Digital Photography and Color Printing*

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Digital photography is a new electronic still imaging system that has appeared in the process of the electronization of photography. It is a fusion of electronic photography and hybrid photography, combining film images and image data. The main frame of this system consists of image pickup, manipulation, and output processes. In the image pickup process, three-dimensional images of objects and two-dimensional film images are recorded by electronic still cameras and scanners, respectively. The image manipulation is digital signal processing using the computer. The image output processes include both hardcopy printing and softcopy display. Digital color printers are the key equipment for hardcopy output. Recent useful applications are electronic picture retouching in photographic studios and desktop publishing for graphics engineers. At present, many small digital cameras have appeared on the consumer market. They are designed to be three-dimensional scanners in the peripheral equipment of personal computers. The development of color non-impact printers producing color prints has succeeded in the early stages, and these technologies have expanded the applications of color hardcopy. Digital photography integrates various imaging equipment and yields new technical problems in image quality. This report reviews the progress of digital photography and its contribution to the development of the hardcopy world, then discusses new problems of data coding and matching in image quality of softcopy and hardcopy prodcopy produced by the same image data.

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Introduction

Digital photography is a newcomer in the imaging world and has appeared in the process of *electronization* and diversification of traditional photography. It is also a system combining *electronic photography* and *hybrid photography*. Moreover, digital photography is one of the most computer-friendly imaging systems after computer graphics.

The purpose of the electronization had been to realize the following four goals: (1) instant capturing and recording of a subject image, (2) reproduced image displayed as hardcopy color print, (3) image displayed by a TV receiver as softcopy, and (4) easy and direct access to telecommunication of the captured image. The additional major goal that appeared afterward was the function of direct and easy connection to the computer.

During the past one and a half decades, the electronization has been progressing stepwise through three generations—still video (SV), electronic photography (EP), and hybrid photography (HB)—and recently it has achieved the tentative goal, digital photography (DP). The progress is mainly due to advances in image acquisition processes.

The image-capturing processes in these systems depended on the successive development of electronic still cameras and scanners. Their progress was slow and it accompanied advances in electronic technologies of solid-state devices for imagers and circuits, the analog video signal, and digital data processing. Close-to-practical digital cameras started appearing only recently.

The image output processes of the new systems have been implemented by softcopy display and color hardcopy printers. The big issue during the electronization was to develop new printers that could reproduce photographic color prints by the non-impact printing (NIP) method. The progress was smoother than that of digital cameras, and small desktop printers now are producing high-definition color prints showing image quality comparable to that of photographic color prints. The development of new NIP methods to produce color photographic prints has helped to open up new applications for color hardcopy.

The present stage, digital photography, has the additional major function of easy access to personal computers for image processing. The image data of subjects captured by digital electronic camera or film scanner are manipulated by personal computer and then printed out by NIP color printers. However, digital photography introduces new problems in imaging. The main features of digital photography are the introduction of digital data for information handling and the integration of various kinds of imaging equipment for softcopy and hardcopy. The first feature addresses the relationship of coding rate of image data to the ability to express output images on terminal equipment. The second feature addresses the matching of output images in softcopy and hardcopy produced from the same image data.

This report first reviews the progress of digital photography and its propagation into the color hardcopy world and then discusses the new problems of data coding and matching of hardcopy and softcopy images in a given system.

Electronization of Photography: From Still Video to Digital Photography

In 1981, the first actual electronic photography, electronic still photography, was proposed by Sony under the name of the Mavica system.[1] The proposal just matched the time of speculative silver shortages in the photography industry, so that electronic photography's debut was very sensational and attracted journalistic attention. In 1982, Sony also announced a new color printer utilizing a sublimation dye transfer method.[2]

Still Video Systems. The first electronic still photography system realized three features. The captured image was the same as a frozen frame of a TV scene and outputs of softcopy and hardcopy could be presented on

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home TV receivers and color printers, respectively. In the first half of the 1980s, many manufacturers joined a tough competition to develop new photographic input cameras, output printers and so on. The configuration of the first system was based on the analog video concept, and its signal design followed TV standards, NTSC and PAL. The captured image was converted to an analog signal and recorded on a small floppy disk. Thus the new system was described as still video (SV).

By the end of the 1980s, about 15 brands of SV cameras and some color printers appeared on the market. These cameras were priced higher than traditional film cameras. The image quality of the output from the SV system was rather poor. In the business field, customers in photojournalism and government agencies appreciated the advantages and purchased expensive professional SV cameras. The advantages of the new system outweighed the marginal image quality of the output. In the consumer field, unfortunately, the quality of the picture from the low-end consumer cameras was poorer than that of the professional cameras, so that customers could not be satisfied.

As a result, the first attempt to replace film cameras with SV cameras in the traditional consumer photography field failed. The first electronization of photography, the SV system, had not achieved a satisfactory result. However the development of color printers was proceeding without a hitch.

Electronic Photography Systems. At the beginning of the 1990s, all-digital cameras utilizing IC cards (card-type semiconductor memory devices) appeared on the market.[3] The information recorded on the IC card was digital image data, not an analog signal. The cameras appeared similar to the previous consumer SV cameras; however, the image quality of the output was improved. From that time until the present, many professional cameras have attached high-density solid-state imagers having from over 1 to 4 million pixels.[4,5] These all-digital cameras were described as electronic photography (EP) cameras, and the output image data were easily supplied to the computer. On the output side, some color printers could receive digital data from those cameras and computers and could then produce high-definition photograph-like color prints. These printers were also digital. The systems utilizing such digital equipment were described as EP systems.

Hybrid Photography Systems. During the early 1990s, Eastman Kodak Company established a new Photo-CD system based on the conversion of film images taken by film cameras into digital data.[6] The digital data were recorded on the self-recording type compact disk. In the new system, the key equipment is a film scanner, and the key device is the CD-ROM disk. The read-out, playback data record from the CD-ROM disk is equivalent to that from the EP camera described earlier, and it is easily manipulated by personal computers. Similar systems using an optomagnetic (MO) disk, Photo-MD system and the high density floppy disk ZIP system were later introduced by Konica Corporation/Sony Corporation[7] and Fuji Photo Film Company, respectively. Such systems are all models of indirect electronization of traditional photography. We refer to these systems as hybrid photography (HP), meaning hybrids between electronic photography and the traditional chemical photography.

Digital Photography Systems. The latter stages in the EP and HB systems are the same, and the image data are compatible. Thus it is feasible to combine the two systems, and the merging has resulted in the digital photography (DP) system.

Figure 1 shows reproductions of a typical digital photographic print. The original picture was taken by a large-format film camera. The developed film image was read out by a scanner and converted to digital data. The data were manipulated by personal computer, using graphic image processing software. In the manipulation, the table and louver images were removed and the images of shoes for the people in the front line were added. Moreover the pale original color was changed to a reddish color. Finally, the picture taken in a banquet room was changed to look like one taken in a large photo studio.

This digital photography system does not accomplish complete electronization, but it indicates a tentative goal of innovation in traditional photography. The digital photography system will expand future photography to include the extremely useful new type of electronic still imaging. Moreover, the system is applicable to multimedia technologies in the National Information Infrastructure (NII) and current networking environment. At that stage, digital photography equipment will become common in offices and homes as graphic communication capturing and terminal equipment.

Advances in Image-Capturing: From SV to DP Cameras and Scanners

The most important equipment for any photographic system is the camera. To realize the advantages described earlier, the first electronic SV cameras were developed by modification of a video camera. The video camera is a simple consumer version of a TV broadcast camera. Figure 2 is a schematic of the Mavica camera, the first SV camera. The main components were the CCD solid-state imager(s) and a small, ~2.2", floppy disk referred to as a video floppy, which was able to store 25 frames of captured image.

In an electronic imaging system, the signal format is important. The Mavica system was analog, and the image signal carrying the information was recorded on the floppy disk by an analog magnetic recording method. Moreover, SV standards to allocate the image signal followed those of TV broadcasting because of the softcopy display using home TV receivers. Thus the equivalent pixel number in a picture was 484×650 for NTSC-compatible standards and 575×700 for PAL-compatible standards, respectively. The camera designed under the former NTSC-compatible signal standards was called the NTSC- or VGA-level camera.

There are two camera types for capturing color images; the single-imager camera and the multi-imager camera. The single-imager camera has one CCD imager attached to a mosaic-type three-color filter [red (R), green (G), and blue (B)] and is mainly used in low-end consumer cameras. The multi-imager camera has three CCD imagers attached to R, G, and B filters, respectively. The multi-imagers were introduced mainly in high-end professional cameras.[8] The multi-imager SV cameras were expensive but they could generate the full specification color signal to satisfy the SV standards. This concept is still effective in the latest digital photography system.

Of the about 15 SV cameras first introduced in the late 1980s, two had multi-imagers for professional use. With the appearance of digital cameras in the early 1990s, interest in analog SV cameras faded, and now only two such cameras remain in the catalogs.

Digital Cameras. In the early 1990s, two all-digital cameras appeared on the market.[3] The information recorded in the memory device was digital image data. The imagers of these cameras were mostly of the same VGA level as the previous consumer SV cameras; however, the image quality of the output was substantially improved by new color signal allocation and digital data recording. From then on, many professional cameras using high-density

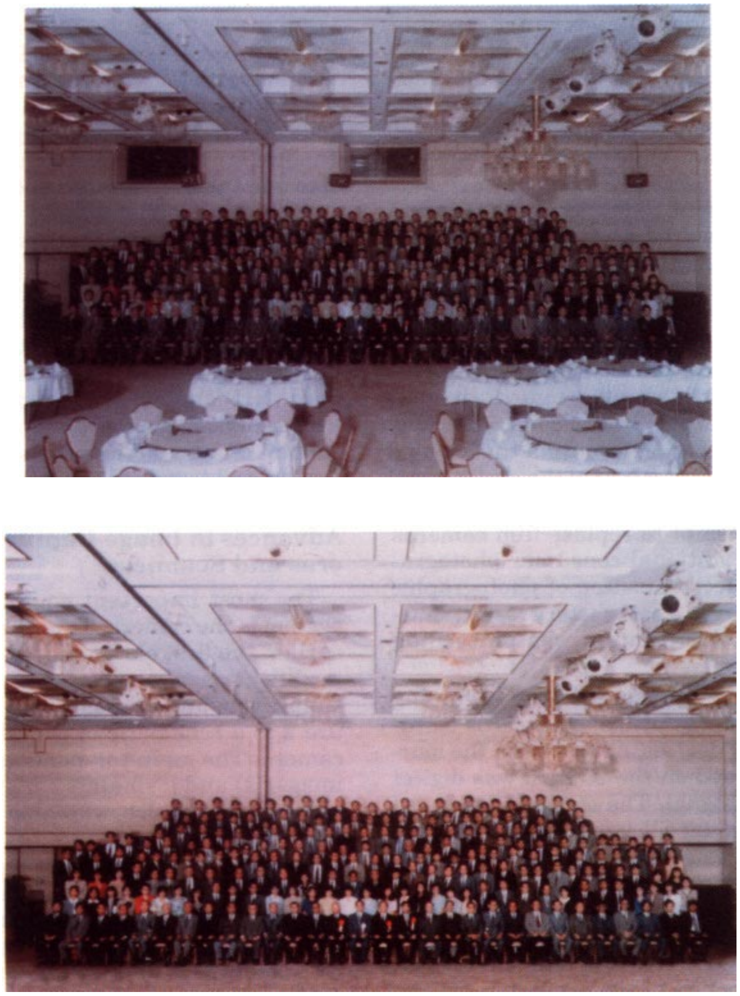


Figure 1. Reproduction of a typical digital photography print. *Top*, original picture; *bottom*, retouched picture. *Courtesy of T. Tsutsumi*.

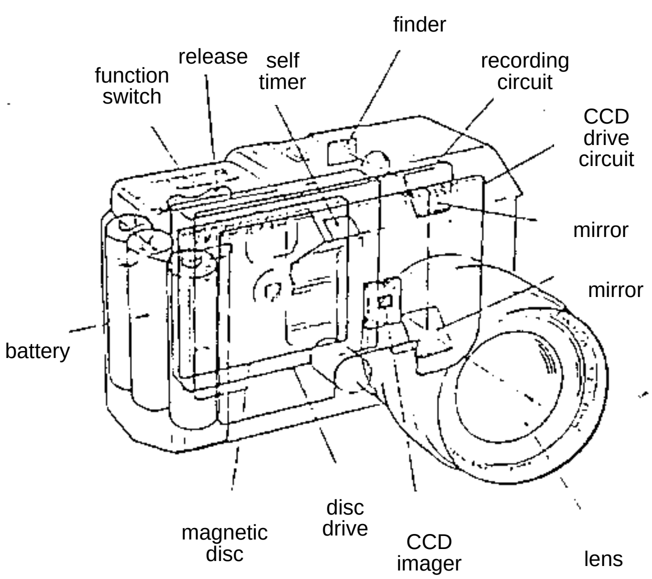


Figure 2. The skeleton of the first electronic still camera (Mavica camera).

CCD imagers with 1.5 (1000 × 1500) to 6 million (2000 × 3000) pixels have been available.[9] These imagers were expensive, and thus most cameras introduced high-density CCDs of the single-imager style with mosaic-type color filters. Some cameras introduced high-density single-CCD imagers without attached filters, using three sequential exposures, each with a different color filter in front of the lens.[5] This type of camera is useful only for capturing still subjects.

Figure 3 shows the range of products that have appeared on the market, from analog SV cameras to digital cameras. At the beginning of the decade, the change to digital cameras started from the low-end single-CCD models and then spread to all kinds of products. These all-digital cameras were first described as EP cameras. Moreover, scanner-type cameras, not listed in Figure 3, have recently appeared on the market. Their imagers are line-array-type CCDs consisting of four or five thousand pixels that record sequentially on the focal plane of the camera.[10] That style camera is a kind of three-dimensional scanner and is used to capture only still subjects. The standardization of electronic still photography systems by the International Standard Organization (ISO) began in 1991.[11]

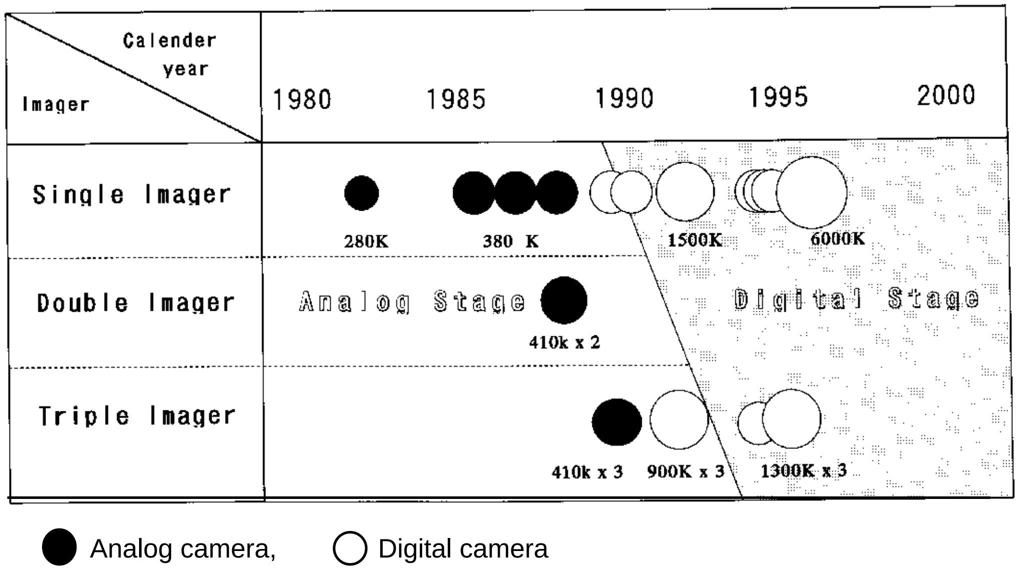


Figure 3. The changes of production of electronic still camera. Numbers indicate pixel numbers in CCD imager(s).

The current EP cameras with high-density imagers are key equipment in digital photography. They are now referred to simply as digital (photography) cameras. The many customers—photojournalists, professionals in design houses, photo studios, and prepress houses for graphic arts have created a demand for these expensive cameras. The output image data from these digital cameras are supplied directly to the computer and are easily manipulated. Instant image capturing and desktop image processing led to cost reduction in those professional fields. The users welcome the current high-end digital cameras and enjoy their profitable operation. The output pictures from the cameras with 6 M pixel CCD imagers are said to be comparable with those from 35-mm still film cameras. Thus the specifications of these new digital cameras are close to those of film cameras.[6]

By the summer of 1995, new digital cameras, orthodox still cameras and digital video cameras (camcorders) had all appeared on the consumer market. The digital cameras are commonly equipped with VGA-class reasonably priced CCD imagers. The marketing strategies for these products are very interesting. The manufacturers of the new digital still cameras advertise their products as computer peripheral equipment for graphic image capture and never as new photographic cameras. In contrast, almost all new digital camcorders have the additional ability to take still images. Advertisements for camcorders advocate both the video image and still image capture. Because they can also utilize photographic images, the advertisements for digitized video printers are combined with those for new digital camcorders, as described later.

Note that the quality level of output images from those two kinds of cameras (digital still cameras and camcorders) is nearly equal; however the use of the orthodox digital still camera is considered restricted to that of a computer peripheral. Typical street prices of the new still cameras in 1995 were around $500, and some manufacturers described monthly production of 30,000 sets. Because the appearance of digital cameras coincided with widespread use of personal computers and graphics manipulating software, computer enthusiasts welcomed them as equipment for desktop image processing in offices or homes. The manufacturers of both cameras may recognize that the ability of still cameras does not really fit photographic demand and the still mode on the digital camcorder is only an additional function.

The main customers for the current digital cameras apparently do not yet complain about the image quality. It is supposed that the customers understand these cameras simply as three-dimensional scanners for personal computers. However, in the near future, consumer-type digital cameras will have to upgrade and introduce higher density megapixel imagers. At present the price of the higher density CCD is expensive, although it will be reduced by mass production for new imaging applications. Thus the current activity of the consumer digital camera cannot directly expand the electronization of photography.

Scanners for Digital Photography. The key equipment of the hybrid photography system is the film scanner. The picture information in the developed film is read out by a film scanner consisting of three CCD line sensors with respective R, G, and B filters and then converted to digital data. At present, many kinds of film scanners are on the market. The imagers in the scanner are mostly simple line sensors and are available at lower cost than the area sensors in digital cameras. Most scanners are desktop equipment and their assemblies are not so complicated as those of handheld digital cameras, which is the main reason why the HB process in the digital photography system is still very useful. Flatbed-type scanners were first introduced for business use to read and convert documents to digital data. However, these scanners are gradually being introduced in the digital photography field to convert photographic images on hardcopy to image data.

Advances in Hardcopy Output: Development of Digital Pictorial Color Printers

In the news conference to announce the Mavica camera in New York, some reporters commented on the lack of picture output equipment. They said that for a new photographic system to be accepted, it had to include both a camera and new equipment to produce color prints. Eight months later, the new Mavigraph thermal printer, which produced color prints instantly with a perfect dry sublimation dye thermal transfer method, was proposed.[2]

Development of SV Color Printers: Competition to Produce Color Prints by NIP Methods. After the appearance of the Mavigraph printer, strong technological competition to develop color printers started, mainly in

Japan. The many manufacturers recognized that the development of a color printer was more difficult than that of a camera. Thus the competitors worked to find NIP printing methods to produce color prints with instant and perfectly dry processes.

Before the 1980s, electrophotography was the most expected NIP system and it was categorized as *unconventional photography*. At first, it was meant to replace the traditional "wet" photography, and various manufacturers tried to produce color equipment; however the image quality of the output was far from that of photographic prints. In the early 1980s, two more NIP color methods, ink-jet printing and the wax-melting-type thermal-transfer printing, were being studied in the laboratory. A new prototype thermal color NIP printer utilizing the sublimation dye transfer method was developed. In the photographic field, monopack instant color photographic materials were supplied by film manufacturers.

Thus the competition to develop color printers for the new photography system began with three-color hardcopy printers using the electrophotography system, instant color film, thermal transfer printers using sublimation dyes and wax-type ink, and ink-jet printers.

Picture size for consumer photography was supposed to be smaller than a hand-held $4 \times 5''$ size and the pictures were to be viewed at a distance of about 1 ft. The picture size and viewing conditions were very important factors in the new photographic pictures. In electronic imaging, the reproduced image consisted of an arrangement of pixels. The number of pixels was limited by the signal standands of the system.

In the hardcopy, the pixel is expressed by increments of colored material on the substrate. The increment size depends on the printing signal supplied by the stylus of the printer and the printing conditions. Thus every picture generated by electronic imaging has a microscopic structure, and viewing conditions in which the structure is visible are not comfortable to the viewer. In the pictures produced by analog printers, the species of pixel are indistinct; however the line of pixels comprising a scanning line is prominent. On the other hand, with images produced by digital printers, the size of the individual pixel itself is a factor of disturbance in the viewing. Moreover, the color and tone reproduction of the output hardcopy depends on the ability to express a wide range of color densities of the printed pixels. The color reproduction depends on both the optical properties of the coloring material itself and the arrangement of pixels on the substrate. In direct viewing of the hardcopy, the resolution of the human eye is a big factor to consider in determining the viewing condition. The resolution of the human eye with normal sight is supposed to be 1 min in steradians, which corresponds to 80 μm at the preferred viewing distance.[12]

The main technical goal in the development of new printers was to realize complete continuous tone and rich color reproduction in the output pictures. The new printers were to produce pictures with the following characteristics: maximum color density around $D = 2.0$ and maximum pixel size smaller than 80 μm^2.

In the above types, two systems and two media were available to realize a continuous density change in the picture element. That tone reproduction method is referred to as a *direct-density* method. Such densities were available in the photographic and thermal prints using, respectively, instant color films and the sublimation dye transfer media. The other types of printers could not express the direct-density change and had to utilize area-type *quasi-density* changes of the printed pixels. The quasi-density expression of pixels is realized by the printing of small dots of colored material. The density change is controlled by the numbers of dots per pixel. This tone reproduction method is described as an *area method*. There are two area methods: the binary area method, which uses uniform printing dots, and the multi-level area method, which uses size-tunable dots. Of the three tone-reproduction methods, the direct-density method is the best, the multi-area method is second, and the binary method is last.

Realization of a Complete Continuous-Tone Reproduction. During the early 1980s, hot technical competition had unfolded, and there were many proposals to realize continuous-tone reproduction in printer systems.[13] Printers utilizing the quasi-density tone reproduction were applicable if the wide range of density change could be realized in smaller pixels than required by the restrictions of visual resolution. There were many so-called digital half-toning methods using electrophotography, ink-jet, and wax-melting transfer-type thermal printing.

Figure 4 shows the efforts to realize direct-density expression and fine digital half-toning in the wax-melting thermal transfer printing and ink-jet printing. Unfortunately, most of the systems could not meet the requirement of small size pictures for the SV system. Figure 5 shows the microstructure of the same part of the ISO/TC130 standard pictures printed by several methods. The only printer system that fit the demand was the sublimation dye transfer thermal printer.

In 1986, the first sublimation dye transfer printers reached the market. The medium contained true sublimation dyes that did not show distinct melting points; however, the output pictures were not stable because of the recrystallization of transferred dye molecules on the surface of the receiving paper. Then the printer manufacturer changed to dyes having distinct melting points, and the stability and image quality were markedly improved.[14] The new transfer mechanism was thermal diffusion dye transfer, so that very tight contact between the ink ribbon and the receiving paper was required for accurate transfer. After that it was understood that the transfer mechanism was not sublimation, although, at present, the printers are still often described as sublimation dye thermal transfer printers or thermal dye transfer printers. Figure 6 shows reproductions of pictures produced by the early sublimation dye transfer printers and current diffusion dye transfer printers.

As a result, the output printers for the SV system concentrated on the so-called thermal dye transfer printers. Small color hardcopies close to photographic print quality were produced by such a printer. The first printers on the market were directed just to the output of SV cameras, but did not succeed in achieving consumer approval for the reasons described earlier. The manufacturers then changed the target to peripherals for the consumer video camera (camcorder) system and TV broadcasting. Thus those printers were designated as video printers and some printers were nicknamed in the marketplace as *movie printers*. This situation was recently emphasized by the introduction of digital camcorders. Thus the marketing strategy to combine the printer with the camcorder has extended, and various reasonably low-priced models have remained on the consumer market.

Appearance of Digital Printers. By the beginning of the 1990s, color handling in the computer had progressed greatly and various graphics manipulating software were on the market at reasonable prices. Thus the advanced computer systems required digital color printers for high-definition photograph-like picture output. The thermal dye transfer printer fit this demand, and large A4 printers have been supplied by several manufacturers. Even in the video

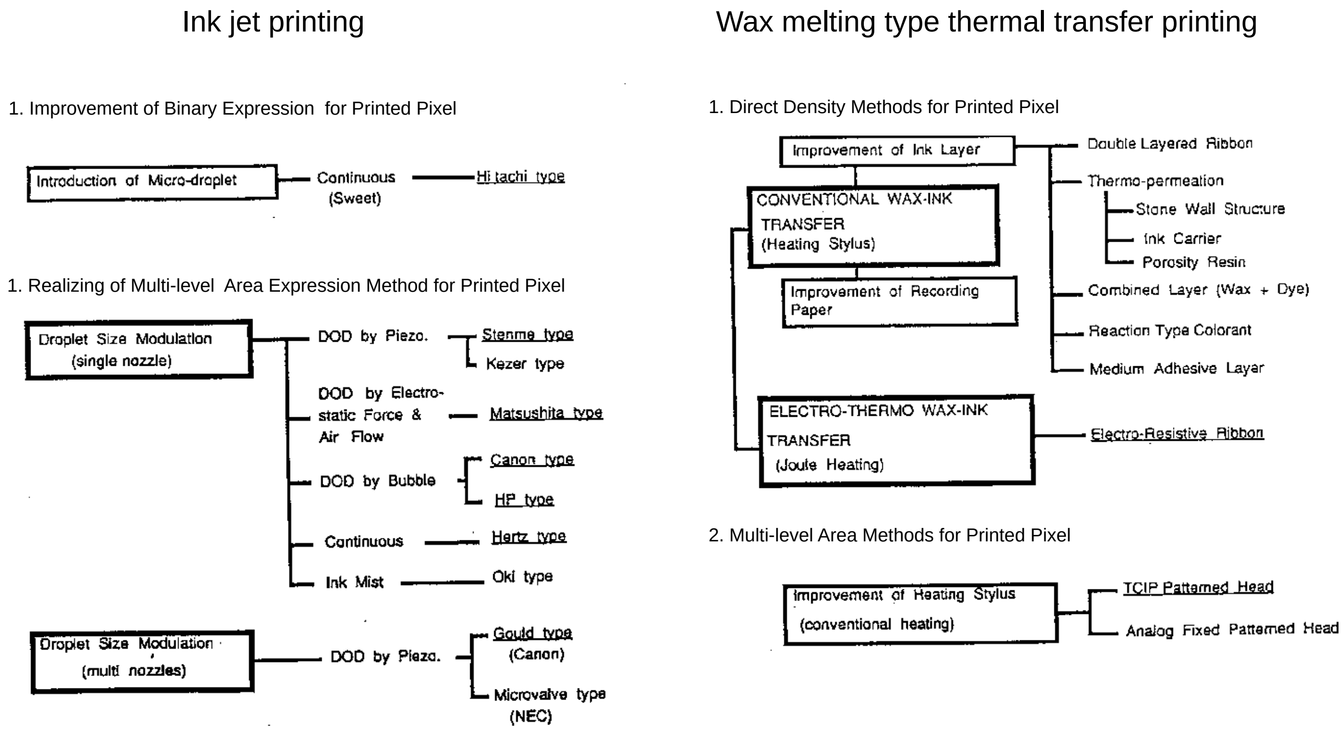


Figure 4. Direct-density and multilevel-area-density ink-jet and wax-melting-type thermal transfer printing systems. Underlined types of printers have been commercialized.

printers receiving analog signals, the heater head was driven by digital signals utilizing pulse-width modulation. Thus it was easy to design printers receiving digital image data. After that, many printers receiving digital data appeared on the market. These printers were compatible with the digital photographic cameras; however, the output of the cameras also worked with the personal computer. Thus this type of printer was the same as computer peripheral equipment and was described as a *digital printer*. At present various digital printers producing color pictures of A6 to A2 sizes are on the market. The color reproduction of these printers improved gradually and soon reached the same level as that of photographic color paper. The enlarged output pictures taken by some digital cameras utilizing the high-density CCD imager surpass those produced by traditional photographic systems. The only points of inferiority in thermal dye transfer printer pictures versus photographic color paper prints are image instability and image fading. Trials to improve those defects have been proposed, and some improvements have been introduced in current products. The chemical fixing methods of chelation and quasi-pigment formation in the receiving layer with transferred dye molecules and additives are remarkably effective in stabilizing the color image.[15,16] The physical method of lamination of an overcoated plastic layer by a fourth transfer from the ribbon after three color transfers is also effective.[17] The chelation and lamination were introduced in the current products by Konica, Kodak and others, respectively. Given the severe competition, many color printing methods have improved markedly; however, these methods do not offer photographic quality small picture printing.

Recently a new printing method to produce high-definition pictures was proposed by Fuji Photo Film Co. The method is a kind of direct thermal printing named *thermo-autochrome*.[18] This process utilizes a novel medium having three coloration layers, as in regular photographic films. Each layer is colored independently by heating at a different temperature, and the non-reacted areas remaining in the noncolored parts are fixed by irradiation with UV light of a different wavelength. This is the first full-color direct thermal printing method and will be the second NIP color printing method showing fine tone and color reproduction to satisfy the demand for photo-graphic-like output.

Expansion of Color Hardcopy by Digital Photography: Pictorial Hardcopy and Its New Applications

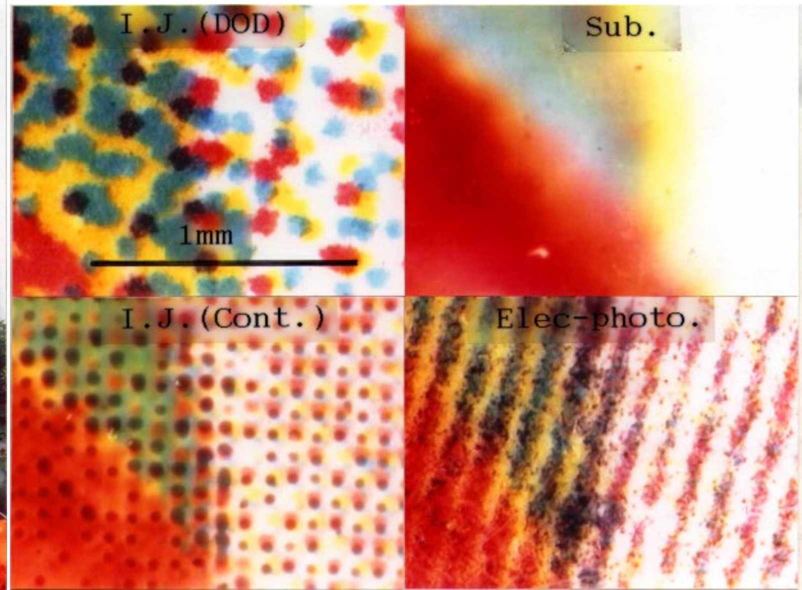
Competition to develop color printers for the new photographic systems in the 1980s accelerated color hardcopy, changed the trends, and invited new applications.

The first hardcopy had appeared as stable, long-lived alpha-numerical text output images from computers of the 1950s. These were pictures produced from electronic sources. Later the term *hardcopy* was extended to cover various sorts of pictures printed on media like paper and read back by reflective light. Recently the majority of hardcopy pictures have returned to the original form.

Actually the first color hardcopy equipment was tried in the mid-1970s. Many manufacturers announced trials of electrophotographic color copiers; however, only a few products reached the market. Most color hardcopy systems had initially appeared with the purpose to improve and replace the traditional photography system, utilizing instant dry processes with light exposure. It was difficult, and none succeeded before the proposal of the SV system.

When the SV system was proposed, most hardcopy pictures had expressed alphanumerical text images and were applied in the business field. Color was also tried in the impact printers and in some NIP equipment, such as wire-dot printers, electrophotographic copiers, ink-jet printers, and thermal transfer printers. However the colors of these output pictures were on the level of partial color or accent color. The structure of text images was binary, and the desired image properties were readability and accuracy.

(a)



(b)

Figure 5. (a) ISO/TC130 standard picture, (b) Image structures of pictures printed by various NIP printers (*upper left*, ink jet, drop-on-demand; *lower left*, ink jet, continuous; *upper right*, dye sublimation; *lower right*, electrophotography).

Sublimation dye transfer print

Thermal diffusion dye transfer print

Figure 6. Reproductions of pictures printed by sublimation dye transfer printer and thermal diffusion dye transfer printer.

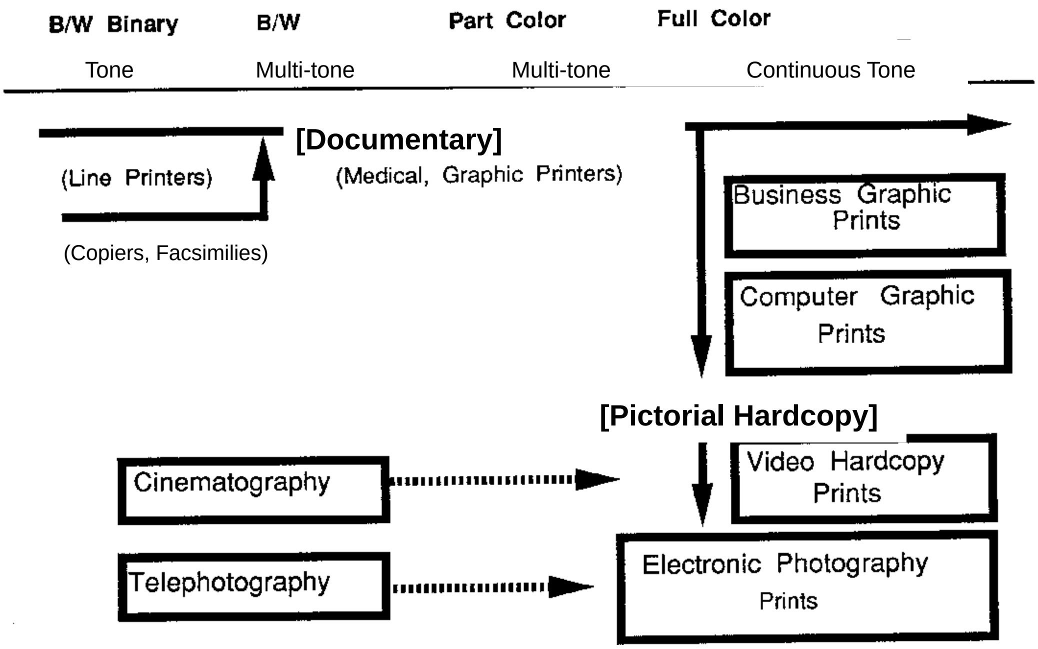


Figure 7. Advances in hardcopy systems.

These pictures were only for documentary use in the business field and were described as *documentary hardcopy.* The color pictures for the new SVphotography had to express aesthetic content and to respond to artistic demand. Thus the new hardcopy of the SV system was classified as *pictorial hardcopy*. The hardcopy would need to realize full color and to expand the level of faithful reproduction of the subjects.

The difference between documentary and pictorial hardcopy is only the information capacity involved in the picture. The full-color continuous-tone image contains much more information than that of a monochrome binary image. A photographic system handles a huge amount of information to meet customer demands. As a result, the SV system, the antecedent of digital photography, had led to the expansion of the hardcopy world. In the past decade, the dye transfer thermal printer has responded to the demands of the new photography. It was the first hardcopy printing system to overcome the restrictions of documentary hardcopy. The rest of the color printing methods also explored the new applications.

Figure 7 shows the advance of formula and content in hardcopy systems after the competition for the SV color outputs. One of the new color hardcopy worlds was computer graphics (CG). Computer-aided imaging has been popular from the designing and drawing for factory use to CG creations and computer animation. Color is essential in the creation field. At present the output color pictures are mostly still on the level of full color with little tonal rendition. Many kinds of printers entered into this field and produced brilliant color hardcopy. Recently some designers have tried the hybrid pictures from computer graphics and natural images taken by camera. The required image quality is the same as for photographs. Thus this field will soon be close to pictorial hardcopy.

One recent application of color hardcopy is the so-called design COMP (comprehensive), for creative output using a computer. COMP hardcopy employs an original picture for printing and consists of an alphanumeric text pattern and natural pictures taken by camera. Now new COMP hybrid printers on the market use a combined method to utilize the thermal dye transfer and the wax-melting-type thermal transfer method. The pictorial graphic is produced by thermal dye transfer and the text is printed by wax transfer, which shows higher resolution. The printer itself is compatible with both kinds of media. The picture printed by dye transfer is smooth, and the characters printed by wax ink are clear.

COMP has the same output as that produced by desktop publishing (DTP). In that field, printed hardcopy is as important as image data stored in the file. At present DTP is aimed only toward professional applications; however, it will produce original pictures for color copiers in the regular office. The color copier cannot work without color originals, and the introduction of office-level DTP will extend the color copier business.

Figure 8 shows the history of hardcopy technologies. The developments have proceeded stepwise; the first stage was established by U.S. industries in the early 1970s, and the main result was color electrophotography copiers. The second stage was established by Japanese industries at the beginning of the 1980s, and the main products were the thermal dye transfer printers. The third stage is now being promoted by U.S., European, and Japanese industries, and the main products are various digital printers, appliance-level home printers and short-run color printers. Digital photography and its predecessors became involved at the second stage and will relate more closely to the third stage.

First stage (1970-80)	Establishing of color electrophotographic copying technology Host country: U.S.A. Products: Analog PPC color copiers
Second stage (1980-85)	Proposals of thermal transfer, ink jet technologies. Introduction of digital copying technology. Host country: Japan Products: Video printers, digital color copiers.
Third stage (present)	Proposals of new printing technologies and revival of current technology. Host country: Japan, U.S.A. and European countries. Products: Digital printers, appliance level home printer, short-run color printer.

Figure 8. Stepwise history of color hardcopy technologies.

New Problems in Imaging Systems Involving Digital Photography

The application of digital photography to new imaging systems will introduce many new problems. Typical problems are the relation of coding rate of image data to the operation of imaging equipment and the coordination of image quality on softcopy display and hardcopy print produced by the same image data.[19] The digital imaging system consists of various kinds of imaging equipment for image capturing, processing, softcopy monitoring, and hardcopy printing. The information transport and exchange in that system utilize image data. The imaging system consisting of such integration of various imaging equipment is described as an *imaging chain*. In the imaging chain, the assignment of image data rate is important for the system design. The monitoring and manipulation of the data handling and the human interfacing of the information utilize the softcopy monitor. Thus the output hardcopy printing is likely to be controlled by the softcopy image on the monitor. As a result, coordination of the image quality of both softcopy and hardcopy images is an important factor for faithful and favorable image reproduction in the digital photography system. We have examined solutions of the above two problems and propose evaluation methods.

Evaluation of Input Image Data and Output Density Level. In the standard digital photography system, the image data carrying the image information is assigned to be 2^8 or 2^{10}, 256 or 1064 levels. The value is supposed to be derived from the data handling capability of the personal computers and the maximum density range of photographic paper, around 2.2. In the photographic image, the digital expression of rendition, digit density change, is not favorable for human vision. Although the capability of distinctive density expression of 256 steps is significant to adjust the design of transport data rate (coding) for the imaging system, if the printing system does not respond to that data rate, the design of the signal system is in vain. The color expression ability of color printers is often advertised as 16.7 million colors. This refers to the simple product of 3×2^8 for the three primary colors cyan (C), magenta (M), and yellow (Y). Reasonable evaluation of that numeral has not yet been approved. The advertising copy was based only on the simple estimation. The relationship of image data and density expression on color hardcopy is a very important matter to be clarified.

The printer technology group in the Electronic Industry Association of Japan (EIAJ) has discussed this matter and proposed a new approval method. An experiment was carried out on an achromatic gray print produced by a sublimation dye printer, Sony UPD-8800, for convenience. Figure 9 shows the pattern for printing 256-level image data. The pattern consisted of 16 groups. Each group was divided into two parts: one part printed by an integral number of 16-level data points, shown as *A*. The other was printed uniformly in the 16th level, shown as *B*. The individual levels in *A* and *B* parts are as follows:

$$A = (16 \times a) - b, B = 16 \times a \quad (a = 1 \sim 16, b = 0 \sim 15).$$

In the printer, 256-level image data was supplied to the printer head as an electric signal controlled by a pulse-width modulation digital signal. The maximum density of the print, $D = 2.2$, was obtained by the 256th level. Thus the electric signal of one step was the simple value of $1/256 \times$ maximum value. Figure 10 shows the sensitometry curve and colorimetric L* curves of the sample print. The 256-level image data were nearly linear with L* values. Figure 11 shows the reproduction of a mosaic-like pattern on the print produced by 256-level image data. The print size was about A4, and the area of each step was 812×6 mm^2.

The visual evaluation of prints was performed subjectively under 6500 K ambient light and illumination of 1700 lx. The step recognition was first checked by detection of the difference between steps of $[16 \times a]$ and $[(16 \times a) - 1]$. For instance, in the first group, the recognition was checked between the 15th and 16th levels.

On the sublimation print showing the maximum density of $D_v = 2.2$, more than 240 steps of print patterns were estimated to be recognized by five viewers. This result meant that the density change between steps was recognized in all 15 groups. Similar results were obtained with a print produced by the thermally developable silver halide medium of Fuji's *Pictrography*. The maximum density, D_v was around 2.10, and nearly 240 levels were estimated to be recognizable under the same condition as mentioned above.

As a result, in the digital photography systems utilizing two hardcopy prints, the sublimation dye transfer print and the Pictrography print, the introduction of the coding rate of image data in 256 levels is considered reasonable. The mosaic pattern of printing described in this paper is an easy way to evaluate the printability of image data on the print.

A Common Evaluation Method of Achromatic Tone Rendition of Softcopy on Cathode Ray Tube (CRT) Monitor and Hardcopy on Color NIP Print. In the digital photography system, the same image data were expressed both as softcopy displayed by CRT and hardcopy printed by color printer. In that system, the softcopy is usually seen prior to the hardcopy. However, both images are similarly expressed by light intensity and commonly perceived by the human eye, although the two images have been utilized independently and the image evaluations were performed in entirely different ways. The image quality of the two images are analyzed by different kinds of apparatus. It is common sense that most photographic image analysis is based on correlative measurement after standard calibration and the measured values are affected by the optical properties of the apparatus. Density and colorimetric measurements using color filters show distinct dependency on the apparatus. Even in the same type of measurement, this effect is apparent. The common analysis of softcopy and hardcopy images with the same apparatus is a key issue in the evaluation of image quality in digital photography.

We have tried to verify a simple common evaluation method for achromatic tone renditions of softcopy displayed on a CRT and hardcopy printed by sublimation dye transfer. The formation of the same test patterns on both softcopy and hardcopy is easy. An experiment was performed to evaluate the reproduction of a gray chart test pattern on both the softcopy and hardcopy by noncontact measurement of luminance, using a telescopic spectrophotometer.

The test target was the achromatic gray-scale part of a Macbeth Color Checker color chart. The original was divided into six parts showing different density (D_v: visual reflection density measured by Xrite-310 densitometer) levels of $D_v = 0.05$, 0.23, 0.44, 0.70, 1.05, and 1.50 and numbered 19 to 24, respectively. The evaluation of the achromatic parts was supposed to be independent of the color characteristics of phosphors and dyes having different spectra. Each gray part was read out and converted to digital data by a flat-bed scanner. The softcopy was displayed on a color-temperature-tunable CRT color monitor, Sony GDM-2000 (21" size). The hardcopy was printed by a sublimation dye transfer printer, Sony UPD-8800. The print size was nearly the same as the original. The

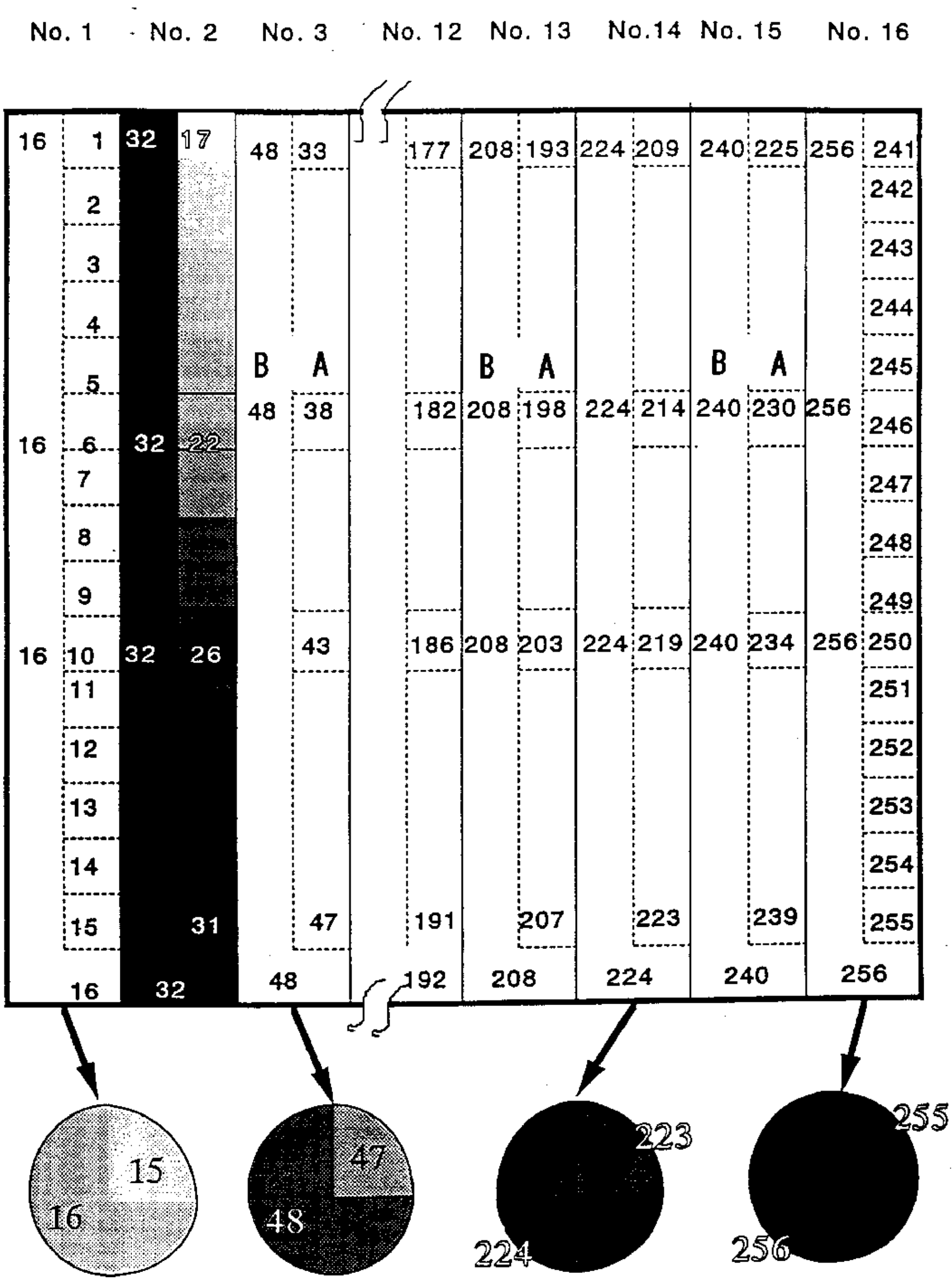


Figure 9. Pattern for printing of 256-level image data.

measuring apparatus was a telescopic spectrophotometer, Topcon SR-1. The viewing angle of the apparatus was 2°.

Figure 12 shows the experimental scheme. The distance between the apparatus and sample images was about 1.5 m. The original chart and its hardcopy reproduction were placed in the light box and illuminated by 6500 K light and illumination of 1000 lx. The color temperature of the white on the monitor was set at 6500 K. Thus the illuminating conditions of both pictures were the same.

The [XYZ] and [L*a*b*] color system data of the original chart and the sublimation dye transfer print and a CRT display are listed in Table I. Figure 13 shows the L* values of the original and reproductions for six achromatic parts on the original chart. The curves of the two hardcopy images entirely overlap; however, the curve of the softcopy shows higher L* values in the highlight part of the originals. This result suggests that common evaluation of achromatic tone rendition on the different type softcopy and hardcopy images, using noncontact luminance measurement, is practical.

Conclusion

At present, digital photography is tentatively established, and the final stage of electronization of photography is supposed to be realized in the near future. The 15-yr history has proceeded by stepwise advances of the still video system, electronic photography, and hybrid photography. Progress has been fast because of development of electronic technologies. At present digital photography is a starting business. It does not yet have a fixed customer base. The prospects of businesses related

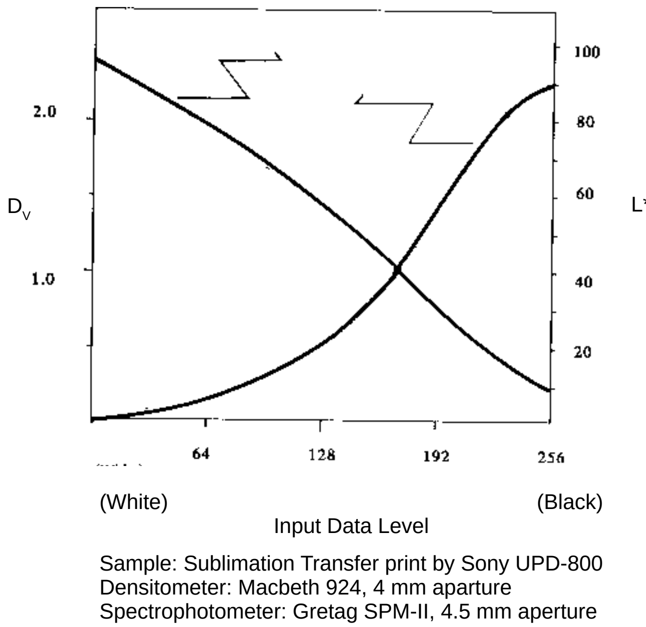


Figure 10. Sensitometric curves of sample prints.

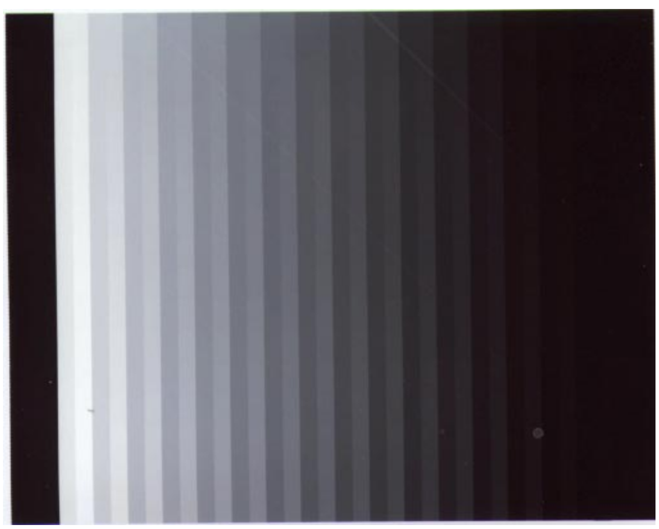


Figure 11. Reproduction of sample print.

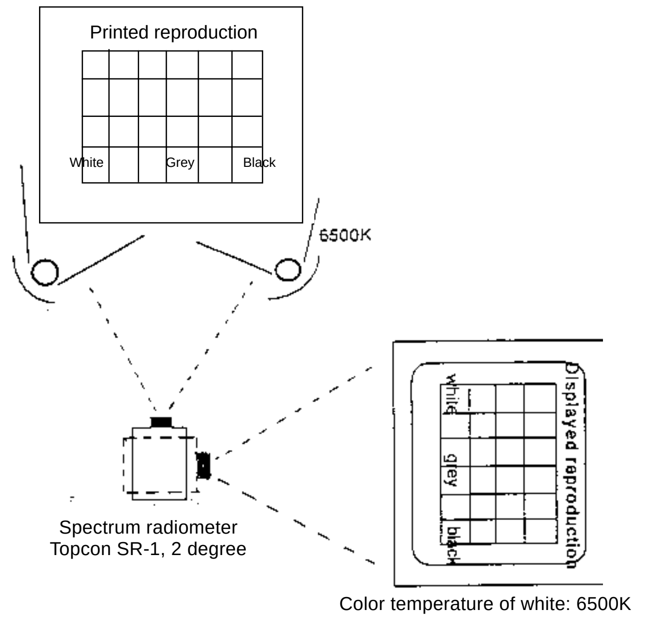


Figure 12. Arrangement of common colorimetric measurements for softcopy and hardcopy.

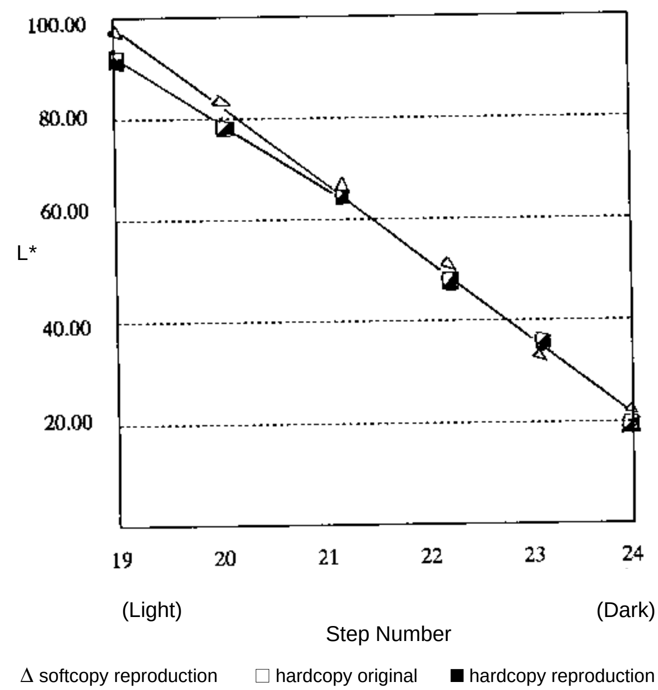


Figure 13. Colorimetric L* values of six achromatic parts of the original chart printed on hardcopy and displayed as softcopy images.

to digital photography appear bright, although the conditions of cost, productivity, and applicability are not yet sufficient to replace the current photography systems. Digital photography has many advantages and will grow more useful with further development.

The key equipment of digital photography has many problems to resolve. In the digital camera, the majority of the current products use the NTSC-class CCD imagers having unit sensors of around 400,000 pixels. That number is estimated to be equivalent to about one-fiftieth of 1 frame of 35-mm negative color film. CCD imagers having higher numbers of pixels are supplied by some manufacturers, although they are very expensive and have been introduced only in professional digital cameras. The cost of semiconductor devices is supposed to be inversely proportional to the level of production. Although the main application of such high-density imagers is expected to be digital cameras, it is a contradictory story and price reduction is not easy. The possibility of introducing high-density imagers to low-price consumer digital cameras is a theme for the future. The only solution at present would be a risky investment of the device supplier to sell them at low prices.

In the digital photography system, the sublimation dye transfer printer leads among NIP printers producing color prints. Its output is the only type print of photographic quality. However, there are various problems to be solved. The first is image stability. Image formation here is due to the simple thermal diffusion of dyes into polyester-like substrate, and the image is not fixed chemically. Thus the retransfer and diffusion of dye from the image position are big problems. Tentative solutions include chelate formation

TABLE I. Color Data for Hardcopy Prints and Displayed Softcopy Images Produced by the Same Image Data

	Species	X	Y	Z	X′	Y′	Z′	L*	a*	b*
Hardcopy prints	Std. White	301.10	327.80	351.00	91.85	100.00	107.08			
Original chart	19	241.20	264.50	275.10	73.58	80.69	83.92	91.99	-1.12	1.80
	20	164.10	178.80	194.30	50.06	54.55	59.27	78.78	-0.11	-0.81
	21	107.10	114.50	123.50	32.67	34.93	37.68	65.69	2.14	-0.34
	22	56.52	61.74	69.90	17.24	18.83	21.32	50.49	-0.32	-2.15
	23	27.10	29.60	35.50	8.27	9.03	10.83	36.04	-0.25	-3.46
	24	10.51	11.25	15.10	3.21	3.43	4.61	21.70	0.92	-5.08
Reproduction	19	248.70	270.80	282.50	75.87	82.61	86.18	92.94	-0.03	1.62
	20	167.00	180.00	191.70	50.95	54.91	58.48	78.99	1.37	0.29
	21	104.20	113.20	121.40	31.79	34.53	37.03	65.38	0.25	-0.07
	22	57.80	62.60	67.60	17.63	19.10	20.62	50.80	0.50	-0.33
	23	25.90	28.80	31.00	7.90	8.79	9.46	35.75	-1.56	-0.16
	24	7.86	9.00	10.55	2.40	2.75	3.22	18.99	-2.56	-1.85
Softcopy image	Std. white	78.24	81.02	81.54	96.57	100.00	100.64			
Reproduction	19	71.39	74.05	76.13	88.11	91.40	93.96	96.57	-0.27	-1.38
	20	48.96	50.06	52.15	60.43	61.79	64.37	82.80	1.81	-1.97
	21	29.05	29.55	31.47	35.86	36.47	38.84	66.88	2.13	-2.72
	22	15.99	16.47	18.14	19.74	20.33	22.39	52.21	0.52	-3.59
	23	7.30	7.49	8.18	9.01	9.25	10.09	36.45	0.64	-2.49
	24	3.14	3.12	3.49	3.87	3.86	4.31	23.19	2.20	-2.40

of the diffused dyes,[15] absorption of dye into some porous additives,[16] and lamination of an overcoat.[17]

The most viable solution will be chemical bonding between the molecules of the diffused dyes and a binder polymer in the receiving paper, as in the case of image dyes in silver halide media. The second issue is the generation of waste from sublimation dye transfer media. In this system, the ink ribbon after the printing is a waste product. This is a basic problem in transfer-type printing. The third issue is the productivity of the print process, which at present is the common problem in all NIP printers. The highest productivity in photography-related printing is the color photographic paper printer, which produces more than 20,000 4R prints per hour. Its speed is more than 300 times faster than that of the current video printers.

New printing methods that have appeared recently overcome some of these issues, although the superiority of the sublimation dye transfer method has not yet waivered. We must continue to develop new NIP printing methods suited to digital photography.

Digital photography and its predecessors have contributed to developing color hardcopy technology. The diversification of hardcopy introduced by digital photography from document to aesthetic applications, has been the most valuable contribution. Color photographic print formation by NIP methods was the useful result. Prints coming from small desktop printers were only a dream before the 1980s. The fine graphic image formation by NIP methods will have a permanent role in hardcopy.

In the new electronic imaging of digital photography systems, various problems not experienced in the current simple systems will appear one after another. For instance in the chain of imaging systems, many people take part remotely in complicated processes. Thus the intention and sense of the photographer are not easily communicated to the final image output process operated by entirely different people located at a distance. We must find new solutions in hardware and software to realize faithful and favorable reproduction in the complicated digital photography system.

Digital photography will grow to be one of the key technologies for pictorial information terminals in the multimedia environment. Simple, high-performance image capturing and output equipment are very useful for information transmission and receipt in offices and homes. The new technical problems discussed in this paper are the beginning and others will appear. Imaging engineers interested in this new system must find the solutions.

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