pretentious customers who often insist on a maximal tolerance of ± 1÷2 ΔE. For some of the Pantone colors, one obtains very good and low values of ΔE such as ΔE_{00} = 0.48 (HP Latex 370).

2. Color gamut and its volume is of special significance when the print quality is defined. The largest color gamut was obtained with HP Indigo 5500 (ΔE^3 =314 299), followed by HP Latex 370 (ΔE^3 =254 321), Canon IPF9400 (ΔE^3 =246 780) and Agfa Anapurna M2540 (ΔE^3 =244 498). The standard color gamut of FOGRA52 was best met by the HP Indigo 5500, followed by HP Latex 370 and Agfa Anapurna M2540.

3. The tone value increase and color characteristics of primary colors are important for the research of comparable visual results of digital print compared to the conventional printing processes. The experiment established that the TVI curves of digital printing systems differ significantly from their standardized counterparts. For the most cases, the curves follow the standards for light and dark hues and differ in the mids.

From the presented graphic material depicting the dependency between the reference and

measured color tone, representing the gradation characteristics, one may observe a uniform increment of the color tone for the four primary colors with all tested media.

For the most part of the tested media, one observes that within the first 5% of the reference there is 0% increase of the color tone for some of the colors. Another interesting fact which becomes apparent from these graphics, is that with most media, the obtained values during the primary colors measurements are slightly lower in the light and mid hues – up to the 60% mark. On the one hand this does not lead to any significant increase of the color tone, but the very fact that there are lower values obtained for the CMYK across most of the media could also lead to some inconsistencies in tonal and color reproduction. From the results obtained herein, one could begin to understand how important it is to adhere as much as possible to the recommendations of the ISO standards in order to be able to optimize and to maintain the print quality so that the customer's highest requirements with respect to the end product are fully met. This is especially important with the print of packages, labels and other.

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