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Does the use of black ink still comprise the "darkest" issue of CMYK printing?

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Abstract

Black ink can be used for multicolor printing to different extent within each of such multiple purposes, as: replacement of the achromatic component of three chromatic inks combination; reproduction of the image achromatic colors; expanding the color gamut; providing print security features … The relationships and effects within these functions are discussed in the paper on the background of prepress facilities evolution starting from the times of photoengraving and analogue scanners of 60's up to the precise digital color control of today. The results of comparative colorimetric analysis of the sets comprising cyan, magenta and yellow (CMY), and cyan, magenta, yellow and black (CMYK) revealing the black in particular effect of expanding the print gamut by providing the darker chromatic colors which aren't available for any combination of the other three process ones are also presented.

Keywords: color gamut, achromatic component, chromatic color, UCR, GCR, UCA

1. Introduction

Looking back in the latest history of graphic technology developments one can find that thirty to forty years ago there were a number of scientifically approved recommendations on direction and degree of tone and color values correction for print quality improvement. However, even at the times of electronic prepress, there was a lack of means for proper control of desired color setting variations. For example: in the 70's of the last century there was published in advertising specification the drum scanner's ability of replacing the CMY acromatic component by the black ink as "up to 75 %" (against the 65 % of the competing model). The clear knowledge of what had to be done with an image data in some other relations was, as well, short of means to realize the task.

The digital image processing of today allows for practically unlimited print parameter variation in any direction with the discretion of just 25 square micrometers of an ink coverage in surface plane. However, quite a contrary situation of adequate resources but lacking in knowledge of what should be done is often met and the need arises of additional research or training which could substantiate the recommendations and procedures for effective use of such precise, recently appeared control facilities (Kuznetsov, 2013). There is variety of purposes and reasons for black ink use in CMYK printing. It can be in different degree applied for reproduction of achromatic colors as well as the achromatic component of chromatic ones. Its use can also differentiate from the large area, stationary image area to sharp edges and fine details, as well as from the highlights to midtones and darker areas. So, there is the theoretically infinite continuum of CMY to CMYK transformations which can result in the same or improved colorimetric print values.

The beginning of K-ink use within the CMY triad stems from the times of photoengraving and camera prepress. The facilities of black control according to certain rendering intent and, especially, in isolation from its other effects on resulting color were rather restricted. However, the mostly heuristically found, scanty collection of black ink settings is until now used in wide practice. One of the reasons is in some isolation of numerous participants (publishers/advertisers, prepress operators, quality managers, printers …) from each other. Lack of facilities or time for finding the optimal adjustments which would match the job/process specifics encourages them to follow the narrow path of guaranteed standard parameters (Euroscale, SWOP …) or of a settings stipulated by the available ICC profile.

The other reason of non-optimal black ink use is in vague interpretation of its settings and their relationship essence in "black boxes" of prepress software applications or commenting manuals. When appealing to their "help" option the user is sometimes sent to get an advice from a printer. In this relation E. Enoksson (2004) notes, for example, that only about a quarter of the Swedish print houses have people ever heard of the UCR (Under Color Removal) and GCR (Gray Component Replacement) functions of Photoshop.

Not much "help" the user can get from academic sources as well. Problems start here from providing the proper definitions for these functions because of similar sense of their abbreviations meanings. For example both UCR and GCR indicate in fact the "removal an achromatic component of chromatic inks (CMY) by replacing them with the black (K) one". Meanwhile the "Complete Color Glossary" defines the UCR procedure as related just to the dark neutral colors (Southworth, McIlroy and Southworth, 1992). In "Handbook of Print Media" one can find the attempt to distinguish UCR, GCR, and UCA (Under Color Addition) functions by the examples of varying just the volume of CMY achromatic part replaced by the black ink (Kipphan, 2001), though this volume can be varied within each of these procedures as well. At last, the "Digital Color Imaging Handbook" stands out GCR as a "generalization" of UCR and K addition (Balasubramanian, 2003, p. 358). There were also attempts to modify UCR under the names of such procedures as PCR (Programmed Color Removal), ICR (Integrated Color Removal), etc., and the new names were as well proposed (Enoksson, 2004).

The number of other explanations of fourth ink application, sufferring from mixing the purposes and methods based on the vast variety of CMYK combinations, is continuing. So, it is not out of place to separately discuss the following black ink functions:

- replacement of the achromatic component of three chromatic inks combination;
- reproduction of the image achromatic colors;
- use of this ink for print security purposes;
- expanding the print color gamut.

2. Relationships of black and balanced CMY in achromatic component of chromatic inks combination

2.1 Volume of achromatic component replacement

This parameter is often used to be formally illustrated by the diagram of the kind presented in Figure 1, where positions 1b and 1c show the examples of partial (50 %) and complete (100 %) volumes of achromatic share replacement.

This variation is historically related to UCR function, which is first of all used for the darker image areas because of total ink limitation. In fact, it can be varied from 0 % up to 100 % independently of the given image area brightness, i.e. in the highlights, middle tones or shadows.

Volume and range of $(CMY)_{min}$ replacement is, except of the ink limit, stipulated by the number of other technological, economic, operating and image quality considerations including:

- ink consumption costs;
- fidelity and stability of the gray balance within a run;
- color disbalance due to rosettes geometry variation, as well as moiré and rosettes visibility (Daels and Delabastita, 1994);
- gamut mapping intents;
- use of inks which colors are complementary to that of CMY ones in Hi-Fi printing, etc.

Nature of these reasons is well known or described in referred literature while the last one is cleared up by the Figure 1d. It shows that the 100 % removal of one of CMY inks is compulsory over all tonal range to make worthwhile the use of an additional ink of opposite, complementary color (red or orange one in this example) to expand the print color gamut. This makes it also clear that the screen of complementary color can safely use the angle of its corresponding process color. The latter should be completely withdrawn in particular image area to get higher chroma.

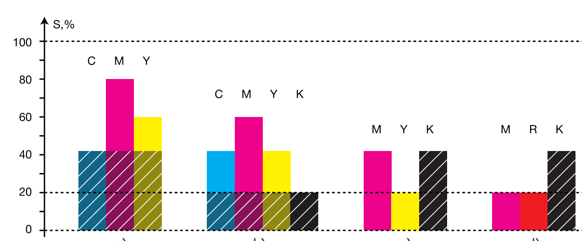

Figure 1: Methods for providing formally the same chromatic color: without black ink (a); at 50 % and 100 % $(CMY)_{min}$ (hatched) replacement by black (b, c); with further removal of equal M and Y on behalf of an orange ink (marked R on the diagram) in HiFi printing

2.2 Varying the replacement volume within the tonal range

The volume variation of such replacement within the tonal range can be illustrated by a diagram in Figure 2, where the straight line 1 corresponds to printing of the whole gray scale of color image exclusively by CMY inks. For simplicity the balanced CMY inks amount changes along lines of this graph in equal proportion (C = M = Y), thereby related to the use of "ideal inks".

With taking the line 1 for a reference, the other curves of Figure 2 demonstrate the possible variants of achromatic CMY and K-ink volumes relationship along the tone range. Thus, curve 2 indicates at its upper point the $(CMY)_{min}$ withdrawal of 40 % where initial C = M = Y = 100 % is replaced by combination of C = M = Y = 60 % and K = 40 % at 220 % of ink total. Following the course of this curve to lighter areas, the use of black ink is gradually reduced to 0 % at middle tone. Starting from C = M = Y = 50 % and until the white point, the achromatic component is again reproduced only by CMY.

Curve 3 illustrates the constant replacement value of 40 % along the whole gray scale. Here, for example, middle tone is presented by C = M = Y = 30 % and K = 20 % with the latter comprising 40 % of achromatic value defined at this point by C = M = Y = 50 % of the reference line 1.

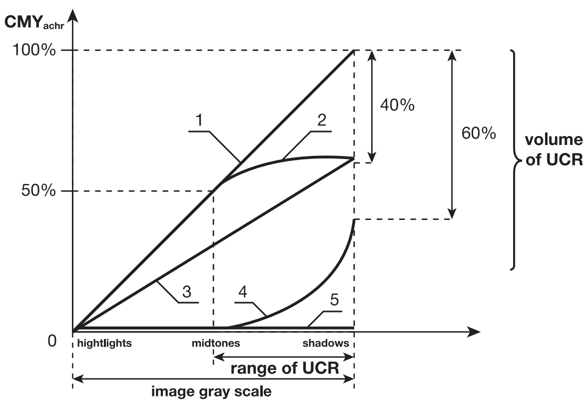

Figure 2: Variation of balanced CMY and K values along the image gray scale, shown with a line/curve: 1 – balanced CMY only, without K; 2 – gradual reduction of CMY replacement by K from 40 % in shadows to 0 % in middle tones; 3 – with 40 % constant volume of replacement along the whole scale; 4 – with gradual growth of CMY replacement by K from 60 % in shadows up to 100 % in middle tones; 5 – without CMY along the whole scale

Gradual replacement increase from 60 % in the darkest areas up to 100 % in middle tones is shown by curve 4. It also indicates the reproduction of lighter part of the gray scale exclusively by black ink.

At last, the curve 5 coincides with horizontal axis of the diagram and relates to complete replacement volume of 100 % along the whole scale. It corresponds to the so called "binary chromatic + black" strategy where CMY inks can't be altogether found in any chromatic area of a print.

As a result, Figure 2 describes two different dimensions of $(CMY)_{min}$ withdrawal, the first of them relating to the volume of K ink use while the other one indicating the location of its certain volume within the tone range.

It is however common to separate this whole continuum just on two strategies: UCR and GCR, relating the first of them to concave curves of the kind of curve 2, and the latter to convex ones like curve 4. The freedom of choice and manipulating these curves faces in wide practice the difficulty due to their impact on the printing system color profile. Coming from one curve to the other inevitably changes color of the same print area due to variations in halftone dots overlap, their total perimeter, etc., resulting especially in the shift of an ink trap and both physical and optical dot gain.

The amount of primaries in Nuberg model (Nuberg, 1932) for resulting print color estimation through the weighted sum of ink coverage combinations also changes. Nuberg's model is based on the physical imitation of resulting print color on the rotated Maxwell disk with its sectors dimensions taken in the given proportion of primaries. It is mostly mentioned in the literature with reference to the five years later published Neugebauer (1937) paper as generalization of somewhat earlier b/w model for two primaries (Murray, 1936; Scheberstov, 1936). For example, the primary color of three inks overlap used in this sum for CMY model isn't included in CMYK model when the strategy of achromatic component replacement corresponds to the case 5 in diagram of Figure 2. At the same time, the colors of CK, MK, YK, CMK, CYK and MYK overlaps become, as it will be shown further, rather significant in such sum.

The black ink effect on the resulting print color should also depend on the "dot-on-dot" or "dot-off-dot" strategy choice of inks placement (Rhodes and Hains, 1993). As Figure 3 shows, their research has evidently indicated the simple form of the 3D color body surface not reaching to the plane for rotated dots in CIELCH space for the first case and the composite one exceeding the plane for rotated dots for the other which should strongly influence the print color gamut.

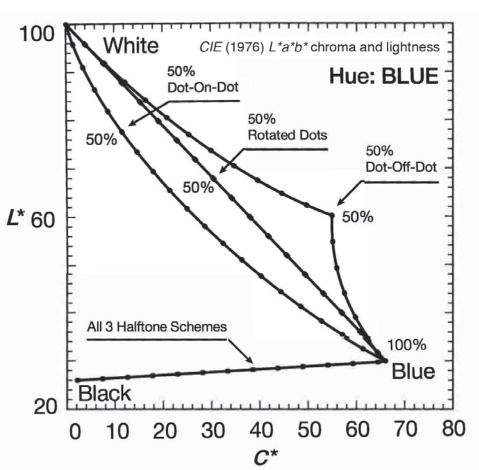

Figure 3: The comparison of the three variants of C and M halftone dots placement in blue (CM) plane of CMY gamut; adapted from Rhodes and Hains (1993)

3. Print security function

The black ink spectral reflectance in the near infrared region is quite different from that of the chromatic inks and, as well, from their neutral combination, as it is shown in Figure 4 for the pigmented black ink and dye based chromatic ones (Bugnon, Brichon and Hersh, 2007). That makes it possible to discern the differently colored neutral print areas under corresponding near infrared illumination and thereby provides the facility of non-costly K-ink use for print security purposes (Žiljak, Žiljak Vujić and Pap, 2008).

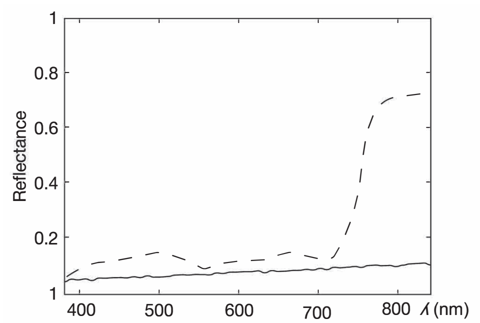

Figure 4: Reflectance spectra of dye based CMY neutral (----) and pigmented black ink (—) of sublimation printer are quite different in the near infrared band (adapted from Bugnon, Brichon and Hersh, 2007)

As we show in Figure 5 for exemplary scan line, it is possible to modulate, for example, the K = $(CMY)_{min}$ component by the auxiliary image with share of K which exceeds the modulating signal value being retrieved after modulation to the balanced CMY to keep the basic image color non-changed.

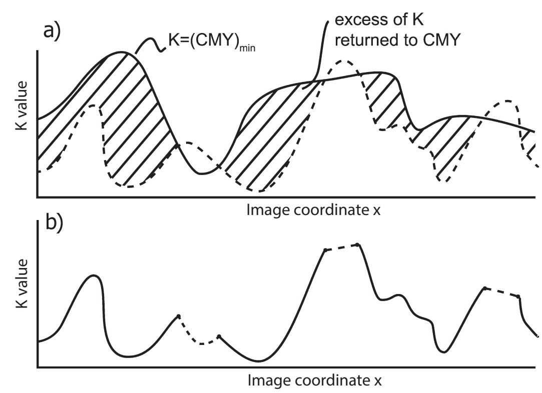

Figure 5: Modulation of K = $(CMY)_{min}$ signal by the security image data (a); resulting dual function signal for the black ink (b)

The resulting black ink signal at the lower part of Figure 5 gets dual function. It both replaces the certain amount of CMY achromatic value and, in spite of being partially distorted, presents the auxiliary image.

This way implemented security image wouldn't formally affect the basic image, stays to be concealed from viewing under any daylight but can be captured in the strong near infrared illumination.

4. Achromatic colors reproduction

Providing the maximum of reproducible gray levels was outlined by R. Hunt (1997) and stipulates the priority of black ink use in color print. The whole achromatic component can be considered as the basic one for image formation while the CMY inks as auxiliary ones, i.e. responsible just for the image chromaticity. Moreover, due to well known degradation of color vision sensitivity with decreasing of detail angular, spatial dimension, the small details and high contrast sharp transitions can also be reproduced with greater share of black or even, as it is done in color TV broadcast, completely achromatic.

The combining of K with accurately balanced CMY is in practicular useful for b/w image when it is simultaneously printed on the same sheet with multicolor ones. Our research based on UCR offset atlas (Avatkova, 1987) has shown, for example, that at 290 % ink limit the addition of C = M = Y = 62 % to K solid expands the gray scale optical density range for about 0.3. The effect is especially apparent at visual comparison of such print with its version using just the black ink and confirms the priority of the latter in achromatic colors formation in CMYK printing. Various ways of combining K ink and balanced CMY are formally possible.

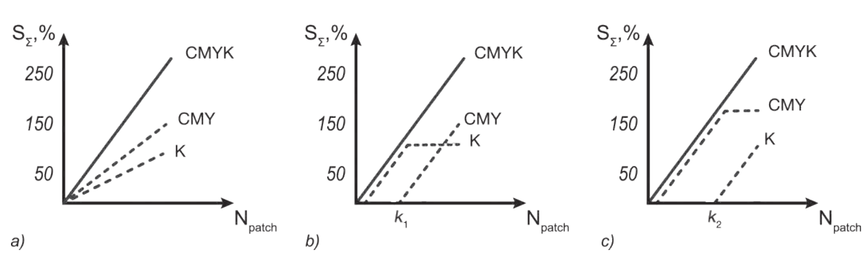

Figure 6: Exemplary variants of the combined use of K and balanced CMY for gray scale optimization at total ink limit S_Σ = 250 %; with constant replacement of CMY with K across the whole scale (a); with GCR settings (b); with UCR settings (c)

Their amounts can be uniformly distributed along the gray scale or each of them alternatively concentrated in its highlights or shadows divided by k_1 and k_2 wedge patch numbers, as indicated in Figure 6 under the assumption of 250 % total ink limit (Kuznetsov, 2002).

It has to be noted that the above considerations to certain extent artificially separate the formation of print achromatic color and achromatic component of chromatic one. In prepress software, these functions are merged in each other being altogether governed by the same curves. Achromatic scale is also influenced by the UCA settings named sometimes as "K addition". However, as it follows from these considerations, such procedure would be more properly defined as "the balanced CMY addition to K".

5. Expanding the print color gamut

The combined use of K and CMY inks discussed above expands the gamut in close vicinity to L^* axis of CIELCH space where colors can still be considered achromatic with taking into account their permissible ΔE^*_{ab}, for example, of 5 units from neutral as illustrated in Figure 7.

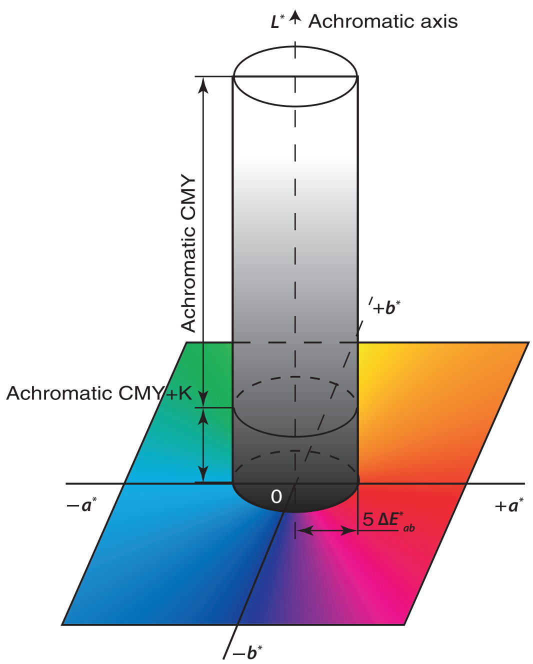

Figure 7: Black ink adds new neutrals to CMY color space in close vicinity of the lower part of its achromatic axis

At the same time, it is practically used to add some K amount to C, M or Y solids to get new, darker chromatic colors. In the analogy to Figure 7, such procedure is formally illustrated in Figure 8 by adding K to one of the lower planes of CMY color body. However, the gamut expanding due to chromatic colors which exclusively appear with applying the fourth, black ink wasn't separately considered in the literature.

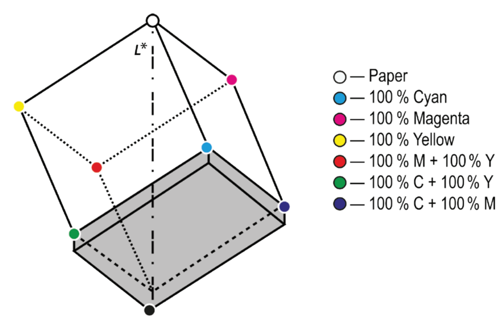

Figure 8: Formal example of color gamut expanding by K adding to CMY solids and their overprints

Moreover, one can find the contrary statement of color gamut reduction with black ink introduction (Balasubramanian, 2003, p. 366). At the same time, the issues of print gamut expanding by the use of intensive inks, addition of complimentary RGB colors to CMY process colors within the so called Hi-Fi Color concept, etc., were widely discussed in last decades.

6. Measurements and results

Our research comprised the comparative analysis of *CIE $L^*a^*b^*$* and *CIE L^*C^*h* data taken by GretagMacbeth Eye-One Pro spectrophotometer calibrated for 2° Standard Observer, D50 illuminant, 0/45° measurement geometry and paper white point from UCR offset atlas (Avatkova, 1987). This atlas was printed in Experimental Print House of All Union Research Print Media Institute in Moscow according the soviet offset standards and comprises the data base of about 1 500 color patches produced for different combinations of CMYK tone values. The main purpose of this atlas was to fix the print colors matching at herein above discussed variants of CMY achromatic component replacing by the black ink. It also helped us to reveal the effect of CMY neutrally balanced addition to K solid for expanding the gray scale range.

However, this atlas lacks combinations of CMY near solids and their binary overlaps with different amounts of K. The ink solids (100 % values) are formally prohibited in halftone printing. The upper tone values of C, M, Y or K are mostly limited in practice by the still controllable ones of 95 % or 97 % (International Organization for Standardization, 2013; Kouznetsov and Alexandrov, 1997). So, the separate printing trial was provided on HP Premium Plus Photo Paper Matt substrate at drop-on-demand printer Canon PF8300S controlled by FlexiSIGN Pro v8.6 RIP to investigate the effect of K addition to such solids as compared with providing darker chromatic colors in CMY print version by simple adding of complementary process colors or their combinations.

The test objects were produced in Adobe Photoshop especially for this purpose for the variety of three and four inks amounts. They comprised the indexed versions of step wedges for C, M, Y and CM, MY, CY, CMY tone value (%) overprints with the stepwise K addition. Each wedge contained 11 patches for demonstration in meridian sections and on *C**h* plane of *CIE L*C*h* color space. The IT8-7.3 target for CMY and CMYK color gamut computation in MathLab was also used.

Examples of these data are given at *CIE L*C*h* color space vertical slices for magenta and blue hues represented in Figure 9. The upper line of the diagram in Figure 9a shows the *L** reduction with continuous addition of the M tone value to the substrate from 5 % to practically used near solids of 95 %, while the upper line of the one in Figure 9b with the similar growth of CM.

It may seem that the further lightness reducing of thus achieved colors can be provided by adding them the complementary process ones. In the first case such color is green produced by the balanced sum of cyan and yellow, while for the blue tint it is yellow. However, the lower lines of both diagrams demonstrate much purer colors generation by adding just the black ink. As compared to said complementary color addition, it increases the target color saturation by 30 chroma units for magenta at *L** = 30 level (Figure 9a) and about 40 units for blue at *L** = 23 (Figure 9b).

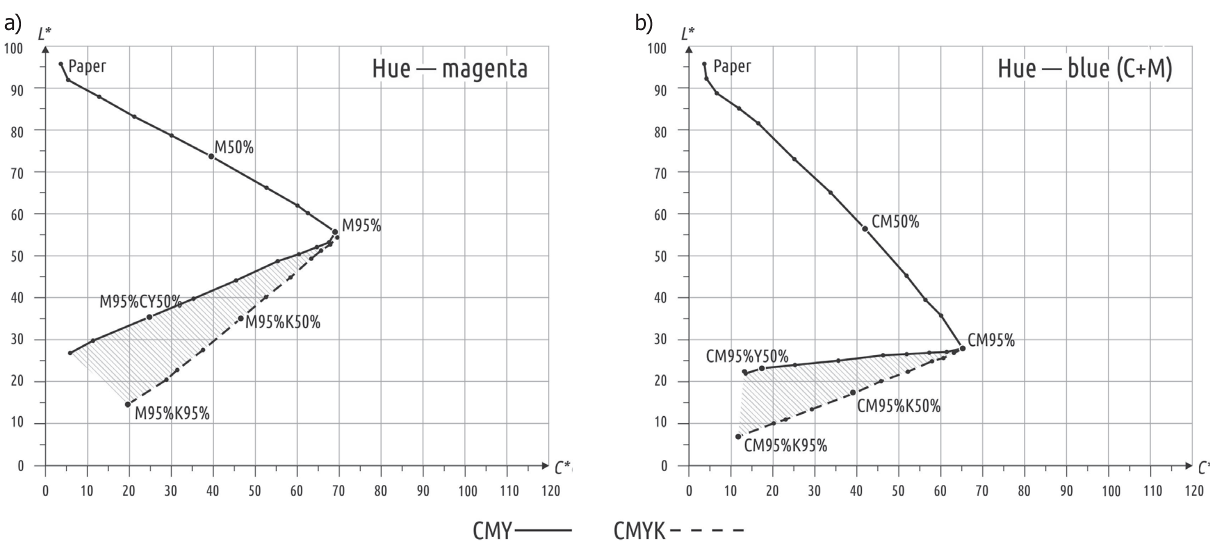

*Figure 9: Coordinates of CMY and CMYK dark chromatic colors on meridian sections of CIE L*C*h space for magenta (a) and blue (b) hues*

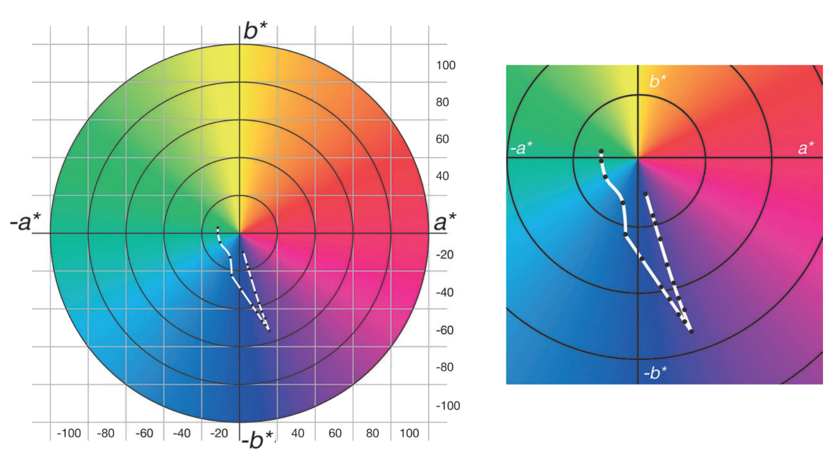

*Figure 10: Lower lines of Figure 9b in projection on a*b* plane*

Such difference is physically explained by that the black ink more or less uniformly reduces reflectance without distortion of source (magenta or blue) spectrum profile. To the contrary, the ink of opposite color not only darkens the source one by suppressing reflectance at its inherent in band of spectrum but also changes its hue as the left curve in Figure 10 shows. However, as the right line of the same figure confirms, the just K addition to 95 % C + 95 % M overprint keeps its blue hue constant.

The hatched areas of the both Figure 9 diagrams, as well as Figure 11, demonstrate the expanding of lower part of color gamut due to the use of the fourth, K color. According our three dimensional calculations it comprises about 10 %.

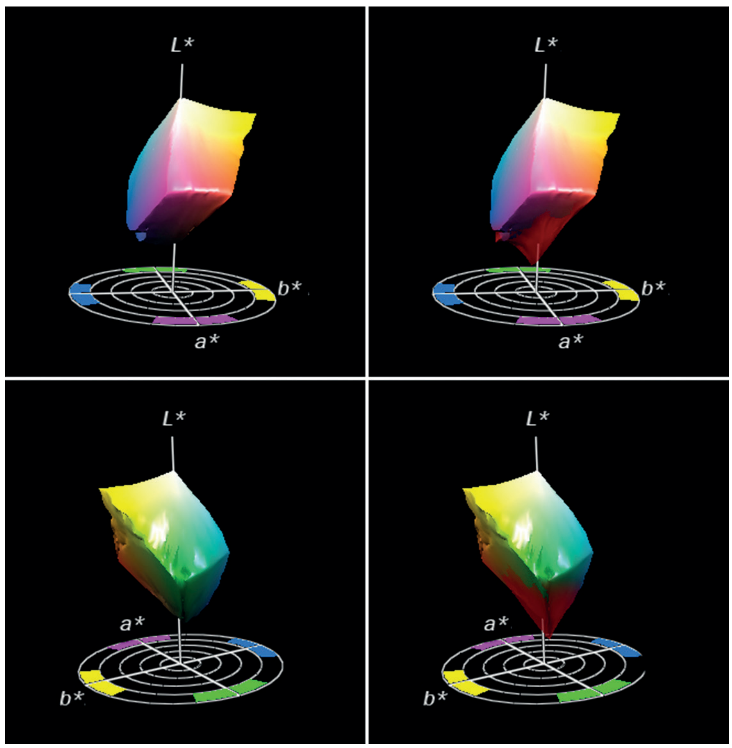

Figure 11: Different views of CMY (left) and CMYK (right) color gamut of the tested ink jet printer

7. Conclusions

It is meaningful to consider the black ink use in CMYK process in relation of its three basic functions:

- replacement of achromatic share of CMY combinations;
- combining black with the certain amount of balanced CMY in reproduction of achromatic colors;
- creating the new chromatic colors unavailable for CMY.

Within the whole continuum of its variants, the first of these functions is in full characterized by two dimensions:

- volume of K as the share of a reference $(CMY)_{min}$;
- location of replacing K volume within the tone value range of a print.

Within this function the facility also exists of non-costly color print protecting by modulating $K = (CMY)_{min}$ by the signal of an auxiliary image discernible in near infrared light. Contrary to the first one, the other two of these functions are completely additional and have no alternatives.

New chromatic colors provided by the black ink use expand the CMY gamut for about 10 %. So, the move from CMY to CMYK which took place in the 30's of the last century can be concerned as the first step to Hi-Fi Color technologies aimed nowadays on a similar effect, reached once again by increasing the number of process inks.

The proper discerning of K use in CMYK printing appears to be beneficial in creating or operating the updated prepress software of foreseen future.

The results of above research and discussion can help to effectively explore the effect of multiple black ink functions in color halftone printing.

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