A DEFINITIVE STRATEGY FOR THE CLOSED LOOP CONTROL OF PROCESS COLOR PRINTING - ROUND ONE

by John MacPhee*

Abstract: This paper describes the results of an initial effort to develop a systematic procedure for controlling or minimizing the color variations which occur during four-color printing by the offset method. The starting point is the preposition that the printing operation can be modeled as a closed loop system. This analogy is used to explain the role of the press operator and where he is located within the system. The demands placed on the operator are set forth in terms of the important attributes of the process output, or desired printed form. These in turn are used to explain the rationale for employing test images, wherever feasible. A systematic procedure, in flow chart form, is then proposed for controlling the color variations which, up to now at least, are inherent in the lithographic printing process.

INTRODUCTION

Rudiments of Process Color Printing

Process color printing is the term used to describe the use of three subtractive primary color inks (cyan, magenta and yellow) to reproduce the three attributes of the full spectrum of colors on a printed form: saturation, hue, and lightness.** The term "process" denotes that such printing comprises a series of progressive and interdependent operations whereby the primary color inks are printed in sequence using a separate plate for each color. The word "process" is also used below in another context. Therefore, process color printing hereafter will be referred to as color printing.

To accommodate the range in color saturation (e.g. pink versus red) the printing plates are screened to produce halftone dots, the areas of which are in proportion to the degree of color saturation. Thus, regions containing highly saturated colors have very large area dots and are referred to as shadows, while light or

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**For a more complete definition of color attributes the reader is referred to Hunter's excellent book (Hunter, 1975).

pastel regions have very small area dots and are referred to as highlights. The intermediate regions are referred to as midtones.

A wide range in the second color attribute, hue (e.g. green versus blue), is achieved by overprinting two or more of the process inks in the same area. This is analogous to the painter who mixes several paints to obtain a desired hue. More often than not, the overprinted regions have difference dot sizes.

The third color attribute, lightness (or grayness) is achieved by overprinting black. In theory, this can be acomplished by overprinting equal areas of all three process inks. In practice, however, a fourth ink, black, is used so as to reduce the total or overprinted ink film thickness of colors containing gray. This explains the term four color (process) printing.

Ideal Printing Conditions

Based on the principles just set forth, it is possible to identify the more important conditions which must be satisfied for printing to be under control. Because of the importance of these conditions, they will now be listed and discussed briefly.

1. Acceptable Color Separations. In order to produce individual printing plates for each color ink, the original image must be divided or separated into the colors corresponding to those of the primary inks. In addition, the plates must be screened to produce the halftone dot sizes corresponding to the various degrees of color saturation. Usually this separation involves making compromises because offset printing is not capable of reproducing the total color range found in most originals. Thus, because there is no such thing as a correct or perfect set of separations, the best that can be achieved is a set that is acceptable or agreeable to the customer. Although the task of obtaining such agreement is outside the scope of this paper, it must be emphasized that the frequent failure to obtain such agreement constitutes a major control problem for the industry.

2. Consistency of Ink Spectral Characteristics. This requirement is obvious, since a shift in the spectral characteristics of even one ink (e.g. due to changing to a new batch of ink) can cause a hue shift in the printed result.

3. Consistency of Paper Spectral Characteristics. The basis for this requirement is the same as for ink, above.

4. Constant Printed Ink Film Thickness. Because the primary color printing inks are not perfect or ideal filters in the desired

selective regions of the spectrum, the saturation of a given printed ink film varies with its thickness. Thus separations are made assuming a given saturation level for each solid printed ink film, and this assumption requires that the solid printed ink film thicknesses be maintained at constant values (i.e., the values assumed in making the separations).

5. Consistency of Halftone Dot Reproduction. The color separations are also based on the assumption that the apparent size* of the various printed dots is predictable and will remain constant throughout the press run. Should dot size vary during a run, shifts in both color saturation and hue will occur.

The Need for Control

At this point, the uninitiated reader might assume that armed with an understanding of the foregoing fundamentals, color printing can be and is easily carried out flawlessly. Unfortunately, this is not the case in that color deviations in printed products remain a significant problem. In general, these deviations stem from two major causes which are typed as follows:

Type 1: Color Errors Due to Faults in Process Parameters

In general, Type 1 Errors can be looked upon as programming problems. They are separated here into two classes because the first, color separation errors, are distinct from other process parameter problems.

(a) Color Errors Due to Unsatisfactory Color Separations - strickly speaking this is not a printing problem because if the color separations are unsatisfactory, it will be impossible to produce a satisfactory print, even if the other four ideal printing conditions are satisfied.

(b) Color Errors Due to Variations in or Incorrect Press Parameters - the differences between this type of problem and Type 2 problems are discussed at length further on. One extreme example which serves to define a Type 1(b) problem is the case where either the plates or inks are installed in the wrong sequence.

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*Apparant size is the term used here to describe the fact that a dot of a given physical size will appear larger to both the human eye and a densitometer, because of the phenomenon of optical dot gain.

Type 2: Color Errors Due to Disturbances During Printing

This common printing problem is due to a failure to consistently satisfy one or more of the latter four ideal conditions outlined above.

Problems Addressed

The problems addressed in this paper are those of the color variations which occur during printing and include some of the Type 1(b) and all of the Type 2 problems just defined. That is, it will be assumed that color separations are satisfactory and that the only color variabililty present is that which occurs after a satisfactory OK sheet has been obtained under the printing conditions assumed in making the separations. Put another way, it is assumed that the only causes of print variability are variations in either ink characteristics, paper characteristics, printed ink film thickness, or apparent dot size. These possible causes can be narrowed down further to either ink film thickness or dot size, since during a given run it is relatively easy to eliminte ink and paper variability.

As the first step in addressing the problem of how to control these color variations, the next two sections of this paper will characterize closed-loop systems and then analyze color printing within that context. This will be followed by a section which presents and describes a proposed systematic procedure or algorithm for controlling color variations.

CHARACTERIZATION OF CLOSED-LOOP SYSTEMS

Closed loop systems represent a class of control systems which are characterized by the fact that control of the variable or quantity in question (the output) is accomplished by constantly measuring it, and comparing it to a desired or reference value (the input); then if an error exists between the two, some action is taken to change the output so as to reduce the error to an acceptable level(Brown and Campbell, 1948). Based on this definition it can be seen that a closed-loop system consists of the four basic elements shown in Figure 1 and which are described as follows:

1. A process which produces a variable output, which is capable of being changed in response to some command. The process may also be subject to disturbances which cause undesired changes in its output. In fact, generally, it is the existence of

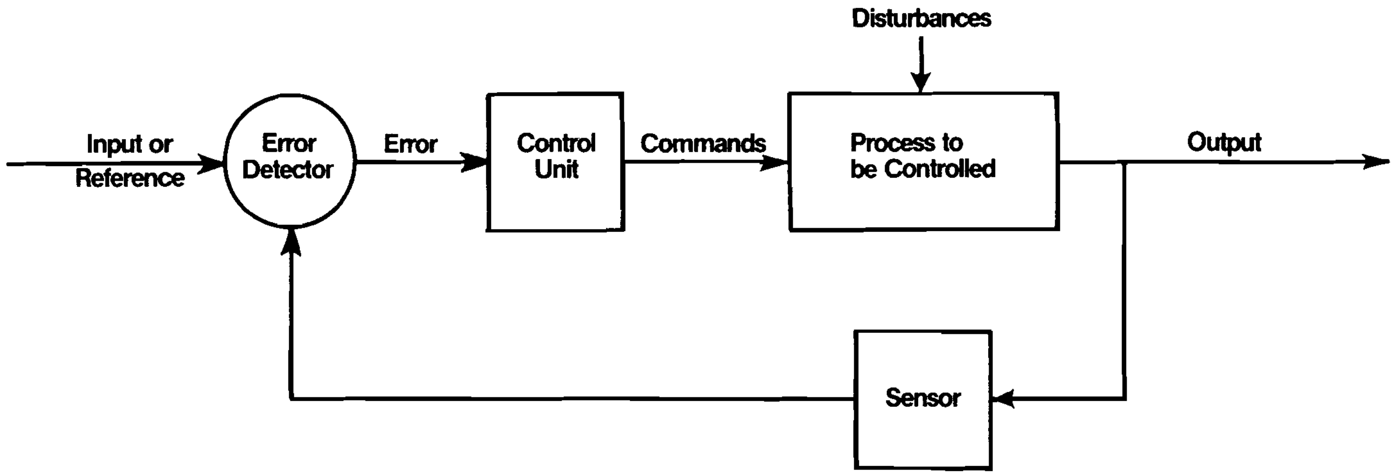

Figure 1   Diagram Showing the Four Basic Elements in a Closed-Loop System

such disturbances which lead to the need for closed-loop control.

2. A sensor which measures the process output and generates a signal which is proportional or analogous to it.

3. An error detector which compares the signals representing the desired (input) and the existing (output) process variable and generates a signal proportional to the difference or error between the two.

4. A control unit which responds to the error signal so as to generate a command signal to the process which will cause the process variable to change to a value at which the error becomes essentially zero.

By way of illustration, consider a system for controlling the room air temperature produced by a home heating system. In this example, room air temperature is the process variable or output while the process itself is the room and its heating unit (such as a gas-fired hot air system). A possible disturbance is the opening and closing of an outside door. A thermostat mounted on the room wall acts as both the sensor and error detector in that it measures room temperature and generates an error signal proportional to the difference between the actual and desired room temperature. The desired room temperature is a setting dialed into the thermostat by the user. The control unit in this example is a relatively simple device which turns the heating system on whenever the error exceeds some small value, i.e., whenever room temperature drops below the setpoint or desired value. Thus, the heating unit is turned on and off in response to changes in room temperature.

The behavior of a given closed-loop system will be governed by the response characteristics of both the process and the control unit. In the case of the process, its response characteristics are generally fixed and govern the range of the output. Thus, the only latitude given the control engineer is in the design of the response function of the control unit. (This respose function can be looked upon as an algorithm for generating the responses of the controller to changes in error signal.) Of course in order to design a control unit, a knowledge of the process's response function is essential. Although such a knowledge may sound trivial in the example of the room temperature control system just described, it is by no means so in the case of the printing process, which will now be discussed.

COLOR PRINTING AS A CLOSED-LOOP SYSTEM

A comparison between color printing and the model given in Figure 1 shows that color printing is indeed a closed-loop control system. The system output is the given desired printed form while the input is represented by the proof or OK sheet, which is used as the reference. Figure 1 also shows that a closed-loop system comprises four elements: a sensor, an error detector, a control unit and a process. Subsequent paragraphs identify these elements within the printing system.

The Process Element

Based on the model described in Figure 1, the process element within the printing system is defined as the printing press itself. Its output is a printed form which is produced in response to commands or inputs to the press controls. These controls are simply the adjustments which determine ink and water feedrates. All of the other process variables such as type of paper, type of ink, printing pressure, roller settings, and plates and blankets, are parameters which determine the response function of the press. Of course, changes can and do occur in these parameters during running. If the changes are small they constitute disturbances which possibly may be compensated for by changes in commands. However, if large changes in parameters occur (such as due to plate wear) the desired output will become unachievable and closed-loop control in the strict sense becomes impossible.

To summarize, once a press is placed into printing operation, the only commands or controls available are ink and water feedrates and closed-loop control will only be feasible so long as the process parameters are such as to make it possible to print the desired form by manipulating these commands. In other words, each set of printing process parameters, which include paper, a set of inks, and a set of plates, narrowly limit the range of the printed output. For this reason, the press commands will only be effective when it is desired to print within those limits.

The Role of the Pressman as Sensor, Error Detector and Control Element

The role of the pressman as part of the closed-loop system is enormous in that he constitutes three elements: the sensor, the error detector and the control unit. Thus, he compares the actual output or printed form with the reference. Based on this comparison, he decides if an error exists. If an error is deemed to exist, he then determines what commands to the press controls are appropriate to bring the output into conformance with the reference.

The Total Role of the Pressman

In addition to providing elements for closed-loop control, the pressman provides another very important function: that of determining if the desired result is within the limits of what the process element (i.e., the press itself) is capable of producing. If it is not, the press must be shut down and changes made in one or more parameters. Such a shutdown of course terminates closed-loop control. Thus, the pressman's total role is dual functioned and can be described in flowchart form, as in Figure 2. The simplicity of this diagram should not obscure the fact that the tasks it describes are exceedingly complex. That is, the pressman is called upon to make two different and difficult types of decisions posed by the questions in Figure 2. In addition, he must decide what the appropriate response is to errors arising under two different situations: when an error can be corrected by making changes in control settings (a Type 2 error) and when an error can be corrected only by making changes in one or more parameters (a Type 1 error).

CONTROL STRATEGY FOR COLOR PRINTING

Figure 2 is a broad outline, in flowchart form, of the procedure followed by pressmen in controlling color printing. The more detailed procedure, to be developed here, is concerned with determining if an error exists between the printed form and the reference and if so, whether it is a Type 1(b) or Type 2 error. It is of great importance in this regard to identify which output variables are of most interest or significance and to discuss how they are evaluated by the human observer. Consequently, these two topics will be taken up first. The use of test images will also be discussed briefly before describing the detailed control strategy.

The Eye as a Sensor

Although the eye cannot make quantative or absolute color measurements, and the brain has a very poor color memory, a human observer can detect very slight differences in color by making a side-by-side comparison between a sample and a reference (Hunter, 1975). Although the resolution which can be achieved depends strongly on image geometry and viewing conditions, instances have been recorded (MacPhee, 1986) where the eye proved more sensitive than a densitometer in detecting variations in a printed solid ink film. What this means is that the

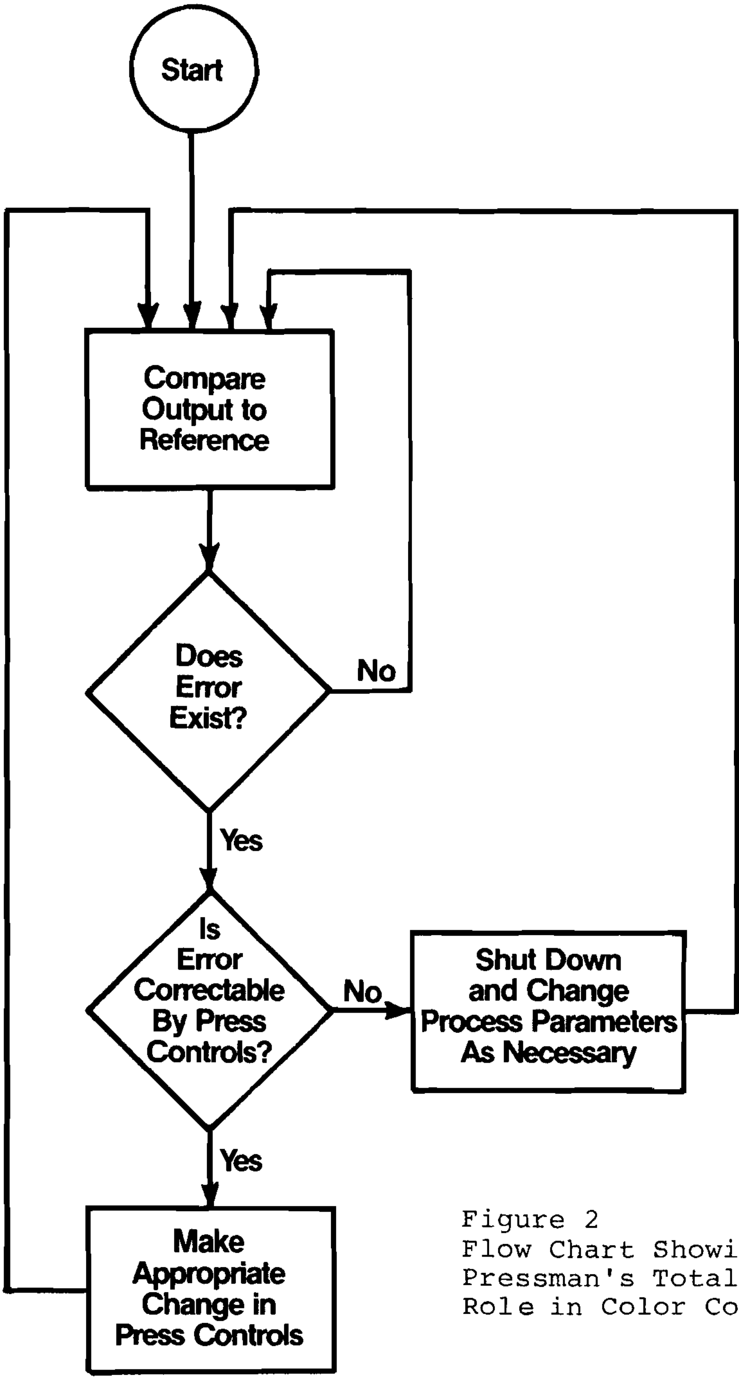

Figure 2
Flow Chart Showing
Pressman's Total
Role in Color Control

eye is more than adequate to detect the second type of color deviations identified in the introduction to this paper, i,e, those which occur due to inconsistencies during printing. Confirmation of this is attested to by both Southworth (Southworth, 1984) and Brunner (Brunner, 1987). However, the first subtype of color deviations identified (and which is not addressed here), errors due to unsatisfactory color separations, can only be evaluated on sheets printed with the ink film thickness assumed in making the separations - and here a densitomer is necessary to obtain an absolute measurement.

Important Output Variables

One measure of the complexity of the printing operation is the fact that there is no obvious singular output variable which can be monitored to control the process. In judging which combination of the many possible variables should be used, there are two considerations: what variables are important to the end viewer, and to what variables is the eye most sensitive. Both of these considerations are discussed in the following paragraphs.

The images created by four color (process) printing consist of solid and halftone areas, made up of both single and overprinted ink films. However, because most of the colors in a reproduction are created by more than one ink, one would conclude that a major fraction of the printed areas is made up of overprinted films of ink. Thus it seems reasonable to conclude that overprinted areas are the most important to the viewer, simply because they appear more frequently.

Jorgensen observed that low-key photographs (ones in which the area on which the viewer concentrates his interest are in the shadows) are rarely used in printed illustrations (Jorgensen, 1974). Thus it can also be concluded that the highlight and midtone overprinted areas are more important than the shadows and solids.

While the overprinted highlight and midtone regions are of greatest interest, they are by no means the most responsive to changes in press commands. This can be demonstrated by making a change in ink feedrate and measuring the resultant changes in the printed output. Such an experiment, wherein ink feedrate to the magenta plate was caused to decay, is reported on in Table I. The color change measurements were made using a colorimeter calibrated in CIELAB units while the density measurements were made using a densitometer equipped with narrow band filters. These results demonstrate two points as follows:

- Solid printed ink films are much more sensitive to changes in commands than are single or overprinted halftones.

- If one believes that the colorimetric scales reflect the way the eye views color, then these results also show that the eye is no more sensitive to the hue shift in overprint areas produced by a given change in the density of one of the overprinted inks, than it is to the change (primarily in saturation) produced by the same given density change in that ink when printed alone.

Table I Colorimetric Difference Measurements On Two Sheets Where Magenta Solid Ink Density was the Only Change

Type of Test Image	Density Readings Sheet No. 1	Density Readings Sheet No. 100	Color change in ΔE Units
Magenta Solid	1.46	1.13	8.8
Cyan Solid	1.55	1.52	0.8
Yellow Solid	1.01	1.02	0.8
45% Magenta Halftone	0.43	0.36	4.2
25% Magenta Halftone	0.23	0.21	2.7
45% Magenta with Yellow Overprint	M:0.44 Y:0.55	M:0.40 Y:0.50	2.8
Gray Balance Patch (45% Magenta)	M:0.62 C:0.54 Y:0.55	M:0.57 C:0.55 Y:0.51	3.6

If the relationship between the densities of halftone areas and their corresponding solid areas were constant then it would make sense to control by simply monitoring solid ink densities - since the densities of the halftone regions would track the solids. However the numerous studies of dot gain, made in the past, have shown that there is no consistent relationship between solid ink density and density of a corresponding screen (Cooke et al 1969, DePaoli 1981, Froslev-Nielsen 1972, Kettinger and Werner 1973, Mill et al 1980, Saleh 1982, Sigg 1970, Takahashi et al 1987, Treff 1987, and Tritton, 1981). This of course suggests that dot gain on press is neither constant nor well behaved. One possible explanation for this apparent lack of a behavior pattern is that physical dot gain is dependent on both ink and water feedrates. To illustrate this, linear relationships based on observations of operating presses were used to calculate the response of a typical press to nine combinations of ink and water feedrate settings, and these results are given in Table II.

Table II Effect of Ink and Water Feedrates on Densities of Solid and Halftone Areas on a Typical Press. Symbols used are SD for solid density, DA for effective dot area, and HD for halftone density.

		Ink Feed		
		Low	Medium	High
WATER FEED	LOW	SD = 1.20 DA = 36 % HD = 0.18	SD = 1.25 DA = 38 % HD = 0.19	SD = 1.30 DA = 40 % HD = 0.21
	MEDIUM	SD = 1.15 DA = 38 % HD = 0.19	SD = 1.20 DA = 40 % HD = 0.20	SD = 1.25 DA = 42 % HD = 0.22
	HIGH	SD = 1.10 DA = 40 % HD = 0.20	SD = 1.15 DA = 42 % HD = 0.22	SD = 1.20 DA = 44 % HD = 0.23

This data points up the complexity of the press response function and clearly shows that any attempt to correlate dot gain with ink film thickness alone will be doomed to failure.

The absence of a constant linkage between dot gain and ink feedrate also means that it is not feasible to control by monitoring only screened regions - because in that event ink film thickness on the press and solid ink density on the print may deviate significantly from reference values. Thus it should now be clear that both the areas of highest interest to the viewer (highlights and midtones), and the areas to which the eye is most sensitive to change (solids) must be monitored as part of the control process.

Before proceeding to the next section, two other aspects of the press response function should be mentioned since they further complicate the control problem. First, the press response function reflected in Table II is an ideal one that does not include the fact that the response of the output to a given change in (say) ink feedrate can and does vary depending on the buildup of debris on the blanket and the amount of pressure between the printing cylinders. Also, the response time of the inking system is not a constant, but instead is strongly dependent on the percent ink coverage on the form (MacPhee, Kolesar, and Federgrun, 1986). For example, for a typical coverage of 15 percent, a representative press would have a response time (three time constants or the time required for 95% of the change to appear in the output) of about 500 impressions. For a very light coverage of 2.5 percent, the response time would be 2500 impressions; and 300 impressions for the relatively heavy coverage of 25 percent.

Use of Test Images to Track Output Variables

Test images are valuable aids to control which help in many ways as follows:

- They provide a consistent indicator from job to job, even though the makeup of jobs may vary significantly.
- They provide a quantitative measure of process performance (when used in conjunction with a densitometer).
- They provide information about many different operating variables, including ink film thickness, effective dot area, dot gain, slurring and /or doubling, changes in trapping, hue error, grayness, and ink-water balance.

- o They aid in establishing limits on how far production sheets can deviate from the standard, or OK sheet.

- o They aid in analyzing the cause or causes of the printing process that is "out of control."

Unfortunately, test images cannot always be used because of space limitations on the printed sheets. However, it is recommended that they be used wherever possible, and for that reason a brief discussion of them is included here.

Over the years, a wide variety of test images have been developed (Field and Jorgensen, 1984). Those to be discussed here are simply a representative sample of what is available. There are two types of test images: those that provide regions of solids and specific halftones, and those that contain specially designed forms or targets. Some of the most commonly used are described in Table III, along with a listing of their uses. The GATF QC Strip is included in this table because it provides an excellent measure of ink-water balance.

Table III Summary of Some Test Images Commonly Used for Color Control

Type of Target	Description	Usual Measurement Method	Primary Advantage
Solid Bar	Single Color	Densitometer Visual	Provides Quantitative Measure of Ink Film Thickness
	Two-color Overprint	Densitometer Visual	Provides a Very Sensitive Visual Indicator
Halftone Bar (40 - 70%)	Single Color	Densitometer Visual	Easy to Use Can be Used to Obtain Quantitative Measure of Change in Dot Gain
	Two-color Overprint	Visual	Provides a Very Sensitive Visual Indicator
	Three-color Overprint	Visual	Provides Early Warning of Problem with Halftones
Halftone Bar (10 - 40%)	Single Color	Densitometer Visual	Excellent Indicator for Detecting Slurring and Doubling
GATF QC Strip	Single Color	Densitometer Visual	Provides Several Bits of Information and Has Very Good Sensitivity
GATF Star Target	Single Color	Visual	Provides Several Bits of Information and Has Very Good Sensitivity

1. Solid Bars. The single-color solid bar is a standby because it makes it possible, when used with a densitometer, to obtain a quantitative measure of ink film thickness on the printed output. Overprinted solid test images are of great value because they provide a means for obtaining a quantitative measure of trapping.

2. Halftone Bars. Test images made up of single and overprinted halftone regions are also capable of providing valuable information. Single-color screens having dot areas in the range of 40-70% are used by many printers to measure dot quality and size. A screen of square dots having a physical area of slightly less than 50% (so that the corners of the dots do not touch) is favored by many for visually detecting dot gain. That is, if the dot grows uniformly, the corners will touch, and this can be readily detected.

   In addition to being useful for visual measurements, single-printed halftone regions make it possible to obtain quantitative measures of dot area using a densitometer. To do this, it is necessary to measure the densities of both the halftone and solid test images. Effective, or optical, dot area can then be calculated. The value of such calculations is that dot gain can be measured over the course of a pressrun.

   Overprinted halftone test images, like overprinted solid images, are very sensitive indicators of whether one or more printing conditions have changed. These can be used to pinpoint a problem with one of the primary colors (cyan, magenta and yellow) since a problem with one of the primaries (say, yellow) causes a hue shift in two of the secondaries (green and red). This relationship is set forth in the truth table, given in Table IV.

   Single-layer halftone test images printed with dots having relatively small areas find favor with some printers because of their visual sensitivity to nonuniform dot gain, that is, slurring or doubling.

3. Gray Balance Patch. A gray overprinted halftone of all three inks (approximately 40% cyan and 30% each magenta and yellow), designed to have a neutral gray appearance, is a valuable test image that usually provides the earliest warning of a printing problem. This is because these patches provide a visual indication of unbalanced dot gain in the three colors, since a change in dot gain of only one color results in a hue

shift away from neutral (Elyjiw, 1968). The eye will be quite sensitive to such a hue shift if a second gray target, obtained, by printing a black ink halftone, is printed alongside the gray balance patch for comparison.

4. QC Strip and Star Target. The last two test images listed in Table II are special designs developed by GATF. They are both distinguised by the fact that they are very sensitive, even though they are printed with a single film of ink. The QC Strip is better for monitoring ink film thickness and laydown, while the Star Target does better monitoring dot gain. Either can be used for monitoring dot quality.

Table IV
Truth Table for Hue Shifts

		Hue Shift Occurs In:		
		Blue	Green	Red
If Printing Problem Occurs With:	Cyan	Yes	Yes	No
	Magenta	Yes	No	Yes
	Yellow	No	Yes	Yes

Hue shift in test images of secondary colors (blue, green and red) can identify printing problems in one of the three process colors. This is because each primary color (cyan, magenta and yellow) uniquely affects a pair of secondary colors. For example, a hue shift in blue and red indicates a problem with magenta.

Proposed Strategy

It is hoped that the material presented up to this point (which has been mainly tutorial in nature) will have demonstrated that the task of defining a systematic protocol or algorithm for controlling color variation during printing is not a straight forward problem for the following reasons:

- o There is no single attribute or variable of the output which can be examined as the basis for closed-loop control.

- o The linkage or relationship of the process outputs to commands is neither simple nor constant, e.g. dot gain is not a fixed function of ink film thickness.

- o The source of color deviations which occur may be relatively minor disturbances which can be corrected by commands to the press or may be changes in process parameters which can only be corrected by shutting down the press.

In recognition of this the following strategy is presented as a "first cut", with the hope that its major contribution will be a better understanding of the scope of this control task. In other words there are no pretentions that this is the last word on systematizing closed-loop color control.

The strategy set forth here is predicated on two assumptions: the pressman plays the key roll in closing the control-loop, as discussed earlier; and his first control priority is to maintain consistency of halftone densities. Other output variables affecting this prime attribute, and which he must control, are summarized in Table V together with the factors which affect them. It is also assumed, though it is not necessary, that test images will be used and that a densitometer will be available for quantitative measurements.

Table V
Important Output Variables in Color Printing

Output Variable	Input Variables and Parameters Which Have a Significant Effect
Dot Size	Ink Feed Rate, Ink-Water Balance, Variables Causing Mechanical Dot Gain or Loss, Printing Pressure
Ink Film Thickness	Ink Feed Rate, Trapping Ability
Dot Quality	Ink Water Balance, Causes of Slurring/Doubling, Printing Pressure
Uniformity of Ink Laydown	Ink Water Balance, Printing Pressure

The recommended control strategy is given in Figure 3, in flowchart form. While (hopefully) progress through it is self explanatory, a discussion of the underlying philosophy is certainly in order. One of the guidelines followed in the design is that the task of ascertaining if the output is within acceptable limits should be a relatively simple one which can be carried out speedily - so as not to encumber the presscrew. This is especially important on modern web presses where little time is available because of the high speeds at which they operate. As a result, the control strategy is made up of a relatively short routine check path from which branch out a variety of troubleshooting paths. When the process is in control, the operator need only follow the routine check path. A gray balance patch was selected as the first image in the check path and is monitored periodically for a signal that a color deviation has occurred. The value of this target is that it responds to a change in either the solid density or the dot size of any one of the three color inks. As already noted, such a change results in a hue shift away from neutral, to which the human eye is quite sensitive. Thus, so long as the gray patch remains gray there is reasonable assurance that a change in color has not occured. The gray patch provides no information about the black printing unit; therefore, a second image area must be observed to ascertain if any deviations have occurred. The GATF Star Target is one such image that can be used.

Even if no color deviations are indicated by the gray patch, and the black Star Target appears normal, it is possible, though highly unlikely, that a problem has occurred affecting all three colors. Accordingly, the routine includes a check of all three color Star Targets and all three solid color bars - the former for simultaneous halftone changes and the latter for simultaneous changes in ink laydown.

The routine check path just described is indicated by heavy solid lines in Figure 3. As can be seen, this path can be followed quickly and thererfore does not place undue demands on the operator. When a problem condition is signaled, the operator is diverted to the appropriate troubleshooting path, all of which are indicated by dotted lines in Figure 3.

The routine check path, as shown in Figure 3, was designed for use with visually sensitive image areas. While test targets of the types described are preferred, it should be possible to use analogous areas of a printed scene in cases where test targets cannot be used. Also there is no requirement that the monitoring be done visually - a densitometer could very well be used along the visual path. Of course, a densitometer is a necessity in certain of the troubleshooting tasks.

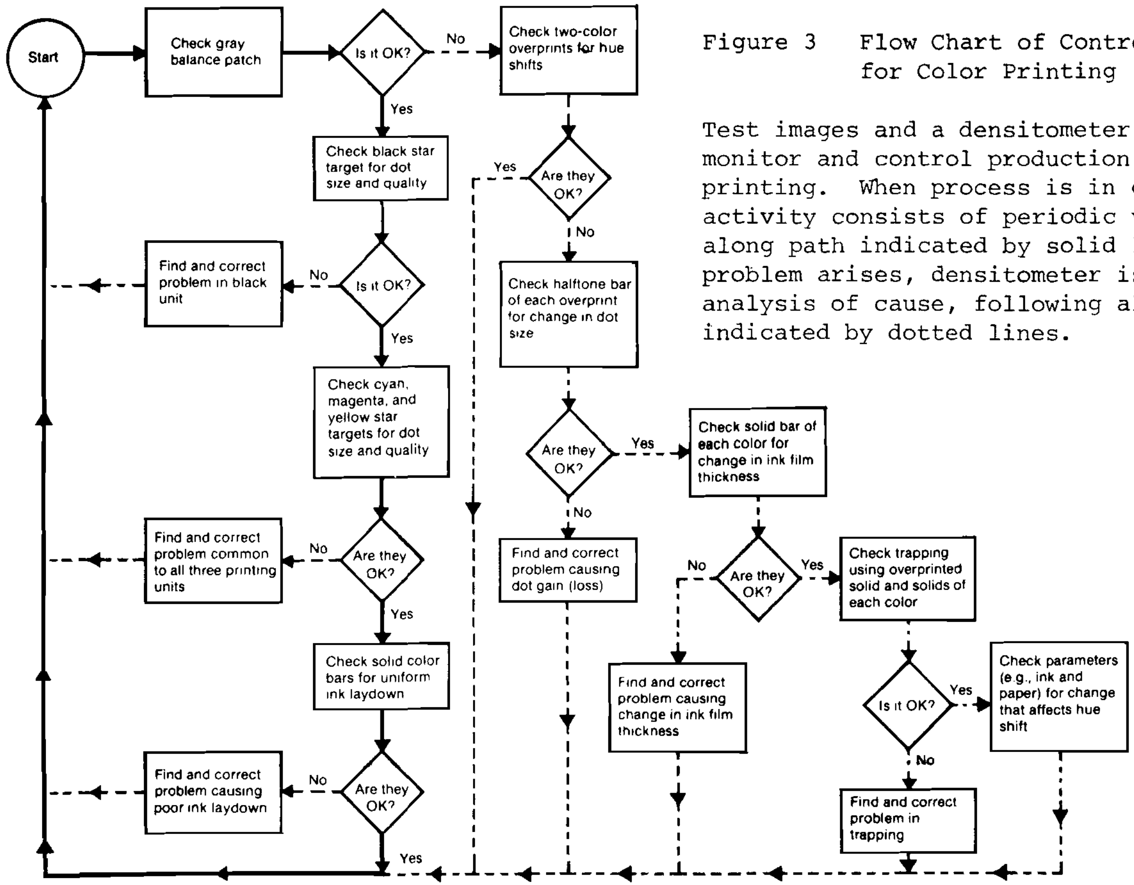

Figure 3 Flow Chart of Control Strategy for Color Printing

Test images and a densitometer are used to monitor and control production mode of color printing. When process is in control, operator activity consists of periodic visual checks along path indicated by solid lines. If a problem arises, densitometer is used to speed analysis of cause, following alternate paths indicated by dotted lines.

DISCUSSION AND SUMMARY

This analysis of the task of controlling color variations in printing has characterized the printing operation as a closed-loop system in which the pressman plays the major role in closing the loop. That is, he serves first as the system sensor when he examines the printed output. When he compares the output to the reference or OK sheet, he functions as an error detector and when he takes action in response to an error he is serving as the systems control unit. The complexity of the pressman's job was emphasized by pointing out that there is no singular attribute of the output which he can track (such as solid densities) to keep the process in control. However, because overprinted halftone areas appear to be of greatest interest to the end viewer, the fidelity of these areas must be maintained relative to the OK or reference sheet. A second complexity exists because the press response function is neither simple nor does it appear to be constant. Yet one more complication arises because errors in color are produced by two different causes: parametric faults and printing disturbances. The existence of two types of causes is significant in that the deviations produced by the latter type can generally be corrected by manipulating the press commands, whereas parametric faults oftentimes can only be corrected by making changes which necessitate a press shutdown.

Figure 3 is a flowchart representation of a proposed control strategy which has the objective of systematizing the functions carried out by the pressman. In this sense it can be looked upon as a first attempt at developing an algorithm for controlling color. The key element in this strategy is the use of a three-color gray balance patch to provide the first indication that a color deviation has occured. When a signal is received that a problem has occurred, the operator is diverted to the appropriate trouble-shooting path which may call for the use of other types of test images or printed areas.

The choice of a gray balance patch was based primarily on the fact that it will provide an error signal in respone to most color printing problems, rather than because the eye is more sensitive to it (which Table I shows that it is not). A second argument for using a gray balance patch as the early warning indicator is that it is relatively easy to print an extremely reliable reference patch alongside it, in the form of a black ink halftone of the same grayness.

Confirmation of the practical value of using gray balance test images for control was provided by Ray Reinertson of Rockwell Graph Systems Training and Development Department. He informed the writer that there may be as many as fifty U.S. newspapers who regularly use a gray balance test image, generally in the form of a horizontal stripe, to monitor and control color (Reinertson, 1988).

Although it is incidental to the main theme of this paper, the data given in Tables I and II is considered to be significant. Table I leads to the conclusion that the eye is not more sensitive to changes produced in overprinted regions, compared to the same change in a single ink region. Table II portrays the dual dependence of density and dot size on ink and water feedrates which the writer has observed on operating presses.

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The bulk of the material presented in this paper was part of a chapter originally prepared for use in a limited distribution GATF publication (MacPhee, 1983). The author is grateful to GATF for allowing him to now publish this material in the open literature. The author makes no claim to have originated the concept of controlling color by monitoring a gray balance patch. That honor appears to belong to Elyjiw (Elyjiw, 1968) while Ray Reinertson alerted the author to the fact that Gordon Warner of Warner Color Laboratories, Goleta, California has been advocating the same since the early 1970's (Reinertson). Thanks are owed to John Lind of GATF for making the colorimetric measurements recorded in Table I. That particular experiment required that the nondecaying printed ink densities be held constant. (A sampling of 21 sheets spread over the run yielded a standard deviation of 0.01 for yellow and 0.013 for cyan.) This was accomplished at Lester Lithograph, Anaheim, California, where the sheets were printed at the end of a normal job. The author is both pleased and grateful to acknowledge such a fine example of precision printing.

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