Control Advances in Production Printing and Publishing Systems

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Abstract

Many digital color printers are based on electro-photographic technology. Many have already been introduced to the market place and their quality and productivity issues are addressed using optical sensing and modern feedback controls. The integration of computing, imaging, marking and controls technology has created modern color printing & publishing systems, such as the iGen3. In this paper, we introduce to the evolution of controls that has taken place in digital electrophotographic printers from an automation perspective developed to achieve improved performance, and then describe briefly the next generation control advances in the pipeline waiting to be deployed in the market place.

1. Introduction

A steady stream of new products from many vendors in digital color is creating new business opportunities for companies. In a more collaborative and distributed electronic production print environment, digital color printers have generated new set of challenges. Since 'color' can enhance the printed message and add more interest to communication of the printed document and 'digital' can provide personalization, on-demand printing with the option of quickly producing more copies as the need arises when compared to off-set, the digital color printing clearly fits today's business model. There are streams of articles being published on the economics of digital production color printing, and in particular trends for the future [1,2].

As the color portion of the digital on-demand business penetrates more into a multi-press environment, color matching across all of the output environments and printers becomes even more important [3]. They required the use multi-vendor front ends for handling streams of color processing in jobs. Also, the printing devices drift over time (or deviate from predetermined optimum standards) due to a variety of factors. These factors include environmental conditions (temperature, relative humidity, etc.), the type of media (e.g., different paper types and paper batches, transparencies, etc.) used, variations in media, variations from original models used in initialization, general wear, etc. Aside from color matching in a complex printing environment, technologies used inside the digital color printers have also become extraordinarily complex; high precision registration, process controls within subsystem and between subsystems, paper-handling, scheduling time-critical jobs etc. A decade ago, much of that precision was accomplished by hardware design -- by specifying tight tolerances on components, subsystems and materials. Largely driven by Xerox Management, researchers first began to think about applying modern control tools to color printing about ten years ago to achieve the tight performance specifications. As in automobiles and aircraft industries, in printing systems modern control systems enable moving the costs from iron to silicon and simultaneously realizing significant cost/performance advantages [4,5]. We are now seeing the early benefits of implementing a complex, multivariable control system on a production-speed digital color press [6]. The results are expected to give far-reaching changes in color printing as we continue to apply these technologies to future digital color products.

The Xerox iGen3™ Digital Production Press, a high-quality, high-speed color digital printer brought to market in 2002, was enabled by multiple control system breakthroughs. It demonstrates how the new technology coupled with advanced controls can deliver higher levels of performance. Among the innovations are controls that enable dynamic color adjustment and color consistency based on hierarchal multi-input-multi-output (MIMO) feedback loops; active control of registration for all four color separations; state of the toner cloud, automated setups based on media attributes; and image to paper registration via a closed loop control system using "learning" algorithms.

Advances in printing with thermal inkjet, liquid immersion development, and water-less direct imaging technology etc., achieved through the choice of controls is also important for printing. Due to severe restrictions on page length, we limit the scope of discussion to electrophotographic printing. The evolution of the controls technology to Xerox' electrophotographic products since the introduction of 914 are discussed first. After that in section 3 key advances in iGen3 products enabled by controls are discussed. The next generation controls, intended for product applications in the future is shown by restricting the discussions to color consistency problems into a single-press and multi-press environment.

2.0 Evolution of Controls Technology for Digital Xerographic Printers: Pre-iGen3

Xerographic printing process used for copying and printing has evolved over many years starting from Xerox' 914 era. In this section we first outline briefly the history of controls in Xerox' monochrome products [7, contributions by Robert Grace] used to achieve consistent quality. This can later help us to understand the complexity of advances required for color.

In Figure 1 we show the time line for three regions; past, present and future. We describe, in this section the 'past' for monochrome products used for both office and production market, in sections 3 for the "present" using Docucolor iGen3 as an example, and in section 4 the "future" with control technologies without any product context waiting to be deployed in the market place.

In the electro-photographic process used for copying and printing, the image content controls the amount of light that selectively discharges a uniformly charged photoreceptor material with a laser or light emitting diodes. The electrostatic image is developed with a charged pigmented thermoplastic powder that is transferred and fused to paper under heat and pressure. The control functions should maintain the mass of the pigmented toner particles on the media by adjusting the electrostatic charge, development field and transfer currents. There was no closed loop controls applied to early copiers and printers (Xerox' 914, 813, 2400) to adjust these control actuators since the sensors were not reliable, although dependency of various parameters to output quality was reasonably well understood. In 1970 Automatic Density Control (ADC) sensors were introduced with Xerox 4000 duplicators and subsequently used in various forms in 5600 and 9200 families. Using the ADC sensors, somewhat frequent manual adjustments were made to the toner control system. Since Selenium-alloy photoreceptors were used, the system was fairly stable. No separate charge control was required in those printers.

Use of different photoreceptors and the demand for improved copy quality lead to the need for better controls n the 1980s since at that time, every 50k prints required copy quality tune-ups. Process quality drifted due to environmental conditions. A two-patch control system was developed in the 1980s which controlled the toner concentration, electrostatic charge and hence the developability on the photoreceptor. Low and high density patches were created as surrogates to customer image in the photoreceptor. Low density patches were measured by the sensor, and the data was used in a Single-Input-Single-Output (SISO) closed loop configuration to control the electrostatic charge on the photoreceptor. Similarly, a high density patch was used to adjust the toner concentration in the developer housing at a lower update rate, which subsequently improved developability. Although high density patch measurements were sensitive to electrostatics and toner concentration, the coupling effects between them was removed with a time hierarchy in the execution of the control loops since electrostatic charge control loop was running at a must faster rate.

The presence of two-patch control scheme in 1075/1090/4050 provided the product differentiation which was a critical factor in the business success of that family of products. This approach reduced service calls for background and density variation by more than a factor of 10 and helped to reduce subsystem costs. Due to architectural choices, unstable charge on the photo-receptor, Xerox developed a low cost charge-measuring sensor called ESV (Electro Static Voltmeter). A cost reduced version of the IRD sensor was also developed. The charge control was done using a separate ESV sensor followed by the developability control with the LCIRD sensor, which appeared in the 1065 marathon copiers in 1987. These controls technologies were subsequently adopted in various forms in 5090, DocuTech 135 (1990), 4135 (1991), 5390 (1993), and the DocuPrint 4635 (1994). The same sensors are used with more advanced software in the 5100 (1991). Apart from runtime controls, these sensors helped to accurately setup the process and perform good diagnostics to reduce cost. With runtime controls, perceptible page-to-page differences were minimized. Automated setups changed photoreceptor replacement from a 45 minute service call to a 10 minute customer operation in many accounts, and contributed to customer satisfaction rating.

For color printers, toner mass has to be tightly regulated so that the printer maps the desired tone into the actual output. This is achieved by creating and implementing inverse maps in one-dimensional coordinate space called Tone Reproduction Curves (TRC) at various stages in the printer path. At minimum, a mid-point tone adjustment is required during runtime. The new density sensors, called ETACs (Extended Toner Area Coverage), were developed for measuring various tone densities for black and white and color toners. Hierarchical multilevel control loop architecture was developed to address these problems, which required the use of modern control theory and methods [8] . Today, we see those feedback loops in DocuColor 2000 series and iGen3 printers.

For production quality color printers, the control challenges grow several orders of magnitude higher since they compete in the traditional offset market with reputation for quality. These control loops should not only maintain process stability for individual color separations, but must have the ability to adjust color to varying media conditions to compensate for overlay colors, sheet-to-sheet

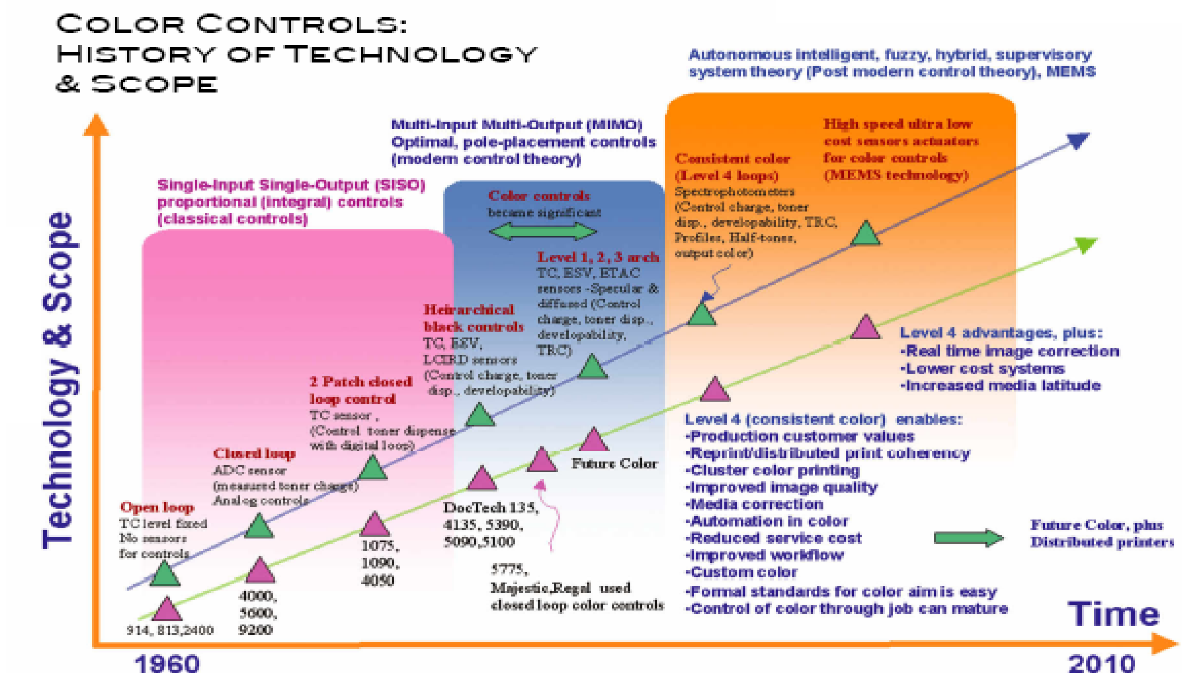

Figure 1: Evolution of the controls technology affecting digital printer quality [TC: Toner Concentration; ADC: Automatic Density Control; ESV: ElectroStatic Voltmeter; LCIRD: Low Cost Infra-Red Densitometer; ETAC: Extended Toner Area Coverage; MEMS: Micro Electro Mechanical Systems]

differences, temperature, humidity, photoreceptor aging and wear in drives etc. They should maintain much tighter control on image registration between separations for simplex and duplex functions and paper motion at various regions in the transports. To make them competitive with offset in operational cost, many of the press make ready cost should be eliminated using automated setups. Thus, due to many new challenges, to deliver the quality at low running cost and high productivity, many new technologies had to be developed, including advances in sensing, algorithms and processes which is described at length in [6] and will be summarized below in the next section.

3.0 Controls Technology in iGen3

Xerox's recently-introduced DocuColor iGen3 is the most recent in a long line of color products. It is acclaimed in the marketplace as a high quality, high speed replacement for short run lithography that can both perform transaction printing and handle complex personalized documents. It is capable of printing 100 pages per minute of high quality color documents. Very enthusiastically received in the press [9] and by customers, this product is covered by a host of patents, some of which are controls related [US Patents# 5,708,916, 5,717,978, 5,749,019, 5,950,040, 6,021,285]. The iGen3 digital press is designed for high volume, short-run, full-color, on-demand and personalized printing. It embodies 85 computers, 192 sensors, 102 motors, 5 million lines of software with sophisticated interface and communications on 3.5 miles long wires for seamless operations of all of the critical press functions via feedback. Summary of the control advances included in iGen3 are:

- The ability to adjust color dynamically and assure color consistency on the belt by monitoring every print using hierarchical Multi-Input-Multi-Output feedback loops
- Constraint-based schedulers to manage time-sensitive activities, which optimize operation of the printer for handling jobs on the fly. It provides electronic collation before sheet one of a job is fed. This produces documents in the finished design.
- Active control of registration for all four color separations. Higher order control loops ensure registration accuracy to better than 40 microns – roughly to two thirds-the thickness of human hair.
- Image to paper registration ensured to within 500 microns in a closed loop control system using 'learning' algorithms. These Loops compensate for sheet-to-sheet differences in the paper as well as drive wear, temperature variations, etc.
- Improved transfer efficiency with precise control of fuser temperature and oil rates.
- Auto adjustment of media decurling based on real-time measurement of image density and paper characteristics.
- Using media attributes, the print engine automatically adjusts its control points on a sheet by sheet basis. Paper related setup time is eliminated.
- Calibration and characterization of the press at intervals desired by the customers, using spectrophotometers as offline sensors to produce output as close as possible to offset quality.
- Active control of environmental factors; noise, ozone, heat, air temperature, humidity and dirt.

Four examples are described below in some detail.

3.1 Hierarchical MIMO Feedback Loops

Controls used in many earlier color products (e.g., Xerox product, 5775) had only solid area control for low density and high density regions of the tone curve. This corresponds to one-point TRC control without any hierarchy. The control algorithms for setpoint tracking were done through "on-off" rules. When certain conditions are met dispense the toner otherwise not. Loops were single-input-single-output (SISO), but were implemented for a coupled MIMO system. On some occasions proportional, integral control was used in the SISO control loop. To solve those problems, modern control theory is helpful, but not essential. Whereas, the challenging offset look and feel that the DocuColor iGen3 has to produce consistently using the image on image development process, required the use of multi-variable time hierarchical controls.

Time hierarchy comes from the 'reduction of complexity' rule used to design complex control systems, which transforms the printing system to many simpler ones while preserving the overall performance goals. Each controller sees the controllers below it as a virtual body from which it gets percepts and sends commands. In a control hierarchy the lower level controllers run faster than higher level loops, at higher measurement-actuation intervals, controlling a group of subsystem variables. They deliver simpler view to higher-level controls. The higher level controls coordinate commands to subsystems at a much lower measurement-actuation interval. In Xerox, we used terms like levels 1,2,3,4 controls to describe the time hierarchy with '1' to describe the lower level subsystem controls such as the 'charge control', 'toner concentration control' etc., '2' to describe controls between subsystems; (e.g., 'charge and development' systems), '3' to describe image control for each separation tone adjustments (e.g., 1D tone reproduction control) and '4' to describe image control for between multiple separation tone adjustments (e.g., 3D profile control) to minimize the interactions between colorants which cause color shift in the output. The control functions managing scheduling of various jobs, managing set points based on media attribute on a sheet-by-sheet basis is done by the constrain-based schedulers, which is executed at a different level. Control functions which require "human/operator-in-the loop", for example, redirecting jobs to a non-faulty printer when one of the printer fails is several layers higher than the subsystem level controls.

In Figure 2 a basic MIMO algorithm is shown for Level 1 charge control system, which uses a voltage sensing of exposed patch area, called V_l, and an unexposed patch area, called V_h, and adjusts the charge corotron bias, called U_g, and the laser beam power, called U_l, to maintain the unexposed and exposed regions of the Photo Induced Discharge Curve (PIDC) to desired setpoints called, V_l^T and V_h^T. The processing of the errors between V_l and V_h and the desired setpoints is done in a MIMO gain, $k_{11}, k_{12}, k_{21}, k_{22}$, since the charge control loop is coupled with two-inputs (corotron charge and laser power) and two-outputs (V_l and V_h). An integrator is also used after processing the error components with gains. This type of control loop should be designed using system theoretic models, often called state models, which could be linear for designing linear controllers, and non-linear for other more sophisticated controllers used to operated under limited actuations. We show an example of such a print-to-print state model denoted by the symbol '*k*' below by defining states as charge at no exposure and full exposure on the photoreceptor. In the state model, the Jacobian matrix is used to denote the input-output sensitivity matrix of the of the electrostatic system which is obtained by characterizing the system at the nominal actuator values; U_{go} and U_{lo}. Now the state model at these actuator values is given by:

$$x(k+1) = Ax(k) + Bu(k); \quad y(k) = Cx(k) + Fr(k)$$

where,

$u(k)$ *the control vector;*

$y(k) = [-E_h(k) - E_l(k)]'$ *the output vector;*

$x(k) = [V_h(k)\ V_l(k)]'$ *the state vector;*

$$matrices \ A = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; \quad F = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}; \quad C = A;$$

$r(k) = [V_h^T(k) \quad V_l^T(k)]'$ *the desired reference vector;*

$$matrix\ B = Jacobian = \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix};$$

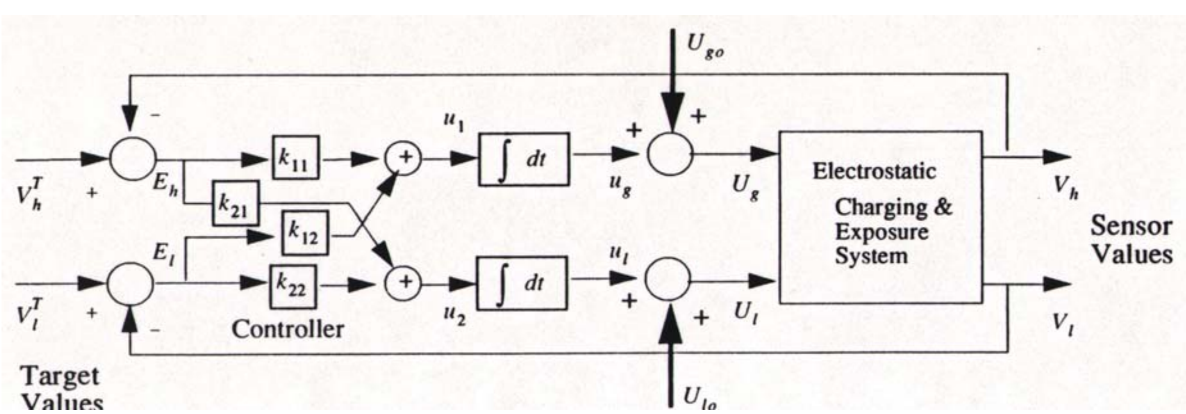

Figure 2: Level 1 MIMO Control Algorithm [Reference, US Patent# 5,754,918]

When the feedback is applied, the control vector $u(k)$ becomes,

$$u(k) = -Ky(k);$$

$$where, the\ feedback\ gain\ matrix\ K = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix}$$

Gain matrix can be designed using a simple pole placement method described in any multivariable digital control text books [10]. For a basic subsystem control structure of this type, if for some reason had we used a SISO gain (i.e., with gains, $k_{12} = k_{21} = 0$), then the performance of the control loop would be unpredictable. There will be transients while tracking to desired set points for the charge control system. These transients can lead to wrong charge on the photoreceptor belt, which can lead to developability errors, hence inconsistent color, which could be reflected in L* or chroma shift for many prints during the production run. Similarly, had we not used the integrator in the loop, then the performance of the charge controller to track variable set points can give rise to tracking errors between V_h and V_h^T and V_l and V_l^T, called steady-state errors in control language. The set points to the charge control system will vary based on the controls commanded by the level 2 controller, which in this case is the developability control loop. Thus algorithms, in each of the control loops in the hierarchical system are extremely important for the overall system to perform the way we would like them to. Once again due to limitations on the maximum laser beam power and the corotron charge, the integral control can give rise to saturation, which can lead to what is known as 'integrator windup'. Hence, we would also need the anti-windup compensator in the algorithm. Since these controllers are designed to be linear, and the charge control system is generally non-linear due to nonlinear photo-induced discharge curve of the photoreceptor, one would also like to design the loop with some kind of feedforward / feedback linearization terms. All these components are additional complexities that go in the algorithm design.

The deviations are processed with all these intricate elements to provide the right amount of actuation. Thus, each element in the algorithm has specific functions and many simple equations. This approach is scientific and the controller behavior can become more predictable.

In Figure 3 we show the MIMO algorithm encompassing the anti-windup compensator for level 2 controller. ETAC sensors are used to measure the tone development on the photoreceptor before transfer and fuse stages for three different input tone conditions; called low, mid and high area coverages leading to photoreceptor developability control model with 3 states. The control actuators are: two set points for the level 1 controller, V_h^T and V_l^T, and the bias voltage for the development system.

Another subsystem control in the hierarchical architecture is the toner concentration control which consists of feedforward and feedback loops. It is required to keep the toner concentration constant for a long print job so that the level 2 process control loops can work together coherently.

A basic loop comprises of making Toner Concentration (TC) measurement on a regular basis using the TC sensor or other kind of sensors and then comparing the sensor values with the desired set points known as targets. The error is processed in a control algorithm to generate the right amount of toner to be dispensed per second (known as dispense rate) so that when the loop is stable the amount of TC in the dispenser is equal to the values specified by the targets. While printing images, toner is consumed depending on the image area coverage. It is important that the feedback system is designed appropriately to stabilize the TC despite the variations in the area coverage for each image. Although many different types of controllers can be used in the loop, at first we could use proportional and integral controllers with proper design of the gains. In [11, *US Patent# 5,839,022*] a new design methodology is described to compute the gains of a

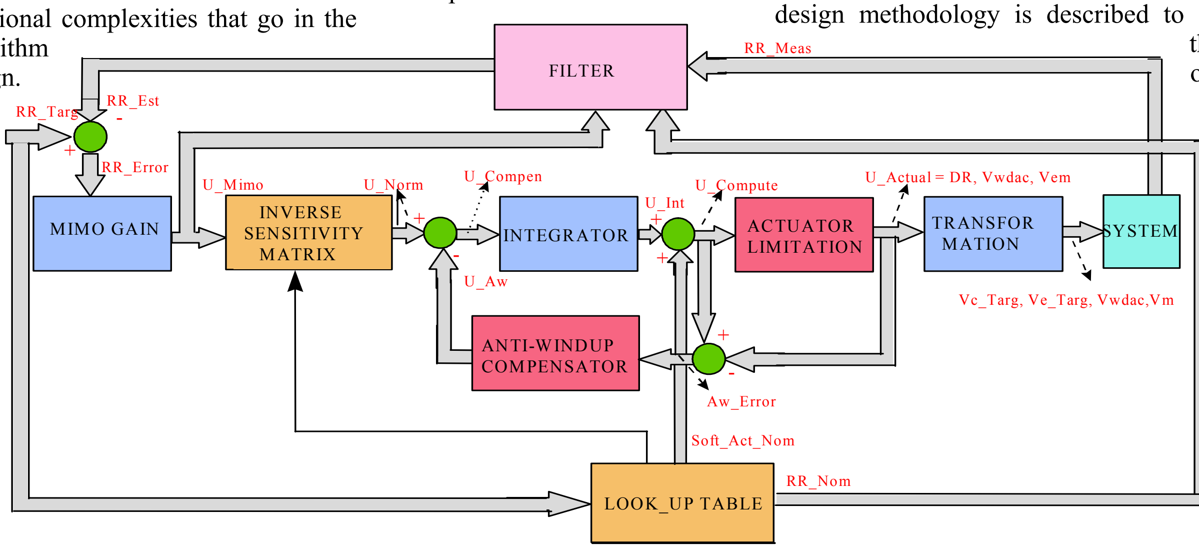

Figure 3: A Level 2 MIMO Control Algorithm [Reference, US Patent# 5,950,040]

proportional and integral controller by developing a discrete state space control model of the TC system with dispenser delay. We use a modern discrete-time domain state space design methodology. Algorithms contain the use of additional compensators such as Smith predictor for compensating for dispenser lag. Antiwindup and feedforward compensators are components used in the algorithm to fine tune the loop performance.

3.2 Image-On-Image Registration Control

In addition to levels 1 and 2 hierarchical controls used for process stability, multiple levels of control loops manage the registration accuracy during print time. The control layers are divided into (1) dynamic loops; comprising registration system and subsystem level closed and open loop controls and (2) static loops managing various setup functions, executed iteratively during setup time. Various algorithms determine the appropriate corrections to be made to the image positions for lateral and process errors, ROS skew and belt skew adjustments.

Image on Image registration strategy adjusts the image registration to better than 40 microns through the use of self-diagnosable MOB (Mark On Belt) and the belt edge sensors and algorithms programmed inside its control system. The measurement strategy used for this control system is embedded in the marker module. The mis-registration between the MOB sensors and the reference color, cyan, is determined and compensated for errors. The sensing system uses special target patterns called Chevron marks on the belt and special calibrations during setup cycle.

3.3 Constraint Based Scheduler

The constraint based scheduler is a real-time software that coordinates time-critical activities for various hardware modules inside the print engine, developed using advances in model based computing [12,13]. Although the approach and algorithms are very much a contribution from the Computer Science community, for the purpose of this paper, we regard this as control advances for printing system, since it affectively allows real-time updates at a different level during system setups, which is one of the levels of control functions required for a dynamic printing system.

The constraint based scheduler provides for automatic scheduling and completion of print jobs using operational constraints and their relationships dynamically. In traditional schedulers, hardware & operational specific interactions are pre-stored and hard coded into the scheduling software, which requires changing software every time a new hardware is added. Constraint-based schedulers have eliminated these drawbacks. Constraints are used to model the printing system, and a constraint solver schedules the operations dynamically to produce a desired document. The rules are not coded into the scheduler anymore, instead they are learnt when the system is powered up, thus increasing the flexibility to change. Due to constraint-based scheduler, following functionalities are integrated in iGen3:

- Electronic collation provided by the constraint-based scheduler eliminates one of the most time-consuming and labor-intensive steps in the production process – the need to collate stacks of sheets into document sets.
- The system is auto-configured to the number of feeding and finishing devices installed, and the constraint based scheduler adjusts accordingly. We refer to this as a mix and match design.
- Various in-line finishing devices are recognized automatically, configured and controlled by the constraint-based scheduler during power-up. They provide the ability to rotate, punch, stack, fold, staple, and bind in a real time operation. This feature enables advanced, inline document construction and finishing. The inline finishing options produce a variety of finished documents; flyers, books, and booklets etc. All are produced at the lowest cost of any digital production color printer.
- Finished documents can be produced in short run lengths – even run lengths of one where every document is unique.

3.4 Image-On-Paper Registration Control Loop

Image on paper control is done in a closed loop control system using 'learning' algorithms and CCD sensing devices for ensuring proper registration between first- and second-side images. Loops compensate for sheet-to-sheet differences in the paper as well as drive system wear, temperature variations. Registration accuracy is achieved to be within 500 microns of nominal, which is a 50% improvement over previous products. Some of the key control functions of the Image-On-Paper registration system are described in [6].

In Xerographic machines the temperatures of many locations around the machine cannot be allowed to increase too much. For example, in some products the temperature of the developer station cannot exceed 45 degree Celsius. Thus various time hierarchical control systems have made the complex iGen3 system emulate the important characteristics of automatic self controllable system by adjusting system parameters, actuator settings, input image bit maps etc., to the printing environment to produce output as close as possible to offset quality.

4.0 Next Generation Controls

As digital production color printers evolve into higher quality printers producing offset like color images, the concern for image quality will be emphasized more for within job, between jobs to remove time dependent and spatially dependent variations. Also, machine-to-machine consistency between any two or more printers of same or different technologies becomes important since customers invent various ways to optimize production by mixing prints from different printers. Advanced controls play a much higher role in those hybrid environments, to produce high quality commercial printing performance. In addition to the recently published papers by researchers [5, 14], in this section we share a glimpse into the future of controls technology that has potential to bring unprecedented quality and productivity to production industry. Descriptions are limited to enabling color consistency.

Particularly for achieving consistency, controls used inside the process; levels 1 and 2, are merely the tip of the iceburg. To control color, the number of actuators required is more than those currently available in levels 1 and 2 process control system. One obvious place to look for more actuators is in the image, since the color documents produced electronically contain pixels with colors described in three-dimensional RGB (red, green, blue) color space. These color pixels are transformed to corresponding digital cyan, magenta, yellow, and black (CMYK) values to a printable form before being received by the printer in a four primary color printing system. So, by linearizing the tone levels to each of the input tone values of the primaries, we can achieve improved controls for all separations individually [8]. This type of tone adjustments are sometimes done on the photoreceptor belt, or on the paper depending on type of sensing methods. At levels 1, 2 and 3 only individual separations are controlled. Level 4 provides mechanism to adjust interactions between colorants which cause color shifts in the printed output. This conversion is required, more often to maintain consistency, because there is no fixed linear relationship between the incoming RGB values to the printed color, which is a mixture of tone values of the primaries, even after linearizing the primaries with level 3 controls. The relationship not only varies with time because color pigments in the toner typically exhibit contamination of their spectra with unwanted absorbencies, process variabilities and the complex interactions of dots.

At the conceptual level, controls for single separation and mixed colors are not new. Professional print vendors recommend performing what is known as ‘printer profiling’ or ‘printer calibration’, also called ‘gray balance’ on the printer, which when done repeatedly can result into consistent, predictable color throughout the printing process. Profiling of printers involve searching for the printer inverse maps in 3D throughout the reproducible color space, using color measurements from the printer. ‘Printer calibration’ or ‘gray balance’ is finding the right gray when primaries are mixed. It is the procedure used by print operators to accurately reproduce a neutral gray image by processing the image through one-dimensional TRCs. For example, a midtone three-color gray can be comprised of 50% yellow; 50% Magenta and 50% Cyan. When the gray balance procedure is implemented, the printer will render a neutral gray tone for these separations, which can be set to give a particular tone level whose color value can be tuned to have the desired aim value (e.g., L*=50, a*=0, b*=0 for neutral gray). Aim values for printed colors can also be set off-neutral in such a way that if equal amounts of cyan, magenta, and yellow are printed, they would make a brownish color rather than a neutral gray. Individual color values are tuned between 0 to 100% with the gray balance procedure to produce the desired tone color, so that the printer will faithfully give pleasing color for all other combinations of process CMY. Advanced controls can take us one step closer to complete closed loop automation of gray balance calibration and profiling procedure. This would require the use of embedded inline color sensors and fast processing algorithms [15, 16].

An approach proposed in US Patent# 6744531, issued on June 1st 2004 uses the description of color printing system in terms of state space model and a digital state feedback with pole-placement for achieving closed loop gray balance controls. This procedure uses control of few critical colors along the specified reference axis for mixed colors, which can deliver higher level of gray performance. Other approaches described in [17,18,19] can be used to develop level 4 controls; printer profile LUTs in two-dimensions and three-dimensions, automatically with reduced measurement samples and inline measurements. Furthermore, due to state space synthesis of color, we can develop algorithms to achieve the best consistency for any color inside or outside the gamut by suitably mapping the out-of-gamut colors to inside the gamut. By using level 4 controls with inverse printer maps generated on real-time and with likely new algorithms developed based on the combined knowledge of color imaging, controls and sensing, we can foresee the emergence of new color management-related applications not seen in today’s digital production world.

In addition to the opportunities discussed for multilevel controls, at a micro level, the level 3 (single separation and gray balance controls) and 4 (mixed color) controls can be extended to control the color by rendering spatially color corrected pixels. A two-dimensional spatial dynamic model structure for development for component primaries, and then to mixed colors on the paper are some of the new developments in the works [20], which would make it easy to incorporate human visual perceptual models for temporal and spatial image quality compensation. This can further spark new advances in digital color printing.

5.0 Summary

Looking back, we see numerous advances in the application of controls in digital color products launched in last few years, and the complexity of controls in those products have steadily evolved into more sophistications that required the use of theories established in the modern controls literature in the last thirty to forty years used for designing complex dynamical systems. While many of these methods have been used in aerospace & automobile industries, they have not been implemented until recently to printing systems. The digital printing platform makes them particularly interesting area for application due to its abilities to write & erase pixels when we want them. In this paper, we discussed largely the color consistency system. Among other fertile areas for application are: print shop automation, active diagnosis of printer defects, dynamic scheduling in multi-print environment to manage prints cooperatively. In a clustered print environment, to improve the availability of systems, sound fault diagnosis and automatic recovery schemes could be put in place. Advanced controls and optimization methods when implemented can help to calculate appropriate optimal policies on real-time as faults occur while keeping the system running with acceptable performance, thus minimizing the impact on overall productivity of the system. Thus, modern controls will continue to play a significant role in improving the performance & the economics of the digital production systems to produce consistently faster and better prints.

One other important point largely ignored in the control literature applied to printing is the usefulness of control advances in the laboratory environment, since when engineers are running tests on test machines to tune the control loop, enormous time can be saved while tuning gains calculated with system theory. Simply plug the gains we reach stability and set point tracking. Thus control advances not only can improve product performance, but is also a tool useful to speed up the time to market process.

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Biography

L.K. Mestha, a Principal Scientist at Xerox, has spent his career studying control of charged particle systems -- at Xerox Corporation, where his focus has been on controlling toner particles in the context of digital printing and imaging systems, and in his prior research, where he studied control of protons and their behavior in particle accelerator systems. Since joining Xerox in 1994, Mestha has significantly advanced modern control theory and modeling as the basis for next-generation marker controls and digital imaging systems. His work has encompassed process & color controls for digital printers and color management systems. He holds 39 US patents with additional 17 pending. Prior to joining Xerox, Mestha was a group leader in charge of beam transfer synchronization systems at the SSC Laboratory in Dallas. While at SSC, he developed a revolutionary digital control system, which has subsequently been adopted by CERN in Switzerland, Fermilab in Chicago and KEK in Japan. Mestha's earlier work was at Oxford's Rutherford Appleton Lab. Has published 26 papers, was an associate editor of the IEEE journal on control system technology, and teaches at RIT as an adjunct faculty. He received his PhD from the University of Bath, England, and his bachelor's degree, both in EE, from the University of Mysore in India. **e-mail: lkmestha@crt.xerox.com.**