Spectral Color Print Quality Control by Using Visual Inspection Technique

Andrew Tak Kin Yan and Timothy Anderson Yan

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Abstract

This paper would like to present a spectral color print quality control method by using a visual inspection technique to determine the harmonic color balance during printing production. This method adopts visual comparison with using human abilities to avoiding subjective color judgment. In addition, a visual userfriendly tool has been developed to demonstrate its simplicity of control, efficiency, and economic benefits for achieving the highest cost effectiveness to give the best rate of return to investment.

Introduction

Cyan (C), Magenta (M), Yellow (Y) and Black (K) ink has been widely used in multi-color printing production for many decades [1]. For the printing process, an accurate amount of inks of those colors are printed onto the nominated substrate to simulate a full color picture as the result of what human can normally see in the nature scene. The common practice for the traditional color printing process relies on a skilled machine operator [2] to manage the appropriate ink dosages, and then the operator will use visual comparison techniques to compare the result against the approved original to see whether any color imbalance condition has occurred. This is a subjective way of collecting color information that is a typical craftsmanship production technique. To achieve an accurate and consistent color balance is always a big issue. Consequentially this costly and inefficient method consumes extensive setup time and results in inconsistencies and unnecessary wastage.

Furthermore, there is an increase in print buyers' demand for high quality printing products. Multi-color inkjet digital printing facilities can easily be found in almost every household as well as in businesses. They can produce a wider color gamut print result by supplementing the CMYK ink with bright magenta and bright cyan

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ink to generate a truer color print. Unfortunately, process color printing can only use CMYK to create a color picture, which is insufficient for true color reproduction to simulate the human visual spectrum. Therefore, color experts have created an additional color printing method called Hi Fi printing [3] to widen the color gamut. In the process control business, visual comparison between the reference sample and the printed sheet is the common traditional quality control process for verifying that the print results match the desired CMYK results. This is a subjective and biased process. In recent years, process control color bars have been introduced as an alternative means to improve the subjective practice. However, such control bars cannot provide a user-friendly environment for the operator to quickly respond to the color shift and determine the adjustment value for correction without a sophisticated measuring tool being used. The following reasons can explain why the traditional process control bar is not user-friendly to the unaided eye.

1) The geometry of the CMYK measurement aim is that color patches are placed in groups, then many groups are repeated to construct a process control bar.
2) All individual patches have a single function, though patches next to each other do not have any functional relationship (e.g. for comparison).
3) Same functional patches are placing apart due to the grouping format so it is impossible to visually compare the shade changes across the sheet.
4) The aim of the color analysis is based on the density value from individual solid patches. However, the printed image is the composite result of CMY in specific percentages, therefore solid density versus the printed image does not have any direct relationship.

Due to the above reasons, any excessive time spent on measuring and conducting the analysis can prolong the color correction time. In certain extreme scenarios, print quality may exceed the quality control threshold limit while the measuring process is still in effect. This practice will increase the unnecessary wastage due to the lag in ink key adjustment response time.

About the color theory, cyan (C), magenta (M), and yellow (Y) are the primary colors of the subtractive rule. According to the color theory, a secondary, tertiary, and quaternary (and beyond) color group also exists in the entire color spectrum. Since the traditional printing process (Appendix 1) can only manage CMYK (where K is black) colors, there are technological and application gaps for print quality control when including more colors for production in conjunction with CMYK, such as orange (O), green (G) (Appendix 2) or red (R), green (G), blue (B)(Appendix 3). Therefore, this paper will introduce an innovative technique to control the process color production as well as to extend the CMYK print quality control for spectral colors. This new technique and tool can directly benefit the industry in its use. It can also be a good educational material to inspire the research community and engineers at large to innovate.

The following issues are the focal points that this paper would address and resolve.

1. How should the common practice of subjective decision-making in color adjustment be replaced?
2. What is the benefit of adopting the neutral gray visual inspection?
3. What technique can be used to achieve the accurate color reproduction for spectral color groups?

Scope and background of research

The following is a list of existing technologies and applications that are the foundations of this new technology.

- Primary, secondary, tertiary, subsequent color groups and black color relationship
- Munsell Gray Balance Theory [4][5]
- Halftone printing technique
- Hi Fi color Printing principle
- Color matching skill [6]

Munsell Theory

The Munsell Theory was invented by Professor Albert Munsell, a color scientist. In 1905, Munsell realized that there was no practical color theory available for common usage to define or describe a color, therefore, he explored and conducted scientific experiments and published a book named 'A Color Notation' about his color management theories and models. In 1915, he had also created 'The Munsell Color Altas'. His color theory is about a three dimensional model as shown in Figure 1 (Cleland 1921) [7] :-

- Hue – The actual color shade, such as Red, Green, Blue, Cyan
- Value – Quantifying the color from light to dark for reading its intensity range.
- Chroma – The Hue measurement of the purity of color, it considers in grayness.

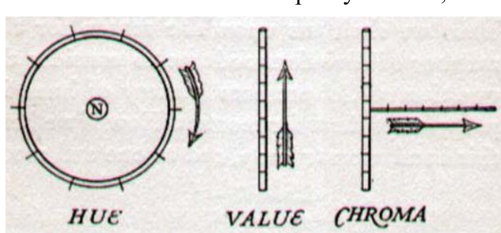

Figure 1: *Hue, Value & Chroma Theory*

Munsell System is a color measuring system that can reflect the human visual perception. Many color scientists have adopted his theories for today's color management development [8] [9].

The Gray Balance Principle (GBP) is one of the Munsell Color System [10]. The GBP is an understanding of the actual dynamic color value in the production environment. The GBP can provide a continuous evaluation of the Hue, Value and Chroma conditions, and then define the appropriate correction value to amend the mixed color condition for the best harmonic balance to achieve the neutral gray. Figure 2 (Cleland 1921) depicts the tug – of – war game to demonstrate the meaning of balance; for the side that has more power, it will establish the dominant force and overpower the other. This is called the imbalanced condition.

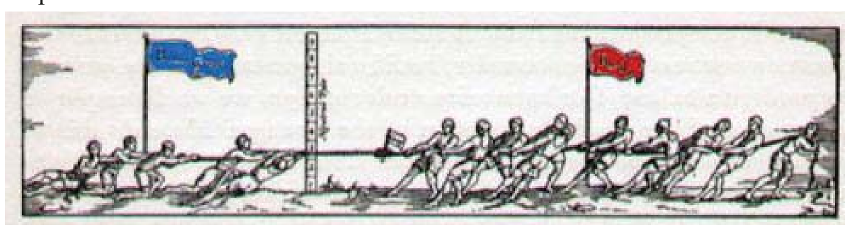

Figure 2: *Tug – of – War*

The Munsell gray balance theory relies on the composition of the primary color such as cyan (C), magenta (M) and yellow (Y). When those three colors are mixed together equally, they will form a harmonic neutral gray. When either color is in excess or deficient, the neutral gray shade will be tinted the color that is in excess or towards its opponent color when it is deficient.

For examples:-

1) The neutral gray will lean towards cyan to become bluish-gray;
2) More magenta becomes reddish-black;
3) More yellow for brownish black.

Figure 3 (Holtzschue 2011) [11] illustrates the neutral gray shade at the centre that consists of equal percentages of cyan, magenta, and yellow halftone dots when overlaying together.

Figure 3: *Neutral Gray Balance Component Model*

Figure 4 (Busch 2003) [12] illustrates the change in the neutral gray when the colors are not in balance. The gray sky on the top is the target color, where the bottom is the print result. The bluish tint is a result of a deficiency of magenta. Adding magenta will restore the image to its target colors.

Figure 4: *Top – Original photo; Bottom – Deficient of magenta*

Figure 5 (Cleland 1921) shows the dominant condition with one side of the beam with an excessive weight. To overcome the imbalanced condition, the excessive portion of the beam is removed as shown in B, where balance is restored.

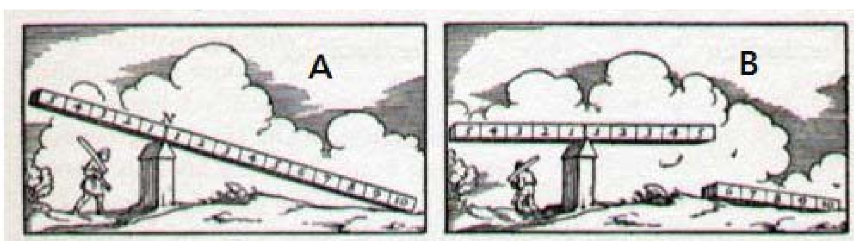

Figure 5: *A – Over dominate; B – Removal the excessive*

Visual Matching technique

Guild and Wright [13] had invented in the 1920's, a visual colorimetric experiment that demonstrates a matching technique. It consists of two semicircles of light, where one half is the reference light and the other is the target light, formed by a combination of RGB light of various intensities. By adjusting the intensities of the RGB light, the hue, value, and chroma can be made to match the reference light once the RGB intensities are appropriately set. This technology was designed around using our human comparison ability to see the differences without using any measurement tools. This is also how the new technique described in this paper was designed.

Physicist Ernst Mach [14] discovered in 1865, an effect of the contrast between the edges of two gray patches where the observed difference in contrast was exaggerated. Figure 6 (Goldstein, 2009) illustrates the contour of a series of uniform gray patches from light to dark as (a), the light intensity measurement graph as (b), and the perceptual effect describes as (c). The working principle of the Mach Bands effect is that the human visual system will cause the perceived difference in luminance of neighboring color patches to be exaggerated to facilitate edge detection. The result is that the contrast between the patches will be increased. Any minor difference in gray tone will be noticeable as long as they are in contact with each other.

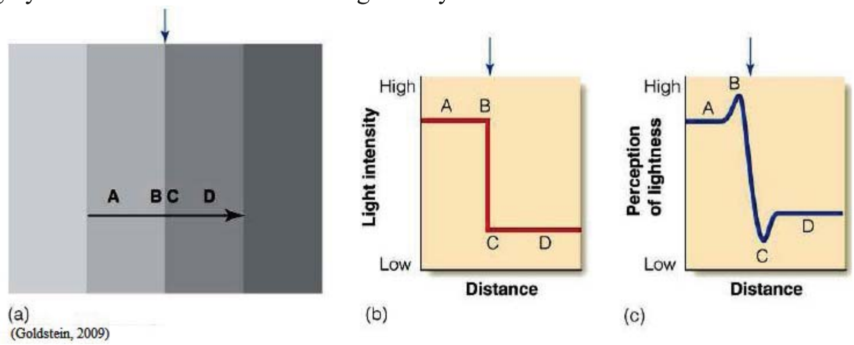

Figure 6: *Mach Bands Effect*

Innovative Technique

Harmonic colors balance printing result is always the production objective, bringing CMYK into evenness of light and tone so that the reproduction is accurate. Neutral gray balance is one of the quality control methodologies that can achieve a harmonic result. This paper discusses a new innovative way to use a visual matching technique that utilizes the neutral gray balance theory to develop a process control tool to manage CMYK as well as spectral colors' print quality. The following is the neutralization formulas and controlling technique:-

A. Munsell neutral gray theory and corrective formulas

Munsell has given an example using a beam balance scale, illustrated in Figure 7 where:-

A – Both trays are equal in weight,
B – Both trays add with same load of Cyan,
C – Imbalanced load of Yellow on one side,
D – Balancing process by adding Yellow on the opposite side but the neutral gray becomes contaminated to become a brownish gray color.

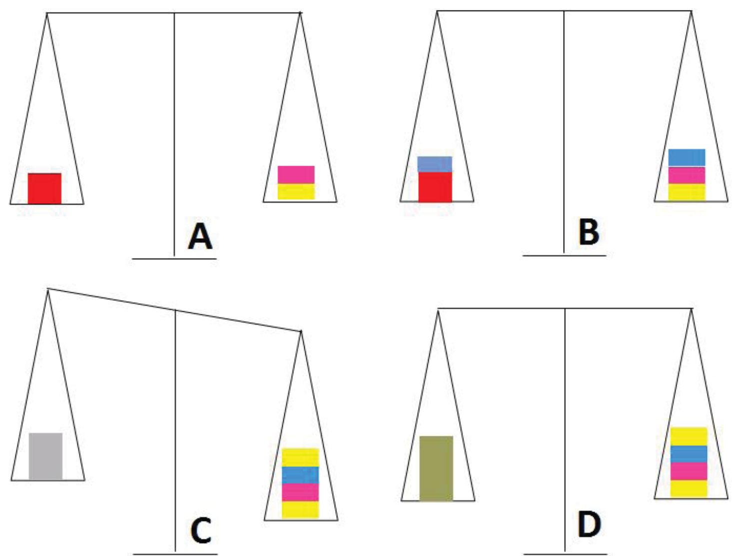

Figure 7: *Munsell's Beam Balance Scale*

Useful Neutral Gray (NG) formulas:-

1) Opponent Color formula for 2 primary colors
   Red (R) = Magenta (M) + Yellow (Y);
   Green (G) = Yellow (Y) + Cyan (C);
   Blue (B) = Magenta (M) + Cyan (C);

2) Munsell Neutral Gray formula for primary colors
   NG = Cyan (C) + Magenta (M) + Yellow (Y)

3) Spectral Gray formula for primary and secondary colors
   NG = Cyan (C) + Red (R)
   NG = Magenta (M) + Green (G)
   NG = Yellow (Y) + Blue (B)

Case study:-

By adding 10 units in neutral gray formula
10 NG = 10 C + 10 M + 10 Y
When either side of the formula in excessive of 5 units of C;
10 NG + 5 C = (10 C + 10 M + 10 Y) + 5 C
= 15 C + 10 M + 10 Y

10 NG's shade is contaminated by 5 units of C, therefore the NG becomes bluish gray. Simply remove 5 units of C to return to the neutral gray.

B. Spectral color gray balance neutralization formula

The Munsell neutral gray theory can manage the CMYK production with successful results. For the Hi Fi color printing process, to achieve a harmonic result becomes a complicated process, involving Red, Green and Blue ink as the major components besides Cyan, Magenta and Yellow. When either color is out of balance, the final print will be off tone and the harmony will be lost. A component of the technique in this paper is to use a new neutralization process to create a neutral gray color with the spectral color element as shown in Figure 8. To achieve the gray balance result, the spectral colors have to be neutralized (balanced) by adding the appropriate values of CMY to form the neutral gray. This resultant gray is now able to be used for visual examination as well as for measurements.

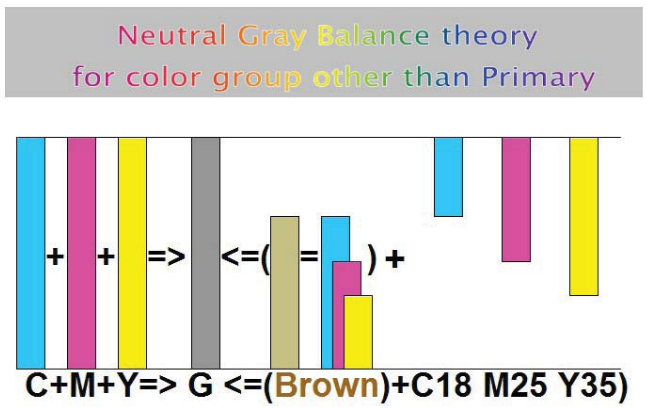

Figure 8: *New Gray Balance Theory for Brown Color*

The Spectral Color Neutralization Method:-

1) Spectral color's CMY equivalent values:
Spectral color = Cx1 + My1 +Yz1

2) Munsell Neutral Gray
NG = C50 + M50 + Y50

Spectral Gray Balance Formula:-

$$NG = \begin{bmatrix} C_{50} \\ M_{50} \\ Y_{50} \end{bmatrix} = \begin{bmatrix} C_{x1} \\ M_{y1} \\ Y_{z1} \end{bmatrix} + \begin{bmatrix} C_{x2} \\ M_{y2} \\ Y_{z2} \end{bmatrix} \quad \text{therefore} \quad \begin{bmatrix} C_{50} = C_{x1} + C_{x2} \\ M_{50} = M_{y1} + M_{y2} \\ Y_{50} = Y_{z1} + Y_{z2} \end{bmatrix}$$

Neutral Gray Components; Spectral color CMY Components; CMY differences

Results

Focal point 1:- How should the common practice of subjective decisionmaking in color adjustment be replaced?

A. Black and CMY neutral black relationship

The basic principle about this new quality control technology relies on the innate characteristic of black ink where it always stays as a neutral shade (grayscale). Theoretically, equal portions of CMY should also form the same neutral black, as the Munsell theory indicates. However, in reality, equal portion of the CMY ink will form a dirty brown shade [15]. A minor modification to the C:M:Y ratio is necessary to achieve the neutral black as the pigments used in the CMY printing do not have the same absorption spectra as the theoretical definitions of pure cyan, magenta, and yellow (which technically absorb at only 1 wavelength). To achieve the neutral gray 50% tone, ISO 12647-2 nominated a mixture of 50C, 40M and 40Y can reduce the reddish colorcast so that the overprinting result will be a neutral gray tone.

B. Formulation of 50% Black and CMY neutral gray

By changing the solid black and CMY into halftone dots such that they are at 50% density, the neutral solid black patches and the combination CMY patches both become 50% neutral gray.

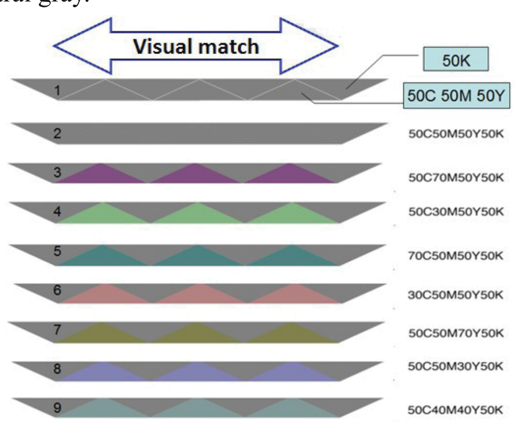

Figure 9: *Neutral Gray Control bars*

Figure 9 is the process control bar with a geometry that is described in U.S. Patent US8,451,503 B2 [16]. The graphic simulation demonstrates the behavior of the control bar under different gray shade imbalance conditions. The following can illustrate the excessive or deficient CMY color conditions as well as the balanced visual condition.

1. The process control bar when visually smooth, where the white lines are added to highlight the geometry. The top portion is an inverted triangle with a series of 50% black halftone patches, interlocking with the lower portion. The lower portion consists of upright triangular CMY 50% gray patches. This geometry can create an instant visual comparison environment.

2. Simulating a perfect neutral gray matching condition. A perfect CMY color balance will yield a neutral gray shade that blends in with the black (K) patches.

3. Indicates an excess of magenta ink in the lower portion, shown by a shift of the gray tone towards a reddish gray.

4. Indicates the gray tone shade changes to a greenish hue due to a deficiency of magenta.

5. Indicates the overdose of cyan that can shift the neutral gray towards bluish gray.

6. A deficiency of cyan can shift the neutral gray towards the opponent orange-gray color.

7. When the yellow ink is in excess, the lower portion will become a greenish-gray shade.

8. A deficiency of yellow can shift the neutral gray towards the opponent purple-gray color.

9. A deficiency of magenta and yellow, the cyan/green shaded gray will appear.

C. Low ΔE achievement

In practice, if either component color shifts its color value, the resultant neutral gray will be tinted with the color that is in excess. In field tests, operators were able to distinguish the different situations that can arise from colors shifting from the balanced condition, and responded correctly to once again balance the inks.

The Mach Bands effect is a good demonstration of how we can utilize the human visual system to manage a low Delta–E (ΔE) condition using only our unaided eyes in conjunction with this unique color bar geometry. ΔE is a quantitative value for defining the color difference of two colors in the CIELAB color space. When the value is equal to zero, there is no color differentiation and the two colors should be in a perfect matching condition. What Rodney [17] discovered was that a ΔE of 1 is the limit of sensitivity of the human visual system, even when the two color patches are placed side by side.

Figure 10 illustrates the geometry of this technology's visual process control bar, where the reference K inserts between Gray 1, Gray 2, and Gray 3. The boundaries of the imbalanced Gray 1 and Gray 2 patches amplified signal for creating more contrast and in return, this phenomenon can make the imbalanced condition more pronounced. Under this demonstration, the human visual system can effectively differentiate ΔE values lower than 1, as the K and Gray 3 boundary is not visible while Gray 1, Gray 2 and K are observably different. The operator can conduct the appropriate color amendment exercise by adopting a quality of the human visual system as one of the great break-through of this visual technique. A ΔE value of 3 to 6 is generally an acceptable tolerance in the industry.

Figure 10: *Visual process control bray bar geometry*

Focal point 2:- What is the benefit of adopting the neutral gray visual inspection?

Since the neutral gray tone is a well-known standard for the photography and printing industry, neutral gray analysis becomes a bridging tool to cross over two color reproduction systems by sharing one gray point. Figure 11 illustrates how to share one neutral gray value across photography and printing disciplines.

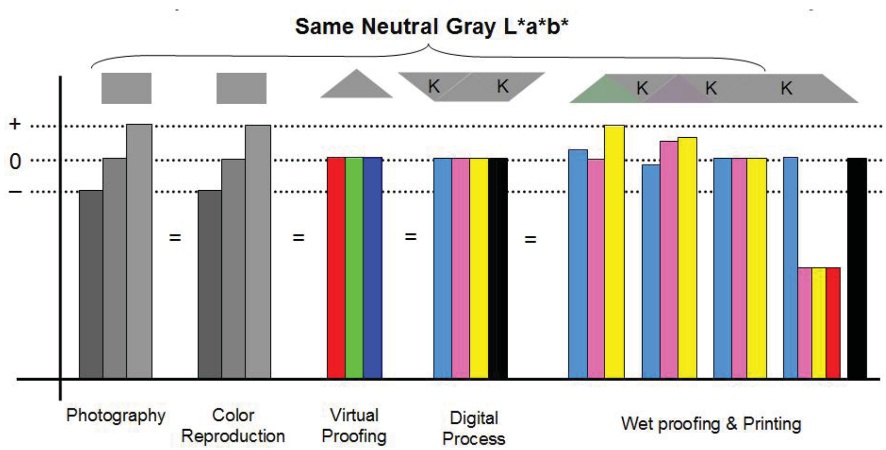

Figure 11: *Sharing the same Neutral Gray*

Focal point 3:- What technique can be used to achieve the accurate color reproduction for spectral color groups?

A. Practicing Spectral color gray neutralization process

The following is a mathematical demonstration of neutralizing the secondary (spectral) color into neutral gray by adding CMY components.

For example, the brown color shown in Figure 8 is the mixture of C, M and Y in specific ratio as following.

1 unit of 50% Brown = C18 + M25 + Y35

Neutralizing Brown into NG, the Spectral Gray Balance formula is:-

NG = C50 + M50 + Y50

NG = 50% Brown + C% M% Y% in specific ratio

NG = C50 + M50 + Y50 = (Cx1 + My1 + Yz1) + (Cx2 + My2 +Yz2)

= (C18 + M25 + Y35) + (C32 + M25 + Y15)

B. Matching technique

As discussed above, this new visual quality control technique relies on a color bar with an innovative geometric design that is constructed by a series of alternating black and neutral gray halftone patches, where the patches are tightly interlocked together to form a gray shaded process control bar. This bar is described in China Patent CN102120384B [18] and the geometry is shown in Figure 12.

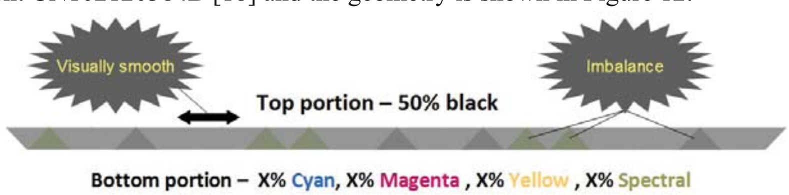

Figure 12: *New Gray balance shade changes*

However, for the Hi-Fi (CMYKRGB) print quality control scenario, a modified version of the aforementioned gray bar needs to be used. The upper K patches remains unchanged. The bottom neutral grey patches will instead consist of alternating patches of CMY and CMY+S (where S is the spectral color). This is vital for identifying whether the color shift is caused by a shift in the spectral color or in the CMY inks. Consider the following scenarios:

When a CMY+S (where S is "green") patch becomes greenish gray, if the nearest CMY patches remain neutral gray, the spectral color (green) is in excess. This is because the CMY patches remaining gray means that CMY has not shifted, and it is the spectral (green) that has shifted.

When a CMY+S patch and the nearby CMY patches become greenish gray, the area is deficient in M. This is because a decrease in M will affect both the CMY and the CMY+S patches, making them shift towards the opponent color, green.

This simple method of differentiation between the patches can increase the operator reaction speed, and therefore results in a reduced setup time as well as the reduction of excessive material wastage and ultimately a reduction in cost.

Special features

The unique geometry of this process control bar can also impart additional benefits beyond simple color control. A summary of the additional benefits are shown in Figure 13.

1. Registration information is contained in the bar as well. No magnifying glass or measurement tool is necessary. Miss-registration can easily be identifiable as the bar is printing with no trapping.

2. All patches can be used to reflect mechanical instabilities as they are at 50% density rather than 100%. Smudged dots can indicate excessive wear and tear, water imbalance, etc.

3. Black and CMY images can vary in shape and size.

4. Gray control component can be part of the content image.

5. Machine readable for data collection devices.

6. Bridges all languages, it is purely visual with no language attached.

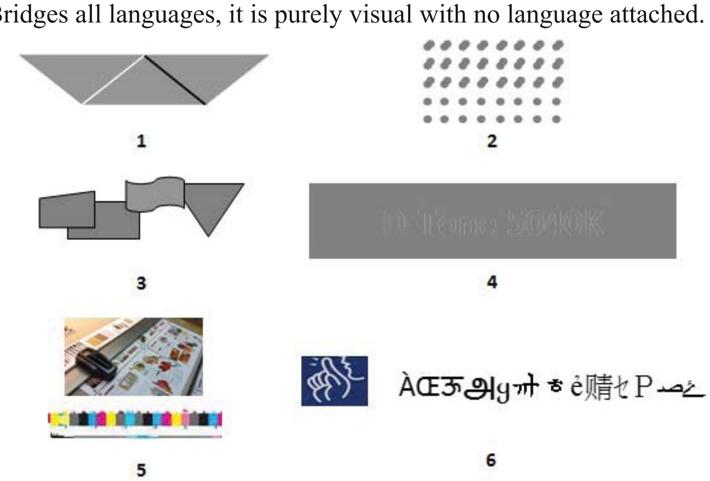

Figure 13: *Special Features*

Significance and Value

The current process control practice of the industry can only deal with the primary color printing production and relies on the density measurements from the individual color patches to determine the color balance correction. Process control on colors other than CMYK is not on the agenda either. Furthermore, visual inspection is also a handicap of the current industry since the color bar geometry cannot provide a practical environment to do so. This technology is about the creation of a new gray balance theory and quality control technique for managing colors beyond the primary. It is also an innovative way to adopt the human ability for instant comparison during the live production.

A. Human visual process efficiency

This design of seamlessly connecting neutral gray and K patches is a simple visual aid for instantly verifying any gray shade changes. When both types of patches are in a visually smooth condition, the E should be less than one, which means the CMYK values are in harmonic balance and is essentially a perfect match. Vice versa, once any neutral gray patch slightly deviates from the harmonic condition, the Mach Bands effect will make the difference obvious. The operator can then simply decide which color requires adjusting by the hue difference between the neutral gray patch and the adjacent K patches. This series of activities can significantly improve the speed of the color verification process, effectively reducing the correction time and effort without using the traditional matching sample method or using sophisticated digital measuring tools. This effect is a vital component of this color control technique as it allows users of this new control system to perceive a very low E value, and therefore will be able to correct for the color deviation.

B. Industrial Standard achievement

ISO 15930 specifies that the portable document format (pdf) is to be used for standardizing digital data exchange. The objective is to disseminate digital data of CMYK, gray, RGB or spot color at the pre-press stage that is intended for printing, so that the final print can accurately reproduce the desired image. This innovative technology effectively provides the operator with a process control environment so that he or she can manage the CMYK as well as the integration of spectral colors during the reproduction by sharing the same neutral gray as illustrates in Figure 11. Therefore this spectral gray balance technology is certainly a complimentary tool to practice the ISO 15930.

C. Training benefit

This quality control technique can get rid of the excessive measuring events and reduce the subjectiveness of human judgment. In return, mechanically dealing with the color management is a simple assessment concept and has a userfriendly learning curve since it synergizes with basic human abilities and gives it a competitive advantage over extensive subjective assessment by using the traditional practice and traditional color bars [19].

D. Cost effectiveness

Deming's Plan – Do – Check – Act (PDCA) is a well-known quality control cycle model [20]. Checking proof against printed sheet and then making proper measurement has been the common practice for decades. Figure 14 is the detail analysis of the traditional measuring process against this new method of neutral gray visual matching process. The traditional method adopts Deming's PDCA quality control model and then modified it as Plan – Do – Measure – Check – Act (PDMCA) that needs an extra step of picking proof for checking and making measurement. The entire cycle adds one extra process to become a 5 step cycle.

There is a potential 20% reduction of setup time compared with the traditional practice. The time saved can then be used for revenue-generating production time instead, making it more cost effective. Manufacturing Cycle Efficiency (MCE) [21] is a useful formula to calculate the difference in efficiency.

Ultimately, this new methodology can save 20% of evaluation time due to the removal of the now unnecessary measuring process for cost saving benefits. It can also be eligible as a "lean manufacturing" [22] practice due to trimming unnecessary manufacturing processes.

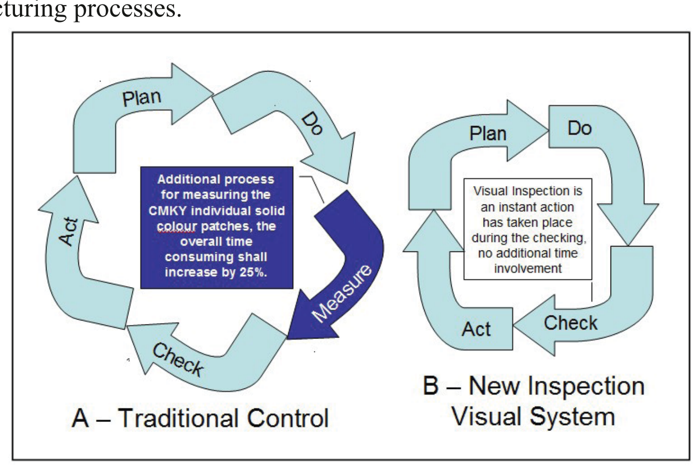

Figure 12: *New Gray balance shade changes*

E. Hi Fi Color Quality control

This visual matching technique and tool will fulfill the technological and application gap in Hi Fi color quality control by creatively extending the CMY gray balance principle to manage the majority of spectral colors. This new approach creates a new dimension and knowledge for better quality control in the color management world.

F. Academic value

This technique can reduce any bias in color correction decision making and be a valuable training model with academic study values [23]. In addition, spectral gray balance is a new dimension of spectral color management, with great opportunity for further development. It is good educational material for inspiring the research community and engineers at large to think outside of the box.

G. Software and Hardware development

Current color analysis technology cannot interpret the new geometry and is unable to compare the referencing K value against the neutral gray patches. There are new software and hardware development opportunities for the interpretation of the new gray bar geometry and comparison aims.

H. Comparison between the New Technique and the Traditional Color Bar

Table 1 is the technological advancement analysis between this new technique and the current practice.

	New Technique	**Traditional Color Bar**	**Advancement**
Design	A series of K and NG gray patches	Repeats of functional groups	Simplify
Functional group(s)	Single Gray patch	Multiple sections	Simplify
Gray element	50% Gray patch	Dual gray patches at 40% and 80%	Simplify
Monitor aim	One to many	One to one	Advance
Reading Technique	Visual / Meter	Meter only	Advance
Measurement Aim	Gray images	CMYK solid patches	Advance
Aim point	Visual matching gray shade across the bar	Interpret from CMYK Solid Density reading	Simplify

Table 1: *Comparison between New Technique and Traditional Color Bar*

Conclusions

The new process control gray bar described in this article has a unique geometry that can help a press operator manage Hi Fi color (or any color) printing effectively by using only their naked eye, and maintain a low E value for accurate color reproduction. The design utilizes the Mach Bands effect to increase sensitivity of the human visual system to give it an advantage over traditional color control bars. The technology can replace the existing practice of visually comparing a printed sheet with the reference proof, thereby reducing the subjectivity and increasing the accuracy. Benefits of this technology include cost reduction, waste reduction, production efficiency, potential technological enhancement, and hopefully, it can inspire more minds to innovate and produce more game-changing technology.

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Appendix 1

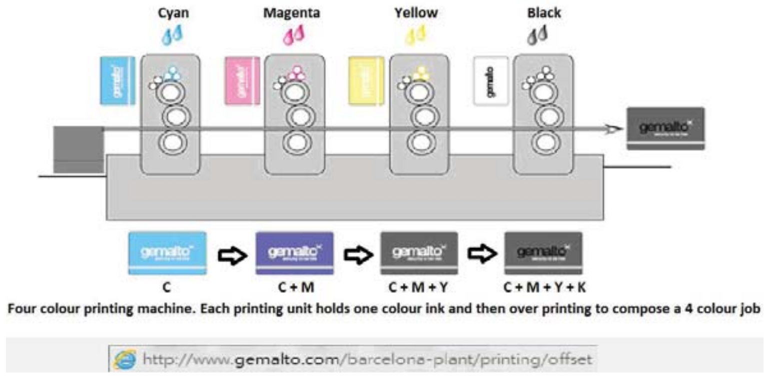

Figure 15: *Four color printing machine*

Appendix 2

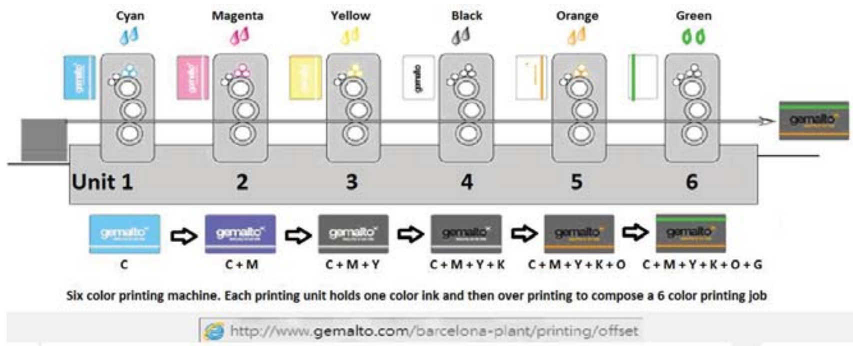

Figure 16: *Six color printing machine*

Appendix 3

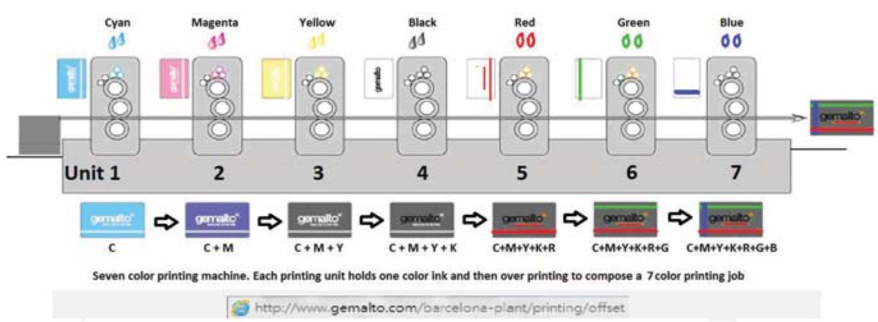

Figure 17: *Seven color printing machine*