# Enhanced Density Resolution with Continuous Ink Jet Printing Using Dual Ink Densities

*Tomas Kirkhorn and Johan Nilsson, Lund Institute of Technology, Sweden and Nils-Gunnar Holmer, Lund University, Lund, Sweden*

## Abstract

A method of enhancing the density resolution of a gray-scale inkjet printer, based on the Hertz continuous inkjet technique is presented. The earlier printer produces up to 32 different density levels in every pixel for each color involved in the printing process. By combining these levels over a small area of adjacent pixels, very high print quality can be obtained. In the lower density region, however, the combination of different levels gives rise to noise and reduced spatial resolution. In the new gray-scale printer the number of true density levels producible in each pixel has been extended to 160 by using two different density inks. By this means, a reflection density range from 0 to 1.63, in steps of 0.01, can be produced. As a measure of the improved print quality obtained, the difference in noise, in terms of the standard deviations of the mean densities over different measured areas, is presented. The dual ink density method yields a considerable improvement in the reproduction of low density areas with a minimum of noise and a spatial resolution unchanged from the nominal 10 pixels/mm.

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## Introduction

The quality of images printed by an inkjet printer, based on the Hertz continuous ink jet method[1] has proved to be very high. A comparison between digital medical images inkjet-printed on paper and laser-printed film copies has shown that the quality is sufficient for at least demonstration purposes.[2] The main reason for the high quality of the inkjet prints is the fact that true halftones can be produced, i.e., different gray levels, or color tones, can be generated in every single pixel. Hertz and Samuelssonl described how this true halftone printing is achieved by varying the number of drops deposited in each pixel. The number of drops can be varied from zero up to around 30 for each color involved in the printing process, thus giving a corresponding number of different density levels per pixel and color. By combining the discrete levels over a small area of adjacent pixels with an error-diffusion algorithm,[3] the number of density levels is further increased to correspond to pixel values from 0 to 255 for each color.

Figure 1 shows an example of reflection densities of black obtained from areas printed with a different number of drops in each pixel. The ideal characteristic for most effective use of the number of drops available would be a diagonal straight line. As can be seen in the diagram however, the ink-paper combination in use gives a reflection density that increases almost linearly only up to a drop number of 10. Thereafter, additional drops give only a small contribution to the density increase, depending on overlapping between neighboring pixels.

For a majority of images the 30 different true density levels producible, together with a spatial printing resolution of 10 pixels/mm, are sufficient to yield very high quality prints. However, there are special kinds of images with extra high demands on density resolution. One example is medical radiographic images in which important information can be hidden as very fine differences in density. If the density difference between a small object and its background is smaller than that between two consecutive drop levels, the error-diffusion algorithm may not be "quick" enough to create the intermediate level required. Thus, the object will not be registered. This matter is specially critical in the low density region where the differences in density between two consecutive drop levels are largest (see Figure 1). When the error diffusion algorithm is applied in this region the result will be a disturbing noise, together with reduced spatial resolution. Therefore, it is of great interest to enable the creation of intermediate density levels to fill up the space between the discrete density steps.

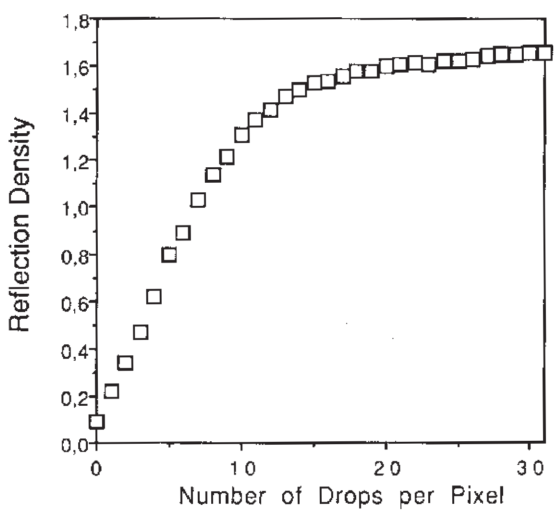



*Figure 1. Reflection density versus the number of drops deposited in every pixel*

Canon Inc. (Kawasaki-shi, Japan) presented in 1986 a drop-on-demand color inkjet printer in which the normal weakness of bi-level printing (ink or no ink in a pixel) was compensated for by a combination of differently dense inks of the same color and variable dot sizes.[4] Two of the four primary colors (cyan and magenta) were printed with three different densities each. The total number of producible color tones in each pixel was 64. However, gray-scale reproduction was still limited to only two levels, i e., black or white. Additional descriptions of dual or triple ink density printing are made in a number of patents.[5-7] Although these techniques use two or three differently dense inks, a pixel matrix must be employed for the creation of a sufficient number of intermediate density levels, because only one or few dot sizes can be generated.

In this study we describe a gray-scale continuous inkjet printer in which we have extended the number of true density levels producible from around 30 up to 160 by using two differently dense inks. Further, comparative measurements of the density variations between images printed with a single ink density and dual ink densities are presented.

## Experimental

### Materials and Methods

***Printing Technique***. The printing method on which the dual ink density printer is based is the Hertz continuous inkjet method.[1,2,8] Figure 2 shows the principle of the present printer, in which two continuous ink jets are generated by forcing ink under high pressure through 10-μm glass capillaries (supplied by Siemens-Elema, Solna, Sweden). By stimulating the capillaries by piezo-electric crystals the jets break up into equally sized drops at a rate of 1 million drops/sec. The two trains of ink drops can be on-off controlled separately by electric charging and deflection. With control electrodes at the points of drop formation, each formed drop can either be charged or be left uncharged. Charged drops are deflected in a deflection field and caught below a knife edge. The uncharged drops fly undisturbed straight through the electrode system toward the recording paper. Thus, either by leaving a separate drop uncharged, or by charging it, the drop will either reach a pixel on the paper or be prevented from reaching it.

The magnified part in Figure 2 shows how varying numbers of separate drops of both the high density (HD) ink and the low density (LD) ink are deposited in each pixel, giving varied dot sizes and thereby varied print density. For each of the two ink jets, it is possible to deposit up to 31 drops in every pixel.

The printhead is located in front of the paper-bearing drum and is slowly moved sideways while the drum is rotating. The spatial print resolution is 10 pixels/mm. Because the two nozzles are mounted beside each other at a distance of 10 mm, with the HD ink as the first printing ink, the image data controlling the LD ink is delayed correspondingly, with 100 lines. The drum is dimensioned to hold a paper that measures $250 \times 360$ mm$^2$, and a print of this size is finished in approximately 5 min.

The two differently densed black inks used in the dual ink jet printer were developed by Iris Graphics, Inc. (Bedford, MA). Both of the inks were developed for this specific study. The ratio of the high and the low density was selected to be 17:1. A mat coated paper for inkjet printing, IJ Mattcoat NM (Mitsubishi Papermills Ltd., Tokyo, Japan) was selected as the print substrate because it gives a high maximum print density and has uniform reception of the ink over its surface.

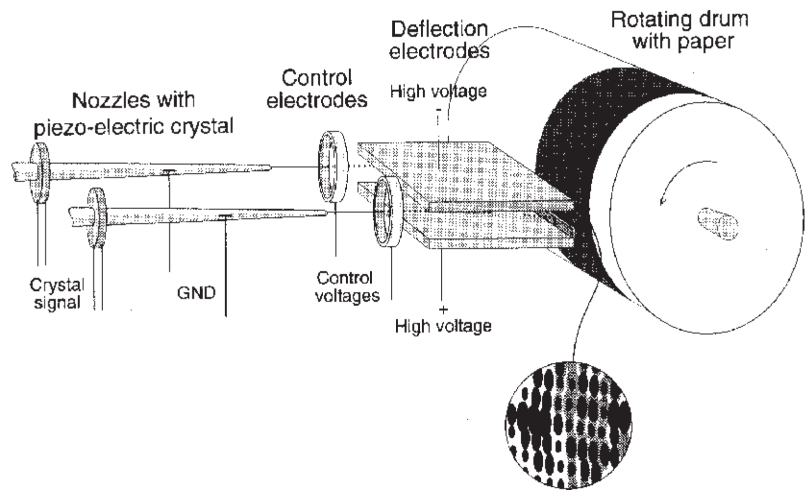



*Figure 2. Principle of the continuous inkjet printer using dual ink densities.*

***Initial Experiments.*** A test image (Figure 3) was prepared to enable measurements of densities from all possible combinations of discrete HD and LD drop levels. Levels of 0-31 HD drops were crossed by levels of 0-31 LD drops, constituting a square pattern according to Figure 3. The reflection density was measured for each level combination with a MacbethQD Reflection Densitometer RD107R (Macbetht Process Measurements, Newburgh, NY).

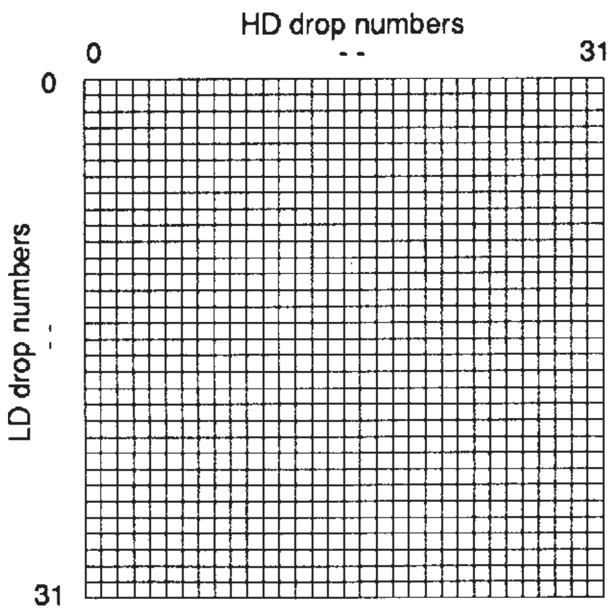



*Figure 3. Test image for the measurement of all possible combinations of true density levels printed with drop numbers from 0-31 of the high density (HD) ink together with 0-31 drops of the low density (LD) ink.*

Figure 4 shows the measured reflection density for drop numbers between 0 and 20 for the HD ink exclusively, and for the combinations of HD and LD ink. For drop numbers up to approximately 8, the density response of the HD ink Figure 4(a) is linear, whereas for higher drop numbers the slope decreases as a result of dot overlapping between neighboring pixels. In the right diagram, Figure 4(b), the measured density values are plotted versus the number of drops of the LD ink on top of different ground levels of HD ink. At the linear part of the HD ink curve, every density space between two consecutive drop numbers of the HD ink is filled up with an average of 12 drops of the LD ink. As the slope of the HD ink curve decreases, the number of LD ink drops in between the HD drop levels decreases.

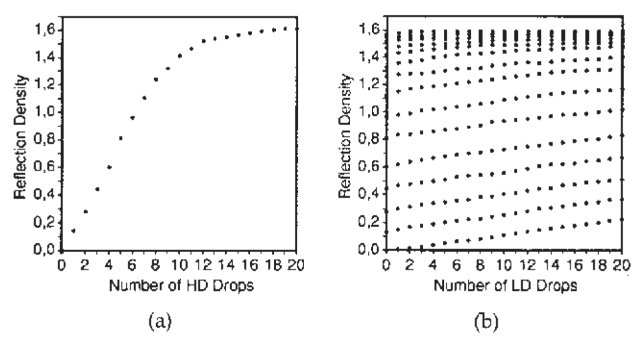
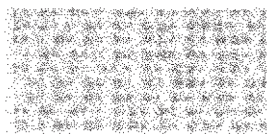


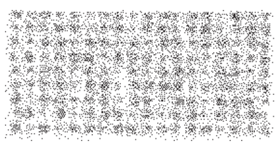

*Figure 4. Diagram of the measured reflection density versus the number of drops of (a) HD ink, and (b) "LD ink Con top" of ground levels of HD ink for drop numbers from 0 to 20.*

From the above density measurements, linearization functions were calculated and a look up table (LUT) of both HD and LD ink numbers was determined for every input value between 0 and 255. The LUTs were organized in such a way that fiom an input value of 0, the number of LD ink drops was increased up to a level where they could be replaced by the first HD ink drop. Then the LD ink drop number restarted from 0 up to a number corresponding to two HD drops, etc. The maximum number of HD drops and LD drops was fixed at 20 and 15, respectively, with decreasing LD drop numbers for higher total density. To avoid neglecting density values for which parts of LD ink drops are needed, a one dimen-sional error-diffusion was applied to the LD ink drop values.

Because the human eye is extremely sensitive to any interruptions in a regular pattern, the described procedure of combining the two inks, by letting drops of the LD ink be replaced by drops of the HD ink at a certain level, and vice versa, puts a large demand on the drop registration precision. A small overlap between HD and LD dots at a transition between the two inks results in a dark line. A corresponding light line, or “Whole”, is noticeable if the dots are too widely separated from each other. To minimize this problem the dot placement was closely controlled. For jet adjustment in the direction perpendicular to the print line the nozzle was mechanically adjusted by a metal pin eccentrically mounted on a plug with a screwdriver slit.[8] In the vertical direction, a relative adjustment between the two ink jets was introduced by electronically delaying the drop train of the LD ink continuously within a pixel as well as over a number of pixels.



(a)



(b)

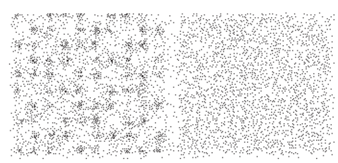
*Figure 5. Magnification of prints showing differences in dot placements. In (a) the one-drop dots are misplaced because of the air resistance acting on the single flying drop, whereas in (b) this effect has been compensated for by “firing” the single drops at an earlier time point.*

Another factor that gives rise to irregular dot placement is the retardation of flying drops because of the air resistance. When one to four drops are to be deposited in a certain pixel, these drops do not reach the paper as separated drops. Instead they will have merged to a larger “Super drop” through the retardation of the leading drops. Because the retardation increases as the drop volume decreases, a single drop will reach the recording paper later than a super drop consisting of several drops. This leads to a corresponding misplacement of the fewdrop dots compared with dots of larger drop numbers (Figure 5a). The difference in placement is most evident between the one-drop dot and the two-drop dot, approximately half a pixel. This misplacement results in overlapping or holes as those mentioned above. In the dual ink density printer this situation has been compensated for by “Monitoring” every pixel value before it reaches the on-off switching control of the jet. Every time a one-drop value shows up, this single drop is “fired” earlier than trains of any other drop number. Figure 5 shows the “dot placement” with one and two drops in each pixel, with and without the compensation for the single-drop retardation.

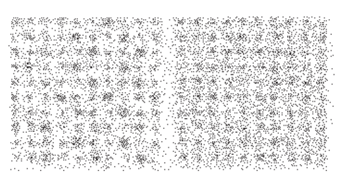
***Measure Rents of the Print Quality Improvement.*** Our goal when introducing dual ink densities was to eliminate the need to combine different discrete density levels for the production of gray scales, a procedure that introduces noise in the image. To get a measure of the print quality improvement obtained we measured the standard deviation of mean densities on print samples from both of the printing methods.

The measurement setup consisted of a microscope (Nikon SMZ-2T), a CCD gray scale video camera (Hamamatsu C5405), and a video image grabber board (Neotech Image Grabber SV) installed in a Macintosh II computer. The measurement target was illuminated by two fluorescent tube lamps positioned parallel to each other, one on each side of the microscope, to obtain uniform illumination. Each grabbed image, which con sisted of $768 \times 512$ video pixels, covered a sample area of 6.4 $\times$ 4.3 mm2, i.e., $64 \times 43$ print pixels. Every print pixel was covered by $12 \times 12$ video pixels. For the analy sis of the grabbed images these were entered into the image analysis public domain program NIH Image ver sion 1.47 (National Institutes of Health). A calibration utility in the program was used to obtain pixel values in units of reflection density. For the calibration procedure, well-defined gray scale standards (Natural Color System, Scandinavian Colour Institute AB, Stockholm, Sweden) were used.

Print samples of different density levels were produced by dual, as well as single, ink density printing. Five density levels were selected: 5, 10, 20, 40, and 70% of black (according to those appearing in the Society for Motion Pictures and Television Engineers test image). The emphasis was laid on the light levels where the difference in performance was estimated to be the largest. Figure 6 shows two examples of magnified print samples with densities of 5% (a) and 10% (b), printed with both single and dual ink densities. Further, Table I shows the number of HD and LD ink drops in each of the measured density levels.



(a)



(b)

*Figure 6. Magnification of print samples with reflection density levels of (a) 5% and (b) 10%. The samples to the left in both (a) and (b) are printed with only one ink density, whereas the ones on the right are printed with dual ink densities.*

In the single ink density printer a one-dimensional error diffusion algorithm is employed, i.e., the average density level is created along the printed line. Therefore when measuring the mean densities over a certain area

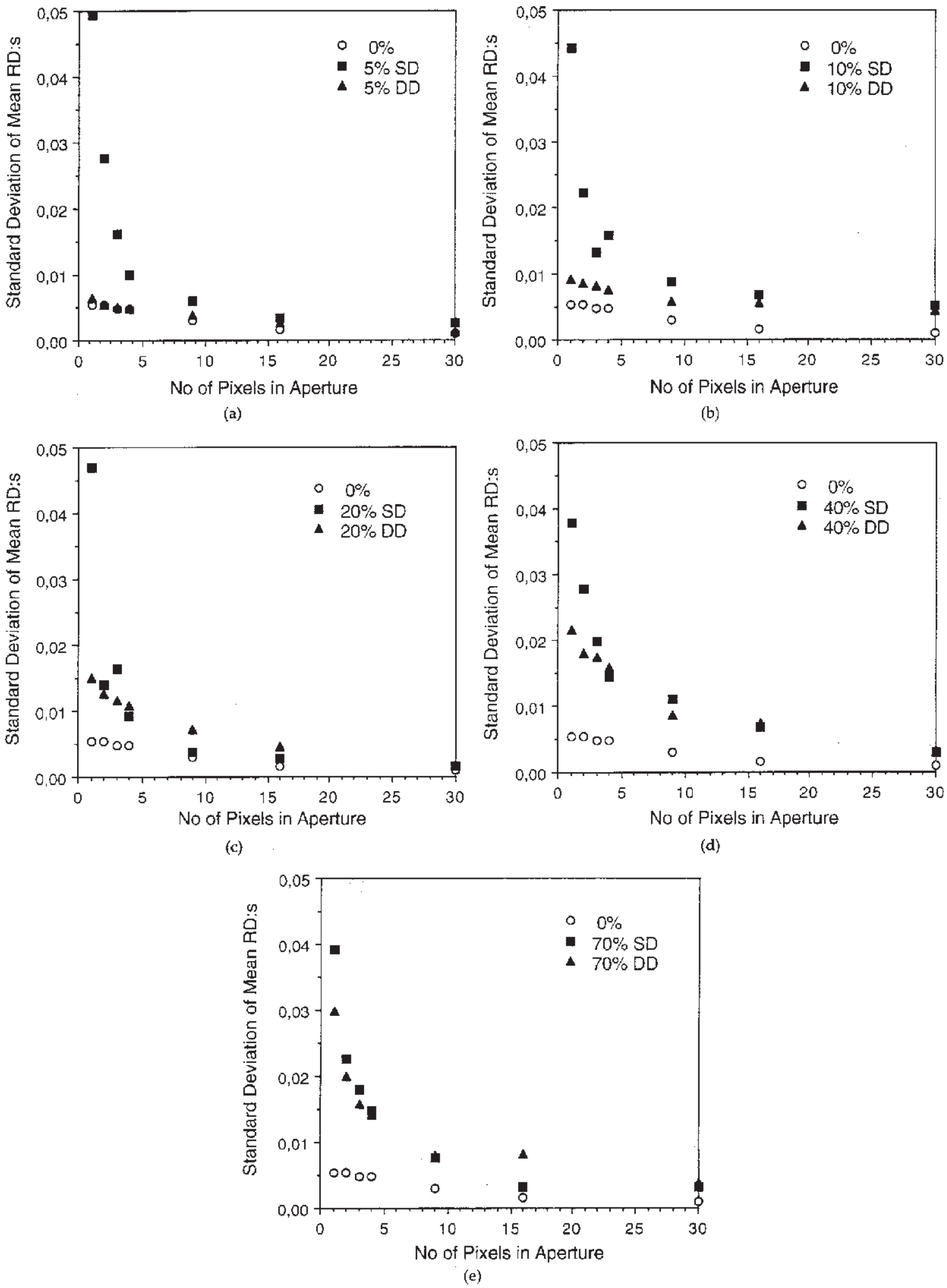



*Figure 7. Diagram showing the standard deviation of mean densities versus different aperture areas, in terms of pixels, over which the means were measured for both single (SD) and dual ink density (DD) printing. The five diagrams (a)-(e) show results from print samples of 5, 10, 20, 40, and 70% of maximum reflection density, respectively. As a reference to the deviation values for the two printing methods the variation of density from the unprinted paper (0%) is also presented in each diagram.*

**Table I. Number of Hıgh Density (HD) and Low Density (LD) Ink Drops DeposRed h each Pixel for the Density Samples Printed with Both Single and Dual Ink Densities**

| Density level (%) | Single ink density printing No of HD drops | Dual ink density printing No of HD drops | |
|---|---|---|---|
| | | No of HD drops | No of LD drops |
| 5 | 0 - 1 | 0 | 8 - 9 (11)* |
| 10 | 1 - 2 | 1 | 3 - 4 (10) |
| 20 | 2 - 3 | 2 | 5 - 6 (12) |
| 40 | 4 - 5 | 4 | 4 - 5 (15) |
| 70 | 7 - 8 | 7 | 5 - 6 (10) |

*Numbers in parentheses denote the rraximum number of LD drops at a certain ground level of number of HD drops

the area was chosen as $1 \times m$ pixels, with m equal to 30, 16, 8, 4, 3, 2, and 1. For each of these areas 15 mean density values were obtained by, shifting the area 15 steps along the print line, with each step equal to one print pixel. From the 15 mean densities a standard deviation was calculated.

## Results

From the diagram in Figure 4 the difference in resolution of discrete density steps between the earlier single density inkjet printing and the presented dual ink density printing methods is clear. The number of different true density levels has been increased from 20 (or 31 for earlier used inks[8]) up to 160. A range of reflection density from 0 to 1.63, excluding the density of the white paper, has been reproduced in steps of 0.01 density units.

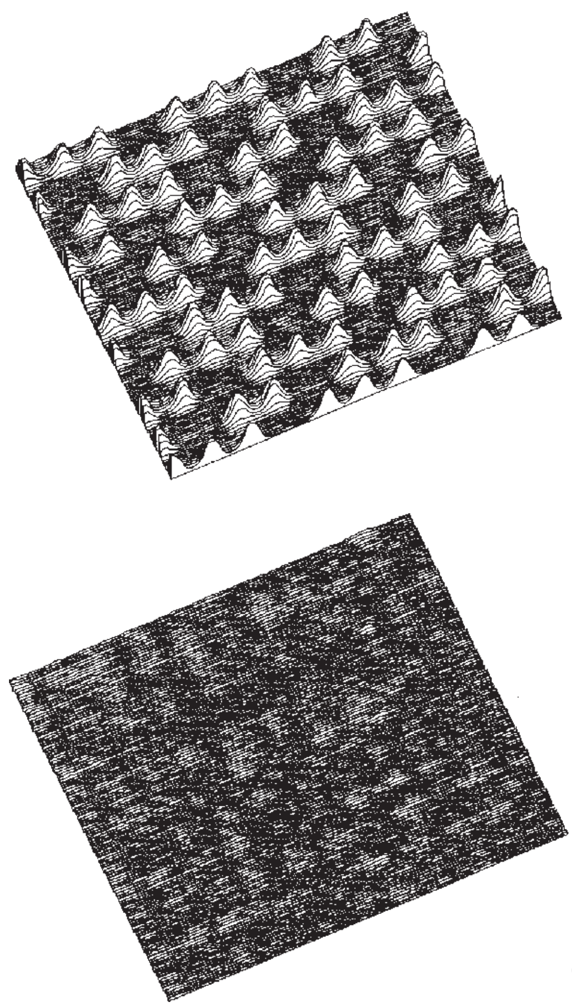
The results of the comparative measurements of density variations obtained by single and dual ink density printing, are presented in Figure 7. The five diagrams show the standard deviations of mean densities as a function of different measurement areas, in terms of numbers of pixels, for density levels of 5, 10, 20, 40, and 70%. As a reference to the deviation values for the two printing methods the variation of density from the unprinted paper is also presented in each diagram. The diagrams show that the difference between the two printing methods is largest in the low density region, especially below levels of one drop per pixel. The different appearances of the 5% levels is further illustrated by the threedimensional surface plot of this level in Figure 8.

The improved density resolution makes it possible to reproduce very fine gray-scale variations of small objects. Figure 9 illustrates this fact by showing a magnified detail of a digital radiograph printed with single as well as dual ink densities. The input data were the same for both of the prints, 8-bit gray scale image data.

As predicted earlier, the most significant improvement is obtained in the low density region (cf. diagrams in Figure 7). With the dual ink density method the spatial resolution can be kept at the nominal resolution of the printer, which is 10 pixels/mm (5 line-pairs/mm), even for very low densities.

## Discussion

By introducing the combination of two differently dense inks in the Hertz continuous inkjet printer, we have extended the number of true producible gray levels from around 30 to 160, ranging from 0 to 1.63 in optical reflection density, in steps of 0.01. The direct consequence of this feature is that the necessity of using more than one pixel to create any desired density level has been almost eliminated. The noise, which is caused by a dither pattern or an error-diffusion algorithm and is visible in images printed with only one ink, has been eliminated by using the dual ink density method. To take care of decimals in LD drop numbers, an error-diffusion algorithm has been applied to LD ink. Thus, over an area of only two pixels more than 300 density levels can be produced.

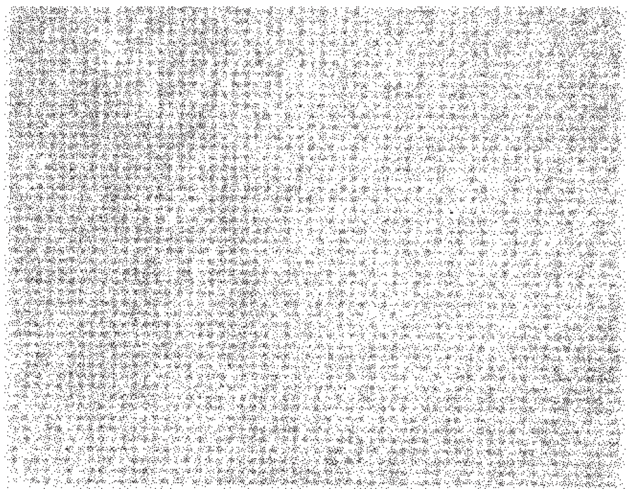


(a)

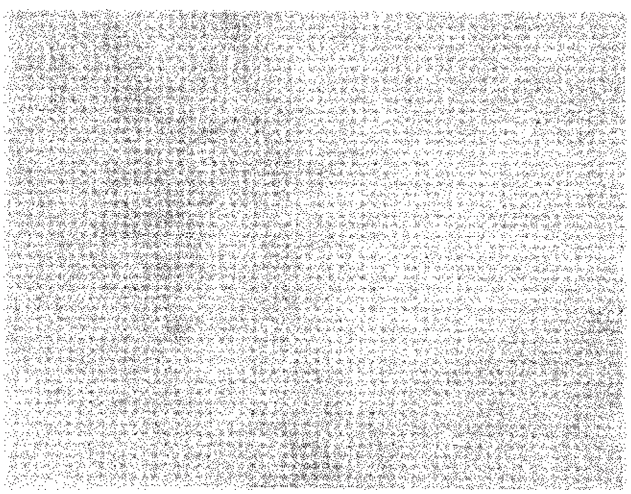
(b)

*Figure 8. Three dimensional plots of the 5% density print samples showıng the local variations in density over 10 x 10 pixels from la) single ink density printing and (b) dual ink density printing.*

The total difference in noise between.the two methods is shown to be largest in the low density region. As can be seen in Figure 7, at levels of 5 and 10% of maximum density, the standard deviation between mean densities of single pixels, printed with dual ink densities, is close to that of the unprinted paper. When the density is increased the difference in noise performance between the methods is reduced, indicating that factors other than the ermrtiffusion algorithm contribute to the noise. In the midJensity region, neighboring dots of HD drops are just beginning to overlap. Then, only a small variation in dot placement will be sufficient to give rise to noise. When the density is further increased so that all dots overlap, the noise is mainly caused by local irregularities in the ink reception characteristics of the paper.



(a)



(b)

*Figure 9. Magnification of a digital radiograph printed with (a) single ink density printing and (b) dual ink density printing. The drop numbers of the high density ink range from 0 to 3.*

An alternative way of extending the density range would be to use smaller drops than those generated in the present printer. With smaller drops the minimum dot size achievable would be less, as well as the differences in sizes between dots of consecutive drop numbers. How much the drop volume can be reduced is, however, limited by practical factors. To create significantly smaller drops the flow rate must sooner or later be reduced. The lower limit of the flow rate will be set by the demands on precision of the dot placement on the paper: Smaller or slower drops will be more sensitive to the air currents induced by the rotating drum, which will lead to unreliable dot placement. An estimation of a realistic reduction in drop volume, compared with that of today's printer, would be by a factor on the order of two. Thus, the effect on the number of available density levels is limited.

In many imaging applications, the gray scale is replaced by a pseudo color scale. It is common knowledge that the human eye is able to detect a larger number of chromaticities than gray levels.[9] As mentioned earlier, in diagnostic radiology, the main task is to find abnormalities that can be hidden as very fine differences in shades of gray. Together with radiologists at the Department of Diagnostic Radiology, Lund University Hospital, we are investigating the possibilities of using color hard copies, printed with a continuous inkjet color printer 10 to obtain an improved means for the presentation of high density resolution projection radiographs from a computed radiography system.[11] The initial density range of 10 bits per pixel is divided in two or three different density windows, each represented by 8 bits. These are further added as the red, green, and blue parts, respectively, of a 24-bit RGB image. The result gives a color image with the "heated-object" spectrum, with the different density regions stretched out as the different color components in the image.

## Conclusions

Our results from the experiments on enhancing the density resolution of the gray scale printer, by using gual ink densities, as well as on increasing the ability to detect a wide densit yrange by color ink-jet printing, are very promising. Therefore, we find it worthwhile to investigate further how much these features may improve the diagnostic performance of radiographic images presented as ink-jet-printed hard copies.

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