

Digital Photofinishing Systems Using Digital Light Processing

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Abstract

Digital Light Processing ™ Systems have been developed at Texas Instruments for display and printing applications. Both utilize a digital silicon spatial light modulator (SLM) called DMD. The DMD array is a three dimensional, micro-electromechanical system (MEMS) that is a very fast, efficient modulator of broad-band light.

The DMD is a reflective SLM, and thus well suited for the exposure of silver halide (AgX) film and color negative print paper, because it can modulate sources that are well matched to the photographic media. DLP ™ exposure subsystems are therefore possible candidates for digital minilabs, inline index printing, and high speed maxilab printing systems. The precise digital control of exposure at high bit-depths, the uniform panchromatic response, and the very high reliability of the DMD lend distinct advantages to the emerging digital photofinishing industry. Ease of calibration and alignment, along with exposure constancy over time, are essential to the new digital products.

This paper discusses the requirements for DLP™ exposure systems for minilab applications. The DMD device, optics, control electronics, and the concept behind the exposing process are described. Details of image quality resulting from inherently square, non-overlapping DMD pixels are discussed and compared with gaussian exposure processes characteristic of laser polygon and CRT systems. The critical image quality details are discussed, and the implementation of a digital resolution translator (DRT) to eliminate banding due to paper transport motion artifacts is described.

Future extensions of DLP ™ systems to wide formats and higher process speeds are considered. Recent announcements incorporating DLP™ subsystems in minilab photofinishing products are included for reference.

Introduction

Photofinishing is a $40 billion-per-year industry associated with the capture and printing of images on silver-halide media. For over 100 years the process has been purely analog. Only in the recent time frame has the industry adopted digital create, capture and print processes alongside conventional analog workflows.

Photofinishing: 135 Year-Old Industry in Transition

Black and white photography evolved between 1816 and the early 1850's. It was not until 1935 that a single-sheet color film based on layered emulsions was perfected. Conceived as a movie film, it was made into Kodacolor™ print film in 1941, and a modern consumer industry was born. The easy-to-use Kodacolor™ print film, and its associated high-quality created mass appeal for the excitement of immortalizing memorable events. By 1963, a major innovation came with the invention of Polaroid instant color photography. Polaroid's 60-second film was so convenient, however, that conventional systems seemed to be at a major disadvantage.[1]

In 1951, the founder of Noritsu Koki, Mr. Kanichi Hishimoto, invented an automatic print washer, followed by a series of photographic processors. In 1976, Noritsu introduced the first small-scale system able to go from film developing to finished-prints in forty-five minutes. This allowed small develop, print, and enlarge (DPE) shops to easily process film, and changed the basic concept of the photofinishing market. As it later became known, the *minilab* is characterized by small size, ease of operation, and modest cost. It is capable of producing several hundred 4 X 6 prints per hour, and typically can run enlargements up to 12 inches wide.

At the other end of the spectrum, the maxilab is a high speed central lab printer used at overnight service bureaus like Qualex, and runs up to 20,000 prints per hour on 4 to 6 inch web fed formats. Index prints, or digital thumbnails, are increasingly popular with the consumer, and are included with the service prints.

Today, about sixteen billion prints per year are made world-wide, with half processed by *maxilabs,* and half on *minilab*s in kiosks and other point of sale stores.

Photographic Market Conditions

Today's photographic market is rapidly changing due to external factors that are driving a digital presence into all aspects of the industry. The Internet enables remote photo services and access to a wide range of digital files. The recent APS format provides digital information in the film negative, and features index prints in lieu of negatives. Personal computers are a major source of easily created digital images, and digital cameras provide convenient electronic capture.

Throughout the imaging chain, digital and analog methods compete for cost, convenience and quality. All focus on the industry's desire to prolong the life of AgX media, and the customer's satisfaction with the look, feel and permanence of photographic paper.

Photofinishing: Technical Overview

Traditional Analog Approaches.
The SLR camera and 35 mm color film account for the majority of the consumer market. Half of all processing is handled on minilab equipment built by companies like Noritsu, Gretag, Fuji Film, or Agfa. About 120,000 minilabs exist worldwide.

These printing systems operate by projecting filtered halogen light through the negative onto color negative paper, and then developing it. Recently introduced color management systems have automated this process by scanning each negative to optimize print exposure.

Digital Approaches and Background

Several digital minilab products exist that utilize a range of technologies including area arrays and line sources (e.g. high resolution CRT, color linear CRT, LCD array, RGB line arrays of LED, vacuum flourescent or other emitter technologies.) The FujiFilm *Frontier* digital lab is the first minilab to commercialize a scanner input from color negatives along with a polygon scanner with solid state lasers providing RGB exposure. The use of miniature light valve arrays in products is limited at this time to the Noritsu MLVA technology, and the DLP™ system described in this paper.

The fundamental advantage of digital photoprinting is that every single pixel can be independently manipulated and optimized throughout the process. This allows the ability to utilize the full latitude of the AgX media, and additionally, opportunity to easily correct many of the normal failures encountered in photography. Density adjustment for backlit negatives and correction for over/under exposed film provides optimal contrast. Flash photos often produce too high a contrast between subjects and backgrounds, requiring both to be adjusted. Sharpness algorithms can be used to enhance images, similarly, compensation for lens falloff found in inexpensive compact cameras can produce a result better than the original negative.

Digital Photofinishing Using DLP™

Prior efforts within the TI Digital Imaging group demonstrated very high quality digital printing with a color Xerographic process and a linear DMD.[2] A novel concept, time-integrated-grayscale (TIG) with a multi-row SLM (64 rows and 7056 columns), was employed. This method corresponded to moving the photoreceptor surface continuously past the image of the DMD, and controlling pixel exposures by successive accumulation from each of the possible 64 rows. TIG row integration required a unique formatting technique, since each pixel's exposure level had to be retained for sixty-four lines, and had to "fall" through the DMD array in synchronization with the speed of the photoreceptor surface moving through the resulting image of the DMD. Therefore it was necessary to store sixty-four of these *microimages* to print a 64 x 7056 pixel image area. Understanding of the critical optical factors, illumination uniformity, stability, and image distortion tolerance was developed on this program.

In addition, the extremely critical problem of synchronizing the DMD microimage exposures to the motion of the photosensitive media had been addressed. A digital signal processor based control system called the Digital Resolution Translator (DRT) was developed to eliminate imaging artifacts resulting from timing and positional errors between the DMD exposure system and the photosensitive media. The DMD exposure was synchronized to match the inevitable velocity variations of the imaging medium in real time. Even with this prior know-how, the specialized requirements for DLP™ photoprinting systems presented significant challenges.

SystemRequirements

At the onset of the project, the basic requirements were determined to be twelve bits of gray scale per color, a process speed of eight inch/sec., and a resolution of at least 300 dpi. Other details are given in Table 1.

Table 1. DLP™ Minilab System Requirements

System Parameter	Requirement
Grayscale	12 bits (4096 levels)
Resolution	300 dpi minimum at 4 in.
Format	4 x 6 inch minimum
4 x 6 prints / hr. (ips)	5000 p/hr. (8 ips)
Source Lifetime	1000 hrs.
Modulation Transfer Function (MTF)	> 70% @ 5 line pairs/mm
Imager distortion	< 0.2%, full field
Registration of pixels (at image plane)	1/3 pixel for 3 colors
Illumination	Tungsten Halogen
Uniformity variation	< 2% across process

It was initially evident that 12 bits per color would require more than 64 DMD rows, so the only option was to opt for the SXGA display DMD, limiting resolution to 320 dpi across a 4 inch format. Since pure row integration required 4096 rows, TIG (spatial) integration was combined with several levels of temporal, or pulse width modulation (PWM). This innovation added a degree of freedom that permitted the generation of 12 bits of gray scale depth using a manageable row count. The digital architecture had to support a process that simultaneously

combined TIG, PWM, and sequential RGB exposure with a color wheel using one DMD. The optical system had to provide sufficient power to allow sequential exposure, one color channel at a time, through an RGB color wheel filter. Since color negative paper is less sensitive in the red, a source with sufficient red spectral content had to be incorporated. Fortunately, a suitable 150 watt tungsten halogen lamp was identified with the desired 1000 hour operating lifetime.

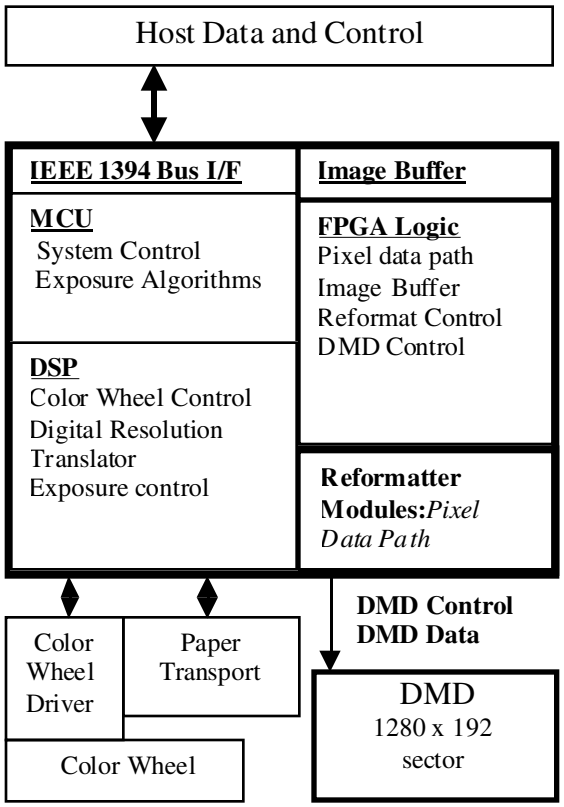

Figure 1. DLP Controller Architecture

Electronics Architecture

The DLP™ photofinishing electronics consists of a controller board, five reformatter modules, an image buffer, and a DMD/flex cable assembly (Figure 1). The controller provides all external electrical interface via a high speed data and command interface utilizing an IEEE 1394 bus. The high speed image data is sent from the host across the isochronous channels with the 1394 communication structure. This data is then stored in the image buffer which is comprised of a high speed FIFO memory and a standard PC100 SDRAM DIMM. The controller board also contains a paper transport interface which outputs paper control signals and inputs paper position and speed information. A DSP runs the Digital Resolution Translator algorithm (DRT) and the color wheel control algorithm. The DRT Algorithm takes the paper position and speed information and generates a synchronization signal (rowsync) which identifies when a pixel on the paper has moved exactly in line under the image of the DMD mirrors. The synchronization for the exposure rate of the DMD and the speed of the color wheel is achieved through this rowsync signal.

All system level electomechanical control and image buffer flow control is handle by a microcontroller (MCU). The MCU also manages a flash EPROM which contains all programmable software files and the exposure algorithm tables. The FPGA logic on the controller board performs all data path and memory control functions including DMD data, address, and analog voltage control.

The reformatter modules provide the ability to convert image pixel data into DMD mirror settings to achieve the 12 bit exposure. They contain a pixel buffer memory and mirror setting look-up-tables (LUT). The pixel buffer stores and tracks each pixel as it moves through the DMD active area. Every rowsync one line within the image buffer is transferred into the pixel buffer memory. The pixel buffer data is then input into the LUT which outputs a DMD mirror setting bit plane which is called a microimage. This bit plane is transferred out of the reformatter modules into the DMD memory underlying the array of DMD mirrors. When the DMD completes exposure of a microimage, equivalent to some fractional percentage of an image line time, it is turned completely off. When the DRT indicates the next line is in position for exposure, the entire DMD array switches to the new image in about 10 microsec., and continues to expose the paper for the desired PWM pulsewidth before turning off. This process is repeated for the next microimage on the next line of the image. The line rate for the 8 in./sec. process is 2560 lines/sec. Figure 1 diagrams the major blocks of the DLP ™ controller architecture described above.

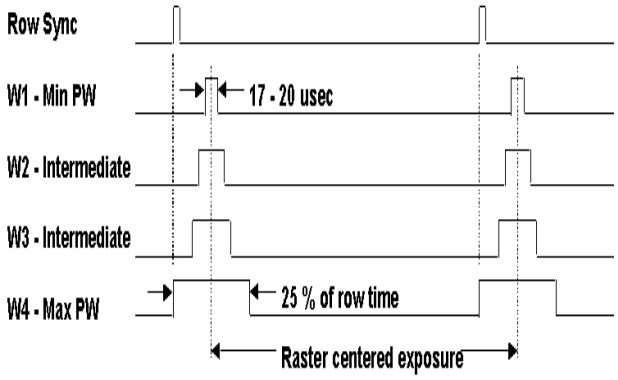

Figure 2. Exposure Timing for PWM Sequences

Figure 2 details the timing of the various exposure pulses of the PWM sequence to the line of exposure in the print. Note that all PWM pulsewidths are timed to fall exactly on the same centerline to preserve image sharpness. The longest of the PWM pulses is typically

selected to be a fraction of the actual line time, 25% for example, to avoid line smearing in the process direction and thus preserve the fidelity and MTF of the imaging system. This puts a significant burden on the total exposure power delivered, but the efficiency of the system allows the benefits of this design trade-off, while still permitting process speeds of 8 ips and beyond.

Optical Reference System

Figure 3 illustrates the general layout of the optical reference system. Illumination is provided from a tungsten-halogen lamp, and imaged onto the DMD through an integrating rod element to achieve the required uniformity. Field-sequential color is provided by a three-segment color wheel 140mm in diameter, with a typical rotation rate of 3200 rpm. The reliability of color wheel assemblies is very high, based on the acquired experience from the DLP™ display business. The imager in the reference design was a purchased Apo-Rodagon-N 105 mm 1:4,, and very satisfactory image formation characteristics were achieved. The source was a 150 watt GE 8MM projection lamp, rated at a color temperature of 3250K at 21 volt operation and incorporating a CC-6 filament wind Rated 200 hours at full voltage, these lamps can provide 1000 hour lifetimes when operated at 3150K filament temperatures, hence are very suitable, inexpensive, readily available sources for photofinishing systems. The ability to match the spectral characteristics of the combined source and color wheel filter assembly to the spectral response curves of the color negative paper without any crosstalk was a significant advantage for the DLP reference design.

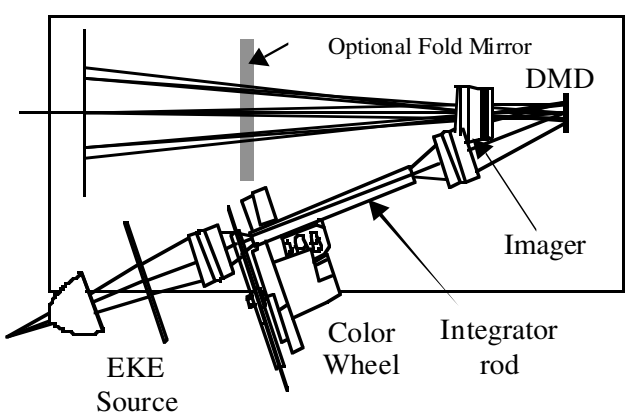

Figure 3. Optics Reference Design

In operation, on-state light from the DMD is directed to the entrance pupil of the projection lens, and off-state light misses the lens aperture entirely. Contrast ratios in excess of 1000:1 can routinely be achieved with DLP™ projection designs.. The DMD image at the paper plane is magnified about 4.5X, resulting in a 320 dpi resolution across a 4 inch width (total 1280 pixels). The imager lens was selected to minimize aberrations which would lead to non-uniformities and pixel misregistration at the image plane. The two percent uniformity requirement presented in Table 1 is among the most stringent ever placed on a DLP™ design, and yet has been successfully achieved with careful optics design and the integrator rod approach. Optical distortion, predominantly due to the imaging lens, can have a deleterious effect on photographic image quality. An example of a common malady present in poorly designed imaging systems is termed "barrel" distortion (along with its counterpart, "pincushion" distortion). The effects of this type of distortion would be amplified by the TIG process due to the resulting inability of the successive DMD rows to spatially align at the edge of the image field.. The impact is eliminated by choice of a good imaging lens and by simply limiting the DMD active area row count so that the image height is minimized, while electing sufficient rows to provide adequate light intensity.

Optical power at the image plane must be sufficient to expose typical photographic papers to an optical density range of 2.2 to 2.5. Modeling shows the light budget is several times the required value to generate five thousand 4 x 6 inch prints per hour. The benefit of this budget is improved source lifetimes and the ability to achieve the desired illumination uniformity in a straightforward design

Additional aspects of the reference design can be found in the 1998 TI Technical Journal issue dedicated to Digital Imaging.[3]

Table 2. Example of DLP Algorithm

Key Exposure Algorithm Features	
Number of Rows Required	192 DMD rows
Color Wheel Color Segment Transition Rows (DMD must be off during transition Rows)	4 – 8 per color
Total number of rows utilized for row integration	56 DMD rows per color
PWM range	4 levels (non-binary) LSB is 17 micro-sec.
Exposure levels per color	4096 linear steps
Pulse width Resolution	25 nsec

DLP Operating Algorithms

Table 2 indicates the basic features of the DLP exposure algorithm as implemented on an SXGA class (1280 x 1024) of DMD. For the reference optics described, and the target process speed of 8 inches/sec., only 192 total rows of the DMD array are actually addressed. Though the image is constantly "falling" through the DMD image as the color wheel rotates through RGB filter sectors, the table "assigns" 56 rows per color, and allows up to 8 rows of blanking time as each color wheel spoke rotates through the image. This assures the DMD is exposing the paper only when illuminated with one distinct filter segment. There are 4 levels of PWM

assigned (2 bits), and each operates for some number of the "available" 56 row count within a color segment depending on the algorithm design. Algorithms are defined with a software design tool that considers a range of input variables including process speed, width of the minimum DMD pulse (the LSB), row number desired, and other factors. It calculates the pulse width and row assignments that give a range of 4096 continuous linear exposure steps (12 bits). As a rule, the majority of the 56 rows are used for the high exposure bits (MSBs), with about one-fourth of them used for all 3 of the remaining shorter PWM exposures.

Gray scale accuracy and smoothness is digitally corrected on a one-time basis by a process of pulse width calibration. Test patches are run to assure combinations of pulse widths that should add up to the same exposure do in fact produce the same measured optical density. The precision of this step when defined in the digital domain is basically the ratio of the pulse width adjustability (25 nsec.) to the LSB time of 17 micro-sec. In effect, the LSB is one part in 4096 exposure levels (12 bits in linear exposure), and has almost a part per 1000 adjustability. In operation, using Kodak Edge 5 paper, a single LSB of exposure corresponds to an optical density step of approximately 0.0008 in the linear range of the paper response curve. Since variations in source output affect exposure uniformly under this type of algorithm, density calibration is very straightforward.

DMD Light Modulator Description

The heart of the system is the DMD chip, shown in Figure 4 with a box indicating the relative size of the imaging area utilized for the minilab system design. The active area is 1280 pixels , each 17 microns wide, for an active width of 21.7 mm. The reflective mirror elements are square, and have a fill factor of 92%. Figure 5 shows details of the mirror level and underlying micromechanical structure under an electron microscope. The reader is again directed to the TI Technical Journal [3] for a number of good articles describing the DMD, its fabrication, operation as an SLM, and its reliability.

The reliability of a device with over 1.3 million tiny moving mirrors is generally an interesting area of discussion. It is counterintuitive at best, and extensive test data on the TI DMD technology has been documented [4]. Under accelerated test conditions, the projections are that the devices should last for more than 100k hours of operation, equivalent to over 100 years in a projection system. Digital Imaging has devices that have been run over 20k actual hours with no defects. This corresponds to about 2 x 10^{12} cycles of operation. Taking the total number of mirrors under test, it corresponds to about 10^{18} total mirror movements.

The DMD is a MEMS light switch fabricated monolithically in a silicon CMOS production facility. Each element is a tiny aluminum mirror that can reflect light into one of two directions depending on the state of the CMOS memory element below the mirror. Figure 5 shows details below the mirror elements including the hinge that supports rotation, and the yoke structure that supports the mirror. The two tiny tips of the yoke land on the underlying surface in response to electrostatic forces applied by the addressing electrodes. Because it lands in one of two precise angular states, +/- 10 degrees, (on, or off), the DMD light modulation is digital in nature. Optical characteristics from pixel to pixel within the array are extraordinarily consistent due to the precision of the semiconductor manufacturing process. Because the DMD is passive and not an emitter, there is no known mechanism for pixel variations to develop with use.

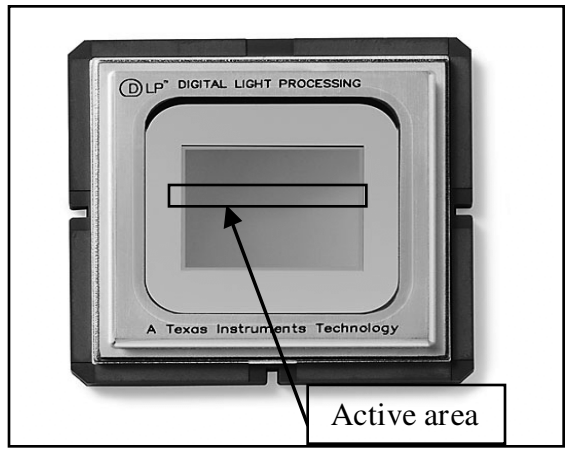

Figure 4. SXGA DMD Chip, 1280 x 1024 pixels

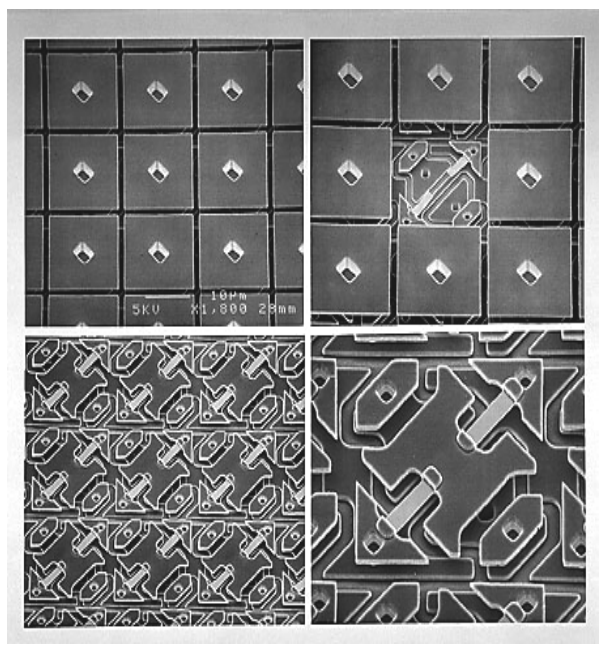

Figure 5. SEM of DMD superstructure clockwise from top left: Mirror Array, Hinges (mirror removed), Yoke detail (hinges and electrodes), Yoke Layer.

Results of Color Image Quality Assessment

The illumination uniformity, spectral quality, contrast ratio, total integrated power and optical distortion are only intermediate specifications for determining image quality. The real test is overall color image quality on photographic paper. At the customer level the print has to look good, meaning no visible artifacts or distortions in color space or content. Unfortunately, in a journal article, it is not possible to do justice to print appearance. There is an intermediate step however, where examination of pixel level detail and process MTF (modulation transfer function) can give a very good basis for image quality expectations. In addition, certain artifacts like banding or streaking can be characterized and quantified accurately and compared to other systems. Image quality data analysis has been performed using a variety of these techniques to characterize the DLP ™ digital photofinishing capability. Kodak Edge-5 paper was used with standard ISO 300 image files to test gray scale uniformity, dynamic range, color gamut, optical distortion, MTF, spatial registration, color pixel registration and text clarity.

One of the distinct advantages of the DMD-based system is images that are formed by sharply resolved pixels with high fill-factor, which are distinctly non-overlapping. This is particularly evident in comparison to dot spread profiles for a laser gaussian source [3]. Even fully exposed DMD spots are very well-resolved and fully contained within their geometric boundry. With good optics design, and the advantages of the DRT algorithms, accuracy and repeatability of pixel placement within the image is very precise. This leads to sharp, low noise images free of digital artifacts.

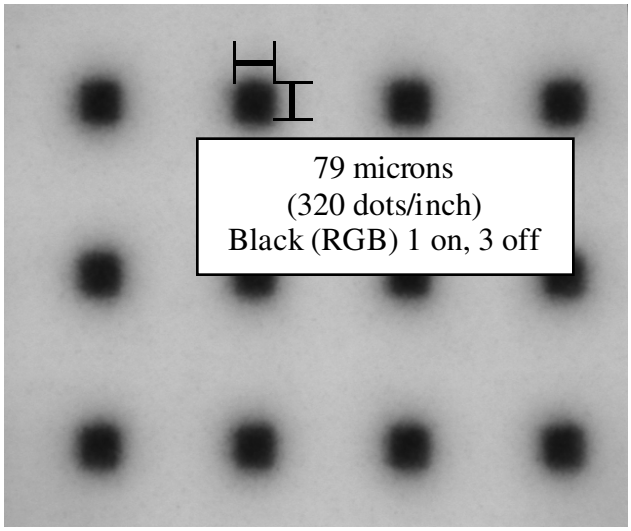

Figure 6. 1-on, 3-off Single Pixel Test Pattern, Each Dot Composed of 192 Integrated Rows of RGB DMD Exposure

To exemplify this point, an example of a one pixel on – three pixels off image is shown in Figure 6. This particular image was exposed with the prototype system running at eight inches per second. In this figure, the "black" dots are actually a composite of 192 overlayed RGB pixels, demonstrating that color registration is well within the design goal (Table 1). Using a one-on, one-off cross-process line pattern MTF measures approximately 60% at 7 lp/mm. All measurements of pixel placement, shape and consistency throughout the test images have met or exceeded the requirements.

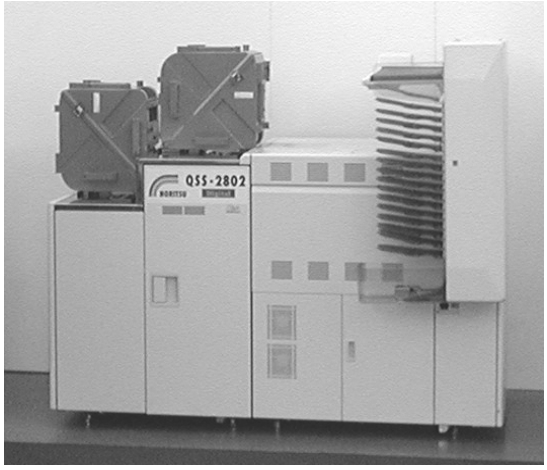

Figure 7. Noritsu QSS-2802 Digital Minilab

Figure 8. Gretag Imaging Masterflex Digital D 1008

Product Implementations of DLP™

The digital photofinishing reference systems described in this paper have been productized recently, and digital minilabs incorporating DLP™ as the exposure subsytem were shown at the PMA (Photo Marketing Association) exhibitions in London in October 1999, and in Las Vegas in Jan. 2000.

Noritsu has announced the QSS-2802, shown in Figure 7, and Gretag Imaging has announced the Masterflex Digital 1008 shown in Figure 8.

Discussion and Conclusions

DLP ™ digital photofinishing systems offer a competitive solution that is capable of very high quality printing for standard 4 x 6 photographs, which make up about 90 % of the consumer print market. The next advance for the technology will be the step from the current DMD format (SXGA) to the wider formats of High Definition TV and Digital Cinema when they become available. These devices should put the DMD in a comfortable resolution range for supporting minilab formats to at least 8 inch paper widths, and possibly even wider. The reliability of the DMD as a light modulator element, and it's long term stability should prove to be a competitive advantage to the digital minilabs using DLP ™.

In the high speed maxilab product area, where print widths are typically 4 inches, no more than 6 inches, the resolution of the SXGA device is adequate. The DMD is a very high speed light modulator, and has been operated to expose photoreceptors at 600 dpi and a meter/second on earlier programs.[2] It is estimated that a data rate approaching 8000 lines per second could be possible, depending on the algorithm selected and other operating conditions. The current optical system design has been simulated, and to first order, the required exposure capability is within the bounds of that estimate.

Acknowledgements

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