Color control in real time

Modeling colorant responses

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In the previous articles in this section, ABB Review explored the challenges of measuring and correcting the color of paper. The description of coloring, of the added dyes and of their effect follows stringent scientific methods. In this article, ABB Review presents some of the mathematical notations involved and explores their implementation in production processes.

The dosing of colorants changes the reflectance of the final paper sheet. This can be expressed in the form of $[L^*, a^*, b^*]^T$ changes. The cause-effect relationship between color measurement $[L^*, a^*, b^*]^T$ and the dye rates u of all colorants are quantified as:

$$[L^*, a^*, b^*]^T = g(u) \qquad (1)$$

where g is a nonlinear vector function determined by the selected color coordinate, the standard observer, the standard illuminant, and the colorant characteristics. For a small change in dye rate, δu, the color change $[\delta L^*, \delta a^*, \delta b^*]^T$ in the paper sheet is approximated by the perturbation model from (1) as:

$$[\delta L^*, \delta a^*, \delta b^*]^T = \boldsymbol{G}\delta u \qquad (2)$$

For a typical paper machine, usually one to three different dyes are used to control paper color. Therefore if three dyes are used to control color, $\boldsymbol{G}$ is a 3×3 matrix:

$$\boldsymbol{G} = \boldsymbol{E}[\partial R/\partial\,(k/s)]\,[\partial\,(k/s)/\partial u] \qquad (3)$$

where $\boldsymbol{E}$ is a matrix of the combined standard observer and illuminant of the coefficients. R is an array of the reflectance at every wavelength of the measured spectrum.

$[\partial R/\partial(k/s)]$ is the partial derivative of reflectance with respect to k/s

evaluated at target color reflectance.

[$\partial(k/s)/\partial u$] also known as the dye coefficient matrix, is the partial derivative of k/s with respect to dye rates evaluated at every wavelength of the measured spectrum.

k/s is defined as a light absorption to scattering ratio and is related to reflectance by the Kubelka-Munk formula:

$$k/s = (1-R)^2 \,/\, (2R) \qquad (4)$$

[$\partial(k/s)/\partial u$] reflects how the colorants change sheet reflectance and can be derived from a set of standard sheets, known as dye samples, where each sample sheet is made with a precise dye rate. For each colorant, two to ten dye sample sheets are made with dye rates typically ranging from 0.01 percent up to 2 percent. Measuring these sheets yields a family of reflectance curves as indicated in 1a. The corresponding k/s curves are shown in 1b.

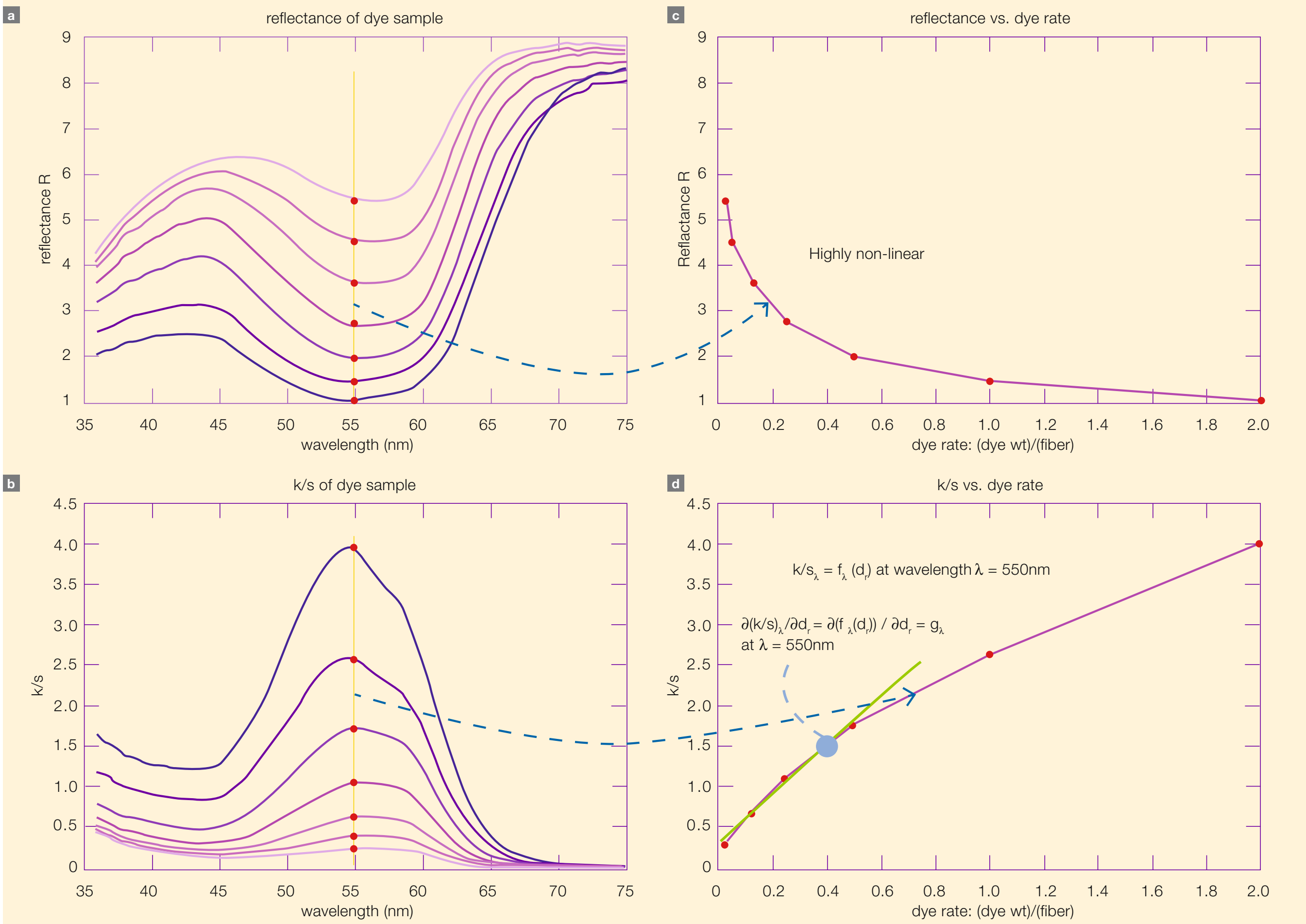
The reflectance and k/s as functions of dye rate at given wavelengths are shown in 1c and 1d, respectively. Noticeably, the relationship in 1d is closest to linear and can easily be approximated with a lower order polynomial. Additionally, the term [$\partial(k/s)/\partial u$] from equation (3) at each wavelength can easily be evaluated from 1d. To automate a color control system, it is necessary to establish a complete library of dye coefficients [$\partial(k/s)/\partial u$] and the $\boldsymbol{G}$ matrix can thus be calculated for any shade of paper from this library.

Dynamics of colorant delivering systems

In a continuous coloring process, the colorant additions have to be precisely measured and delivered at the correct stages of the process, usually by positive displacement, rotary, or peristaltic pumps.

Colorants are usually carried with a constant water flow through a mixing tank and piping before they enter the fiber flow. The volumes of the mixing tank and carrying water should be minimized to reduce response times and delays. Any pulsation of the colorant is to be avoided. Colorants delivered to different points in the coloring process may have different dynamic responses and time delays. The dynamics of each colorant addition to the process can be modeled as the combination of transport (or dead time) delay and a response with appropriate orders. The dynamics of a colorant delivery system are typically formulated as a diagonal matrix $\boldsymbol{D}(s)$ with transfer functions:

1 Dye characteristic calibration



$$\mathbf{D}(s) = diag(d_j(s)e^{\theta_j s}) \qquad (5)$$

where $d_j(s)$ is the first order dynamic and θ_j is the transport delay of the j^{th} colorant dosing point in the process.

Each element in the diagonal matrix represents the dynamics of each colorant dosing point in the coloring process. Since colorants are delivered to various locations in a sheet-forming process, the dynamics of colorants are usually represented by groups of transport delays and time constants.

Each colorant addition point may also exhibit different dynamic response behavior.

Multivariable feedback control

According to the Kubelka-Munk theory, if the colorants are mainly light absorbers, then the *k/s* of a paper sheet is the sum of the *k/s* of each individual colorant and the *k/s* of base fiber at every wavelength. This relationship is illustrated in the following equation:

$$(k/s)_{product} = (k/s)_{base\ fiber} + \sum_j (k/s)_{j\text{-}th\ colorant} \qquad (6)$$

Formula (6) allows the use of colorant response from formula (2) for implementing a multivariable feedback color control system. The color reflectance target is usually established by measuring a standard shade sample sheet with an on-line color sensor. The control objective is to reduce the deviation between the measurement and color target. This is defined as:

$$J = w_L\,(L^*\text{-}L^*_{target})^2 + w_a(a^*\text{-}a^*_{target})^2 + w_b(b^*\text{-}b^*_{target})^2 \qquad (7)$$

where w_L, w_a, and w_b are weighting factors to prioritize the importance of each color measurement at each coordinate. In some cases, the color deviations are not controllable under all conditions. For example, if the sheet color is already too dark and too green, it is impossible to simultaneously reduce both shade and lightness deviations by adding further dyes. In this situation, the trade-off between lightness and shade deviations can be made by adjusting the related weighting factors.

To implement a multivariable feedback color control system, the paper color must be measured continuously with on-line color sensors. The measured reflectances are converted to color values [L^*, a^*, b^*] and then compared with the color target. The required colorant adjustments are calculated from the model (formulae 2 and 5) of coloring process while minimizing the control objective (formula 7) and satisfying all control constraint conditions.

The transport distances between colorant addition points and the color sensor location normally appear as dead time delays for a color feedback control system. Each colorant addition point may also exhibit different dynamic response behavior. A multivariable model-based control scheme is implemented to accommodate the long dead time delays and the multiple dynamic responses.

Feedforward compensation

The throughput of the paper machine may change as the result of fluctuations in stock consistency, stock flow rate, and/or machine speed. The colorant flows can also change if the head size of pumps, the metering drive speeds, or the colorant consistencies change. In order to maintain the dye rates at the desired levels, all these changes must be compensated for with a feedforward control scheme. The feedforward control is integrated with the feedback control that adjusts the dye rates in order to reduce the color deviations. The feedforward for color control is calculated with the following formula:

$$\delta u_a = (\delta u\,P) / (H_p\,S_s\,C_c\,K) \qquad (8)$$

where

δu_a is the desired setpoint changes to dye metering pumps or valves

2 Color deviation correction after a shade change

3 Stable color control over a long period of time

P is the production throughput of paper machine
H_p is the head size of metering pump
S_s is the shaft speed that drives metering pumps
C_c is the concentration of colorant if the colorant is diluted
K is a conversion constant for matching up different units

Application aspects of color control system

There are several practical aspects that are crucial to the implementation of a closed-loop color control system for production applications. They are:

Handling shade target and dosing information

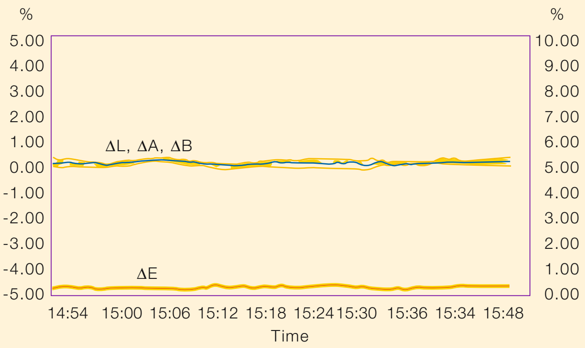
To enable a paper machine to achieve the required shades, appropriate shade targets are saved in a database. These targets are expressed in reflectance, tristimulus, color coordinates and dosing information for the colorants. The automated color control system retrieves these data before making a shade change. The shade database is crucial for shade repeatability. The characteristics of each colorant are also saved in a colorant library. Both databases are also used for deriving the coloring process models that the control system implements.

The average shade change time is reduced from over 40 minutes to less than 20 minutes.

Shade change coordination and boosting

Shade change transition is the most critical operation in every color production. Without coordination, paper makers can easily generate large numbers of color discontinuities. To coordinate a shade change, both the active and the upcoming (preliminary) shade information should be retrieved from a database and brought to a single user-friendly display for operators to examine and make adjustment before the execution of a shade change.

4 Reproducible and reliable color control



Man-machine interfaces and Visualization

According to survey responses from a broad range of paper mills, operators prefer to have all process information, such as color trends, plots of *a*–*b* coordinates, pump setpoint and status, alarm messages and operator entry points, all appear on one display. 2 and 3 show examples of this display. At first glance, this display may appear overcrowded. But after the operator gets used to it, this single display becomes the main interface for operator to manage all aspects of color production.

This sophisticated product has enabled the manufacturer to elevate production levels and quality significantly.

Application results

A color measurement and control system as described here has been implemented and installed in many paper machines. The performance of this control system can be highlighted in the following sample results:

2 illustrates a case where the color control was turned on after a shade change. The color deviations were quickly corrected by the control as shown in the color trends.

3 shows the color trends of a process with and without automatic color control. The long-term color stability and the small magnitude of color deviations indicate the significant improvements made by control.

Performance statistics

Based on the production statistics from machines controlled by the above color control system, the average **Δ*E*** is reduced to less than 0.5 for deep shade and 0.1 for white paper, or an average of up to 70 percent reduction. The average shade change time is reduced from over 40 minutes to less than 20 minutes, a reduction of more than 50 percent. The utilization of a color control system is typically more than 92 percent. These results can be further improved if both the process and the controller are fine-tuned.

Color satisfaction

The advanced color sensing and control described in this article are built on the experience of more than a quarter-century and have been supplied to leading papermakers around the world. In all cases, this sophisticated product has enabled the manufacturer to elevate production levels and quality significantly 4. In some cases it has led to month-on-month record production increases. The sales of, and customer satisfaction with, these products speak for themselves.

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