Interchannel Crosstalk Compensation in a Continuous Ink-Jet System

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Abstract

This paper describes a method that produces a correct drop charge in a continuous ink-jet system with crosstalk between the electrical fields that control the drop charge for the different jets. The method involves compensation of the charge potential by utilization of a precomputed table and a computer algorithm to calculate said table. It is shown that the remaining drop charge error meets the stated requirement.

Introduction

The recent impact of personal computers on desktop publishing and multimedia has created a great demand for high-quality printers suitable for character printing, as well as for color hardcopy printing. Ink-jet technology has attracted a great deal of interest for these kinds of applications. There are in principle two different ink-jet modalities: the drop-on-demand (DOD) and the continuous ink jet. When it comes to high image quality, the continuous ink jet shows an edge over the DOD and can now produce stunning computer printouts of almost photographic image quality.

In the Hertz continuous ink-jet technology,[1] high-speed continuous jets are on-off controlled by electrical signals, as shown in Figure 1. The ink jet issues from a nozzle and breaks up into drops at its *point of drop formation*, which is situated close to the control electrode C. When a signal voltage different from the ink-jet potential is applied to the control electrode, the formed drops become electrically charged. The charged drops will be deflected by the electrical field generated between the deflection electrodes D and caught by the knife edge K (off-state). Uncharged drops, which are generated by applying a signal voltage equal to the ink potential to the control electrode, will pass unaffected through the deflection field and reach the printing surface R (on-state).

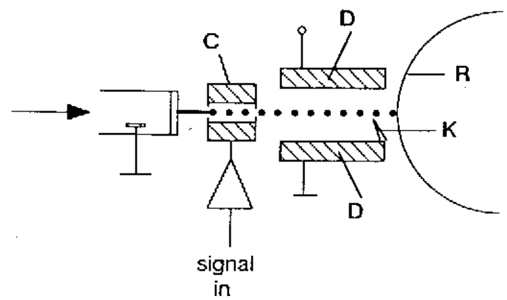

Figure 1. Electrode system for on-off modulation of continuous jets. The jet breaks up into drops near the charge electrode C. Charged drops are deflected by the electrodes D and intercepted by the catcher K Uncharged drops pass the catcher and deposit on the drum surface R.

An ink-jet printer implementing the above method with one jet per color (magenta, yellow, cyan, black) needs about 2-3 minutes to print an A4 page. This may be regarded as too slow if the printer is to be used as a shared resource in a network. If print parameters such as jet speed are increased to shorten the time for printout, a degradation of the output quality will appear with increasing print speed. To increase the print speed substantially without changing the print parameters, a design with multiple ink jets per color can be used. A system with, for example, eight jets per color will be able to print an A4 page in about 20 sec.

A system with multiple jets must be designed so that the electrical field between a charge electrode and its corresponding jet does not inadvertently induce a charge on the drops of adjacent jets; otherwise a degradation of the output quality would occur. One way of preventing the problems of this interchannel crosstalk is to design the charge electrode structure schematically shown in Figure 2a, wherein each jet is shielded by its corresponding charge electrode from the influence of adjacent charge electrodes.[2,3] However, in systems where the ink jets are positioned relatively close to each other, this method may lead to printing failure through stray drops hitting the charge electrode and filling the charge electrode slit with ink.

Therefore, new printheads have been developed with charge electrode structures less susceptible to failure, making use of a structure schematically shown in Fig-

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ure 2b combined with an electronic compensation circuit.[4] This study shows that an analysis of the compensation table used in the method has led to an unexpected compensation strategy.[5] Under certain conditions with compensation for more than the closest channel on each side, the compensation for a potential change of the second-closest channel on either side results in a compensating potential change of the same sign as the potential change of said channel.

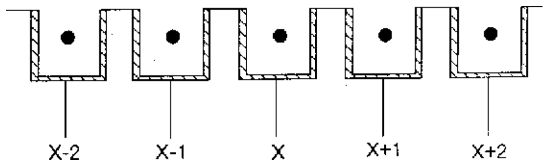

Figure 2a. Charge electrode structure that eliminates interchannel crosstalk. The black dots represent jets, and the striped areas represent the charge electrodes. The narrow slit may lead to functional failure due to stray drops.

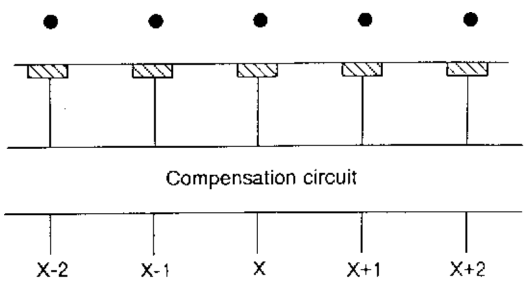

Figure 2b. Improved charge electrode structure less susceptible to stray drops. The interchannel crosstalk is compensated by the electronic circuit, and a correct drop charge is achieved. Typical dimensions are 500 µm between jets and 150 µm between a jet and its charge electrode.

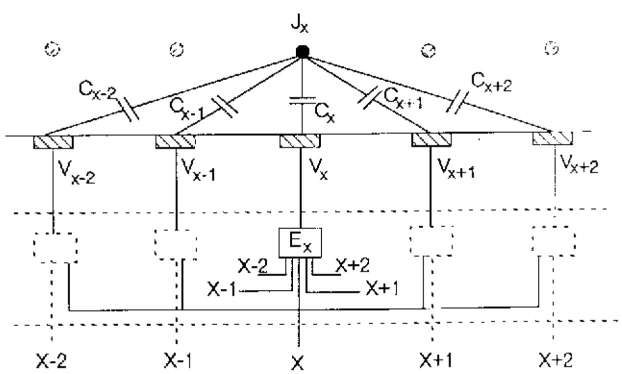

Figure 3. System model used to compute the compensation table implemented in the circuits E_x.

System Modeling

Figure 3 shows the jet J_x of the x-th channel and the five charge electrodes closest to J_x, their potentials labeled V_{x-2} to V_{x+2}. The charge Q_x induced on J_x is equal to the sum of the induced charges from the surrounding charge electrodes. These terms are given by the product between the potential V_n of the charge electrode of the nth channel and the capacitance C_n between said charge electrode and the jet J_x.

$$Q_x = \sum C_n V_n = C_x V_x + \sum_{n \neq x} C_n V_n \tag{1}$$

To achieve the on-off control explained in the Introduction, the charge Q_x is allowed to attain only two different values, Q_{on} or Q_{off}. In the described ink-jet method, Q_{on} is equal to zero, regardless of system parameters such as jet speed, drop size, deflection field strength, etc., while the value of Q_{off} depends on these parameters. As seen in Eq. 1, different crosstalk contributions from neighboring channels ($\sum C_n V_n$; $n \neq x$) will give different charge values Q_x, unless this crosstalk is compensated by the potential V_x on the charge electrode belonging to J_x.

The system model assumes that the capacitances Cn diminish with the distance from channel x.

$$C_{|x-n|} \rightarrow 0; \quad |x\text{-}n| \rightarrow \infty \tag{2}$$

The compensation circuit E_x receives as input not only the binary on-off signal belonging to channel x, but also the on-off signals from surrounding channels. The output is the compensated potential V_x that results in a charge on the jet J_x of either Q_{on} or Q_{off}. All channels have identical compensation circuits with input taken from surrounding channels.

From Eq. 2 it can be concluded that the induced charge from a neighboring channel diminishes with the distance from channel x. This indicates that it may be possible to omit from the model all channels outside the closest group around channel x with only a minor deviation of the outcome of Eq. 1. As shown in the Discussion, a minor charge error is made acceptable by selecting a sufficiently large group of neighboring channels.

To limit the matrix sizes and equations, it is assumed in the following that compensating for the two nearest channels on each side results in an acceptable error.

$$Q_x = \sum_{n=X-2}^{n=X+2} C_n V_n \tag{3}$$

Computational Algorithm

The compensation circuit E_x (cf. Fig. 3) receives as input five binary signals and outputs the compensation voltage V_x that for the current input state yields correct charge on the jet J_x. This compensation voltage is precomputed and stored in the compensation circuit. Because five binary signals can generate 32 different input states, precomputed compensation voltages for each input state must be stored in E_x.

$$V_x = \begin{array}{llll} V(0) & V(1) & V(2) & V(3) \\ V(4) & V(5) & V(6) & V(7) \\ V(8) & V(9) & V(10) & V(11) \\ V(12) & V(13) & V(14) & V(15) \\ V(16) & V(17) & V(18) & V(19) \\ V(20) & V(21) & V(22) & V(23) \\ V(24) & V(25) & V(26) & V(27) \\ V(28) & V(29) & V(30) & V(31) \end{array} \tag{4}$$

The index I used in the following to denote matrix elements, such as $V(I)$, is computed as

$$I = 2^4 Z_{x-2} + 2^3 Z_{x-1} + 2^2 Z_x + 2^1 Z_{x+1} + 2^0 Z_{x+2}, \quad (5)$$

where Z_y has the value 1 if channel y is in the off-state and the value 0 if channel y is in the on-state. This means that index 0 denotes the state in which all five jets are uncharged and index 31 denotes the state in which all five jets are charged.

To compute the matrix V_x, an iterative method is used. The elements of V_x are assigned start values, and then Eq. 1 is used to compute the matrix Q_x. V_x is then updated by the following equation:

$$V_x = V_x + K \times (Q_{x\text{ - desired}} - Q_x)/C_x, \quad (6)$$

where K *is* a constant affecting convergence of the iteration and $Q_{x\text{ - desired}}$ is a matrix whose elements have the desired charge values of either Q_{on} or Q_{off}.

Before the iteration starts, the variables of the equations are standardized as follows.

$$V_{x\text{ - initial}} = \begin{matrix} 0.0 & 0.0 & 0.0 & 0.0 \\ 1.0 & 1.0 & 1.0 & 1.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 1.0 & 1.0 & 1.0 & 1.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 1.0 & 1.0 & 1.0 & 1.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 1.0 & 1.0 & 1.0 & 1.0 \end{matrix} \quad (7)$$

$$[C_{x-2}, C_{x-1}, C_x, C_{x+1}, C_{x+2}] = [C_{x-2}/C_x, C_{x-1}/C_x, 1, C_{x+1}/C_x, C_{x+2}/C_x] \quad (8)$$

$$Q_{x\text{ - desired}} = \begin{matrix} 0.0 & 0.0 & 0.0 & 0.0 \\ 1.0 & 1.0 & 1.0 & 1.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 1.0 & 1.0 & 1.0 & 1.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 1.0 & 1.0 & 1.0 & 1.0 \\ 0.0 & 0.0 & 0.0 & 0.0 \\ 1.0 & 1.0 & 1.0 & 1.0 \end{matrix} \quad (9)$$

Equation 7 shows the initial values assigned to the elements of V_x. The value 0 represents the standardized voltage applied to the charge electrode in the on-state of a system without crosstalk (provided that the ink potential has the value 0); the value 1 represents the standardized voltage applied to the charge electrode in the off-state of a system without crosstalk. The capacitances are standardized by dividing by the capacitance value of C_x. The charge value 0 in Eq. 9 represents the standardized value of Q_{on}, and the charge value 1 represents the standardized charge value of Q_{off}.

When computing the elements of Q_x using Eq. 1, all the voltage values of different channels V_n are selected from the same matrix V_x. For channel x the element $V(I)$ with the same index I as the currently computed element $Q(I)$ is selected. For the other channels it is not possible to select a single element, because the available state information includes only the two closest channels on each side of channel x (cf. Fig. 4). For example, the matrix element to be selected for channel $x + 2$ depends partly on the binary input state of channels $x + 3$ and $x + 4$, respectively. To solve this problem, $Q(I)$ is computed for all possible situations of the binary states of channels not included in the state information, but affecting the voltage values of channels that are included, and then $Q(I)$ is set to the average charge value of these possible situations.

The iteration continues until the maximum charge error of any on-state has changed less than 0.05% per iteration during 10 consecutive iterations. In the case of a diverging iteration, the computer program supports a keyboard option for user termination.

Results

Before running the computer program realizing the iterative algorithm previously described, the set of standardized capacitance values that the program takes as input must be evaluated. One way to do this is to measure these values experimentally by assembling the charge electrode structure and the related nozzle, starting up the jets, and then measuring the current created by the charged drops of one of the jets, denoted J_x, when the charge electrode of one channel at a time is set to a potential V_{off}, while keeping all the other charge electrodes at the potential of the jet. Then all the measured current values are divided by the current value measured for the channel related to J_x. This set of values constitutes the set of standardized capacitance values of Eq. 8 that relates to the measured system.

From such a measurement the following set of capacitance values was derived:

$$[C_{x-2}, C_{x-1}, C_x, C_{x+1}, C_{x+2}] = [0.024, 0.187, 1.00, 0.187, 0.024], \quad (10)$$

which, when used as input to the computer program, yielded the following matrix of standardized voltages.

$$Q_{x\text{ - desired}} = \begin{matrix} 0.000 & 0.011 & -0.205 & -0.194 \\ 1.107 & 1.118 & 0.902 & 0.913 \\ -0.205 & -0.194 & -0.410 & -0.399 \\ 0.902 & 0.913 & 0.697 & 0.708 \\ 0.011 & 0.022 & -0.194 & -0.183 \\ 1.118 & 1.129 & 0.913 & 0.924 \\ -0.194 & -0.183 & -0.399 & -0.388 \\ 0.913 & 0.924 & 0.708 & 0.719 \end{matrix} \quad (11)$$

Equation 11 is transformed to the voltage values that will be applied to the charge electrodes by multiplying the matrix elements by the voltage value that would properly deflect a single jet in the system in question.

Discussion

One interesting result from the analysis of matrices produced by the described algorithm is found when comparing the matrix elements $V(0)$ and $V(1)$. Index 0 denotes the state when all five jets are uncharged, and, as expected, the compensation voltage $V(0)$ in Eq. 11 has a value of 0. Index 1 denotes the state when the second-closest jet J_{x+2} is charged and the other jets are uncharged. This means that a positive voltage is applied to the charge electrode of channel $x + 2$, which leads one to believe that a negative voltage should be applied to the charge electrode of channel x to compensate for channel $x + 2$; however, as seen in Eq. 11, the matrix element $V(1)$ has the positive value 0.011. The explanation for this unexpected result is that the transition of channel $x + 2$ from its on-state to its off-state changed not only the voltage on the charge electrode of channel x but also the voltage on the charge electrode of channel $x + 1$ (and on two other channels that are irrelevant in this context) and because the voltage applied to the charge electrode of channel $x + 1$ is negative [$V(2)$ or $V(3)$], the net result of the crosstalk from channels x + 2 and x + 1 is compensated by a positive voltage on channel x.

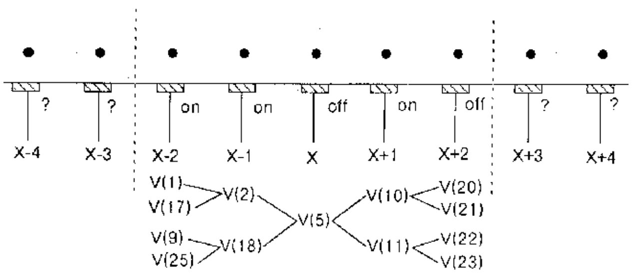

Figure 4. An example in which the compensation circuit (not shown in the figure) has access to the state information (on/off) of two channels on each side. The channels participating in the compensation for channel x *can, in the compensation state denoted by index 5, assume the different matrix values shown in the figure (cf. Eqs. 4 and 5), depending on the states of channels* x - 4, x - 3, x + 3, *and* x + 4, *respectively.*

Another interesting result that can be found in the matrix of Eq. 11 is that the voltage value of any matrix element $V(I)$ can be expressed as

$$V(I) = 0.011Z_{x-2} + (-0.205)\,Z_{x-1} + 1.107Z_x + (-0.205)Z_{x+1} + 0.011Z_{x+2}, \quad (12)$$

where Z_y has the value 1 if channel y is off and the value 0 if channel y is on, and Z_y is related to the index I as given in Eq. 5. As seen from Eq. 11, the term multiplied with Z_{x-2} and Z_{x+2} is equal to the matrix element $V(1)$, and the other terms are equal to $V(2)$ and $V(4)$, respectively. Equation 12 makes possible a realization of the compensation circuit E_x using two inverters, five resistors, and a current-to-voltage converter, which represents a significant cost reduction as compared with a realization using a read-only memory and a digital-toanalog converter. The symmetry of Eqs. 11 and 12 indicates that it should be possible to reduce the calculation effort in the computational algorithm described earlier. This reduction has not yet been implemented.

Figure 5a shows a situation in which every other charge electrode is assigned the potential 999 V or 0 V (the latter voltage being the assumed potential of the jets). A common electrode set to the potential 0 V is added at the bottom of the figure. This arrangement provides a controlled and known environment and reduces the crosstalk somewhat; it is therefore included in the model, as well as in the experimental systems.

The potential of Figure 5a would be applied to the charge electrodes of a system without crosstalk. Figure 5b shows the electrical field between the dotted lines of Figure 5a, with the jets removed. As seen in Figure 5b, the potential 166 V at the position of the "uncharged" jet (encircled) is about a third of the potential 480 V at the position of the "charged" jet (encircled). If the potential 480 V gives a charge that correctly deflects the drops, then having a third of that charge on the drops that are supposed to be undeflected is unacceptable.

Because the compensation matrix of Eq. 11 is valid for the geometry of Figure 5a, it can be used to compute the charge electrode voltage that should be applied to generate uncharged drops. In the situation of Figure 5a, with every other channel in the off- or on-state, respectively, all charge electrodes in the off-state will have the potential related to the matrix element $V(21)$, while all charge electrodes in the on-state will have the potential related to the matrix element $V(10)$. If the potential 999 V is kept at the charge electrodes in the off-state, then the potential on the charge electrodes in the on-state should be $V(10)/V(21) \times 999$ V = -362 V. Figure 5c shows the electrical field with this compensation, and, as can be seen, the potential at the position of the uncharged jet (encircled) has a value of - 7 V, which probably gives an acceptable charge error if the potential 420 V at the position of the charged jet (encircled) gives a correct deflection.

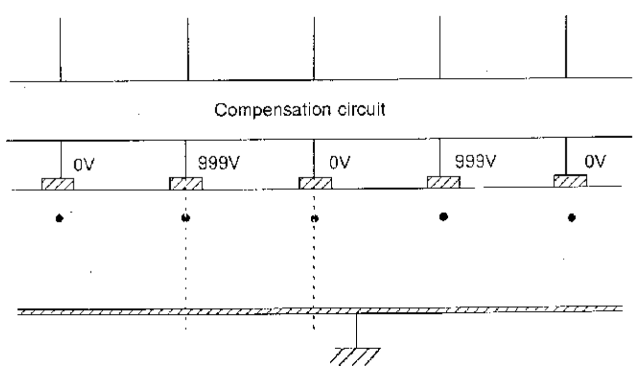

Figure 5a. Situation with a potential on every other charge electrode of either 999 V or O V. The field between the dotted lines is shown in Figs. 5b and 5c. Typical dimensions are given in Fig. 2b.

The following reasoning can be used to determine the acceptable charge error. A correctly charged drop is deflected a distance L from the jet axis when it is properly caught by the knife edge K in Figure 1. The charge of the drop corresponds to the standardized charge value 1 in the model (cf. Eq. 9). By using Eq. 1 with standardized capacitance values and the output from the computer program, the standardized charge value $Q(I)$ can be computed for any situation I. The deflection yielded by this charge $Q(I)$ is

$$L(I) = Q(I) \times L. \tag{13}$$

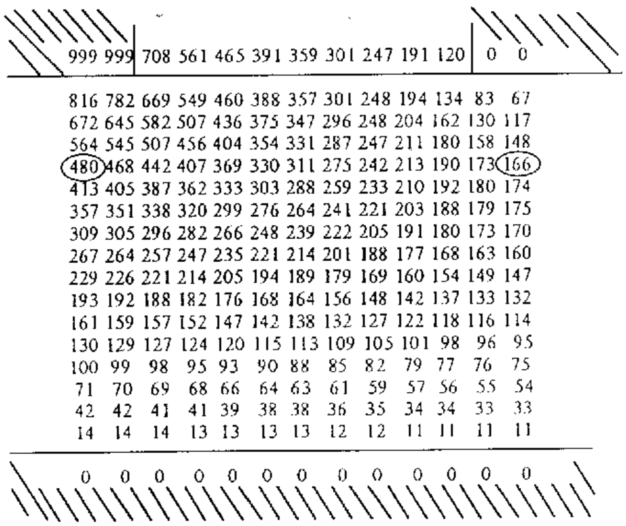

Figure 5b. Numerical representation of the electrical field between the dotted lines in Figure 5a with the jets removed. The two circles indicate the positions of the jets in the figure.

If we assume that the printing surface R in Figure 1 is located close to the knife edge K, then, if the drop is not caught by the knife edge, the distance $L(I)$ represents a misplacement of the pixel, and the question is transformed into "What is an acceptable misplacement?" A rule of thumb says 25% of the pixel resolution. In a typical system with L = 1 mm and a resolution of 10 lines/mm, this gives an acceptable charge error of $\pm$ 2.5% of the charge on a correctly deflected drop.

The maximum charge error due to the incomplete state information in the system represented by Eqs. 10 and 11 is less than $\pm$ 0.9%. If the charge error due to the truncation of Eq. 1 into five terms is added, the maximum charge error is estimated to be less than $\pm$ 1.75%. This indicates that the described compensation model can control the drop charge within typical tolerance requirements.

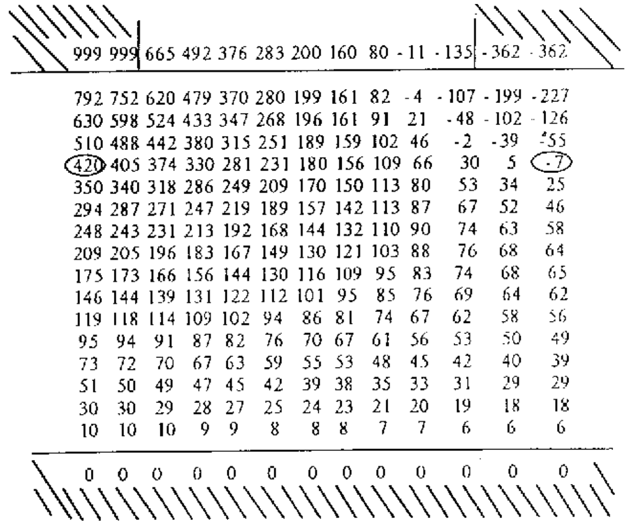

Figure 5c. Numerical representation of the electrical field with a compensation voltage of - 362 V applied

The compensation method described here is currently being experimentally evaluated, using a newly developed multijet printhead. Data from the experiments will be presented elsewhere.

Acknowledgments

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