ELPHI, A New Approach to Electrophoretic Imaging

G. Bartscher, J. Breithaupt, and B. Hill*

Technical Electronics Institute, Aachen University of Technology, 52056 Aachen, Germany

A new printing process called ELPHI (*EL*ectro*PH*oretic *I*maging) is presented. An electronic print plate with an electrode for each pixel of the final image generates an electric field. Charged dye particles of a liquid toner suspension migrate under the influence of the electric field and deposit on the pixel electrodes. The gray scale of each pixel is controlled by the applied voltage and by the time during which the voltage is applied. After development the toner image is transferred to paper. A comparison of the ELPHI process with common imaging technologies shows the advantages of the new approach. An experimental printing setup that is described is used for measuring the process characteristics. The electronic control of the process allows for correction of the nonlinear characteristics. Printing samples of two different electrode test structures are presented to demonstrate the potential of the ELPHI process for the printing of high-quality gray-scale images.

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Introduction

The increasing use of computer and communication technologies has led to a rapidly growing market in hardcopy devices for high-quality images. Naturally these devices should record the desired image in a short time period and do so at low cost. Currently no process exists to fulfill all three requirements of high quality, high speed, and low cost for gray-scale images.

On one hand, we have processes that produce high-quality pictures in relatively short time periods but at high cost (for example, thermal dye sublimation, which consumes rather large quantities of dyed foil relative to the size of the recorded image). On the other hand, there are fast processes with low costs but they have limited application in terms of high quality; consider, for example, laser and ink-jet printers. Problems here arise out of the absence of true gray-scale capability. A gray scale can be realized only by rastering, which results in reduced effective spatial resolution.

Also conventional printing processes such as offset printing have their disadvantages. Low cost is achieved only if many copies are printed, and some preparation time is necessary before printing can start.

Electrophoretic Imaging in the Past

Processes that use electronically controlled electrophoretic recording techniques may overcome the above difficulties, thus fulfilling the three requirements of high quality, high speed and low cost.

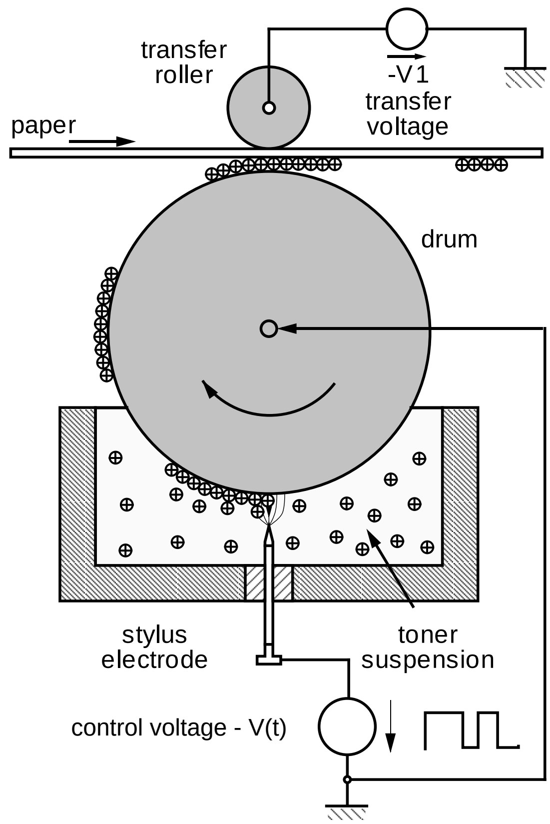

Figure 1. Principle of an older electrophoretic recording process.[1] The amount of toner deposited on the image drum is controlled by the voltage applied to the recording electrode. For a complete image, the drum rotates and additionally the electrode moves parallel to the axis of the image drum.

An approach to electrophoretic image recording has been made by Rothgordt and colleagues.[1–3] The basic principles of their process are shown in Fig. 1. A metal stylus with a narrow tip is held near a rotating drum with a conducting surface. Liquid electrostatic toner is fed into the gap between stylus and drum. This toner consists of an insulating carrier fluid in which electrically charged dye particles (toner particles) are suspended. Similar toners are used for liquid development with photoconductors or electrostatic plotters.

A voltage of several hundred volts is applied to the stylus so that an electric field is created in the gap to the electrically grounded drum. Charged dye particles of the liquid toner are moved under the influence of the electric field (this phenomenon is called *electrophoresis*) and deposited on the surface of the drum. By varying the applied voltage the amount of deposited toner particles can be controlled so that arbitrary gray scales can be recorded.

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* IS&T Member.

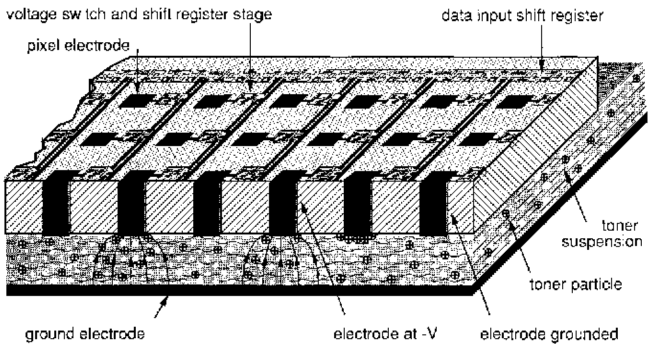

Figure 2. Basic principles of the ELPHI process. All pixel electrodes of the electronic print plate are activated simultaneously so that a complete image is recorded in a single development step. This image is electrostatically transferred to paper (not shown).

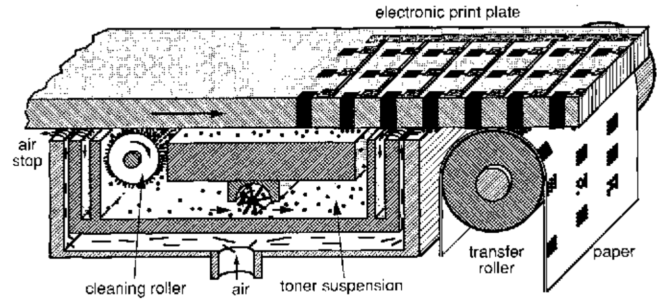

Figure 3. Sketch of the complete ELPHI process with cleaning, development, and transfer. The depicted development station is surrounded by an air stop in order to keep the toner suspension inside so that background caused by excessive liquid is minimized.

To record a complete image, the stylus has to be moved in two dimensions over the surface of the image drum. One dimension is accomplished by rotation of the drum and the other by scanning the stylus parallel to the axis of the drum. At the end, the recorded image has to be transferred from the drum to a final image carrier (e.g., paper).

Although the authors demonstrated the ability of the process to achieve good gray scales and even full-color images, some major disadvantages remain. With only one stylus the recording time for a single picture is about 15 min for an image of A4 size.[1] For an improvement in recording speed, bars with parallel electrodes have been used. This led to lower voltages that prevented electrical breakdown between neighboring styli, thus prolonging development time per pixel.

The basic problem of the described process is its limited spatial resolution. A maximum of about 4 lines/mm has been achieved.[3] Higher resolutions are very difficult to obtain because the electric field broadens from the tip of the stylus to the surface of the drum, resulting in a pixel diameter that is larger than the diameter of the stylus. Of course, this broadening also depends on the distance between stylus and drum. This distance cannot be too small because some liquid toner is needed in the gap to supply enough dye for the deposition of a satured black pixel.

ELPHI, A New Approach

The basics of our new approach for a process of **el**ectro**ph**oretic **i**maging (ELPHI) are shown in Fig. 2. An important component is the electronic print plate, which contains pixel electrodes in an insulating material, as well as electronic drive circuits to control the voltage of each pixel electrode individually. The process has two major steps: development and transfer.

For the development step the print plate contacts a liquid electrostatic toner, just as the stylus does in Rothgort's device. Instead of a rotating drum, we use a simple grounded metal plate. Through the electronic control system, voltages are applied individually to each pixel electrode. These voltages result in an electric field between electrode and grounded plate. Toner polarity and direction of electric field are chosen to deposit particles directly on the electrodes. By modulating the applied voltage or the time during which the voltage is applied, the amount of deposited toner particles and thus optical density may be controlled.

If all pixel electrodes are activated simultaneously, a complete image can be recorded in one single development step. This results in a short recording time for an image because the time needed to develop a single pixel may be the same as that needed for the whole image.

After development, the second process step, transfer, is realized. The toner image on the print plate is transferred to a final image carrier. This may be accomplished by an electrostatic transfer as used, for example, in xerography.

For a complete recording process some additional steps are necessary, as depicted in Fig. 3. The electronic print plate moves from the left to the right. Prior to development a brush cleans the print plate so that toner particles remaining from earlier pictures are removed. Afterward, the development step produces a gray-scale image on the surface of the print plate. To avoid a background caused by excessive liquid remaining on the surface, this liquid has to be removed. This is accomplished by a specially constructed development station, so that the toner fluid is kept inside. At the end, the image is transferred to the final image carrier by pressing paper against the print plate with a drum of conducting rubber. To assist in the transfer of electrically charged toner particles, a voltage is applied to the drum.

Some Characteristics of ELPHI

If we compare the ELPHI process with the well-established xerographic process of laser printers, ELPHI reveals some advantages. The xerographic process has four major steps: charging, exposure, development, and transfer. In the first step the photoconductor receives a uniform electrostatic charge. In the second step the surface of the photoconductor is scanned by a modulated laser beam. The charge is dissipated in proportion to light intensity and exposure time, thus producing a latent electrostatic image. The remaining steps (development and transfer) are the same as those of the ELPHI process.

An important advantage of the ELPHI process, especially for gray-scale images, is that it has only two steps; the first two steps of xerography (charging and exposure) are not necessary. Problems with xerography arise from the charging step and the photoconductor. It is difficult to obtain a stable and reproducible amount of charge on the surface of the photoconductor because charging depends on parameters such as air humidity and temperature. Different amounts of charge lead to different gray scales, even if the controlling device (exposure) supplies the same signal. Another instability is caused by temperature- and history-dependent behavior of the photoconductor. The ability of a photoconductor to conduct changes with temperature and with previous charging and exposure cycles, thus affecting gray-scale reproducibility. These problems are avoided by ELPHI because neither charging nor exposure is necessary. The electrostatic image that is necessary for development is produced by the electronic print plate. With electronic control circuits it is easy to achieve a very high accuracy compared to that of a photoconductor/charging device system.

During development (and afterward) the electronic print plate enhances the possibility of direct electronic control of every single pixel. This provides the opportunity to compensate electronically for changes in, for example, toner concentration. Taken together, these are advantages for a basically stable, simple, and reproducible process and for the straightforward transformation of electronically stored pictures into permanent images on paper.

Spatial resolution with ELPHI is not limited as with Rothgort's device by broadening of the electric field because the pixel size is precisely defined by the shape of the electrodes. No deposition will take place on the surrounding insulating material.

Because direct control of the optical density of every single pixel may be possible with the ELPHI process, only rather low spatial resolution is necessary, compared to that of a process that achieves gray scales by dithering techniques. High-quality images for normal visual perception with true gray-scale pixels require resolutions of about 300 to 600 dpi (pixel sizes of about 84 to 42 μm) compared to some 1000 dpi for raster gray scales.

With regard to continuous-tone images, ELPHI also shows some advantages when compared with conventional printing technologies such as offset printing, in which different optical densities are obtained by varying the dot size, which results in different patterns depending on the printed halftone. For the described ELPHI process dot size and shape principally stay the same, even for different halftones, so that homogeneous areas can be printed for any density.

Electrophoretic processes were proved capable of printing full-color images[2] by superimposing pictures of, for example, three different colors such as cyan, magenta, and yellow. Liquid electrostatic toners in these colors as well as black are commonly available. A full-color ELPHI process might work with or without an intermediate carrier. With an intermediate carrier the different colors are sequentially collected on the carrier. Then the complete picture is transferred to paper. Without an intermediate carrier different colors are superimposed on the print plate and at the end the full-color picture is transferred from the print plate directly to paper.

The ELPHI process requires an electronic print plate with individually switchable electrodes. At first glance, this seems to be a severe problem if the desired number of pixels is considered. For example, for a print plate of A4 size with 300 dpi about 2,500 × 3,500 = 8,750,000 pixels are needed. Such structures are under investigation for flat panel displays, for example, for active matrix liquid crystal displays (AMLCDs). Recently the fabrication of an AMLCD in approximately A4 size with 6,300,000 pixels has been reported.[4] As a consequence, it is expected that the technology necessary to produce the desired ELPHI print plates will be available in the near future.

The Experimental Printing Setup

Figure 4 shows the experimental printing system developed to demonstrate the basic principles of ELPHI in the laboratory. It comprises the already depicted printing mechanics (Fig. 3) and some electronic equipment for controlling the mechanics and for computing the data to be printed. The "handmade" print plate that we use in a first step is aimed at a resolution of 40 dots per inch in the final printout. Fabrication of such a print plate needs no complicated technology steps. Quadratic print electrodes of 500 × 500 μm in a square are embedded in an insulating resin. The grid of the electrodes is adapted to electronic raster sizes (1/10 in. in the x direction and 1/20 in. in the y direction) to facilitate connections to the controlling driver circuits. In this early stage of the technology, we use discrete driver electronics in the form of cascaded high-voltage integrated circuits, originally designed for use as display drivers. Voltages up to 150 V can be supplied. An image produced with this print plate has 128 × 128 pixels in the final printout.

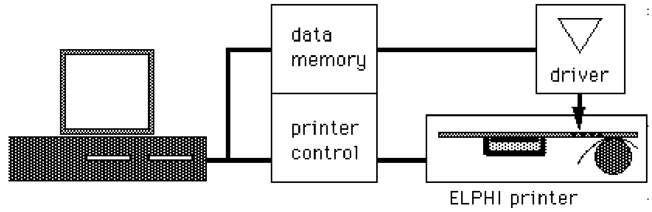

Figure 4. Block schematic of the experimental printing system. The system is controlled by a PC, which delivers the image data as well as the process control data to the corresponding control units (e.g., motor speed and the beginning of the development step).

An enhanced electrode test structure with a resolution of 150 μm for dot size was also studied (Fig. 5). In addition to the mere print electrodes a secondary electrode structure is arranged between. Two advantages are attained with this additional electrode structure. First, an electrostatic field enhancement is achieved, resulting in a faster development period and, second, electrostatic coupling effects between neighboring electrodes can be reduced. These electrostatic effects are dependent on development geometry and appear when resolution is increased by smaller electrode structures. The print plate carries 100 × 100 electrodes on a ceramic plate. However, it is not yet possible to control each electrode individually. Therefore the electrodes are combined into groups by a fixed connection pattern on the backside of the ceramic plate.

The present print plates both have metal electrode structures. This is the result of thorough investigations. Different types of metals with different surface roughnesses as well as several types of thin (e.g., 3 μm) insulating coatings were tested.[5] The investigations showed that an insulated coating leads to a lower efficiency for the transfer of the toner image from the print plate to paper. Uncoated metal electrodes show a slightly higher edge definition. The type of metal has no significant influence on the printed image and the surface roughness is not crucial as long as it is below 20 μm.

The development in our process is controlled by a time modulation method. Typical development times for black pixels are for the coarse structure in the range of about 1 to 5 s with an applied voltage of 50 V. The development

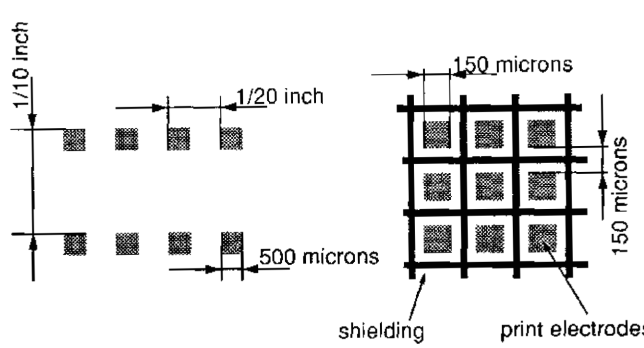

Figure 5. Electrode structures of two different printheads for the experimental system. The structure on the left side aims at a resolution of 40 dpi with eight printing steps. The other structure leads through four printing steps to a resolution of approximately 150 dpi.

Figure 6. ELPHI print sample, 500-μm dot size (the structure of the print plate is depicted on the left side of Figure 5), 128× 128 dots. The original image has 64 gray scales (6 bits). Through the nonlinearity of the ELPHI process characteristic an accurate reproduction of the original image is achieved by an electronic linearization with a maximum of 512 time steps (9 bits).

electrode is arranged here with a spacing of 1 mm. For the 150-μm structure a typical development occurs in less than 1 s with voltage ranges of 30 V. The faster development results from the stronger electrostatical fields (fringe fields) of the smaller structures.

Both electrode structures have in common the fact that they cannot provide a one-step image reproduction process. Although this is, in principle, possible when using closely spaced structures with nearly unresolvable gaps, with our laboratory equipment more than one printing step is necessary to complete an image. The 150-μm structure needs four steps on the whole, whereas the image of Fig. 6 was reproduced with eight steps in order to fill all of the uncovered spaces of one printout. The mutual electrostatic influence of the electrodes can be approximately neglected here, because in this geometry neighboring pixels are so far apart that the individual fields of the electrodes are mainly expanded to the opposing development electrode. Figure 7 shows an enlarged portion of a print sample produced with the 150-μm structure and one single printing step. We can see that within a toned dot the deposition of toner is inhomogeneous because of edge effects. Although this affects image quality, it will be no problem when dot size is further decreased. Then slight inhomogeneities in toner deposition within a dot cannot be resolved.

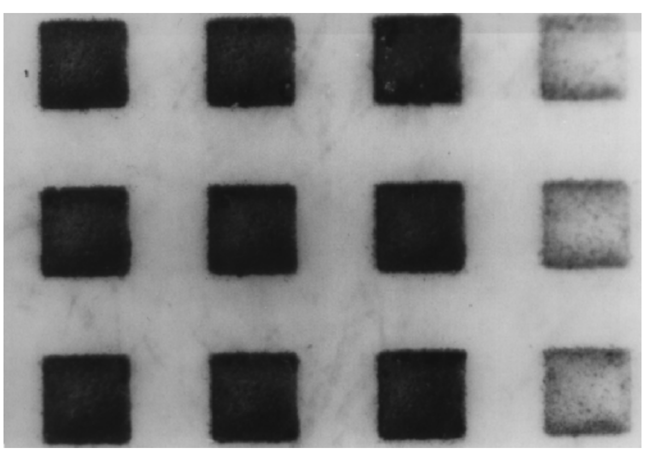

Figure 7. ELPHI print sample (enlarged) of the structure of Fig. 5. (right-hand side). The sample shows the accurate definition of the edges, which demonstrates the ability to achieve high spatial resolution. Inhomogeneities are due to the edge effect of the electric field.

All print samples were produced with a commercially available liquid toner. Investigations with different developer types were performed, and we found that the best results could be obtained with a type of developer that was originally designed for a direct development method based on ZnO binder paper.[5] Although these developers are not intended for a transfer step, our investigations showed that a reproducible electrostatic transfer with sufficient transfer efficiency could be attained. We chose this developer primarily because of its stable and uncritical behavior when once deposited on the print plate. Other types of developers tend to blur shortly after development, which leads to a reduced edge sharpness or even to a heavy distortion of the developed image.

Experimental Results

Good gray-scale reproduction is one of the main goals in developing this new technology. Thus the process characteristics were investigated first. Although it is possible to control development in a voltage-driven process, we show here only a time-controlled characteristic (Fig. 8) for a fixed voltage (50 V). The gray scale has been measured with a microdensitometer. For this test, print samples were scanned with an aperture of 50 μm, and about 100 samples

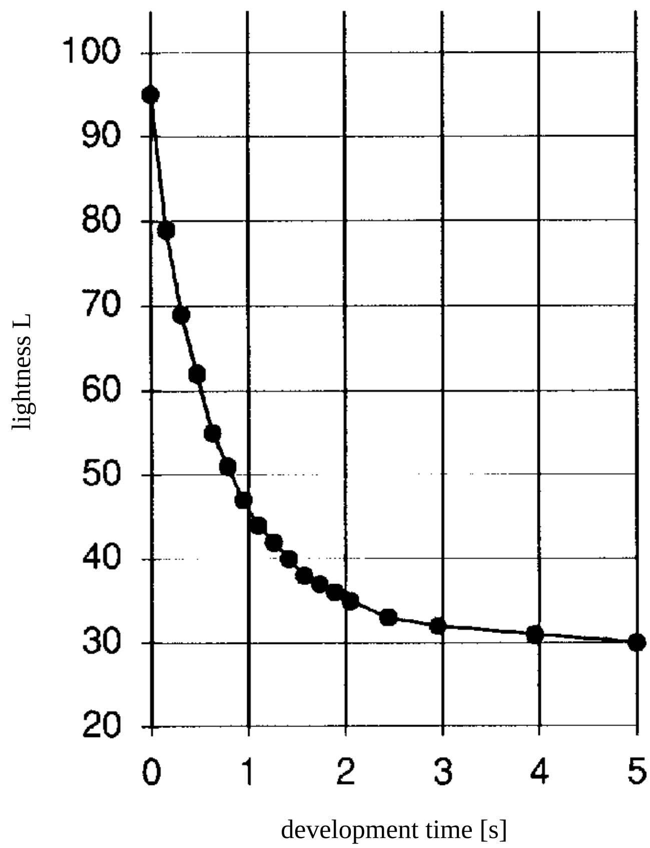

Figure 8. Original process characteristic. Lightness L as a function of time t for a development voltage of 50 V is shown. The nonlinear behavior is most pronounced in the dark region.

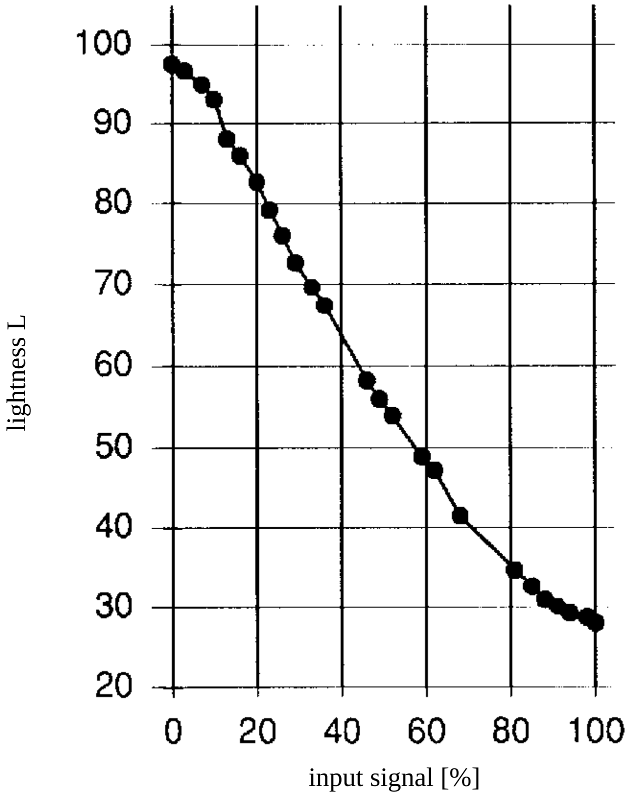

Figure 9. Linearized process characteristic. This figure shows lightness L as a function of an input signal. The linear relationship is obtained through a correction algorithm that makes use of the data shown in Fig. 8. The algorithm "knows" which gray scale is printed for every possible development time, so that it is able to calculate an appropriate development time t if a specific gray scale is to be printed.

of one printed dot were analyzed, evaluating a mean optical reflection density D_r. Instead of the optical density we prefer to describe the gray scaling in terms of lightness L, thus considering the nonlinear characteristics of human perception. Optical densities can therefore be transformed by the relation

$$L = 116 \times 10\hat{}(-D_r/3) - 16 \quad (1)$$

into lightness L.[6]

As expected, the characteristic in Fig. 8 behaves nonlinearly when lightness L is plotted as a function of development time. This nonlinearity is primarily caused by the applied visual perception transformation (Eq. 1) in addition to the nonlinear relationship between reflection and particle densities.[7] Particle densities, however, are to first approximation a linear function of the product of development time t and applied voltage U, i.e.,

$$N = K \times U \times t, \quad (2)$$

with K as a proportional factor depending on electrode geometry and the properties of the developer used.

The characteristic in Fig. 8, $L = L(t)$, shows that we achieved a minimum lightness L of about 30 for black dots, which corresponds to a maximum optical density of about 1.2. Also some background development is observed. Although we used an additional bias voltage during development in order to reduce this effect, we could not eliminate it completely. The background is primarily caused by a toner film of about 1 to 2 μm thickness that remains on the print plate after development. However, this film is necessary to ensure good transfer quality for the applied developer. A further reduction of background can be achieved only by reducing the toner concentration, thus prolonging development time.

To accommodate gray-scale recording, we performed an electronic linearization of the process. This can be achieved by using the inverted relationship of lightness L and development time t of Fig. 8. It results in a nonlinear coding of the process controlling time lengths that are assigned to the individual gray shades. More precisely, we generate a look-up table containing the information of Fig. 8 in an inverted form $[t = f(L)]$. Thus, the lightness L, which is to be printed, is the input for the table and the appropriate development time t is the output.

In the range for light gray scales the characteristic is much steeper than in the dark range. For this nonlinearity of the process characteristic about three additional bits in the coding of the time lengths are required relative to the coding of the image information, because only slots of equal time length can be controlled.

For example, the information for the image shown in Fig. 6 was originally coded with 64 gray scales (6 bits). Due to the linearization algorithm and the steep part of the characteristic in the range for light gray scales, the image data are developed with a resolution of 512 time slots (9 bits).

As a result of this electronic correction, a good linearization of the process is achieved (Fig. 9). The remaining nonlinearity, especially in the dark range of the gray scale, is because of a not quite stable transfer step and variations in toner concentration. Controlling this developer parameter, however, should further improve the achievable linearization.

Further Investigations

Many effects still need closer investigation. We are working on a model for describing the development process in detail. Equation (2) is only a simple approximation for the toner development as a function of voltage and time. Not taken into account are, for example, space charges affecting this relationship. Despite that, a detailed analysis of the electrostatic coupling behavior of closely arranged electrode structures is needed and will be published. Further investigations are planned to study the development behavior of dry toners on the electronic print plates described above.

Conclusions

The ELPHI process bears the potential to become a new printing process with good gray-scale abilities. Compared with competitive technologies its processing step is simple. One of its main advantages is the direct electronic control of gray shades, which makes correction methods possible. In a first approach an electronic linearization with good results has been performed.

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