THE SYSTEMS APPROACH TO COLOR REPRODUCTION - A CRITIQUE

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Abstract: The adaptation of theoretical concepts from systems engineering to color reproduction is introduced. A comprehensive review of published works detailing color systems approaches is then presented. The major omissions in systems approaches, as discussed in the literature, are examined, namely: the influence of the original; the question of optimal printing conditions; and, the variability of the process as a constraint on precise programming. The paper concludes with recommendations for research directions on optimal color reproduction, optimal press conditions, and process variability.

Introduction

The term "systems approach" suggests a comprehensive and integrated treatment of a given subject. Such a systems approach to color reproduction should consider the properties of inks and substrates, the interaction of these materials on press, the image carrier, the color separation films, the original, the observer, and the viewing conditions. The influence of each of these variables must also be examined from the point of view of how they interact with each other. The effect of all these properties and interactions are summed when the final reproduction is viewed by an observer under given lighting conditions.

In almost 100 years of process color printing it has only been possible to make practical use of systems concepts for the past 10-15 years. Prior to this, the lack of process control technology made it very difficult to achieve precise and

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repeatable results in color reproduction. With today's digital color scanners, automatic film and plate processors, on-press densitometry, improved inking systems, and similar examples of microprocessor technology, it is possible to achieve levels of precision and consistency which now make a systems approach to color reproduction feasible.

Systems Theory

The idea of a systems approach to color reproduction can best be illustrated by a systems diagram from the field of control engineering.

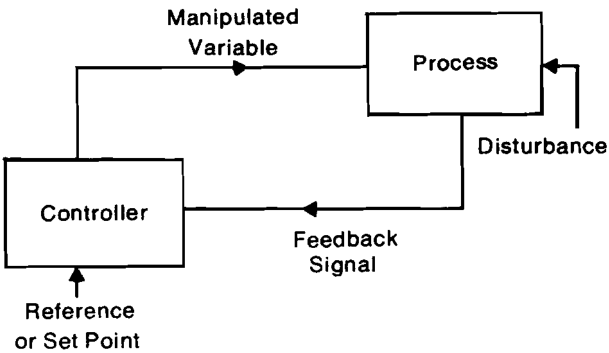

Figure 1. Control System Block Diagram

In figure 1 the set point represents the optimal condition of the process. If a disturbance is introduced to the process, it is sensed through a feedback signal which is sent to the controller. The controller uses a manipulated variable to compensate for the disturbance and bring the process back to the optimal point. A heating/air conditioning system is a good example of this control principle. A desired temperature is first established. As the temperature in the room rises or falls from this level a thermostat senses this change, and the control mechanism pumps correspondingly cooler or warmer air into the room to return the temperature to the set point.

The same concept can be easily applied to color reproduction (figure 2). The set point represents camera or scanner settings which represent optimal color reproduction. The process is the ink-paper-press system plus the contacting and platemaking processes, i.e. those processes which for a given set of raw materials should always be run consistently. A disturbance to the system could be a different press, a changed color sequence, or a different substrate. To be classified as a disturbance it must exert a significant influence on the appearance of the reproduction. The feedback signal is provided by a special feedback control chart such as a gray balance or a color chart. The controller is the color separation department where the feedback chart is examined and changes made to the color separations (the manipulated variable) in order to compensate for the influence of the disturbance.

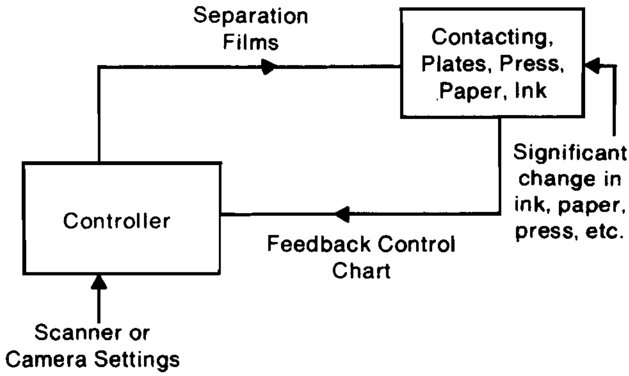

Figure 2. Color Reproduction Feedback Control Diagram

Over the years, many researchers have advocated systems approaches to color reproduction (although few have phrased it this way). Both theory and practice have been addressed from narrow to broad perspectives. At this point it is appropriate to consider these contributions.

Color Systems - Theoretical

An important analytical systems approach to tone reproduction was published by L.A. Jones in 1920. This is the familiar 4-quadrant "Jones Diagram". H.E. Ives (1926) adapted Jones' method to halftone photo engraving analysis. Yule and Clapper (1958) used an expanded version of the Jones diagram for the analysis of the multiple steps sometimes necessary in photomechanical color reproduction. Today the Jones diagram is typically used to relate press dot gain behavior back to color separation films, via contacting and platemaking steps.

The color properties of printing inks that necessitate color correction and gray balance adjustments have received considerable attention over the years. J.A.C. Yule (1938) published two papers detailing mathematical and graphical approaches to color correction. Archer (1954) demonstrated how gray balance could be determined by empirical methods. Clapper (1959) and Pobboravsky (1966) showed how graphical and mathematical techniques could be employed for gray balance determination.

Other important developments toward a systems approach to color reproduction included the Neugebauer equations (Neugebauer 1937), the Murray-Davies equation (Murray 1936), and the Yule-Nielsen modification of the Murray-Davies equation (Yule and Nielsen 1951). In "Principles of Color Reproduction" Yule (1967) reviews much of the pioneering work that laid the foundation for engineering principles to be applied to color reproduction.

The "Engineering Approach" to color reproduction suggested by Pobboravsky in 1962 further developed mathematical approaches to matching original colors to reproduced colors. His work considered only flat colors rather than pictorial subjects. More importantly, however, he examined the effect of press variability on the accuracy of reproduced colors.

Subsequent papers on color systems approaches tended to be more conceptual and descriptive rather than mathematical. They included work by Cox (1973), Field (1974), and Sunderland (1979, 1982). These papers first used the word "systems" as applied to color reproduction.

Further systems conceptual work by Maurer (1968, 1971) was combined with comprehensive practical guidelines in the form of instruction books and dial-type computers. These publications did much to make the printing industry aware of the importance of gray balance and tone reproduction in color separation. Maurer expanded this work (1982) to encoumpass individualized computer analysis of printing systems to allow the production of customized color separations. He also incorporated the possibility of using different optimal tone reproduction curves, depending on the type of original being reproduced.

The relationship of the original to the final reproduction had been discussed at the Inter Society Color Council 1971 Conference on Optimum Reproduction of Color (Pearson, 1971). This conference, even though it did not provide the answers to the question of optimal color reproduction, it clearly shifted the emphasis in graphic color reproduction research away from ways of characterizing the printing process through feedback charts, and towards what should be the optimal set point. That is, what is the correct tonal (and color) relationship between the original and the reproduction?

Color Systems - Practical

The ultimate form of feedback control chart in color reproduction is a full scale color chart. These charts are produced from a set of master films under actual production conditions. They are used as guides for color separation, dot etching, color communication, as well as serving as references for color printing. Other feedback charts such as gray balance charts or color correction guides have, as their names suggest, more limited uses.

The LTF Color Chart (White, 1957) was the first commercially available film set made for the purpose of allowing printers to characterize their printing conditions. This was followed by the RIT Process Ink Gamut chart (Elyjiw and Yule, 1970) and the Munsell-Foss Color Chart (Foss and Field, 1973). Gray balance film sets were produced by the Graphic Arts Technical Foundation (Cox, 1969) and the Rochester Institute of Technology (Elyjiw and Archer, 1972). A film set for a "Color Reproduction Guide" (primarily intended for judging color correction) was also developed by the Graphic Arts Technical Foundation (Elyjiw and Preucil, 1964).

Frank Preucil of LTF/GATF did much during the 1950s and 1960s to convince plants to customize their color correction procedures to suit the ink-paper-press conditions being used. The work of Murray, Yule, Clapper, Montrois, and Maurer of Eastman Kodak also did much to popularize color masking and the importance of tone reproduction and gray balance to good color reproduction.

The research described to date has dealt with the problems of tone reproduction, gray balance, and color correction as they relate to the ink-paper-press combination. Relatively little of this research has dealt with the relationship of the original to the final printed sheet, and virtually none has dealt with such concerns as sharpness, resolution, or gloss as to how they influence color reproduction.

Color Systems - A Critique

The gaps in the color systems work to date can be summarized under the following headings:

1. Optimal Tone and Color Reproduction

a. Printing Conditions. The densities of the individual cyan, magenta, and yellow inks, as well as the sequence in which they are printed will influence the resulting color gamut. It is not known whether it is preferable to maximize the total gamut, or to emphasize certain colors at the expense of others. Most research on this topic has focussed on process concerns (for example dot gain vs. color strength) rather than on the appearance of individual reproductions.

b. Tone Reproduction and Color Correction. Where the density range of the original is greater than that of the reproduction (almost always) a tonal compression must be made. No systematic study with the answers to the compression problem has been published. Color correction for the ink-paper combination is only partial correction, hence it is also necessary to correct for colors in the original. The optimal relationship between the original colors and the reproduced colors is not known. In fact, Hunt (1970) has suggested there may be as many as six different ways of judging color reproduction: spectral, colorimetric, exact, equivalent, corresponding, and preferred. The problem is that the "original" used for reproduction is usually itself a reproduction from a real life scene or object, hence is rarely a realistic guide to either what the original really looked like or what the customer really wants. (An exception being where the original is an artists' painting or watercolor. If the objective is to reproduce the painting in a catalog, then the original and reproduction should match. Such is rarely the case for photographic originals.) The problem of color correction becomes especially acute when there colors in the original which fall outside the color gamut of the ink-paper being used.

c. Process Disturbances and their Adjustment
The question of how much process variability (e.g. different brands of the same ink types) can be tolerated before the system has to be reprogrammed is an open one. We don't know what is a significant disturbance to the system. Likewise, if we do know the optimal tone and color requirements for the separations, how much can they vary from this optimum and still be acceptable?

2. Other Quality Factors
George Jorgensen (1955, 1960, 1972) has suggested four general areas of classification for print quality factors:

a. Tone and Color Reproduction - concerns the hue, saturation, and lightness relationships of the original to the reproduction.

b. Interference Patterns - can be either random or periodic and includes wash marks, gear streaks, graininess and moire.

c. Image Definition - concerns the sharpness and resolution of fine detail in the image.

d. Surface Characteristics - includes gloss, texture, and flatness.

Factors b, c, and d have rarely been mentioned in color reproduction research. Some of these factors such as gear streaks, wash marks, texture, and flatness, while valid print quality concerns, can be set aside for a more narrow discussion of color reproduction quality.

The criticism of the systems approaches to color reproduction does not mean that the diagrams in the introduction (figures 1 & 2) are incorrect. Rather, it is suggested that too much emphasis in the past has been placed on the feedback loop link between the process (press-paper-ink) and the controller (color separation). The future emphasis should be on three different areas of figures 1 & 2:

1. Set Point Adjustment - What are the optimal tone, color, sharpness, resolution, and interference pattern settings?

2. Process Balance - What are the optimal process ink levels and what is the best color sequence?

3. Disturbance-Manipulated Variable Relationship.- How much variation in manufacturing conditions/materials is allowable before the system must be recalibrated? How accurately must the color separations (manipulated variable) be made to still be acceptable?

Answering any one of the above questions is very difficult because it is probable that many of questions are interrelated. However, some separation of the knowns from the unknowns is possible, and from a research point of view, is probably desirable.

Color Reproduction Requirements - Defined

Without taking into account acceptability limits or factor tradeoffs, the following objectives in color reproduction can be defined with a fairly high degree of certainty:

1. Resolution - very high, screenless printing would be ideal if it were not accompanied by graininess problems.
2. Graininess - very low, no more than that in the original.
3. Tone Reproduction (Press) - compensate in the separations for press dot gain. A Jones-type diagram is used for analysis of this gain.
4. Gray Balance - a gray balance chart is used to determine the optimal balance between the yellow, magenta, and cyan separations. This is defined by the optical properties of the ink-paper-press interaction.
5. Color Correction (Inks) - a feedback color guide is used to determine the correct masking/ scanner settings for the ink-paper-press being used.
6. Moire Patterns - none, but with a halftone process there must be some pattern, therefore it must be the least noticable. (This has become an

issue with some laser screening systems).

7. Gloss - High for photographic originals (to try and match the saturation of the originals) and about the same gloss as the original for artists' drawings. (Paper gloss is a materials selection question and not really a control item in the color reproduction cycle, however, its influence on color reproduction can be great and therefore should not be overlooked.)

Color Reproduction Requirements - Undefined

The following color reproduction factors are undefined:

1. Tone Reproduction (Original) - Jorgensen (1976, 1977) has developed optimal tone reproduction curves for black and white reproduction. He presented curves for high-key originals and normal-key originals. "Interest Areas" in the original were best reproduced at about gamma 1.0. Similar research must be done for color originals (reflection and transparency copy) where compressions are often greater than black and white.

2. Color Correction (Original) - Although some useful work has been done on characterizing the behaviors of different types of color film in the color separation process (Bellis and Moon, 1981), little can be said (with the possible exception of product color matches in catalogs) as to what the exact relationship between the original color and reproduced color should be (see Hunt, 1970), especially when there are non-gamut colors in the original.

3. Sharpness - Certain photographs, for example of watches and jewelery probably look better with higher sharpness than that of a soft focus portrait of a woman. Optimal sharpness is not known.

4. Other - Some customers may prefer coarse screen halftones, ultra high contrast, or bizarre colors for special "shock" effects. These requirements are very rare and can be thought of as outside the scope of this paper.

Color Reproduction Tradeoffs

When some of the defined color reproduction requirements are maximized or emphasized, they tend to have the reverse effect on some other defined color reproduction requirement. Thus one factor can be maximized only at the expense of another. These tradeoffs virtually all occur in relation to the yellow, magenta, and cyan ink levels, their sequence, and their balance. Tradeoffs within the color separation process are minimal by comparison and will be ignored. Some of the major tradeoffs on press are:

Ink Film Thickness (IFT) Increasing the IFT will increase the lightness (strength) of the color but can also shift the hue and decrease the saturation (make it grayer). Increasing IFT will also increase the sharpness and the gloss of the reproduction. However, on the negative side, graininess will increase and resolution will decrease.

Resolution. Finer screen rulings will give higher resolution and cleaner highlight colors. But, register is more critical with finer screens and dot gain and contrast are more difficult to control.

Other factors that changing IFT will affect include pick, tack (hence trapping), and drying time. Jorgensen and Lavi (1973) have prepared an extensive reference manual of press-paper-ink interactions in lithography.

Color Balance. Varying an individual IFT while holding the other two constant will cause color shifts in two of the 2-color overlaps as well as the 3-color overlap. These shifts will not only be due to the changed ink feed, but will also be influenced by the changed trapping behavior, in turn affecting dot gain (Saleh, 1982).

Color Sequence. The absence of perfect transparency in process inks will cause the color of overprints to shift towards the color of the last down ink. Because there are three 2-color overprints, changing the sequence of one ink to "improve" a particular overprint color, may have the effect of "worsening" the other 2-color overprint in which that ink is present. Sequence is also influenced by other appearance and physical factors (Field, 1983).

System Stability and Tolerances

A further unknown in color reproduction is how much variation in the actual press operation is allowable before the reproduction is unsuitable.

To some degree this is related to the end use of the printed product. For example, a mail order catalog probably has higher consistency requirements than editorial color in newspapers. The U.S. Government Printing Office has published extensive quality specifications for the purchase of printing (GPO, 1979) but it is not known how they relate to commercial quality acceptability practices. Jorgensen has recently published a series of reports (1981, 1982a, 1982b, 1983, 1984) on the control of lithographic printing which offer practical guidelines for establishing control limits for color printing.

A related unknown in color reproduction is that _if_ the conditions for optimal color reproduction are known and _if_ there is no color variation on press, how close to optimal do separations need to be made to still be classified as optimal? A recent report by GATF (Warner et al, 1982) showed the wide differences in color scanner settings necessary to correct for two different magenta inks. However, the printed results where the "wrong" separations were used with each magenta, suggest that high precision in color correction may not be necessary. We know there is an optimal band of acceptable room temperatures(set points), therefore, we can speculate that there is a band of acceptability for color reproduction set points.

Conclusion

A major reason for the gaps in color reproduction research has been the sheer difficulty in conducting the research. A considerable number of separations would have to be made from a variety of subjects and printed with a range of materials under controlled, but different printing conditions. The subsequent samples would have to be ranked by panels of observers to determine the optimal reproductions.

With color scanners it is possible to quickly generate large numbers of color separations from a given subject. Slight, but predictable changes can be introduced into these separations to test, say, tone reproduction curves. The problem arises when attempting to incorporate dynamic press adjustments when printing these separations. Printing interactions can distort the color separation changes, possibly nullifying them. Because the press interactions are so numerous, they can be difficult to predict and control. Consequently, the dual approach of holding the printing constant and varying the separations (from several originals), contrasted to varying the printing and keeping constant the separations (one set from each of several originals) may be advisable.

The advent of digital color scanners with video display monitors (such as the Eikonix Designmaster 8000) offers the possiblity of real-time adjustments in color reproduction. Changes in hue, saturation, and lightness can be made easily, thus allowing tests for optimality (and bands of acceptance) to be made quickly from a variety of originals. The internal memory which relates colorimetric values of the printed colors to corresponding percentage dot values, can be simply recalibrated for other printing conditions. The tests for optimality could then be repeated as many times as seems to be productive.

Tests of tone and color reproduction using a video monitor would not address the influence of interference patterns, image definition, or surface characteristics on the reproduction. Also, the self luminous display of the video monitor, contrasted to a printed reproduction illuminated by reflected light, may introduce some tonal or color distortions that could prove to be significant.

Nevertheless, color reproduction research utilizing video monitors may at least greatly reduce the complexity of more traditional approaches by reducing the range of printing conditions or separation characteristics that need to be considered.

The shift in focus of color reproduction research awar from methods of compensating for the properties of the ink-paper-press interaction via the separations, is complete. New research tools must now be further employed to determine optimal color reproduction, optimal printing conditions, and print/separation acceptability limits. Visual examination and ranking of color reproductions is most likely the best way to accomplish these objectives. It is hoped that the existance of video monitor systems will give added impetus to this kind of research.

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