A Control-Oriented Survey of Xerographic Systems: Basic Concepts to New Frontiers

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Abstract—**Xerography is the dry ink marking process underlying electrophotographic copiers and printers. Xerographic systems have had commercial success for over 45 years and currently drive a segment of the printing market valued at over $150 billion worldwide. Especially in the case of color printing, performance requirements are stringent and must be achieved under uncertain conditions. Of course, the notion of feedback is motivated by such systems. Yet, xerographic systems have not received widespread attention in the control literature. Nevertheless, control has played an important role in the evolution of xerographic marking engines.**

The purpose of this paper is to motivate xerographic systems as an application area for the systems and control community. Because this paper is tutorial, we begin with a control-oriented description of the xerographic process followed by an overview of the digital printing industry. Next, we provide an illustration of the use of control in DocuColor iGen3, a state-of-the-art digital color press. Finally, we identify a set of challenging modeling and control problems relevant to xerographic systems and draw connections to the literature.

I. INTRODUCTION

I**N** 1959, a disruptive technology referred to as xerography entered the marketplace in the form of the 914 copier. This product revolutionized the office, eliminating the need for hand copying, carbon paper, and mimeographs, and ushered in the era of personal publishing. Even back then, the essential elements of the modern printer or copier were present in the 914. The xerographic process consists of creating an electrostatic image on a photoconducting drum or belt; developing this latent image with a pigmented, charged powder called toner; transferring the developed image to a given media, usually paper; bonding, or "fusing," the developed image to the media and then cleaning any residual toner from the photoconducting drum or belt in preparation for the next image. By blending

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digital electronics, computing, and communications with the xerographic process, the DocuTech product line, introduced in 1990, was able to combine the steps of prepress (i.e. preparation of pages for reproduction), digital printing, and finishing (e.g. book binding) into an end-to-end digital publishing system. This innovation spawned the print-on-demand market, a market that in 2002 had a retail print value of nearly $28 billion in the United States [12]. Continuing along these innovative lines, the DocuColor iGen3 Digital Production Press, a 100 print-per-minute (ppm) color product launched in 2002, is expected to be as revolutionary for color printing and publishing as DocuTech was for black and white printing and publishing.

Producing high quality color prints is difficult; much more difficult than it is for black and white printing. An obvious reason for this is that color printing requires at least three development stations, one for cyan, magenta, and yellow, compared to a single development station for monochrome printing. This extra hardware naturally increases the uncertainty and complexity associated with the printing process. In addition to the extra xerographic hardware, substantial image processing is required by the digital prepress, further adding to the complexity of a color printing system. Another underlying reason color is difficult is because the human visual system is extremely sensitive to color variations. This sensitivity results in a larger number of image quality requirements for color images that are also significantly more stringent than those for black and white images. Superimposed on the above challenges are market pressures that demand products capable of producing prints reliably at a cost that is more consistent with monochrome printing.

In short, transitioning from black and white to color printing implies increased process uncertainty and tighter performance specifications. From a theoretical viewpoint, these trends increase the coupling between control and system design [7, 18]. In practice, industry seems to intensify control efforts when faced with similar trends, more so as the cost of computing continues to drop dramatically according to Moore's Law. Often, the reward for these efforts is a *radical* performance improvement. For instance, in the automotive industry, government

mandated fuel efficiency and emissions standards led to electronic engine control systems that enabled the internal-combustion engine to more than double its average horsepower per liter while, at the same time, significantly lowering cost and sharply reducing emissions [16].

Consequently, it would not be surprising to see control efforts intensify in the digital color printing industry. In fact, this is already happening. While control system technology has played a role throughout the evolution of digital printing, product performance in the past was primarily achieved by specifying tight tolerances on components and by emphasizing subsystem and material (both consumables and components) optimization. Now, the realization is that control, along with subsystem, system, and material design optimization together will enable next generation printing performance. DocuColor iGen3 with its "SmartPress" technology represents a significant step forward in the use of control principles. As the market for color printing continues to grow, so will the control opportunities.

In the literature, control applied to digital printing has received little attention compared to other industrial applications of control. At the same time, however, digital printing is big business and the potential for systems and control principles to impact this industry are enormous. Hence, the purpose of this paper is to motivate digital printing as an important application area for the systems and control community.

What is digital printing? Digital printing can be defined such that the image carrier or source, typically referred to as a "master image", is physically reproduced for each image that is rendered. The lack of a physical master, an engraved plate for example, to carry the image information can eliminate costs and increase the flexibility of the printing process.

Digital printing involves transforming a desired two-dimensional (2D) image into a printed image using, roughly speaking, two main processes: image processing and marking. While both processes are critical for digital printing, this document focuses on control in the context of a particular marking process: xerography. Image processing is mentioned briefly below but only for the sake of providing a schematic illustration of the image flow through a digital printer. For an introduction to image processing in digital printing, the interested reader should consult [36] and the references therein.

During image processing, the desired 2D image is transformed into a binary form as follows

$$I^{digital}(x, y) = P^{image} \circ I^0(x, y) \qquad (1)$$

where $I^0(x, y)$ is the desired image, $I^{digital}(x, y)$ is the transformed image, x and y are generic spatial coordinates, and P^{image}, represents the composition of all necessary image processing steps such as compression, color plane separation, halftoning, etc. The marking process then transforms the digital version of the image into a printed image as follows

$$I^{print}(x, y) = P^{marking} \circ I^{digital}(x, y), \qquad (2)$$

where $P^{marking}$ represents the composition of the steps in the xerographic process. Ultimately, the quality of the printed image is determined by a human observer, which we represent as

$$I^{customer}(x, y) = P^{visual} \circ I^{print}(x, y), \qquad (3)$$

where $I^{customer}(x, y)$ denotes the customer perception of the printed image and P^{visual} corresponds to the human visual system. In turn, customer perceptions along with cost and reliability are what determine the market success of the digital printer.

Because this paper is tutorial in nature, our basic approach is to keep the discussion at a high-level so that we can cover a broad range of topics. When details are omitted for the sake of brevity, we cite references to "fill in the blanks." To supplement the general discussion, we do, however, provide several concrete examples in order to highlight specific applications. We begin in Section II by providing an overview of the printing industry in which xerographic systems reside, followed by a control-oriented discussion of the xerographic process in Section III. In Section IV, we provide an illustration of the use of control in the DocuColor iGen3 state-of-the-art digital color press. Section V focuses on the marking process and motivates several modeling, image quality, and control design topics relevant to systems and control. Examples are given and connections to the existing control literature are made. Conclusions appear in Section VI.

II. DIGITAL PRINTING INDUSTRY OVERVIEW

This section discusses important market segments within the digital printing industry and includes a glimpse into the economics, both present and future. The goal is to convey that control, if applied successfully, has the potential for making a huge economic impact. The economic data presented below comes from CAP Ventures, a digital print strategic consulting firm [12].

Contrary to past predictions of a decline in the communication medium of print (e.g. "paperless office"), CAP Ventures projects total US print volume growth at a compounded annual growth rate (CAGR) of 3%. The volume of 1.6 trillion prints in 2002 is headed towards the 1.8 trillion level by 2005. Of this, xerographic processes account for an estimated 85% of the print volume in 2002

and are projected to account for 89% of print volume by 2005. The market for xerographic engine consumables, primarily photoconductor and toner replacement, is projected to grow from $10.5 billion in revenue in 2002 to $14 billion by 2007, which corresponds to a CAGR of 6%. Digital printing is driving much of the growth in that it has spurred development in two related marketing thrusts termed *print on demand* and *variable data*. Print on demand is the production of customized documents at low cost and short turn around time (a manifestation of flexible manufacturing). For example, if the cost per book, based on, say, printing 10,000 copies, were made the same as the cost of printing a single copy, then the economy of scale constraint would be removed. This can drastically reduce warehousing costs, reduce distribution costs (via distribute then print), and reduce the risk of wasteful production (unsold material). The variable data thrust enables each document produced to be customized for the intended recipient. This, combined with advances in data mining, can create efficiencies in targeted marketing that where unimaginable just a few years ago. In addition to print on demand and variable data capabilities, web based fulfillment is streamlining engagements between customers and print shops.

CAP Ventures projects the print on demand market segment of digital printing to grow from approximately $28 billion in retail value in 2002 to about $50.5 billion by 2006. By 2006 the color segment of the print on demand market is projected to be $33.4 billion (up from about $22.5 billion in 2003) in retail value and one third of digital color work will be personalized.

The demand for the services that full color digital printing can provide is strong for the foreseeable future. Challenges abound, but the market still justifies investments in xerographic systems because the technology has remained competitive in the areas of cost, reliability, adaptability, speed, and image quality. The latter five areas of differentiation all are impacted by the choice of control system objectives and design. Advances in joint xerographic and control system design are expected to keep this technology a competitive choice for the foreseeable future.

III. THE XEROGRAPHIC PROCESS

The purpose of this section is two-fold. First we provide an overview of the sequential steps in the xerographic process: 1) charge, 2) expose, 3) develop, 4) transfer, 5) fuse, and 6) clean (see Figure 1). Then, in order to set the stage for the control discussion in the succeeding sections, we discuss various inputs, both actuators and disturbances, that influence the xerographic process, and we also describe common approaches for sensing outputs of the process. Additional areas of importance for control

applications such as media path and image registration are mentioned in section IV. Because of the scope of this document, the discussion regarding the process steps is brief. Detailed descriptions of the physics, chemistry and surface science aspects of xerography can be found elsewhere [15, 23, 33, 37].

The unifying element in the xerographic process is the photoreceptor—the surface for image generation and transportation that is conductive in the presence of light and insulative otherwise. Photoreceptors typically take the form of either a drum or a belt and must be capable of providing a consistent surface for image creation while cycling through the xerographic process for hundreds of thousands of prints. Moreover, this surface must be capable of supporting resolutions of 1200 spots per inch (or more) [15]. Typically, the photoreceptor is velocity controlled, where the velocity along with the image size determines the print rate (ppm).
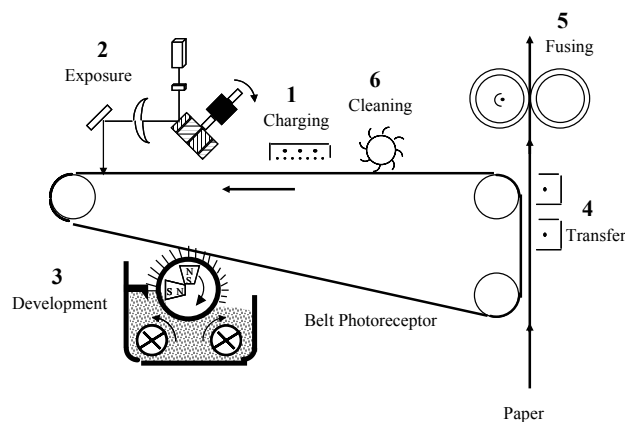

Figure 1. Schematic diagram of a monochrome xerographic process.

A. Charging

A corona device (a conductor at high voltage) attempts to apply a uniform charge to the surface of the photoreceptor. The high electric field near the wire of a corona device sustains a plasma of positive and negatively charged ions. Ions of the same polarity as the wire will direct themselves to the surface of the photoconductor. Charge uniformity of the photoconductor surface is an important parameter for achieving high levels of image quality.

B. Exposure

Light reflected by an actual image (as in a copier) or produced either by a laser or a light emitting diode as in a printer, discharges select areas of the photoreceptor. The pattern of charged and uncharged areas of the photoreceptor produces a latent image.

C. Development

Development is the means by which pigmented polymers

are electrostatically charged and brought within the vicinity of the photoreceptor where local electric fields will force the toner to adhere appropriately to the latent image.

The development process is challenging for three primary reasons: 1) this step usually sets the limit on achievable image quality; 2) many aspects of the underlying physics are not well understood; 3) because of many factors influencing development performance, substantial empirical material and hardware searches are required for system identification and optimization [37].

For printers/copiers of speeds greater than 30 ppm the most common development system is some variant of magnetic brush, (conductive, hybrid scavengeless, … [37]). Magnetic brush development requires a two component developer material in which two powders, toner and carrier (see Figure 2), are mixed together (there are additional chemical additives in two component developers to control charging and material flow). Contact between the carrier and toner causes charge to be exchanged. By means of a roller and internal set of stationary magnets, the carrier, a polymer coated magnetic soft material, is attracted by the magnets and through a combination of friction and magnetic forces is carried around the rotating roller to the latent image. The toner, which attaches to the carrier, is likewise brought to the latent image. Under the right conditions the toner then adheres to the appropriate areas of the latent image by virtue of the distribution of charge on the photoreceptor. If the print engine is hard stopped at this point, the image is visually observed on the photoreceptor.

Additional development system tasks are to provide a supply of toner to the sump containing the two component mixture and sufficiently mixing toner and carrier to achieve the necessary charge exchange and toner concentration (ratio of mass of toner to mass of carrier, referred to as TC). Sensing depleted toner and initiating re-supply can be challenging. Errors in maintaining an optimal level of toner in the housing can lead to unacceptable image quality variation and catastrophic failure (excess toner can jam the dispense auger or spread throughout the machine, generically referred to as "dirt").
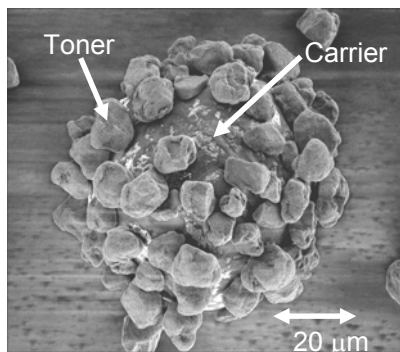

Figure 2. Two-component developer (carrier and toner)

D. Transfer

The toned image on the photoconductor is then brought physically in contact with the final print medium (usually paper). Transfer from the photoreceptor to the paper is aided by corona charging the back of the medium with a charge opposite that of the toner. This attracts the paper to the photoreceptor and brings the toner into contact with the paper creating a force that repels the toner from the photoreceptor to the paper. Many image quality defects can occur at transfer. The physics of transfer are most likely dominated by the competition of adhesion forces of the toner to the photoreceptor and the force on toner due to the electric field caused by charge on the paper [37].

E. Fuse

The toner must be permanently bonded to the paper surface. Various methods of fusing include hot roll fusing, cold pressure fusing, radiant fusing, flash fusing, and vapor fusing. For paper, the heated toner melts and bonds to the paper fiber. Thermal transients can lead to image quality variation – particularly at the start of a print job. Temperature control is required along with careful design of the toner properties of coalescence, spreading, and penetration. The rolls in contact with the toner are typically operated at high temperatures and must be composed of material to which toner does not adhere. The fuser must operate over many hundreds of thousands of cycles and over a wide range of substrates.

F. Clean

Prior to repeating the process with charging, the photoreceptor, following transfer, is cleaned of any residual toner. The cleaner typically involves a combination of corona, light sources, brushes, scraper blades, and vacuum devices. A failure of the cleaning system to reduce residual toner on the belt to an acceptable level can be a significant source of customer image quality complaints. The cleaner is a main source of periodic maintenance and the waste toner must be periodically removed.

G. Actuators

For the development technology of iGen3 there are about 40 electrostatic actuators among the four development stations. It was found appropriate to utilize laser intensity, and the electrostatic fields of development (latent image) and background (the undeveloped image area where toner deposition is to be suppressed) to regulate image quality. The large number of potential actuators was paired down by means of repeated fractional factorial experiments. In addition, toner concentration, environmental state, material residence time, and digital area coverage, are all parameters that can be used to regulate the customers image to precise specifications.

H. Disturbances

As it turns out, there are many sources of variation in the xerographic marking process, which is not surprising given the complex nature of the process. Much of the process variation results from changes in various material states. In this context, the term "materials" refers to the various consumables associated with the marking process e.g. toner, carrier, photoreceptor, media, etc. The time scales of these material state changes range considerably. Slowly varying material state changes are typically in response to external disturbances and/or wear. For instance, the electrical and or adhesion state of the toner particles may change as a function of the humidity level in the developer housing, which, in turn, impacts the ability of the toner to develop and transfer.[1] Gradual wear alters photoreceptor properties resulting in changes to the behavior of development and transfer. Materials properties can also change quickly. Consider, for example, a customer print job that involves multiple media types such as lightweight coated paper and heavyweight card stock. These paper types have vastly different transfer and fusing performance characteristics. Moreover, a marking engine may undergo periodic maintenance that results in a step change in printing performance.

The primary external disturbances that drive changes in the states of the materials in a marking engine are the environment and the customer image. Environment refers to the ambient operating temperature, relative humidity, and altitude of the marking engine, which can all vary significantly depending on whether the marking engine is operating, say, in Orlando, Florida in August or in Denver, Colorado in February. In particular, the ambient environment affects the electrical properties of developer and media materials, which, in turn, influence the development and transfer processes. Because the marking engine designer has no control over the content of the print jobs that any given customer will print, the customer image is also viewed as an external disturbance. This too is an important disturbance because switching between jobs with a vast amount of image content (e.g. a photograph) to jobs with relatively little image content (e.g. text) can lead to large image quality transients that must be compensated.

I. Sensors

There are a number of sensors to detect the xerographic state of the machine. Some xerographic critical parameters, such as the developer triboelectric charge distribution are most easily measured off line. For others a real time economical measuring process exists.

Optical techniques are used to measure color or mass of toner on the photoreceptor and/or printed image. These measurements take the form of relative light transmission, relative reflectance (both diffuse and specular), or spectral measurement techniques (spectrophotometers).

Electrostatic voltmeters are used to measure static charge typically on the photoreceptor. This device measures surface potential with no physical contact and so does not transfer charge with the entity being measured.

Toner concentration in a two component developer system (magnetic beads mixed with pigmented polymers) is an important critical parameter. Permeability sensors to infer the toner concentration are typically used. To infer permeability the inductance of a coil in proximity to the material is measured. Typically the correlation must be empirically established. If the correlation is not sufficient opportunities for sensor fusion abound. For example, the accuracy by which toner concentration can be inferred may be enhanced by combining the permeability read with photoreceptor background reads (high TC produces background), patch lightness reads (low TC yields light patches), high development fields (also indicates insufficient TC). Document area coverage (toner consumption) and dispenser past trajectories (toner addition to the developer housing) can also aide in making inferences.

The distribution of particle charge (caused by tribo electrification of the toner material) is another important critical parameter as it is the charge on the particles that permits the electric fields to impose a force to place them appropriately. After all, printing can be thought of as a spatially variable coating process to which controls are added to determine where on the substrate the coating shall be placed. The mean tribo per unit mass is measured offline by placing a sample of material in a Farady cage and physically blowing the toner off of the carrier and measuring the residual charge. An economical in situ device has yet to be developed.

In summary, the xerographic process is highly interactive with multiple inputs and multiple outputs, and is subject to a broad range of disturbances and uncertainty. In the next section, we discuss a xerographic control architecture that addresses these issues.

IV. CONTROL SYSTEM TECHNOLOGY APPLIED TO DOCUCOLOR IGEN3

DocuColor iGen3 is a digital color press designed for high volume, short-run, full-color, on-demand, and personalized printing. This xerographic-based system is able to produce color prints on a wide array of media types and sheet sizes at a rate of 6000 prints an hour with a sheet feeding capacity of 10,000 to 30,000 sheets. To accomplish this, the system uses 85 microprocessors, 192 sensors, 102 motors, and over 5 million lines of code. Control system technology played a significant role in bringing this complex product to market. In particular, control systems are used to:

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[1] To appreciate the effect of humidity on tribo charging of toner, consider the build-up of static electricity that one encounters from walking across a carpeted floor in the winter (low humidity) compared to the summer (high humidity).

- Dynamically regulate color using a hierarchical, multivariable xerographic process control architecture (discussed in the next section).
- Actively manipulate the registration of each color separation. Registration is defined as the over printing of separate colors. This is a significant issue in color printing. iGen3 is a four separation print engine (with magenta, yellow, cyan, and black development stations). The color gamut is spanned by developing various amounts of magenta, yellow, cyan, and black toner. Each color separation is rendered directly on the preceding image. Poor alignment in the over printing of separate colors can result in poor image quality. The registration control measures the relative position of each separation by printing chevron patches and adjusts the position of each laser to compensate. Registration errors are maintained below 65 microns.
- Automatically steer sheet trajectories to provide image registration to paper within 500 microns. In particular, media path control systems adapt to different media types as well as media property variations, component wear, and environmental disturbances. The paper path must reliably feed paper from a stack, bring the paper within close vicinity of the image on the photoreceptor at transfer, assure proper orientation and registration, accommodate simplex or duplex modes, and then supply finishers for stacking and binding. It must do this reliably over a wide range of media types, environmental conditions, and at high throughput rates. Paper jamming is an area of common customer frustration and significant engineering challenges. Intelligent jam avoidance and recovery all provide ample opportunity for the application of robust control methodologies. Reference [11] demonstrated hierarchical architectures to coordinate among separate and independent sections of the paper path. This hybrid control approach allows for more effective sheet to sheet spacing regulation and has demonstrated improved robustness.
- Adjust the amount of decurling applied to the media taking into account media characteristics and image density.
- Monitor and adjust environmental factors within the machine such as temperature, humidity and ozone.
- Calibrate and characterize system performance using spectrophotometers as offline sensors to ensure high quality prints.

Providing more detail for each of the above areas where control appears in DocuColor iGen3 is beyond the scope of this paper. Instead, this section emphasizes the xerographic process controls. We first provide an overview of the general hierarchical xerographic process control architecture, which then establishes the setting for the discussion on digital Tone Reproduction Curve (TRC) regulation that follows. Our intent is to provide a more concrete example of how control is used in a modern

digital printing press. In this sense, the discussion given below compliments the work in [30], where DocuColor iGen3 is presented in a much broader context that includes a description of all of the key elements used in this end-to-end publishing system.

A. Xerographic Process Control Architecture

The hierarchical xerographic process control architecture shown in Figure 3 was patented in 1995 [40] and has also been described elsewhere [30]. Commands are cascaded from Level 3 to 2 and then to Level 1. The Level 1 loops typically operate at fast sample rates and closely regulate specific subsystem critical parameters. Actuation and control occurs locally. As an example, when the development system calls for a specific voltage bias, the Level 1 loop ensures that it is achieved. In the event that a set point request is not achieved, a diagnostic inquiry may be initiated.

Level 2's main task is to determine the Level 1 set points to achieve the desired xerographic behavior as embodied by the tone reproduction and development curves. That is Level 2 is the decision making module to manage Level 1 set points to maximize performance. The various set points in Level 1 are highly coupled in their effect on image quality, and operating conditions can change rapidly.

Lastly, once the print engine has been stabilized by the Level 1 and Level 2 loops, Level 3 compensates (compensation applied in the image) for slowly moving transfer and fusing disturbances and accommodates specific TRC behaviors requested by the customer.

To provide the reader with some insight into the nature of the control design process for xerographic systems, we next highlight the Level 2 TRC control design in some detail below.
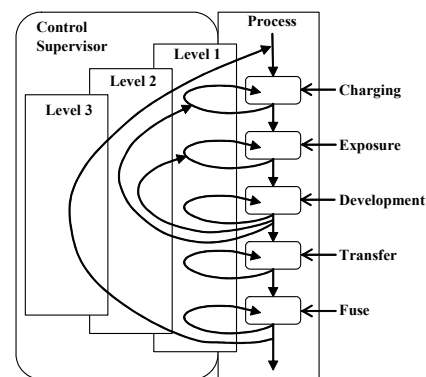

Figure 3. A hierarchical xerographic process control architecture.

B. Level 2 Tone Reproduction Curve Control

Tone refers to the lightness or darkness of a color. The TRC is a transformation of input tones (from an original document or an electronic request) to output tones. Anyone who has photocopied a document and observed a copy that was much lighter than the original has

experienced the transformation, perhaps an undesirable one, of a tone reproduction curve. The lightness/darkness knob on many copiers is a single manual actuator to increase or decrease the maximum density of the TRC curve. TRC control usually regulates only the solid tone (or the tone rendered when at or close to the maximum density) and the mid and light tones are left as outcomes. This can lead to unacceptable tone variation.

Why is the TRC an important characteristic to regulate? "Virtually all researchers in this field (color reproduction as it is applied to the printing and related industries) agree that reproducing good tone is the first and foremost objective in achieving good color reproduction" [19]. In fact, regulating the TRC has been empirically shown to approximately regulate a host of other image quality attributes. However, regulating only the TRC is not sufficient. Actuator levels and change rates are also important. Certain actuator levels exacerbate variation in color uniformity and some actuator levels will shorten the life of machine components (for example high voltage levels shorten photoreceptor life). Also, sudden actuator changes can yield discontinuities in the output that are very objectionable. There is a cost in being off target from a desirable TRC, but there can be costs in sampling (toner consumption) and costs in manipulating actuators. A sensible tradeoff is required. An example of a TRC is shown in Figure 4 below.
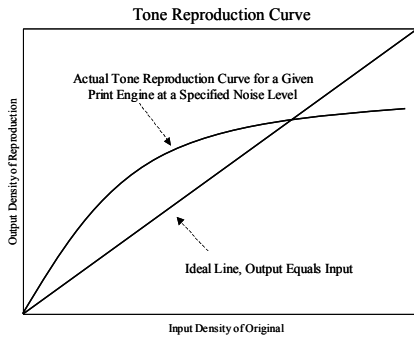

Figure 4. Tone Reproduction Curve

In digital printing, the illusion of a continuous range of tone is created by tiny halftone cells. The halftone cells create a range of gray tones from light to dark by varying the number of rendered dots per cell. The number of halftone cells per inch, termed lines per inch (lpi), is an important printer characteristic. The halftoning approach is necessary since a digital printer either places a dot on a substrate or it does not. If the halftone cell is completely filled with dots, one is at a maximum darkness, which is achieved at 100% digital area coverage (dac). If the halftone cell is completely empty, one is at maximum lightness, which is achieved with at 0% dac. The range of reproducible tones that a print engine can produce is typically restricted both in terms of maximum darkness, and number of levels (maximum lightness is determined by

the substrate). Figure 5 illustrates an example of a 31.25% dac halftone cell.
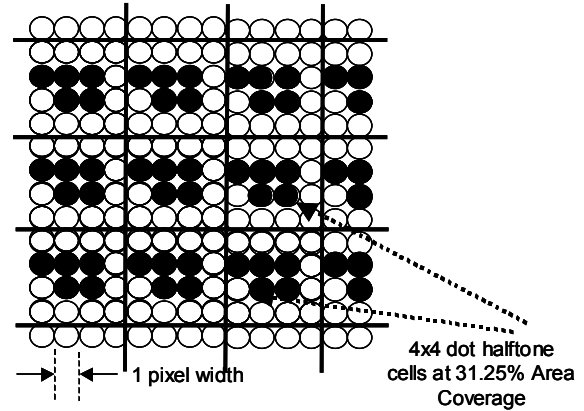

Figure 5. A sample halftone structure.

Following the notation from [28] we formulate the TRC model as,

$$TRC := \Phi(\overline{u}(k), \overline{d}(k)) = \begin{bmatrix} \phi(\overline{u}(k), \overline{d}(k), dac_1) \\ \phi(\overline{u}(k), \overline{d}(k), dac_2) \\ .... \\ \phi(\overline{u}(k), \overline{d}(k), dac_p) \end{bmatrix} \quad (4)$$

$$\overline{y}(k) = C(\Phi(\overline{u}(k), \overline{d}(k)))$$

where k is a time index between measurements and actuator updates, $\overline{u}(k) \in R^m$ is a vector of m actuator settings, $\overline{d}(k) \in R^{r_d}$ a vector of r_d disturbances, and $dac_1, ...dac_p$, are the digital area coverage values, which are determined by the number of discrete tones a digital printer is capable of rendering. $C \in R^{n \times p}$ is a matrix populated by 1's on each row to indicate which digital area coverages are sampled, and $\overline{y}(k) \in R^n$ is the vector of TRC measurements.

The objective of the TRC control system is to achieve an acceptable tradeoff between maintaining the TRC and minimizing actuator levels and change rates that reduce component life and degrade image quality metrics not captured by the TRC. The TRC desired by the customer depends on a number of factors. The TRC should be such that over the range of tones in the master image the engine has sufficient resolution. The image being reproduced has implications for control. For example an image of a white polar bear in snow will require small errors in the light tones while large TRC errors in dark tones can be safely ignored.

The print engine (defined as the xerographic system and excludes image processing) TRC does not need to match that desired by the customer. The print engine TRC targets

can be chosen more on the basis of physical constraints. Once the physical process is stabilized, the customer's TRC can be achieved by feedforward means. This approach may be embodied in the 3 level xerographic process control architecture discussed in section above. Key architectural questions for TRC controller design are:

1. How best to regulate the TRC with a relatively small set of actuators? How to select the actuators? Recall that the TRC is a mapping of a large number of digital area coverages (256 for iGen3) to tone level outputs. For iGen3 there are about 40 electrostatic actuators among the four development stations. Each development station presently uses only 3 actuators.

2. At what points, dac_p, should one sample along the TRC? Some tone regions are more important than others depending on the customer image. For iGen3, three digital area coverages where selected to adequately cover the important areas of light, mid, and dark tones.

3. How often should the TRC be sampled? Disturbance rates are highly variable. At start of print or after a long rest period fast transients can be large. In open loop, after producing the same document repeatedly xerographic systems typically reach some steady state. In job streaming however, a large area coverage change can act as a fast disturbance by changing material properties.

4. Sampling the TRC utilizes toner and possibly paper, both of which are costly. If the TRC is sampled on the photoreceptor then no paper is wasted but transfer and fusing disturbances are not compensated. Sampling on paper captures fusing and transfer disturbances but is wasteful and necessitates removing the sheets from the customer's job. Sampling also utilizes photoreceptor space thereby reducing ppm.

5. What metric best captures adequate performance? What norm on the sampled TRC point errors should be minimized? Should one minimize a dynamically changing (based on customer image data) weighted mean square error between the targeted TRC and the actual?

Not surprisingly the answers to these questions depend on understanding the disturbances, the behavior of the TRC, customer preferences, reliability and the costs.

The primary actuators used to regulate the TRC are dependent on the development technology and the source of disturbances. For the case of iGen3, it was found appropriate to utilize laser power, and the electrostatic fields of development (latent image) and background (the undeveloped image area where toner deposition is to be suppressed). The large number of potential actuators was paired down by means of repeated fractional factorial experiments in which the candidate actuators are manipulated over normalized ranges and their effectiveness

evaluated. During this set of experiments it was assumed that the system could be adequately modeled as static under a given set of noise settings.

A proposed approach is to first, stabilize to a xerographic print engine TRC at low, mid and solid digital area coverages and then fine tune to achieve the customers desired TRC by feedforward means. The print engine targets are chosen to guarantee adequate resolution. Second, if the actuators are at an unacceptable level (with respect to image quality or component life) then change the target to bring the actuators to acceptable levels and recompute the feedforward compensation. Third, to periodically monitor the actuator levels required to maintain the TRC and alter the TRC target if necessary to bring actuators back into line.

The iGen3 xerographic TRC controller can be classified as Singular Value Decomposition based controller (SVD) [38]. SVD is normally applied to decouple the system at a specific frequency but our model is static and so in the analysis and design the decoupling is applicable across all frequencies. The linear approximation of the TRC function $\Phi(\cdot)$, at the important low, mid, and solid regions exhibited a large condition number. This is typical of xerographic print engine TRC behavior. This does not necessarily indicate control problems, unless the disturbances that enter the process are large in comparison to our ability to compensate. Unfortunately this is the case for disturbances correlated with environment, material age, and photoreceptor age.

Following the notation from [38], the singular value decomposition of the linearization of $\Phi(\cdot)$, termed G, at three dac levels can be expressed as $G = U\Sigma V^T$. Where $U \in R^{3x3}$ is a unitary set of output directions, $V \in R^{3x3}$ is the unitary set of input directions, and $\Sigma \in R^{3x3}$ is the diagonal matrix of singular values arranged in descending order. V^T is the transpose of V. The controller, $K(s)$, is constrained to be of the form $K(s) = VK_sU^T$ and K_s is of the form $K_s = l(s)\Sigma^{-1}$ with $l(s)$ a 3x3 diagonal matrix of integral terms differing only by gain. The design then consists of properly selecting the gains.

Empirically, the directions expressed by U and V have been sufficiently insensitive to disturbances. Also disturbances that had roughly equal and opposite effects on the mid and low toned areas where in the direction with least disturbance to gain ratio (the same direction as that with minimum singular value). Disturbances in this "weak direction" are most responsible for large actuator swings.

An anti-wind up loop was closed about the direction with the minimum singular value. The anti-windup threshold and gain can be made a function of operating conditions and is the tuning knob to manage a tradeoff between minimizing TRC errors and maintaining actuators over certain ranges.

V. CONTROL CHALLENGES FOR XEROGRAPHIC MARKING PROCESSES

For the future, marking engines must produce higher quality prints, more reliably, under a broader range of conditions and at a reduced per-print cost. As a result, our point of view is that systems and control principles will play an increasingly important role in marking engine design. Proceeding along these lines, we motivate specific modeling, image quality, and control system design challenges in this section.

A. Control-Oriented Modeling

The marking engine transformation of the digitized desired image into a printed image can be viewed as the composition of several transformations as follows:

$$P^{marking} = P^6 \circ P^5 \circ \cdots \circ P^1, \tag{5}$$

where P^1 to P^6 represent subsystem transformations starting with charging and ending with cleaning. Generally speaking, the P^i transformations are dynamic, spatial, and nonlinear; affected by multiple actuator inputs and disturbances; and subject to uncertainty. Marking process models useful for control as well as printer calibration have appeared in the literature previously [21, 26, 28], and, as it turns out, these models treat $P^{marking}$ is a static, nonlinear, uncertain map. On the other hand, a more complete control-oriented model of $P^{marking}$ may provide the basis for novel control strategies that leverage both the dynamic and spatial characteristics of the marking process to significantly improve system performance.

In this sub-section, we discuss two complimentary control-oriented modeling problems relevant to xerographic marking processes and draw connections to the existing control literature. First, we take a "macroscopic" viewpoint, where we assume that the marking process is spatially "lumped" and emphasis is placed on the dynamics in the marking process. Next, we consider a more "microscopic" viewpoint, where the effects of the marking process on the fine details of a 2D structured image are explicitly taken into account.

1) Temporal Model Structure

First, we propose a model structure for the marking process that focuses on the dynamic and nonlinear characteristics of $P^{marking}$. For now, we assume that $P^{marking}$ is spatially lumped, which may appear restrictive since the very essence of the marking engine is to produce a 2D printed image. However, consider the TRC control example described above, and recall that the marking process is subject to various disturbances such as environment, wear, etc. that alter $P^{marking}$ dynamically. As it turns out, regulating the TRC, which is also assumed to be spatially "lumped" in current applications (see previous section), is difficult, in part, because $P^{marking}$ changes over time.

Hence, constructing control models of $P^{marking}$ that capture dynamic behavior is important for analyzing and designing marking engine control strategies.

Generally speaking, the individual process transformations share three common features that are of interest from a control-oriented modeling viewpoint. First, for the time scales typically associated with process controls (e.g. print-to-print), the sensed response to the process actuators is nearly instantaneous. Second, these responses tend to be nonlinear in the actuator commands. Third, the parameters that characterize the mapping from actuator input-to-measured response tend to vary according to the states of various materials in the system (e.g. toner and photoreceptor), which we assume can be described using linear dynamics. These observations motivate the Wiener modeling structure for the marking process defined below and illustrated schematically in Figure 6.

$$\hat{P}^{marking} : \begin{cases} \dot{x} = Ax + Bu + Ed, \\ \quad \theta = Cx, \\ \quad y = h(\theta, u), \end{cases} \tag{6}$$

where the "^" in $\hat{P}^{marking}$ denotes a model of the marking process, $x \in \mathbb{R}^n$ is the material state vector, $u \in \mathbb{R}^m$ is the control input, $d \in \mathbb{R}^r$ is the disturbance input, $\theta \in \mathbb{R}^p$ denotes the model parameters, $y \in \mathbb{R}^o$ represents the measured process outputs, and $h : \mathbb{R}^m \times \mathbb{R}^p \to \mathbb{R}^o$ is a static, nonlinear, map that relates process inputs to measured process outputs according to the scaling provided by the model parameters.
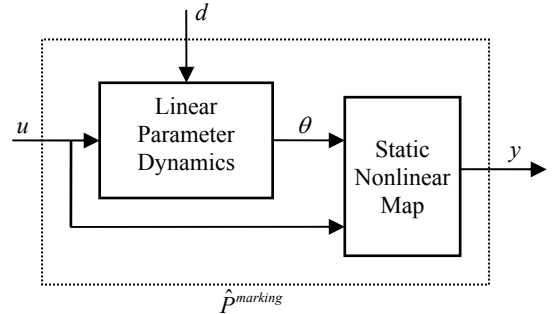

Figure 6. A Weiner model structure for the marking process.

To illustrate this modeling framework, we consider the so-called "solid area development curve," a classic xerographic model [37]. The development curve relates the development potential, V_{dev}, to the developed toner mass per unit area, DMA, as shown in Figure 7. This input-output relationship is static, nonlinear and characterized by three parameters as follows

$$DMA = \alpha \left(1 - e^{-\frac{\gamma}{\alpha}(V_{dev} - V_{D0})} \right), \tag{7}$$

where V_{D0} is the potential required for the onset of development, γ is the slope of the development curve at V_{D0}, and α represents the maximum achievable DMA (see Figure 7). For this example, *DMA* corresponds to the output, y, V_{dev} corresponds to the actuator input, u, and the model parameter vector, θ, is $\theta = \begin{bmatrix} \gamma & \alpha & V_{D0} \end{bmatrix}^T$. As it turns out, the development curve tends to drift subject to disturbances impacting development. For instance, under some operating conditions, α and V_{D0} remain relatively fixed while γ evolves according to $\dot{\gamma} = -\tau\gamma + Kd$, where τ is a time constant associated with a particular disturbance and K scales the disturbance. These dynamics coupled with Eq. (7) motivate the above Wiener model structure.
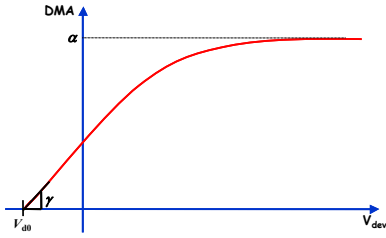

Figure 7. Prototypical solid area development curve.

Due to the complexity of the xerographic process, analytic models such as the development curve are difficult to obtain [43]. However, system identification methods for constructing Wiener models from experimental data are readily available c.f. [1]. Applying these types of methods to construct control models of $P^{marking}$ will help determine the usefulness of the proposed Wiener model structure and, potentially, provide valuable insight for xerographic process controls.

Finally, the proposed model structure needs a characterization of the uncertainty in the model. For a xerographic process, statistical descriptions (as opposed to hard bounds) of uncertainty are quite natural. This is because the physical/chemical properties of toner are statistical in nature. As it turns out, toner does not have a fixed size, shape, charge, etc. Rather, these properties of toners are described in terms of distributions, and the size and shape of these distributions significantly impact the marking process.

2) A Spatiotemporal Model Structure

In addition to modeling dynamic changes in $P^{marking}$, the spatial characteristics of the marking process need to be considered for control analysis and design. The spatial aspects of the marking process are important because, ultimately, the printed image is evaluated by a human observer, and since image content is arranged spatially, perceived image quality has a strong spatial component. Going forward, the viewpoint is that the composition of the xerographic process steps in Eq. (5) represents a composition of two-dimensional (2D) image transformations.

As discussed in the previous section, current control strategies do not directly treat $P^{marking}$ as a spatial transformation. Yet, advances in control theory and increased availability of affordable scan-bar sensors, MEMS-based actuators, and low-cost embedded processors enable opportunities to implement spatially distributed control systems [39]. Investigating spatially distributed control systems for the marking engine requires 2D control-oriented models of $P^{marking}$. In the imaging science literature, phenomenological models based on the concept of a "modulation transfer function" (MTF) have been used to characterize the spatial effects of xerographic processes [25, 29]. These models should provide a good foundation for building 2D control models and are briefly reviewed below.

In optics, the MTF has long been used to quantify the spatial resolution capability of an imaging (element) system e.g. the resolving power of lenses is characterized using an MTF. The basic idea behind the MTF is to model the "blurring" of an image that results from an input image being transformed by a given imaging (element) system (see Figure 8). This "blurring" effect is typically assumed to be a linear, spatially invariant transformation. Under this assumption, the input-output relationship for the imaging (element) system can modeled in the spatial frequency domain as

$$I^{out}\left(\omega_x, \omega_y\right) = M\left(\omega_x, \omega_y\right) I^{in}\left(\omega_x, \omega_y\right), \qquad (8)$$

or in the spatial domain as

$$I^{out}\left(x, y\right) = \iint m(x-\varsigma, y-\xi) I^{in}\left(\varsigma, \xi\right) d\varsigma\, d\xi, \qquad (9)$$

where $I^{in}\left(\omega_x, \omega_y\right)$ and $I^{out}\left(\omega_x, \omega_y\right)$ are the 2D Fourier transforms of the input and output images, respectively, ω_x and ω_y are spatial frequencies, $M\left(\omega_x, \omega_y\right)$ is the 2D transfer function of the given imaging (element) system, and, in the imaging science parlance, $m(x, y)$ is referred to as a "point spread function" and is generally Gaussian in shape [24]. While the imaging science literature defines the MTF as the *magnitude* of *M* over the range of spatial frequencies, in this document "MTF" generically refers to the transfer function, *M*. Generally speaking, the MTF resembles a "low-pass" spatial filter. Referring back to Figure 8, the low-pass characteristics of *M* account for the observation that the "thick," widely spaced bars in the output image are more faithfully reproduced than the "thin" bars that are spaced closely together.

Figure 8. An (exaggerated) illustration of an input-output image transformation.

Roughly speaking, references [25] and [29] model xerographic systems as a cascade of MTF's composed with static nonlinearities. The order of MTF and static nonlinearity depends on the process in question. For instance, in development, recall that the incoming digital image is transformed into a series of imager (e.g. laser intensity) commands which are then used to create the exposed, or "latent," image on the photoconductor. Building the latent image results in "blurring" of the original image, which is captured by the development MTF. The latent image (in units of voltage) is then developed into a toned image (in units of mg/cm^2) according to the nonlinear mapping given by the solid area development curve (see Figure 7). Hence, in development, the MTF precedes the static nonlinearity (Figure 9). In transfer, however, it turns out that the static nonlinearity precedes the MTF [29]. Consequently, both 2D model structures shown in Figure 10 are of interest.
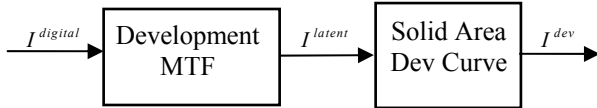

Figure 9. Two-dimensional spatial model for development

To close this sub-section, we point out some of the issues to be addressed in building 2D control models of xerographic systems (similar issues are discussed in [41]). For the model structures in Figure 10, first consider the identification problem of estimating parameters of the models from experimental data. Along these lines, notice that the models in Figure 10 are the spatial analogs of Wiener/Hammerstein model structures used with nonlinear, temporal systems. Translating Wiener/ Hammerstein results to the spatial domain may be useful for model identification. Next, while the model structures shown in Figure 10 emphasize 2D image transformation, the models also need to explicitly account for the effects of actuator and disturbance inputs as well ad uncertainty in order to be used as control models. For such a control model, it may turn out that the model parameters characterizing both the MTF and the static nonlinearity vary dynamically according to the disturbance inputs, as described in the previous sub-section. Given parameter dynamics on one scale and spatial dynamics on a different scale, wavelets may be a useful modeling tool for characterizing the spatiotemporal behavior of the marking engine. Finally, we point out that the spatially invariant assumption used in the above MTF discussion implies spatial uniformity in the marking process, which, strictly speaking, is not true (non-uniform artifacts occasionally do appear in the printed image). In practice, a "microscopic" viewpoint of the image is observed, where the spatial models are assumed to be valid over a small spatial range. Accounting for spatial print non-uniformities is a challenging problem that may require coupling several of the structured spatial models with an unstructured, "black-box" model of the non-uniformity.
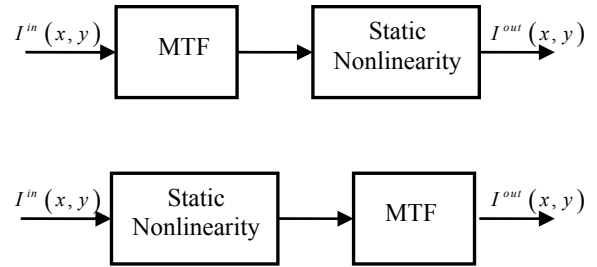

Figure 10. Wiener/Hammerstein structure of 2D image transforms.

B. Image Quality and Control

Image quality is a key factor for establishing the success of a marking engine in the marketplace. Generally speaking, "image quality" refers to the difference between the printed image, $I^{print}(x,y)$, and the desired image, $I^0(x,y)$. Whereas the majority of other industrial control applications aim at regulating and/or modifying the *temporal* aspects of a given system's behavior, control applied to printing systems must address both the inherent *spatial* characteristics associated with image quality and the dynamic effects of disturbances on the marking process. In this sub-section, we provide a brief overview of image quality characterization, show an imaging science view on the application of image quality, and describe two examples that show how control fits into this view.

1) Image Quality: Metrics and Preference

In the imaging science literature, image quality has traditionally been evaluated in two complimentary ways: 1) using *image quality metrics*, which are objective measurements of physical characteristics of the image, and 2) using *image preference*, which consists of more subjective measures to determine whether or not a customer would like a particular image [14].

Image quality metrics refer to quantitative measures that address structure in the printed image. These metrics are based on reflectance and/or transmissive profiles of the printed image recorded with a CCD camera, scanner, and/or scanning microdensitometer. Image analysis tools (such as Image Quality Analysis Facility (IQAF), a proprietary software package widely used at Xerox) then

transform the measured image profiles into various image quality metrics. Examples are metrics to quantify image uniformity (e.g. graininess, mottle, streaks, and bands) and metrics to quantify the extent to which the edge of a line is straight (e.g. free from raggedness) [35]. Because marking engine performance specifications typically specify targets for *dozens* of image quality metrics, these metrics are relevant for control.

Incorporating image quality metrics into control analysis and design is an open area of research. The sheer number of image quality metrics to be managed and questions of how the process measurements relate to image quality motivate work in "sensor fusion." In addition to their spatial nature, image quality metrics are also dynamic (driven by marking process disturbances), which raises the question of how to "sample" image quality both temporally and spatially for use in a control system (e.g. the notion of "time-sequential" sampling is discussed in [27]). For this type of research, various tools developed in the imaging science and signal processing literature, such as feature extraction, image registration, and statistical signal processing, would likely be useful.

The human visual system certainly plays a role in customer preference and not all metrics account for visual perception. For instance, a line density measurement is a purely physical measurement [14]. On the other hand, perceptual studies of spatial color variations indicate that the spatial frequency dependence of lightness variations is different than the spatial frequency dependence of chromatic variations [20]. The notion of "image preference" attempts to capture customer likes and dislikes and tends to be somewhat subjective. Generally speaking, preference is evaluated by showing customers various reference images (e.g. pictorials, graphics, newsletters, etc.) and quantifying their responses [35]. Customer preference has important implications for control because it provides direction on what areas require tight closed-loop performance.

In both the automotive and aerospace industries, customer preferences in terms of vehicle ride and handling qualities are factors in control design. Furthermore, both industries have established "human-in-the-loop" control results. In digital printing, control design results that directly consider the human visual system have started to appear (see examples below), however, control analysis and design that accounts for customer preference is another open area of research.

2) Control in the Context of the Image Quality Circle
Industrial applications of image quality have been described in terms of the Image Quality Circle (IQC) as illustrated in Figure 11 [17]. The basic idea is to consider the effects of "technology variables" (e.g. subsystem set points, material selections, roll spacings, etc.) on customer quality preference. As shown by the heavy arrow in the figure, this relationship could be established directly. For

each choice of the technology variables, images could be printed and evaluated by customers. From this direct viewpoint, control, as a technology variable, has a clear impact on the IQC e.g. customers prefer the tight regulation of their TRC afforded by closed-loop control. It turns out, however, that the direct approach is inefficient because correlations need to be reestablished each time a technology variable is adjusted. Consequently, the direct approach is not conducive to "what-if" analyses. According to Figure 11, the relationship between technology variables and customer quality preference can also be established indirectly. Following this indirect approach relies on modeling, simulation, and experiment, where system models, such as $\hat{P}^{marking}$, are linked to image quality models using models of human visual perception, $\hat{P}^{visual}$. From the indirect viewpoint, control also has several important implications for the IQC. For instance, $\hat{P}^{marking}$ could have a very different structure for analyzing closed-loop performance than, say, a model structure used for predicting open-loop performance. Furthermore, considering control as a technology variable leads to questions of design trade-offs between control and other technology variables.
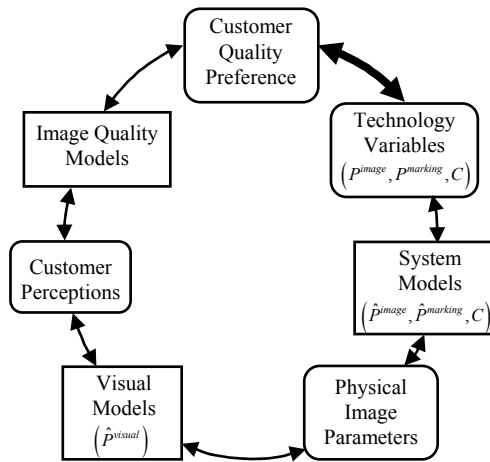

Figure 11. Image quality circle [17]

3) Examples: Consistent Color and Banding Mitigation
Below, we briefly discuss two examples from the literature that illustrate how applications linking control to perception are emerging.

- *Consistent Color*: An important requirement for color marking engines is that colors are consistently reproduced from page-to-page despite variations in media properties, materials, environment and other disturbances. Color can be described in a 3-dimensional space, where each point in the space corresponds to a particular color. Two types of color coordinates are of interest for color printing: device independent color coordinates such as CIE (International Commission on Illumination) $L^*a^*b^*$ and device specific

color coordinates based on the amount of three or more primary colorants, typically cyan (*C*), magenta (*M*), and yellow (*Y*). In the $L^*a^*b^*$ coordinate system, L^* refers to lightness, a^* refers to the level of red or green, and b^* refers to the level of blue or yellow [2]. Differences between colors are described in the $L^*a^*b^*$ space using a Euclidean distance metric, referred to as ΔE; hence, the ΔE metric is relevant to consistent color applications. As it turns out, the average human visual system is sensitive to ΔE values greater than 1.

Input images to a printer contain color specifications that are characterized in terms of $L^*a^*b^*$ coordinates. Image processing within the printer transforms these device independent coordinates into the device dependent *CMY* coordinates used by the marking process to produce the printed image. The printed image, in turn, is evaluated back in $L^*a^*b^*$ space. Figure 12 illustrates these various transformations [22].
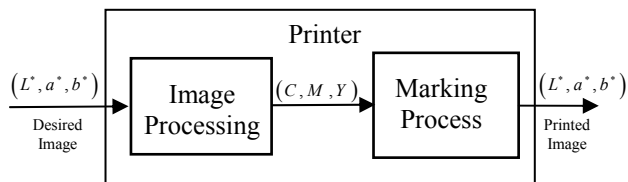

Figure 12. Printer from a color space transformation viewpoint [22].

As alluded to in Figure 12, the marking process embodies a transformation, $T:\mathbb{R}^3 \to \mathbb{R}^3$, from device dependent *CMY* coordinates to device independent coordinates $L^*a^*b^*$. The color mixing algorithms used in image processing contain an approximate inverse of *T*, denoted by $\widehat{T}^{-1}$, so that the composition of the marking process with image processing, $T \circ \widehat{T}^{-1}$, is close to the identity map. When this is the case, the printed color will be close to the desired color [22].

Colors may not be reproduced consistently from page-to-page or from printer-to-printer because *T* drifts subject to various disturbances. Research efforts have focused on developing computationally efficient control models of *T* that are capable of being updated periodically using print sample data [21, 26]. Ultimately, the goal is to then use these models to perform real-time updates to the color mixing algorithms (i.e. $\widehat{T}^{-1}$) in order to keep page-to-page and printer-to-printer color variations below a perceptibility threshold.

● *Banding Mitigation*: Banding refers to a macro-uniformity artifact manifested as a color variation extending in one direction typically either parallel or perpendicular to the process direction (i.e. the direction of travel for the media within the marking engine) [35]. Figure 13 shows a cartoon example of periodic banding in

a printed image for the case where the desired image was a uniform gray page. For a xerographic marking engine, banding has a variety of sources such as developer roll run-out, photoreceptor drum velocity variations, and imager imperfections.
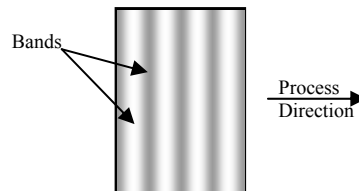

Figure 13. A cartoon of a printed image illustrating banding.

As it turns out, the response of the human visual system to banding depends on the spatial frequency of the bands. In particular, perceived banding has bandpass-like characteristics indicating that a banding reduction scheme should emphasize a specific spatial frequency range. References [9] and [10] consider modulating photoreceptor drum velocity in order to mitigate banding associated with motion quality problems. For this approach, the controller was designed using a loop-shaping approach that incorporated a model of the human visual system response to banding, $\widehat{P}^{visual}$.

These two examples illustrate the role of control in the IQC. This role will become even more prominent as the demand for tight image quality performance at reduced cost.

C. Other System Theoretic Areas Relevant to Xerographic Systems

Controlling the xerographic process is a complex tradeoff between actuator levels, regulation error, and image quality, applied to a process that is noisy and difficult to characterize. There are a number of additional control design methodologies that may show promise in this challenging area of application.

MPC, or model predictive control [3,8] methods are especially effective with systems that have constraints imposed on the actuator and the manipulated variable and so may be quite applicable to xerographic systems.

In addition EVOP [6] may also prove effective. EVOP, or EVolutionary Operation, is a mode such that in real time simple experimental designs are conducted during operation to learn and update models of the system. Box defines EVOP as "designed to be run, …., on a full-scale manufacturing process while it continues to produce satisfactory product". Only small changes are made in the process control actuators such that the output remains acceptable. Information learned during this system identification phase can result in control design updates. If some loss of productivity is acceptable the experimental

designs can be conducted during dead cycling. Dead cycling is defined as the system fully operating except that printing the customer's image to paper is suspended.

A digital press such as iGen3 can be conceived as a self contained manufacturing plant. However, a production shop normally performs a wide range of jobs that call for the use of different print engines, prepress tools, and finishing options. To remain competitive the proper control of cycle time, throughput, work in progress, quality, inventory, and capacity is critical. The application of control concepts to improve print shop manufacturing operations will likely grow in importance. An example of this can be found in [34]. Wherein the architecture for a lean document production controller is developed and implementation results for job ID assignment, routing, and workflow optimization are discussed.

Statistical Process Control (SPC) for diagnostics and process improvement is a promising area. Reducing the frequency required to service print engines and to perform the right service at the right time can reduce costs and enhance customer satisfaction substantially.

When one speaks of process control, a statistical quality control practitioner thinks of process monitoring and intervention for improvement but a controls engineer generally thinks in terms sensing/measurement, algorithm design, and automatic real time feedback. Box (et al) presents a compelling case that the two views are the result of roots in separate industries, parts and processing, with different sets of circumstances. The parts industry had inputs that where relatively stable. In the process industries external variables had to be compensated by frequent manipulation via feedback. In the parts industry adjustment was costly. In process industries the real cost was in being off target. Applying feedback without first removing system bugs can be a losing endeavor. Yet simply monitoring view charts and making adjustments is inefficient and incompatible for systems that undergo rapid changes.

Since the print engine is conceived as a manufacturing facility for the production of prints, it can benefit from both approaches. SPC is the means of continuous process improvement par excellence – it is the primary basis for off line (though not to exclude real time) action. Real time feedback and measurement will provide the compensation necessary for rapid changes, mean centering, and variation reduction.

VI. Conclusion

In this paper we identified a set of challenging modeling and control problems relevant to xerographic systems and have drawn connections to the literature. Though the paper was structured as a survey, we spent some time in depth outlining the TRC controller for the DocuColor iGen3 digital press. The TRC topic spans a large set of issues

prevalent in printing processes, xerographic or otherwise. Challenges abound. This is especially so in the case of digital color printing that is now engineered in an environment of ever increasing performance expectations, complexity (full color, variable data, and print on demand), cost reduction, and timeliness. Printing is also big business and xerographic processes play a central role. We believe that within a focused academic partnership with industry lies the most effective organization to achieve rapid progress and create economic value. Even small incremental improvements can pay off handsomely. From the beginning controls has played an important role in the evolution of xerographic marking engines. The role has grown to a level larger today than ever before.

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