Momentum-Control Scavenge-less Jumping Development

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Abstract

A new toner-based electrographic development process is presented, which we call "Momentum-Control Scavenge-less Jumping Development" (MC-SJD). It is similar to conventional jumping development in that an AC waveform is used to drive charged toner particles across a small gap from a toned donor roll towards a photoreceptor with a latent electrostatic image. Rather than allowing toner particles to impact the photoreceptor and potentially damage any existing toned image, a four-phase waveform is used to reduce the normal component of the toner's momentum prior to its impact with the photoreceptor. The toner thus forms a nearly static cloud of charged particles near the latent image, which then gently develops onto the photoreceptor. The MC-SJD process is equally applicable to both single and dual-component development subsystems. This approach is particularly useful for image-on-image color printing architectures, but may also help improve the image quality of monochrome and conventional color prints.

Introduction

Using the *Xerox Particle Simulation Environment* (XPSE) [1-3], we invented a new flavor of dry-power jumping development for electrographic print engines. Although jumping development has been used successfully in electrographic print engines for many years, it is generally not considered for high-quality image-on-image printers due the inherent scavenging nature of the process. By "scavenging", we mean the process by which impacting toner particles disturb previously deposited toned images on a photoreceptor. Other scavenge-less development subsystems do exist. For example, the *Hybrid Scavenge-less Development* (HSD) process uses thin charged wires within the development nip to create "gentle clouds" of toner particles [4]. Unfortunately, such systems can experience long-term reliability issues due to contaminates coating the wires over time.

In this paper, we modified the AC waveform that is normally used to drive toner back and forth across the air gap in a jumping development nip. The technique relies on a detailed understanding of the toner dynamics within the gap. For that, physically realistic simulations of the development process have proved invaluable.

A brief overview of XPSE is presented, and some details of the simulation technique discussed. Examples will be shown based on a small, highly detailed, kanji character. Realistic particle size, charge, and adhesion distributions are used by the simulation code. The ultimate goal of these studies is to understand the interaction between a jumping powder cloud, and any pre-deposited (*i.e.,* toned) images on the photoreceptor.

Overview of XPSE

XPSE is a set of C^{++} libraries and computer programs that are designed to enable the simulation of xerographic subsystems; such as erasure, charging, exposure, development, transfer, and fusing. The underlying code uses the particle-in-cell technique [5] to model individual toner particles in three spatial dimensions and time. Appropriate forces are calculated which describe the effects of collisions with other particles and geometric objects. The software architecture is fully object-orientated and can be thought of as an "operating system for particles". As the simulation time progresses, *events* (*e.g.,* particle-to-particle collisions) are detected, posted, and subsequently processed by registered *event handlers* (*e.g.,* the force between two colliding particles is computed).

XPSE provides a small three-dimensional CAD-like class library where all geometric objects (*e.g.,* blocks, plates, cylinders, and spheres) are "physically active". Moving donor and receiver surfaces are available for a number of development subsystem models. Simulations of transfer and fusing are evolving to include detailed air breakdown effects and pressure-driven flow of melted toner layers on paper. Many aspects of toner, carrier bead, and ion particles can be represented, including: stochastic size and charge distributions, inter-particle conduction, magnetic interactions (*i.e.,* for simulating the formation of magnetic brushes), particle-particle cohesion, and particle-boundary adhesion. The particle cohesion and adhesion models support a variety of force components such as: hard-core collisions, complex short-range forces due to charged surface patches and *Van der Waals* effects, induced electrostatic and magnetic polarization, and friction. Long-range electrostatic fields are solved on finite-element grids and blended with shorter-range forces that are calculated within the event-handler functions.

By assembling XPSE components (*e.g.,* finite-element grids, collections of toner particles, geometric objects, numerical field-solvers, *etc*.), it is possible to create digital simulators that emulate the behavior of specific pieces of hardware. These constructs may be thought of as *virtual fixtures*, and can be used by scientists and engineers to supplement experimentation on conventional *physical fixtures*. XPSE is suitable for problems where the number of cells and particles are on the order of 10^3 to 10^6. Run times vary widely with the problem being solved, but can range from minutes to tens of CPU hours on a modern PC/Linux workstation.

It should be noted that XPSE is capable of modeling far more complex xerographic systems than those presented in this short paper. A multilayered photoreceptor model is available that supports a number of virtual imagers (*e.g.,* a conventional or VECSEL laser ROS, and a LED-bar array). Detailed exposure profiles can be computed within the virtual photoreceptor's charge-generation layer; and the resulting free charge transported to its surface using realistic transport physics. Several variations of field-dependent quantum efficiency and electron-hole mobility models are supported by the underlying simulation codes.

Hybrid Scavenge-less Development

Consider the square waveform shown in figure 1 that drives the inner-gap wire(s) in an HSD subsystem. The potentials are referenced to the donor electrode. In a practical apparatus, there will also be a DC bias potential that is applied between the donor and receiver (*i.e.*, photoreceptor) electrodes. For purposes of this discussion, assume that the donor surface is located just below the wire in the -Z direction, and the receiver's surface (which happens to be a photoreceptor) is located some distance way from the wire in the +Z direction.

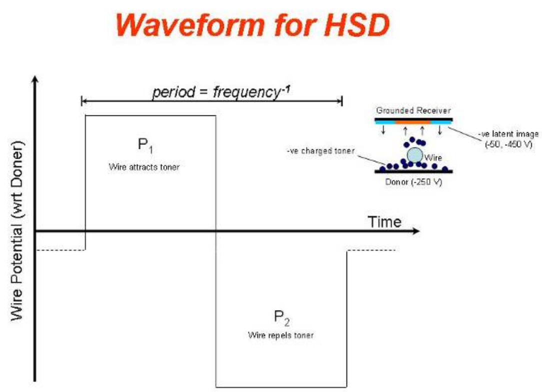

Figure 1. Waveform for Hybrid Scavenge-less Development. Note that this waveform is applied between the wire and donor, not between the donor and receiver! The diameter of the wire is approximately 70 μm. The air gap is of O(500 μm), so the schematic is not to scale.

Assuming negatively charged toner is available on the donor's surface, the positive potential of phase P_1 attracts toner onto the wire from below. Note that it also attracts toner that is already in the nip that is moving towards the receiver's surface, thus preventing high-energy particles from impacting toner that has already developed. During phase P_2, the wire reverses polarity, so the strong local electric field ejects toner particles away from it. Approximately one-half of the toner returns to the donor, but the other half moves towards the photoreceptor. By picking the correct magnitude (*e.g.,* ~2000 Volts) and frequency (*e.g.,* ~10 kHz) of the wire's driving potential, a significant number of toner particles can be persuaded to form a near-stationary cloud relatively near to the photoreceptor. As a charged latent image moves though this toner cloud, particles are attracted to the charged areas that form the latent image. As the toner cloud carries little kinetic energy near the photoreceptor, it has minimal effect on already developed particles.

The Momentum-Control Waveform

The trick to obtaining a powder cloud that behaves in a similar fashion to HSD, but without the use of wires, is to apply a four-phase signal across the donor and receiver's surfaces, as illustrated by figure 2.

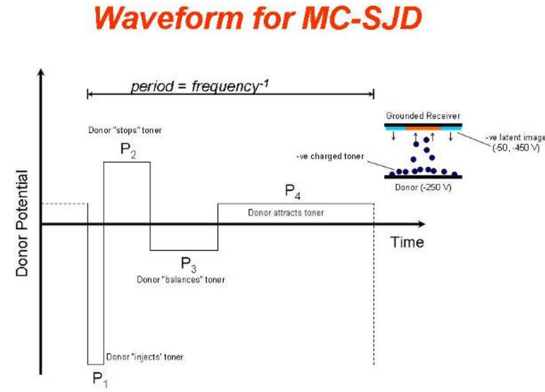

Figure 2. Waveform for Momentum-Control Development. The potentials are referenced to the donor electrode, so negative values drive particles up towards the receiver, while positive values return particles back down towards the donor.

During phase P_1, negatively charged toner on the donor's surface is driven into the air gap. The magnitude of the applied potential is rather high, but its duration is kept short (*e.g.,* ~25 µs). The idea is to only introduce toner into the air gap, not to transport it across to the photoreceptor. In phase P_2, reversing the polarity of the signal forms a retarding field.

The magnitude and duration of this pulse slows the advancing wave of toner and effectively halts it before most particles impact the receiver. This is the "momentum control" (MC) aspect of the invention. Taken together, the first two phases of the MC waveform emulate the first phase of the HSD waveform. That is, a near-stationary cloud of toner particles is generated near the receiver's surface. In order to improve the development efficiency of the system, a small negative potential P_3 is applied for few hundred microseconds. The imposed electrostatic field tends to hold the powder cloud near the receiver as the latent image passes though it. The reason that the sign of the P_3 potential is negative is to counter-act the space charge of the (negative) toner particles within the gap. Finally, a low-value positive pulse P_4 is applied that returns any undeveloped particles back towards the donor's surface. This resets the cycle and the process repeats.

As a practical matter, a sharp waveform is not required. The signal shown in figure 3 is similar to what can be applied with reasonable effort. Of particular concern is that the large initial pulse P_1 does not cause significant air breakdown to occur. When this happens, undesirable artifacts are observed in the final developed image. This limits the magnitude of the applied electric field to less than ~3.0 Volts/µm. If the toner-to-donor adhesion is too high, it may not be possible to eject enough toner into the air gap to achieve acceptable mass development for some chosen process speed. We believe that this limitation can be overcome by a careful selection of the donor material's coating.

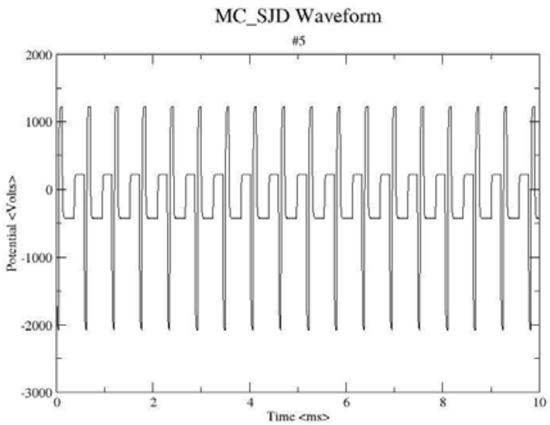

Figure 3: A practical MC-SJD waveform. The large negative pulse ejects particles from the donor's surface into the air gap, while the large positive pulse stops the particles before they impact the photoreceptor.

Figure 6, which is located near the end of this paper, shows a time sequence of eight images taken from an XPSE simulation of MC development. The pictures are orientated so that one is looking into a small section of the development nip. The donor surface is represented as the lower green plane, and the receiver as the (mostly) blue upper plane. A charged latent image of a 4-point Kanji character, which shows up in orange, has been written onto the receiver. The time sequence depicts the creation of a toner cloud during the first cycle of the MC waveform. The cloud is formed during the first 75 µs of the cycle. Approximately halfway though the cycle (*i.e.,* 125 - 220 µs), the cloud is essentially stationary. During this period, toner particles collect onto the less-negatively charged regions of the latent image. The latter images (*i.e.,* 350 – 540 µs) show the cloud retreating back onto the donor surface in preparation for the next cycle.

The image is approximately 75% complete after the first MC cycle. Given that a typical nip transit time is of O(5 - 10) ms, it is possible for the latent image to experience several MC cycles as it traverses the nip region, thus ensuring adequate development has taken place. Figure 4 shows a developed layer of toner particles covering the orange latent image. Note the lack of background particles and the reasonably good coverage of the latent image area. As the simulation was only allowed to run for 2 ms, which is considerably less that a typical nip transit time in a production printer, the development process has not yet reached completion. Simulations indicate that MC-SJD can produce images as good as or better than the HSD process.

The main advantage of wires is that they produce very high local electric fields near the donor's surface, thus they have no problem dislodging nearly all toner on the donor roll. The MC-SJD process must rely on lower AC fields to pull toner from the donor roll. Although conventional jumping systems often have high development efficiency, the MC system tends not to scavenge toner from the donor and thus has more trouble generating dense powder clouds in the nip.

Figure 4: Simulated development of a 4-point Kanji character using 4 µm toner. The simulation was terminated after approximately 2 ms of run time. As this is considerably less than a typical nip's transit time, the image has not yet fully developed.

Experimental Verification

A series of experiments were carried out on a small test rig to verify how well MC-SJD performs in practice. The fixture shown in figure 5 consists of a donor roll that is loaded with a uniform layer of negatively charged toner particles using a magnetic brush. An aluminum cylinder serves as a surrogate for the photoreceptor. To determine how severely a conventional jumping system scavenges toner, a square AC waveform of several hundred Volts is applied between the donor and receiver. The donor is negatively biased for a short period of time, which causes a small solid patch to develop on the receiver. While keeping the AC waveform in place, the DC bias field is reversed. This tends to move toner off the receiver and back onto the donor. As the magnitude of the DC bias field is chosen so as not to overcome the adhesion of the toner particles stuck to the receiver, only toner that has been hit by sufficiently energetic particles will be dislodged and return to the donor. The mass density of the patch is monitored over time using an optical sensor. One typically observes that the mass of the patch decreases very rapidly during this mode of operation, and the patch is essentially gone after only two or three "cleaning cycles".

Figure 5: Experimental apparatus to verify the effectiveness of MC-SJD. The donor roll is to the left, and the aluminum receiver roll is to the right. An AC field, as either a simple jumping waveform or the move complex MC waveform, is applied between the two rolls. If the donor has a negative DC bias, negative toner tends to develop on the receiver. If the donor is positively biased, toner tends to return to it.

In contrast, if the AC jumping waveform is replaced by the MC waveform, a patch will still develop in the presence of a positive DC bias but it will likely have a lower mass density. However, when the DC bias field is reversed, the patch will remain in place for several hundred cleaning cycles.

Conclusion

Though the use of physically realistic computer simulations, we gain insight into how the momentum-control waveform drives charged toner particles across an electrographic development nip. Although equivalent hardware experiments can be performed, it is often difficult to control unwanted side effects and isolate the underlying physics of such complex processes. Of particular note is the observation that the principle driver of scavenging in image-on-image development systems is the normal component of momentum of the toner cloud, at least near the photoreceptor. The relation between their charge, the applied electric field, and forces imposed by air drag largely determines the mean speed of the particles. As the size of a particle is reduced, its mass (and thus momentum) falls as the inverse cube of its radius. This implies that relatively small toner (*e.g.,* in the 3 to 4 µm range) is highly advantaged for this particular technology. The remaining challenge is to manufacture donor surfaces with reduced particle adhesion to allow for sufficient development in high-speed printers.

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Author Biography

John G. Shaw received a PhD in applied physics from the University of Manitoba in 1983. Since then he has worked in the Research and Technology Division of Xerox Corporation in Palo Alto, CA, Ithaca, NY (while visiting at Cornell University), and Webster, NY. His early career revolved around solid-state physics and amorphous-silicon technology. His recent work has focused on the development of toner adhesion models and particle-transport simulations.

Figure 6: Simulated time sequence of a single cycle of the MC waveform. The cycle begins at time 0 µs. A powder cloud is generated as the toner is pulled from the donor's surface into the air gap, peaking after ~100 µs. During the central part of the cycle, the cloud is relatively stationary and has little kinetic energy. The latter pictures show the cloud returning to the receiver's surface, thus resetting in preparation for the next cycle.