Three Dimensional Simulation of Transfer Process

Masami KADONAGA ; Digital Engineering Center, RICOH Company, LTD; Ebina-City, Kanagawa/Japan

Abstract

A three-dimensional calculation of a first transfer subsystem in an electrophotograpy is carried out and toner scatterings on a transfer belt are simulated. This simulation consists of an electric field calculation and a toner movement calculation. In order to estimate electric field precisely, Boundary Fitted Coordinate (BFC) is used for the finite deference method to consider shapes of a photoconductor drum and rollers. To calculate force on a toner in detail, force from electric field, discharge phenomenon, resistivity of materials and toner adhesion force are considered. A toner detaches from the photoconductor and begins to move downward to the belt when the force on the toner is greater than adhesion force between the toner and the photoconductor. Toner movement is calculated according to Newton's law of motion and the dot image on the belt is simulated. Toner scatterings, which result in a loss of sharpness and resolution, are recognized around the peripheral of the dot. The simulation shows that toner scattering formation arises from the toner jumping across the transfer gap before the photoconductor contacts the belt. The effects of transfer parameters on toner scatterings are investigated with the simulation. To suppress toner scattering, the position of the roller, transfer bias, and the resistivity of the belt should be optimized to create an appropriate electric field distribution and to realize that the toner transfer happens in a small gap or in a contact nip with the photoconductor and the belt.

Introduction

Intermediate transfer belt system has been widely used in an electrophotography. The system includes two transfer processes; a first and a second transfer, and image degradation in the transfer processes is a serious problem to obtain a fine image. Image degradation, such as toner scattering(satellites), halo, hollow character, and mottle, degrade a print image. The degradation is not readily examined using a real electrophotograpy machine because it is difficult to precisely determine under what specific conditions transfer occurs. It is useful to investigate transfer phenomena with a numerical simulation under well-defined conditions and some interesting studies have been carried out[1,2]. To investigate alphanumeric images and halftone dots, two dimensional analysis is not appropriate, because it can not reproduce such images. In this study, a three dimensional simulation for the first transfer process is developed to investigate toner scatterings with such images. An example of toner scattering around a 2x2 dot image is presented in Fig. 1. One can easily imagine such toner scattering would adversely affect image quality such as resolution and granularity. This is one of persistent problems in a development of transfer system and will be discussed in this article with simulation results. The simulation includes calculations of electric filed, and toner motion to reproduce toner scatterings around a dot image in a first transfer process.

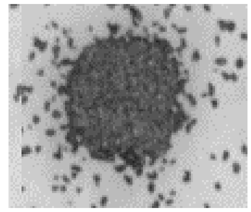

Figure 1. *Toner scatterings around a dot image.*

Simulation model

A schematic diagram of a first transfer process is presented in Fig. 2. It consists of an organic photoconductor, a transfer belt and a transfer roller.

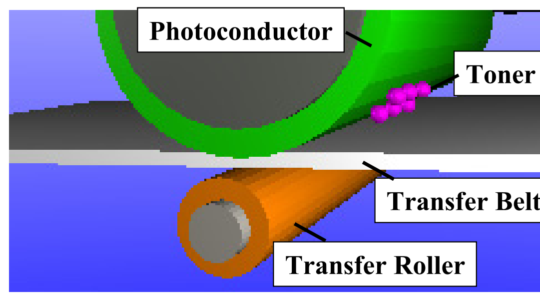

Figure 2. *A first transfer process that consists of a photoconductor, a transfer belt and a transfer roller.*

At the initial state, a latent image and toner particles are deposited on the surface of the photoconductor, and toner particles are adhering to the photoconductor because of an adhesion force, which includes an electrostatic and Van der Waals forces. Figure 3 shows the simulation area of the first transfer process, which includes a photoconductor, toners, a belt, and a transfer roller. Figure 4 shows the magnified view of the calculation mesh around the toner particles deposited on the photoconductor.

With our previous study, toner scattering happens in the pre-nip region of the first transfer area due to the repulsive force between toner particles[3]. Therefore electric field and motion of toner should be calculated simultaneously because the movement of toner alters the electric field distribution around it. The electric field E and the electric potential ϕ in the analysis area are obtained with the Poisson equation:

$$\mathrm{div}\, E = -\mathrm{div}\,(\mathrm{grad}\, \phi) = \rho / \varepsilon \qquad (1)$$

where ρ is the electric charge density and ε is the permittivity. The electric charge density ρ is obtained by considering transport of electric charges and electrostatic discharge. The transport of the electric charges is expressed by the equation of continuity:

$$\partial\rho/\partial t = -\mathrm{div}\, J \qquad (2)$$

where t is the time and J is the current density.

The current density J is calculated including the electrical conduction and the convection as follows:

$$J = \sigma E + \rho v_p \quad (3)$$

where σ is the electrical conductivity and v_p is the process velocity of the transfer system.

Electrostatic discharges happen in some air gaps; photoconductor - belt, and belt - roller. The effect of the discharge is considered by adding electric charges on the object surfaces forming an air gap, when the electric potential difference across the air gap exceeds the Paschen limit. The relations between the Paschen limit ϕ_{pa} and the air gap G are as follows [4]:

$$\phi_{pa} = \begin{cases} 75.4 \times 10^6 \times G & (G < 4.8 \times 10^{-6}) \\ 362 & (8 \times 10^{-6} \geq G \geq 4.8 \times 10^{-6}) \\ 312 + 6.2 \times 10^6 \times G & (G > 8 \times 10^{-6}) \end{cases} \quad (4)$$

The amount of electrostatic discharge Q is estimated by the following equation:

$$Q = \varepsilon_o (\Delta\phi - \phi_{pa}) (\Sigma(d_i / \varepsilon_i) + G) / (G\Sigma(d_i / \varepsilon_i)) \quad (5)$$

where $\Delta\phi$ is the electric potential difference across the air gap, ε_o is the vacuum permittivity, and ε_i and d_i are the relative dielectric constant and the thickness of objects, respectively.

The electrostatic force acting on a toner particle Fe is related to the quantity of electric charge of the toner particle q and the electric field E as the following Eq. 6:

$$\mathbf{F_e} = q\mathbf{E} \quad (6)$$

and the motion of the toner is calculated by Newton's second law of motion:

$$\mathbf{F_e} = d(m_t \mathbf{v_t}) / dt \quad (7)$$

where m_t and v_t are the mass and the velocity of the toner, respectively. In the present model, the toner begins to move when the electrostatic force acting on the toner(Fe) overcomes the adhesion force, and continues to move until it reaches the surface of the belt. Collisions between toner particles are not considered.

The electric field E and the electric potential ϕ are solved again by the Poisson equation (Eq. 1) because the electrical conduction, the advection, the discharges and the movement of toners alter the electric field distribution. These steps are repeated until all the toners are transferred to the belt.

Simulation Result

The simulation is carried out with a boundary fitted coordinate system to transform an irregularly shaped region onto a rectangular region. With the system, the Cartesian coordinates (x,y,z) are transferred into the boundary-fitted coordinates (ξ,η,ζ) and finite difference methods can readily be used to solve the equations mentioned above. Figure 5 shows the sequence of the simulation results, which demonstrate the movement of toner particles. The diameter of the toner is 6μm and its adhesion force is 70nN, which is the sum of the electrostatic and Van der Waals forces. On the photoconductor, 2x2 dot latent image and 480 toners are deposited and transfer bias(600V) is applied on the transfer roller. At T=5ms, some toners are transferred, and at T=15ms, all the toners are transferred on the belt. Figure 6 shows the TOP-view of the toner particles transferred on the belt; except (a), which indicates the toner image on the photoconductor before transfer. Comparison between Fig. 6(a) and Fig. 6(d) shows that toner scattering and image degradation are easily recognized.

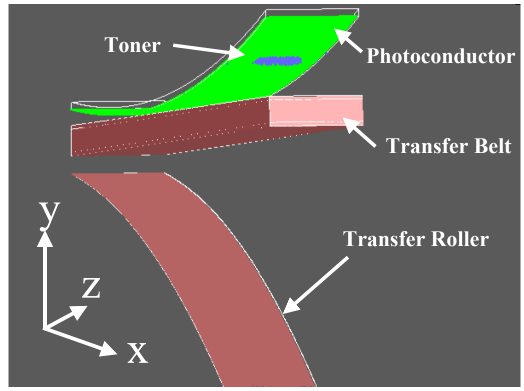

Figure 3. *A first transfer subsystem that consists of a photoconductor, a transfer belt and a transfer roller.*

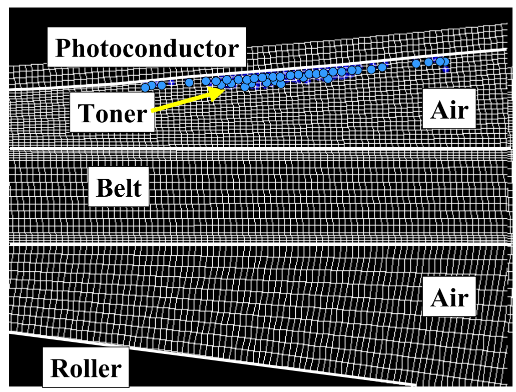

Figure 4. *Magnified view of calculation mesh around toner.*

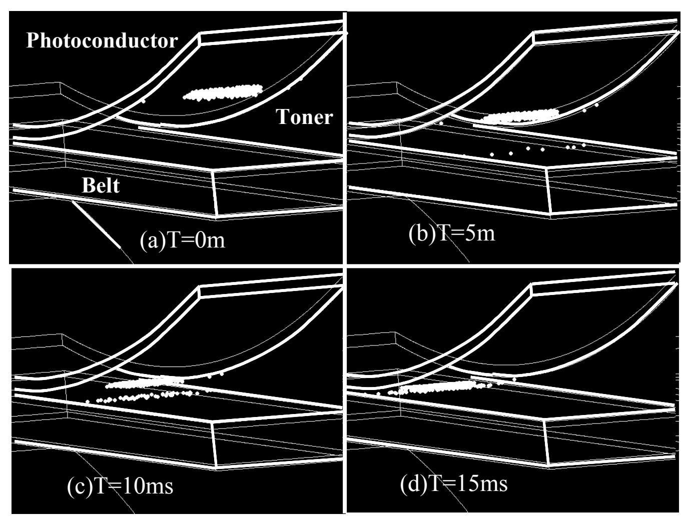

Figure 5. *Sequence of the simulation results, which demonstrate the movement of toner scattering.*

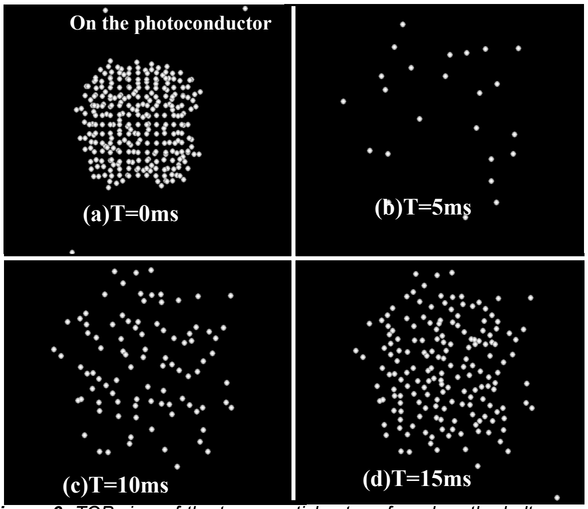

Figure 6. *TOP-view of the toner particles transferred on the belt; except (a), which indicates the toner image on the photoconductor before transfer.*

Parallel Computation

Three dimensional calculation needs enormous number of calculation meshes. Furthermore, consideration of discharge, resistivity, convection and toner movement makes the simulation complicated. It is so large and complex that it is impractical to solve it on a single computer with limited computer memory because it need a considerable computational load. In order to reduce the load, the calculation is carried on the large-scale supercomputer;TSUME in Tokyo Institute of Technology[5] and hybridization of parallel computation techniques, using Multi Processing (OpenMP) in conjunction with the Message Passing Interface(MPI), is adopted. The simulation program starts with MPI initialization and creates OpenMP parallel regions within the each MPI process. Figure 7 shows the relation between calculation efficiency and the number of threads for OpenMP without MPI. The calculation efficiency is the ratio defined as follows,

Calculation efficiency = (calculation time with parallel computation) / (calculation time without parallel computation) .

As the number of threads for OpenMP increases, calculation time reduces, but more effective reduction is needed for the 3D calculation. Figure 8 shows the relation between the calculation efficiency and the number of cores with MPI and OpenMP. The numbers of (a,b,c) indicate the number of devisions for ξ, η, ζ directions of BFC system, respectively, and the total number of tasks is a*b*c. Division in ξ or η direction offers a good calculation efficiency. On the other hand, the division in ζ direction deteriorates the efficiency. It is probably due to a memory contention because MPI is a shared memory method. Memory allocation of ζ direction is probably not suitable for MPI. Figure 9 shows the comparison between the calculation efficiency without MPI and that with the best configuration of MPI. The best configuration of MPI is (4,3,1), and the best performance is realized wtih MPI:(4,3,1) and OpenMP:4 threads. About the 20 times faster calculation than that without parallel technique is realized. More than 4 threads for OpenMP with (4,3,1) for MPI, calculation performance becomes worse and it is probably due to the memory contention. All the calculations shown in the next section are carried out with MPI:4*3*1-tasks and OpenMP:4 threads.

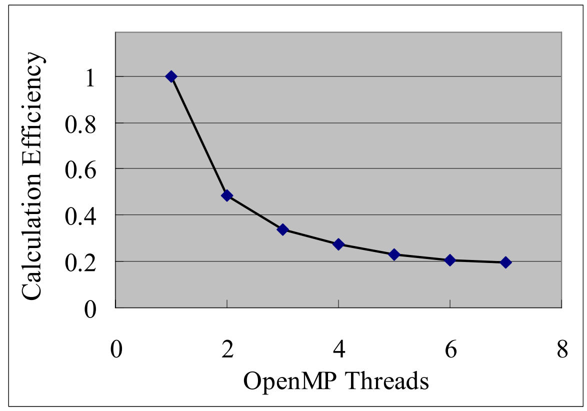

Figure 7. *Relation between the calculation efficiency and the number of threads for OpenMP without MPI.*

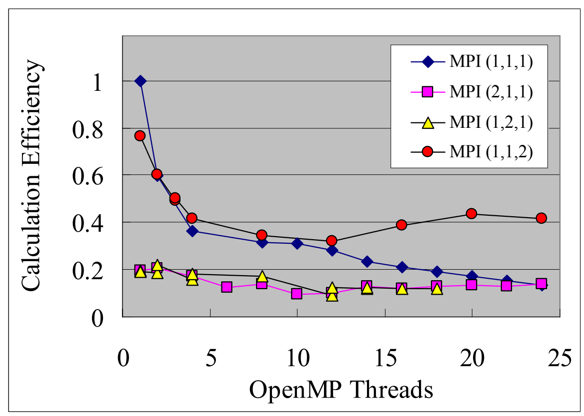

Figure 8. *Relation between the calculation efficiency and the number of threads with MPI/OpenMP. The numbers of (a,b,c) indicate the number of division for (ξ, η, ζ) directions, respectively.*

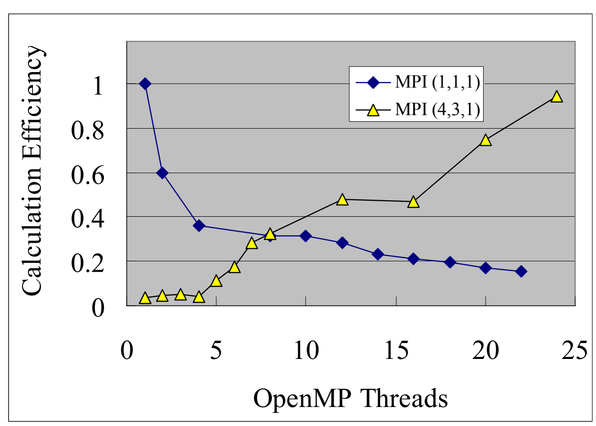

Figure 9. *Comparison between the calculation efficiency without MPI and that with the best configuration of MPI.*

Parameter Study

The simulaton is used to optimize parameters of the first transfer to prevent toner scattering. Figure 10 shows the calculated images on the belt with the transfer bias of 600V and 1200V. Higher transfer bias causes more image degradation and this tendency is well known with many experiments. The effect of the position of the roller, the resistivity of the belt, and the transfer bias are investigated and results are shown in Fig. 11. Table 1 shows the values of parameters of the calculations for Fig. 11. The position of the roller is the distance between the center of the transfer roller and that of the photoconductor. "+2mm" indicates that the roller is set in the upper stream direction and the distance is 2mm. The result of (a) is the worst case and (d) is the best one. The simulation can investigate the effect of transfer parameters on images, and the result shows that the parameters should be optimized to create an appropriate electric field distribution and to realize that the toner transfer happens in a small gap or in a contact nip with the photoconductor and the belt.

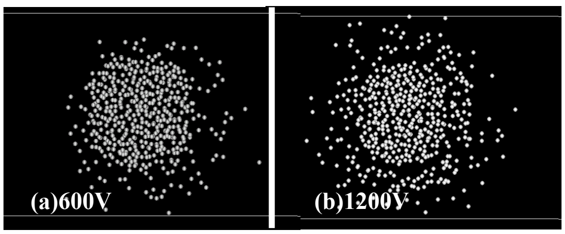

Figure 10. *Iimage on the belt with the transfer bias of 600V and 1200V.*

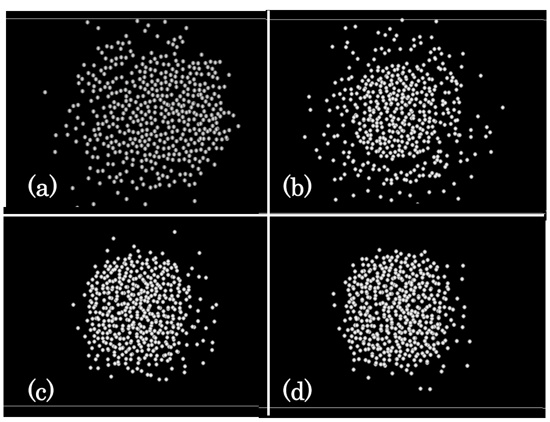

Figure 11. *Investigation of the effect of parameters on toner scattering.*

Table 1 The values of parameters for Fig. 11

	Position of Roller	Resistivity of the belt	Transfer bias
(a)	+2mm	$10^4 \Omega m$	1200V
(b)	+2mm	Insulator	1200V
(c)	-2mm	Insulator	1200V
(d)	-2mm	Insulator	600V

Conclusion

A three-dimensional simulation of a transfer process is developed and carried out on the supercomputer;TSUBAME, and toner scatterings are simulated. This simulation consists of an electric field calculation and a toner movement calculation. Parallel calculation methods of OpenMP and MPI are used to reduce calculation time. In order to calculate electric field precisely, Boundary Fitted Coordinate is adopted, and to estimate force on toner in detail, force from electric field, discharge phenomenon and toner adhesion force are considered. Toner separates from photoconductor and begins to move downward when an electrostatic force is greater than the adhesion force and toner movement is calculated according to Newton's law of motion. The effects of the position of a transfer roller, transfer voltage and resistivity of a transfer belt are investigated with this simulation and the simulation can indicate the optimal condition to prevent toner scattering. To suppress toner scattering, the position of the roller, transfer bias, and the resistivity of the belt should be optimized to create an appropriate electric field distribution and to realize that the toner transfer happens in a small gap or in a contact nip with the photoconductor and the belt.

Farther work

The simulation needs more detail models for more useful calculation. Toner charge and diameter distributions, a distribution of adhesion force, wider calculation area, collision between toners, and electric field dependence of conductivity, should be considered for a more realistic calculation. In near future, with the advancing parallel calculation techniques, a more realistic 3D simulation will be established and will become a useful tool to design a transfer process.

References

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Author Biography

Masami Kadonaga received his B.S. and M.S. degrees in applied physics from University of Tokyo in 1987 and 1989, respectively. He joined Ricoh in 1989 as a member of research scientist, and has been working in the area of computational dynamics. Firstly, he studied the inkjet printing technology, and recently he has been working on the field of electrophotography. He received his Doctor of Engineering from Tokyo University of Agriculture and Technology in 2003.