Trade-Offs in On-Board Densitometry

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Abstract

Variability inherent in the electrophotographic (EP) process often mandates some kind of process control strategy to provide the required image consistency. Both photoconductor and toner generally exhibit substantial unit-to-unit variability and environmental sensitivity, plus variability over the rest-run duty cycle and long-term aging. Another challenge addressed by process control is maximizing toner yield (prints from a given quantity of toner) without compromising image quality. Many process control strategies rely on on-board densitometers to monitor the process and provide the basis for automatic process control adjustments. Laboratory bench-top densitometers are too big and expensive, and have more capability than needed for process control. The specialized on-board densitometer typically doesn't need the user interface, nor certain other features, and the cost of the on-board densitometer must be reasonable vis-a-vis the total print engine cost. However, in certain respects the on-board densitometer may have to meet higher performance standards than the laboratory instrument. This paper provides an overview of on-board densitometer performance requirements and technology trends, in dry electrophotographic applications.

Introduction

In the field of EP process control, many issued patent drawings show a basic EP process, with the major subsystems of charge, expose, develop, transfer, clean, and fuse. They also show process control sensors, notably on-board electrometers and on-board densitometers. The electrometer and the densitometer measure test patches and output to a logic and control unit (LCU) that automatically adjusts and regulates the EP process settings. Patent drawings from manufacturers in North America, Europe, and Japan illustrate the pervasiveness of densitometers, as well as electrometers, in EP process control, at least in the higher-end machines. For the future, we can expect increasing application of digital technology to on-board densitometers, making them cost-effective even in low-cost, low-volume copiers and printers.

For their electrometer needs, EP original equipment manufacturers (OEMs) are well served by vendors offering small, low-cost electrometers. These vendors often work with the OEMs to customize the electrometer for the particular application. Outsourcing electrometers from established vendors specializing in these instruments has been common for many years. Not needing to produce electrometers in-house, the OEM can focus limited engineering and manufacturing resources on their core EP technology rather than on sensors and instrumentation.

With respect to densitometers, the situation is rather different. Logically, the electrometer and densitometer are companion sensors in EP process control. The first monitors the electrostatic latent image, while the latter monitors the toned image. Many EP process control strategies depend upon both, sometimes several of each type. But vendors today have little to offer the OEM in the area of small, low-cost, on-board densitometers. Old-timers in EP technology might liken the densitometer situation today to the electrometer situation a few decades ago, before on-board electrometers were commercially available for the OEM to buy.

Of course a variety of bench-top densitometers are available, and some can be seen in the conference exhibit hall. They are rich in features, displays, and operator controls. They are also too big and costly for integration within copiers and printers. These laboratory instruments conform to established densitometry standards (ANSI and ISO) to facilitate scientific evaluation and comparison of data.

The few commercially available densitometers specifically for on-board applications run into the $100's -- still too expensive for all but the largest and most sophisticated EP products. The next step down in commercially available hardware takes us to the component level. Basic detectors such as photodiodes or phototransistors are certainly small enough and cheap enough. They can be designed into the copier or printer, along with an LED light source, to monitor reflected or transmitted light from the toned image. But by themselves these components are capable of only the most crude density measurements.

This leaves a broad gap where EP OEMs must custom design densitometers for their copiers and printers. These custom densitometers support increasingly stringent image consistency requirements, but the cost must be commensurate with the overall product cost. Little immediate help is available from either the laboratory instrument vendors or the component manufacturers, who are often unfamiliar with the special needs of on-board EP applications.

This paper addresses the issues and engineering trade-offs faced by EP OEMs who design on-board densitometers for integration within their copiers and printers.

Reflection or Transmission

Once the need for an on-board densitometer is established, the first fundamental issue is reflection mode versus transmission mode. Often there is a choice whether to monitor light reflected from the toned test patch, or light transmitted through it. Sometimes the choice is clear, other times not so clear. In the case of an opaque support, such as a drum, the only choice is reflection. However, a configuration in which toner is first applied on a drum might subsequently transfer the toner to a transmissive web, where transmission densitometry would be possible.

In reflection densitometry, the reflective characteristics of both support and toner must be considered. Both depend on the color or wavelength of the light used. The reflection characteristics also depend upon the geometry, i.e., specular or diffuse. Ideally a geometry and an emitter are selected with a peak emission wavelength that provides high contrast between the bare support and the toner-covered areas. If the support is at least somewhat reflective, the toner should block the light. Conversely, if the support is not reflective, the toner should be reflective to provide a strong decreasing density signal as coverage increases. Black toner is highly absorbing and reflects little, while color toners diffusely reflect or scatter a substantial portion of the incident light. When both black and color toners are to be monitored on a moderately reflective photoreceptor, the somewhat contradictory requirements present a challenge. In such cases, it has been found advantageous to use infrared light and separate sensors to isolate the specular component for black, and the diffuse component for color toners.

In transmission densitometry, the transmission characteristics of the support (including photoconductive layer, conducting layer, and any other layers) as well as the toner must be considered. Both depend on the color or wavelength of the light used. A straight-through optical path, normal to the toned surface, simplifies the geometric issues. The emitter may be on either the toned side or the reverse side of the support. In the case of a highly transmissive support and highly absorbing toner, neither toned nor untoned areas reflect light, so transmission density is the clear choice. Ideally, the emitter peak emission wavelength provides high transmissive contrast between the bare support and the areas covered with light-blocking toner. At this emitter wavelength, the support should be highly transmissive, while the toner should efficiently block the emitted light by absorption or scattering.

Transmission density has the advantage, compared to reflection density, of better linearity with toner coverage. Reflection density has a strong saturation characteristic at medium-high toner coverage. That is, as coverage increases on a moderately reflective support, black toner approaches a minimum reflectance (maximum density), and color toner approaches a maximum reflectance (minimum density). A drawback of transmission density is that wear and contamination of both front and rear surfaces may be of concern.

With the host of considerations mentioned above, and more to be discussed later, selecting the best on-board densitometer configuration for a given process can be fairly complex. With no intention to underrate the importance of reflection densitometry or liquid toner, the remaining sections specifically address only transmission densitometry of unfused dry toner.

Spectral Considerations

Typical black toners are highly absorbing throughout the visible spectrum and into the infrared (IR). An IR LED emitter (880-950 nm) is typically used for black. One advantage of IR is the good match to the spectral sensitivity of the typical silicon PIN photodiode detector. Another advantage is that the emitter IR is often outside the spectral absorption and sensitivity of the photoconductive support. In this case the photoconductor is highly transparent to the IR and unharmed by the IR exposure. The support transparency to the IR also permits the use of a lower-intensity IR emitter.

Unfused color toners typically are not nearly as absorptive as black, even at their complementary wavelengths. They block incident light primarily by scattering, rather than absorption. The scattering is often not highly selective across the spectrum. Indeed, the strongest density signal may be obtained with an emitter color other than the complementary color to the toner. For example, a magenta toner may provide the strongest transmission density signal using a blue emitter rather than green.

Some commercial color copiers have used a cost-effective approach of a single-channel densitometer with an IR emitter to measure all 3 process colors (C,M, and Y) plus black. For black toner an IR emitter typically provides the strongest density signal. For color toners the IR transmission density signal is weaker but useable. An appropriate visible wavelength for color toner densitometry will provide a strong density signal from the toner, without excessive absorption by the support. The best emitter choice is not necessarily the color most efficiently blocked by the toner, if that color is also strongly absorbed by the support, harming the photoconductor or allowing too little light to reach the detector.

Continuous or Pulse-Mode

The simplest emitter drive circuit for the densitometer LED biases the LED for continuous emission. To avoid warm-up effects and simplify the controls, the LED may remain energized at all times, even while the machine is idle between jobs.

Pulse-mode operation cuts LED temperature-rise and reduces warm-up and aging effects. The pulse width must be compatible with the detector circuitry. The pulse width should be short compared with the LED thermal response time, say 100 µs or less. The pulse frequency must be compatible with the process velocity and the required density measurement spacing on the support. For example, it may be required not to have gaps between measured spots on the toned surface.

For a given instantaneous intensity, pulse-mode operation reduces the photoconductor exposure. This is important where the densitometer light emission can harm (i.e., "fatigue" or "fog") the photoconductor. Alternatively, pulsing permits higher emitter intensity and measurement of higher density levels than could be measured in continuous mode. This can be effective for transmission densitometry through very dense supports.

Optical Geometry and Spot Size

Typical LED's emit a highly divergent beam, even with an integral dome or lens on the LED. The bright central spot may not align perfectly with the mechanical axis. Aiming the LED through a collimating hole produces a smaller, more precisely positioned beam. Using a large-area detector at a close spacing captures the entire beam, and accommodates beam nonuniformities and alignment tolerances. A cheaper alternative is a beam designed for a broad uniform central spot, and a relatively small-area (cheap) photodetector. The photodetector remains entirely within the central spot, despite some misalignment. To avoid measurement error, it is important that misalignment remain constant between calibrations, i.e. between re-zeroing.

The illuminated area on the support determines the effective measurement spot size, if a large detector captures all the light from this illuminated area. If a small-area detector is used, it can be the limiting factor in the measurement spot size. A large measurement spot size averages out more nonuniformity within the spot, such as granularity or halftone patterns. This reduces the noise in process control patch measurement, where the patches may be a few centimeters in dimension. On the other hand, a small measurement spot size permits higher spatial resolution. This could be important if the densitometer is used to detect small-dimension features such as toned lines or the support belt seam.

Logarithmic Functionality

The mathematical definition of optical density involves the negative logarithm of reflectance or transmittance. The logarithm function makes optical density a better match to the human visual perception of darkness. The logarithm function also makes optical density match with Beer's Law. Materials following Beer's Law have an optical transmission density proportional to the layer thickness, and layers are additive in optical density. Single-color toner coverage normally ranges from sub-monolayer up to a few monolayers for D_{max}. While it may not be meaningful to characterize sub-monolayer toner coverage in terms of thickness, measured density generally increases approximately linearly with toner mass coverage, averaged over an area.

To be true to the optical density definition, a densitometer must have some means to logarithmically convert the detector light intensity signal. Traditionally an analog logarithmic amplifier does this. More recently, digital logarithmic conversion has also been used, enabling cost reduction and increased versatility. A densitometer with true logarithmic functionality outputs a signal approximately linear with toner coverage, and is readily re-zeroed, to compensate for contamination, aging, wear, unit-to-unit variation, etc.

Some crude on-board sensors may be labeled as densitometers, but lacking the logarithmic conversion. They can be satisfactory for limited purposes, such as detecting a reference mark. The output from such a crude sensor is not proportional to toner coverage. Accurate compensation for contamination, aging, and so forth, if attempted at all, requires more than simply subtracting a base reading.

Range

The foremost EP process control objective, for both simple and sophisticated strategies, is usually to regulate the net toner D_{max} density above the base density. The densitometer range should therefore span the entire toner density range, plus the range of the support density. Additional "headroom" range should be provided to cover occasional abnormally high toner coverage, wear and scumming of the support, contamination on the densitometer, and degradation of the densitometer light emitter.

Target density for unfused toner is usually highest for black, typically 1.0 to 1.4 density units (not strongly dependent on wavelength) above base. A total range sufficient to cover the normal black toner density, plus the aforementioned variabilities with extra "headroom" to be conservative, could be 3.0 or more, depending on the application.

In densitometer development and testing, one is cautioned about using the "neutral density" filters common in photography and graphic arts, such as Kodak Wratten filters. The stated filter density applies only to the visible spectrum. Such filters may not be very "neutral" at all in the IR, where the density may be more or less than the stated density, depending on the filter material. Another caution: ink jet ink, unlike EP toner, is typically transparent to IR.

Resolution and Accuracy

Optical density is usually specified and reported to two digits after the decimal point; most laboratory instruments provide density readouts with resolution of .01 density units. A density difference this small is usually not perceptible, but some laboratory densitometers offer a 3rd digit after the decimal point. Some commercial copiers and printers feed the analog density signal from the on-board densitometer into a standard 8-bit A/D converter at the LCU. For a density range of 0 to 3.0, 8-bit resolution corresponds to a density resolution of 3/255 = .012, if the A/D range exactly matches the density signal. Other commercial EP printers move up to the next standard A/D resolution at 10-bits, to be assured that resolution is not a limiting factor in performance. A digital densitometer with at least 9-bit density output resolution is normally sufficient for process control purposes.

For the on-board densitometer, absolute accuracy is less important than densitometer stability and resolution. A periodic re-zeroing strategy is typically needed to compensate for contamination and aging. Target density values can be set and adjusted to compensate for imperfect accuracy. The on-board densitometer's primary purpose is process control. Unnecessary features and extravagant performance are avoided to control costs. Designing for integration into a single specific machine can enable simplification and cost savings. The objective is image consistency in the target machine, rather than conformance to laboratory standards and absolutely accurate data in general purpose use.

Update Rate

The required update rate depends upon the size of the test patches to be measured, the number of measurements needed within the patch, and the process velocity. It may be important not to have gaps on the photoconductor where density is unmeasured. For analog densitometers using an unpulsed emitter, the analog density signal output is continuous, but sampled at prescribed times by the LCU. The analog signal represents density in a continuous track on the photoconductor, with no gaps. Pulse-mode operation, however, sets a sample rate or measurement update rate equal to the pulse frequency. For a digital densitometer, the computational cycle-time may be the limiting factor in update rate.

For a digital densitometer, a related consideration is latency, i.e., the delay before the measurement value is available at the output. Owing to the digital processing time required, at any instant the density output represents a measurement made some short time previously. This delay may be significant with respect to the timing of the process control measurements. Depending on the support velocity and the densitometer digital processing speed, the support advances, perhaps a few millimeters, during the latency period.

Smart (Digital) Densitometers

Besides eliminating the costly analog logarithmic amplifier, digital densitometers also enable additional functionality. Process control computations have traditionally been a task for the LCU controlling the overall machine operation. A distributed computing approach may have a separate processor specialized for process control. With a digital densitometer, the distributed approach may be carried further, with basic computations performed on the densitometer circuit board itself. Furthermore, some adjustments can be determined and applied directly by the densitometer board itself--adjustments to the emitter intensity or pulse frequency, for example.

A microcontroller on the densitometer circuit board can be programmed for a variety of functions. It can collect and save base density data during a calibrate or re-zero mode. Later, during the run mode, the microcontroller subtracts the base values from the raw values in real time, without requiring attention from the LCU. If the measurements are synchronized with the endless belt support motion, the base values can be unique for each measured spot. A density moving average can be maintained to average out noise, and the averaged signal output to the process control computer. Photoconductor motion can be inferred from patterns or variability in the measurements, and the emitter "put to sleep" between jobs, to avoid "burning" a spot on the photoconductor. During diagnostic and service modes, statistics of variability can be computed to characterize photoconductor or toning uniformity, which are vital signs of EP process "health", and output to the LCU.

A digital densitometer can further cut costs by supporting multiple densitometer "heads", i.e., emitter-detector pairs, from a single microcontroller, eliminating a costly log amp for each head. This multi-channel approach can be exploited in color machines requiring separate heads for the individual colors. A single-color machine might utilize multiple densitometer heads to monitor density at multiple cross-track positions, or at different stages of the imaging process, e.g., pre- and post-transfer.

I/O—Analog, Digital, and Visual

An analog on-board densitometer outputs an analog voltage proportional to density, scaled to a voltage range of, say, 0-10 volts. Normally this is connected to an A/D converter at the LCU for subsequent process control computations. A digital densitometer may output its digital measurement directly to the LCU, either in parallel or serial format. However, a digital densitometer designed as a "drop-in" replacement for an analog densitometer may include a D/A converter, for connection to the existing A/D converter at the LCU.

Where the on-board densitometer is used as a service aid, a visual digital readout may be provided. In one approach, a density output test point is provided for a connection, either digital or analog, to the portable service display device, such as an ordinary digital voltmeter. In another approach, a permanent connection to the copier/printer operator interface displays density data during a service routine. The display can be in the form of a conveniently scaled count, e.g., 0-255, or, preferably, in actual density units.

Conclusion

Designing a densitometer for integration within an EP process requires consideration of many factors, not the least of which is cost. Fortunately, digital technology is driving on-board densitometer costs down, and enabling new features. On-board densitometers can now be considered even for moderate-cost copiers and printers.

Biography

Allen Rushing received his Ph.D. in Electrical Engineering in 1973 from the University of Missouri--Rolla. Since then he has worked in electrophotographic R&D, primarily at Eastman Kodak, specializing in process control. In January, 2000 he founded LogLight Designs to apply digital technology to on-board densitometers for copiers and printers. He has 26 U. S. Patents, and was a Kodak Distinguished Inventor. He is a member of the IS&T and a senior member of the IEEE.
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