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Technology of the IBM 3800 Printing Subsystem Model 3

IBM has introduced the 3800 Model 3 electrophotographic printer, which is a modified version of the previously developed Model 1. The Model 3 improves the print density of the 3800 Model 1 from 180 × 144 pels/in.^{2} to 240 × 240 pels/in.^{2} and permits each pel to be addressed individually. The laser print head was modified to create the higher density by using the same laser, focusing to a smaller spot size, slowing down the speed of the rotating mirror, and developing a dual-beam system. Beam-power balance and beam separation were selected for optimum print quality. The dual-beam print head required the development of a new photoconductor with improved sensitivity. That photoconductor also displayed a significantly increased lifetime. Improved manufacturing techniques were developed to reduce photoconductor defects. A digital voltmeter and a new processor were introduced that reduced the cost of the process servos by eliminating previously hard-wired elements.

Introduction

As indicated in the introductory paper [1], the IBM 3800 Printing Subsystem Model 3 is a high-speed, all-points-addressable printer that provides improvements in print quality, function, and ease of use. It utilizes many of the reliable features of the 3800 Model 1, originally introduced in 1976. Print quality is improved because of the higher print-element density of 240 × 240 pels (picture elements) per square inch over the Model 1 density of 180 × 144 pels/in.^{2}. This, coupled with all-point addressability, gives the user access to previously unavailable printing capability and flexibility. The electronic forms feature allows the user to easily create a large number of standard forms, which are stored in computer storage for printing out as required. Proportional spacing of a larger number of type fonts is now also available. The improved resolution also offers the opportunity to print smaller type fonts.

The Model 8 is a version of the Model 3, which can be used to print kanji characters. The number of kanji characters that the Model 8 can print (22 500) is now three times larger than was possible using its predecessor, the Model 2. With the 240 × 240 pels/in.^{2} density, kanji legibility is also enhanced.

The rationale for developing the 3800 Model 3 was based upon three key considerations:

- Users needed improved print resolution.
- Users needed to have a more flexible printer with all-point addressability and improved capability to manipulate page composition. This item, combined with the first item, now permits users to have a graphics capability.
- Increased labor costs for service dictated improved reliability and diagnostic capabilities.

The basic electrophotographic process of the 3800 Model 1 is described elsewhere in this issue [1]. This basic process has remained unchanged for both the 3800 Models 3 and 8. The key technology areas that have been modified are the laser print head, the photoconductor, and the process servos.

The reduced pel (dot) size is produced by a smaller laser spot size. A new photoconductor has been developed, which not only has greater sensitivity required for 240 × 240 pels/in.^{2} but has improved life. A digital voltmeter and a new processor are used to monitor and cost-reduce the servo control of many of the process variables, such as print contrast and fuser temperature. As an added benefit, these variables are actually more closely controlled than in the Model 1.

Laser print head

In order to achieve the 240 × 240 pels/in.^{2} density while maintaining the Model 1's process speed of 0.81 m/s (32 in./s), design modifications were required to the laser print

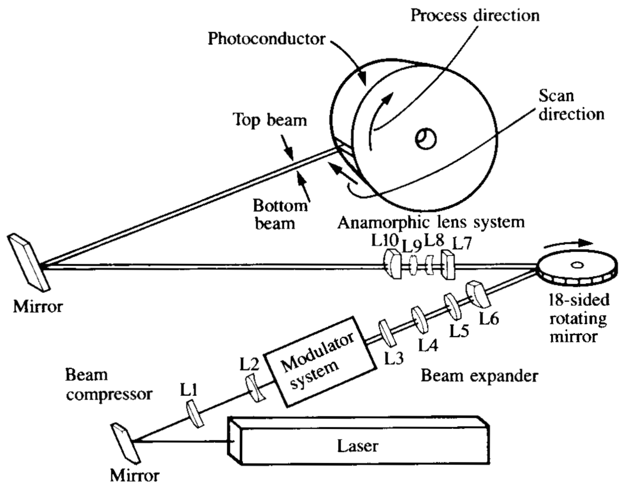

Figure 1 The laser-optical system of the IBM 3800 Model 3 showing the top and bottom beams reflecting off the 18-facet rotating mirror.

head [2, 3]. A change in the speed of the rotating mirror was required to compensate for the fact that the Model 3 produces 2.2 times more addressable spots per unit area than the Model 1. A smaller laser spot size was also required to produce the smaller printed dot.

A decision was made early in the program to retain the same helium-neon laser as the Model 1 for reasons of design, testing, and procurement economy. It was also decided for reasons of economy not to change the process speed. In order to produce the 240 × 240 pels/in.^{2} two methods were considered: first, increasing the mirror speed from 15 300 rpm to about 25 400 rpm utilizing a single beam as in the 3800 Model 1; second, reducing the mirror speed to 12 700 rpm and developing a two-beam system. The first method was considered to have significant difficulties in the areas of the high-speed rotating mirror and in the fast rise times required from a single-beam modulator. It was decided to explore a two-beam system with the lower rotating mirror speed.

The Model 3 spot size was reduced from that of the Model 1, which had a nominal diameter of 0.36 mm (0.014 in.) measured at the 10% points of its Gaussian distribution. The Model 3 permits a slightly elliptical spot to compensate for scan-line velocity so that a round dot is produced. The spot size is nominally 0.19 mm (0.073 in.) in width and 0.22 mm (0.0088 in.) in height at 10% of its Gaussian distribution.

The Model 3 uses two printing beams to achieve the higher scan-line density of 240 scans per inch. The beams scan across the photoconductor from reflections off a spinning multifaceted mirror, which rotates at 12 700 rpm, 83% of the Model 1 mirror speed of 15 300 rpm, as shown in **Figure 1**. These two coherent laser beams do not lie side by side on adjacent scan lines because their proximity would cause interference fringes. Instead, they are separated by two dot positions and interlaced to create the full scan pattern, as shown in **Figure 2** and discussed in [4]. The interlaced scan pattern begins on scan line 1 with the top (T) beam of rotating mirror facet 2. Scan line 2 is created by the bottom (B) beam of facet 1. Note that the top beam of facet 1 is not used. Scan line 3 is created by the top beam of facet 3, and so forth for the remainder of the scan lines.

The plastic toroidal lens used in the Model 1 was already being manufactured to state-of-the-art tolerances for lenses of its size. It was not possible to further reduce those tolerances to achieve the smaller and slightly elliptical spot shape of the Model 3. Therefore, a new anamorphic (unequal magnification along orthogonal axes) lens system [5] that does not employ a toroidal surface was developed.

The entire optical system from laser to photoconductor surface must be diffraction-limited. Analysis showed that only a 5% wavelength of wave-front distortion would increase the focused beam diameter by about 20%. It was also necessary for manufacturing tolerances to limit the total optical path difference (OPD) between the axial and marginal rays caused by optical aberrations to 2.5% of a wavelength.

The lens elements L1, L2, and L3 shown in Fig. 1 were each designed to have less than a 1% wavelength of OPD by using sufficiently low-numbered apertures. A type of image distortion, known as coma, was minimized by glass selection.

Lenses L4 and L5 were designed to be very nearly aberration-free as a pair. Lens L6 was designed for acceptable spherical aberration and focal range at the rotating mirror by selecting the focal length, and, therefore, the numerical aperture at which the lens works. Coma was also minimized by glass selection.

Lens L7 is a negative cylindrical lens whose axis is perpendicular to the plane of scan. Lenses L8 and L9 are spherical elements, and L10 is a positive cylindrical lens whose axis is parallel to the plane of the scan. This combination of elements was designed to produce low wave-front distortions over the entire scan length. It also corrects the distortions introduced by the constant angular velocity of the rotating mirror so that constant linear velocity is produced at the photoconductor. Lens L7 flattens the field while contributing some of the required power; lenses L8 and L9 are bent to minimize aberrations, particularly field curvature. Lens element L10 contributes the final power required to bring horizontal and vertical fans of rays to a common focal point. Both cylindrical surfaces of L6 and L7 have opposing plane surfaces to eliminate the need for alignment of axes between opposite surfaces.

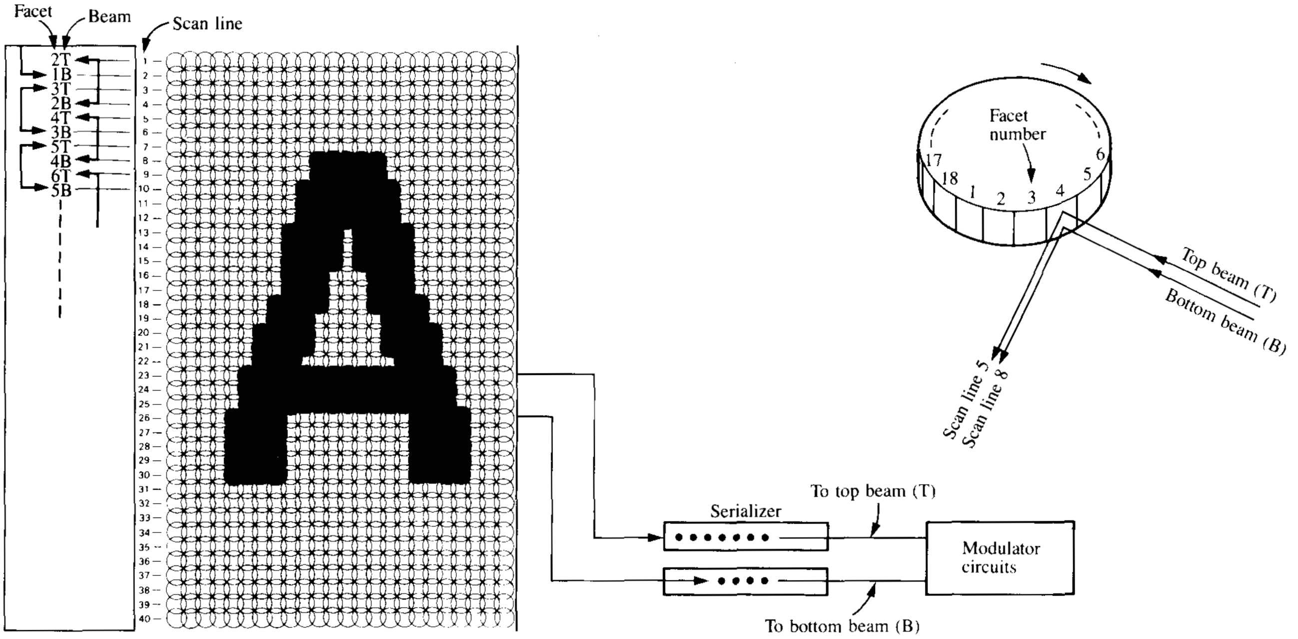

Figure 2 Scan interlace is produced by reflecting the top and bottom beams off a single mirror facet and separating these beams by two scan lines.

With this anamorphic system of cylindrical and spherical lenses, all the elements are now manufactured to standard industrial tolerances. The high tolerances of the plastic toroidal lens have been eliminated. However, the alignment of the elements is now more critical and requires accurate alignment techniques and tooling.

Photoconductor requirements

For a number of reasons the Model 3 required use of a more sensitive photoconductor. The laser power in the Model 1 beam was 19 mW, while in one of the Model 3 beams it is 2.5 mW. The maximum Model 3 print plane power is limited by the optical efficiency of the modulator system. The dot exposure time for the Model 1 was 75 ns, while for the Model 3 it is 62.5 ns. The density in the scan direction (Fig. 1) was 180 dots per inch for the Model 1 and is 240 dots per inch for the Model 3. In the process direction (Fig. 1), the Model 1 density was 144 scans per inch and the Model 3's is 240 scans per inch. From these parameters the sensitivity requirement for the Model 1 can then be calculated to be an exposure energy of 5.7×10^{-6} W-s/cm^2, or 5.7×10^{-6} J/cm^2. Similarly, the sensitivity requirement for the Model 3 can be calculated to be an exposure energy of 1.4×10^{-6} J/cm^2. It can be seen from comparing the sensitivity requirements that a photoconductor over four times as sensitive was needed for the Model 3. The decision was made to move from the single-layer photoconductor of the Model 1 to a multilayer photoconductor structure, similar to that developed for use in the IBM Copier Series III program.

In the characterization of photoconductor sensitivity, an analytical model was useful. The sensimetric curve of a given film follows an exponential curve and can be described by the equation

$$V_L = V_{SAT} + (V_D - V_{SAT})e^{-E/E_a},$$

where

V_L = Exposed potential (volts),
V_D = Dark potential (volts),
V_{SAT} = Saturation voltage obtained at very high exposure energy (volts),
E_a = "Energy constant" for a given photoconductor (joules/cm^2), and
E = Actual exposure energy (joules/cm^2).

By characterizing a number of photoconductor films from various lots, it was possible to define an expected range of E_a.

A key photoconductor characteristic was found to be in the slope of the sensimetric curve shown in **Figure 3**. If the laser exposure energy is allowed to reside in the saturated region of the sensimetric curve, the effective size of the Gaussian laser spot, as indicated by a developed dot, varies as the laser exposure energy varies. In other words, character-stroke width would increase with an increase in laser exposure energy. This phenomenon results from the development of the exposed image by toner, which is controlled by the developer's bias voltage and photoconductor's exposed potential. This effect is

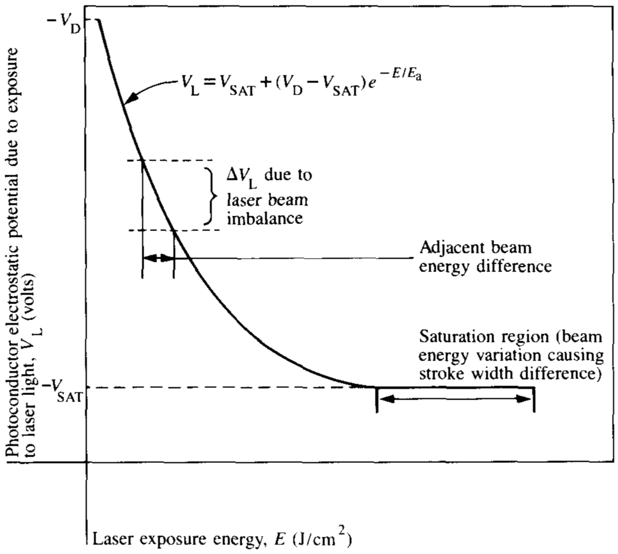

Figure 3 Photoconductor sensimetric curve. Typical photoconductor discharge response to laser exposure.

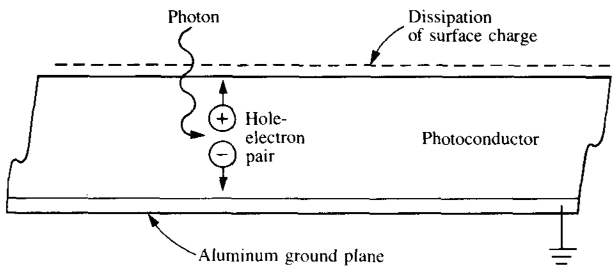

Figure 4 Charge dissipation in a single-layer photoconductor (not to scale).

minimized both by selecting an operating point out of the saturation region and by maintaining the laser exposure energy within a specified tolerance.

Because of the two beams, the slope of the sensimetric curve became quite important in the selection of the correct operating point. The power in each of the two beams should preferably be equal, but some tolerance had to be allowed. Because of the number of variables in the Model 3 print head, this beam-power tolerance, or beam imbalance, turned out to be a key parameter.

Referring to the sensimetric curve, it can be seen that as the laser exposure energy decreases, small amounts of beam imbalance cause significant differences in the exposed potential, ΔV_L, for two adjacent scan lines. This results in variations in optical density on the printed page. The stroke-width requirements and laser-beam-power imbalance created a need to specify the slope of the photoconductor's sensimetric curve, as well as the sum of the power contained in both beams.

Photoconductor

The photoconductor is the medium on which the latent images are generated by either laser or optical means and on which are subsequently developed the toned image for transfer to paper. Photoconductivity, or the dramatic increase in conductivity by exposure to photons of light energy, is the property that allows the selective neutralization of the photoconductor's surface charge. This process begins with charge generation when a photon generates a hole-electron pair. The charge at the surface is then dissipated when the hole is transported to the negatively charged surface and the electron is transported to the aluminum ground plane, as shown in **Figure 4**, which represents charge dissipation in a single-layer photoconductor.

Significant improvements in charge-injection efficiency and charge-carrier mobility are possible over that of the single-layer embodiment, when the charge generation and transport functions are separated. This modification results in a sensitivity increase of approximately 4× over the organic single-layer photoconductors (See **Figure 5**).

The IBM Series III copier photoconductor embodiment of this concept [6] used chlorodiane blue as the charge-generating dye and p-Diethylaminobenzaldehydediphenyl hydrazone (DEH) as the transport material, as shown in **Figures 6** and **7**.

While an early evaluation of this multilayer photoconductor indicated it would meet the electrical charging and discharging requirements of the Model 3, it was also obvious that it would not meet the print quality requirements because of the presence of random defects. These defects were not visible on Series III copiers because of the nature of the copying and printing process employed. They employ a negative-imaging process that discharges the white background (or untoned area). The Model 3 employs a positive-imaging process that discharges the black print (or toned area). The difference in imaging polarity is offset by a difference in developer polarity, which is needed to produce the same black print on white background. The defects in the photoconductor resulted in tiny discharge spots, which in a copier tended to be invisible (white on white) unless they happened to be superimposed in a black area. Even then they were rarely visible because of the toner fill-in during development. However, on the Model 3 they reproduced as black spots and lines on white background.

These defects were traced to contamination of the manufacturing photoconductor coater, and an extensive process development and manufacturing engineering effort was required to minimize them. A process modification was made to eliminate process directionality (which tended to elongate spot defects) on the critical adhesive sublayer. In addition, a new process was implemented on the charge-generation layer to improve its uniformity. Solution concentrations and viscosities were modified to accommodate these process changes. Stringent manufacturing-process controls and an operator training program were developed. A quality-control plan for raw-material inspection was implemented.

The improved sensitivity of the multilayer photoconductor, however, also had its disadvantages: it could be permanently damaged by excess exposure to room ambient light. The amount of damage is a function of light intensity and wavelength. Light shields were installed around critical areas of the printer to prevent this damage and procedures were updated to educate service personnel.

Another characteristic of the new photoconductor required a design refinement to the cleaning system. There are phenomena that can cause toner to permanently fuse to the photoconductor and form small spots and line defects on its surface. For example, the impact of brush fibers on the drum transmits sufficient energy to the toner-photoconductor interface to melt a few of the toner particles and fuse them to the photoconductor. With the single-layer Model 1 photoconductor, small defects printed out as gray or black spots and lines on white paper. This was because the fused-on toner could not support an adequate electrostatic charge to repel toner particles at the developer station.

The presence of the top layer of DEH allows the fused-on toner spots and lines to support an electrostatic charge and therefore repel toner at the developer. This results in the appearance of voids in black areas, which can result in degradation of print quality. It was discovered that careful chamfering of the brush's fiber tips controlled the situation effectively by decreasing the amount of energy dissipated at impact.

The multilayer photoconductor was found to be less fragile than the single-layer photoconductor, thus reducing the frequency of damage caused by scratches. Not only did the multilayer photoconductor meet the print quality requirements at the beginning of a new panel advance on the drum, but it has been shown to be stable over its entire panel life. The life of the new photoconductor is more than six times greater than that of the original Model 1 photoconductor, which led to the decision to install it on all existing Model 1 machines.

Process control

The Model 3 contains a series of improvements in monitoring and process control. Improved monitoring capabilities of a number of key machine parameters were required due to increasing labor costs. As a result, a digital voltmeter (DVM) was developed to monitor the analog voltage levels from a number of machine test points and sensors. These levels can now be monitored directly by the customer engineer.

The user's need for improved printer flexibility cited in the Introduction required that all printed dots be individually addressable. This in turn required that a new system processor called the instruction execution unit (IEU) be developed [7]. It was then decided to utilize the DVM in conjunction with the new IEU to control the various servos throughout the machine. As a result, a number of analog servo circuits could be eliminated, resulting in a cost savings and improved reliability. The new IEU continuously monitors the DVM output to servo-control a number of variable parameters. The desired value of these parameters is stored in nonvolatile storage for use by the IEU. This permits improved accuracy of the servoed parameters such as temperature of the fuser roll, where rise time and overshoot of the heating elements are minimized.

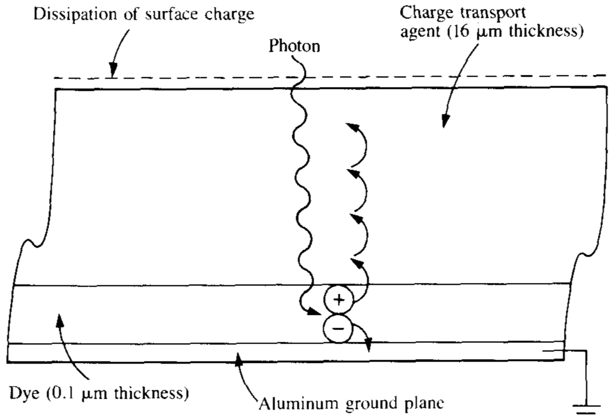

Figure 5 Charge dissipation in a multilayer photoconductor (not to scale).

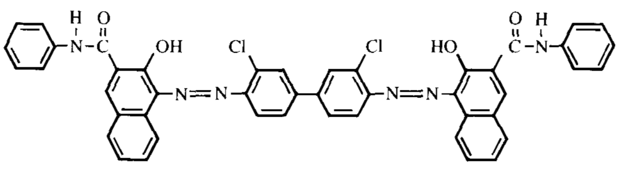

Figure 6 Chlorodiane blue (CDB)–charge generation agent.

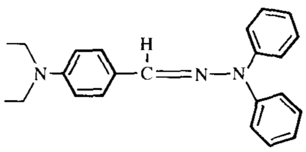

Figure 7 p-Diethylaminobenzaldehydediphenylhydrazone (DEH)–charge transport agent.

During the development of the Model 3, engineering changes could be more easily implemented than previously, because the IEU's microcode could be more easily altered than the Model 1's hard-wired circuits.

The optical-mark-sensor (OMS) head, which senses the darkness of a control mark printed on the edge of the page, was redesigned for improved reliability. Instead of sensing the absolute darkness level, as was done on the Model 1, it now senses the ratio of black mark to light paper. The voltages from the OMS head are monitored by the DVM, and the amount of toner dispensed in the developer is controlled by the IEU's servo algorithm. In this manner, the reliability of the OMS head itself is increased while the accuracy of the print contrast servo system is somewhat improved.

Summary

The technology features of the 3800 Model 3 and the rationale for its development have been described. A discussion has been presented on the redesign of the laser print head. The analysis method for selecting the laser-beam powers with the new photoconductor has been described. The design of the photoconductor and the manufacturing improvements have been presented. The combination of the digital voltmeter and the instruction execution unit to reduce servo costs was also discussed.

Acknowledgments

In the development of the 3800 Model 3, there were many people who made important contributions to ensure its success. While it is not possible to mention each individual, we will attempt to identify those persons who were responsible for seminal aspects or played a key role in the basic technology: H. Anderson, J. Donahue, W. Hayter, P. Jachimiak, R. A. Jensen, M. R. Latta, M. E. Rabedeau, R. Rectenwald, R. Voge, and R. Whitefield.

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