Holographic recording using a digital micromirror device

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ABSTRACT

We describe the use of a digital micromirror device (Texas Instruments, Inc.'s DMD™) as a spatial light modulator for holographic applications. Questions of the interferometric effects of the moving mirror structure and the appropriateness of pulse-width modulation for grayscale imaging are addressed. Compensation for the particular attributes of DMD imaging has allowed the creation of full-color holographic stereograms of high image quality.

Keywords: holography, spatial light modulator (SLM), digital micromirror device (DMD)

1. INTRODUCTION

Spatial light modulators (SLMs) are key components of holographic stereogram printer systems. They are used to display the sequence of two-dimensional stereoscopic perspective views that are being holographically recorded. Because all information about the object scene is transduced by the SLM, it is a very important factor in the determination of the final holographic image quality. Some SLMs typically used for holography include: positive transparency film (35 mm film), liquid crystal displays (LCDs) and, more recently, digital micromirror devices (e.g., Texas Instruments, Inc.'s DMD™).

LCDs have been our group's first choice of SLM for holographic printer research for several years because of their ability to rapidly present images for recording. This allows the rapid production of holographic stereograms with reduced costs. Our present full-parallax one-step printer system records over 10,000 separate holograms for each image so film is not practical in this application. On the other hand, transmissive LCDs typically have very low light throughput, wasting up to 90% of the available laser light.

The promise of higher throughput and improved image quality led us to consider the digital micromirror device (DMD) as a spatial light modulator for holography. At first glance, the moving-mirror structure of the DMD would seem to preclude its use for holographic recording, but this turns out to not be the case. Early tests have demonstrated the usefulness of the device, leading to more analytical testing to compare the optical qualities of holograms made with DMDs to those made with the LCDs usually used in our systems. The DMD has proven to be superior to the LCD from a number of points of view, leading to its wider use in our systems.

2. DIGITAL LIGHT PROCESSING SYSTEMS

In-depth data and specifications of typical digital light processing (DLP) systems are located on the Texas Instruments Inc. (TI) DLP website (http://www.ti.com/dlp/…). Most of the product specifications described below were obtained from this site and from documentation[1,2,3,4] of the InFocus projector.

The DLP system, of which the DMD is the light-modulating component, performs a variety of functions. These include: source interface; video processing; and DMD interface. The DLP system enables the DMD to display images in VGA, SVGA, NTSC, PAL, and SECAM formats, as well as allowing control of output image brightness, contrast, and grayscale mapping functions.

DLP systems with one-, two-, and three-chip DMD configurations are currently commercially available in pixel counts of 640 x 480 (VGA) up to 1280 x 1024 pixel resolutions. Until recently, VGA and SVGA (848 x 600 pixel) product development kits have been available from TI (currently discontinued).

The DLP video processor system separates 24-bit color images into their RGB components for display. The one- and two-chip versions employ a revolving color filter wheel synchronized to the RGB image separations displayed by the DMD. Three-chip projectors assign one DMD chip for each RGB color component. We typically utilize only monochromatic laser light for holographic recording, so that for the purposes of this paper we are concerned only with the grayscale performance of single-chip systems.

Two SVGA-resolution DLP systems were used for our tests. The first was a one-chip system harvested from an InFocus Inc., LightPro 620 projector (projector) and the second was a TI product development kit without optics. The development kit is a fully digital system requiring use of a PC with Windows 3.11/95, while the projector performs conversion to digital from external analog video sources. There are slight differences between the two systems, however, their holograms have essentially the same qualities. The differences between the two systems are described below.

2.1 DMD structure

The DMD component of DLP systems is a micro-lithographically machined device comprising an array of 16 µm x 16 µm tiltable aluminum mirrors mounted on hinges over a complementary metal oxide semiconductor (CMOS) static random access memory (SRAM) chip (Figure 1). The mirrors are arrayed on a 17µm pitch, providing a fill factor of nearly 90%. The SVGA (848 x 600 pixel) DMD chips measure 15 mm x 13 mm and contain 508,800 micromirrors. Binary data sent by the DLP system to the DMD's SRAM produces an electrostatic charge distribution, causing the individually addressed mirrors to tilt either -10° ("on") or +10° ("off") along an axis that is a diagonal of the micromirror (Figures 1,2).

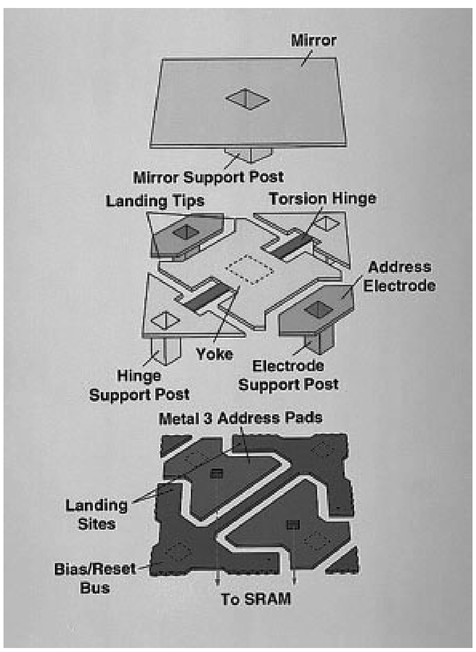

Figure 1. DMD microstructure

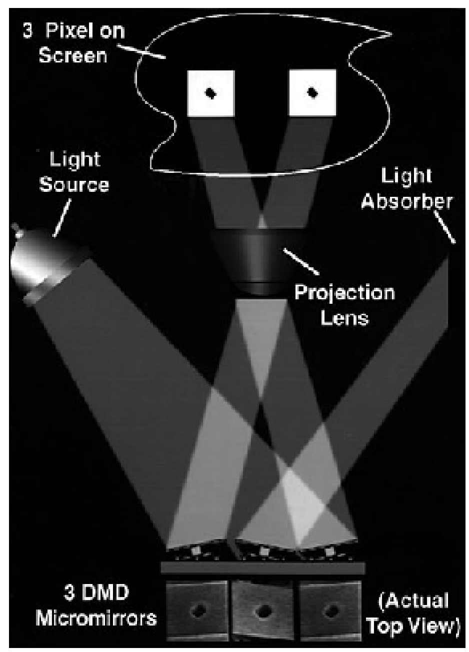

Figure 2. DMD optical switching method

2.2 Optical switching and binary pulse-width modulation

Figure Two depicts the optical switching geometry for three DMD micromirrors. This example is representative of all micromirrors in a DMD array. When a mirror is switched "on," it directs light from the illumination source toward the entrance pupil of the projection lens. Each mirror switches from "on" to "off" in approximately 20 µs. However the optical transition time, as far as the entrance pupil of the projection lens is concerned, is on the order of 2 µs. The maximum modulation rate of the mirrors (determined by the electronics) is 180 Hz. The maximum time spent in the "on" state is 19 ms, to avoid "sticking" of the mirrors.

Binary pulse-width modulation, determined by the optical switching times of the mirrors, is used to provide grayscale by varying the ratio of "on" versus "off" times of the micromirrors. They are allowed to stay in either position only 19 ms or less, so that at every gray level they are constantly "flipping," but the duty cycle goes from almost zero to almost 100%. Thus, to obtain a mid-gray value (pixel value = 128), the mirror is switched "on" for half of the time and "off" for the other half, sending half of the available light through the output lens' entrance pupil. A total of 256 different combinations of on/off ratios are available, corresponding to digital pixel grayscale values of 0 to 255.

2.2.1 Observation of the light output behavior to specified input

A test image of ten grayscale steps from 0 to 255 was created. Each step increased in value by 28. The image was displayed by the DMD, enlarged to the size of the test hologram and the output light measured with a Newport Research Model 840c power meter. The signal from the power meter was routed to a Textronix Model TDS-540 digital oscilloscope. The light meter's probe was placed in each of the grayscale steps and an "on" signal time corresponding to a specific grayscale value is captured by the oscilloscope and displayed for evaluation. Both the projector and the development kit were evaluated in this manner at their default "power-on" settings. Figures Three and Four show examples of the pulse-width modulated output light as captured when imaging 10 step grayscale (four samples from the "blue" channel of each are shown for brevity). "On" time is determined by the time spent by the mirrors at the top of the curves.

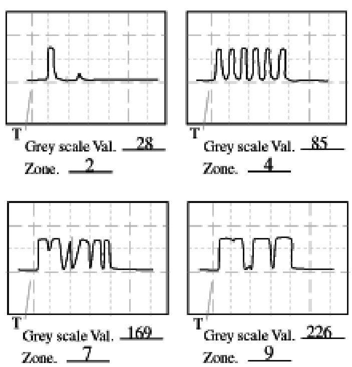

Figure 3. Mirror switching by projector

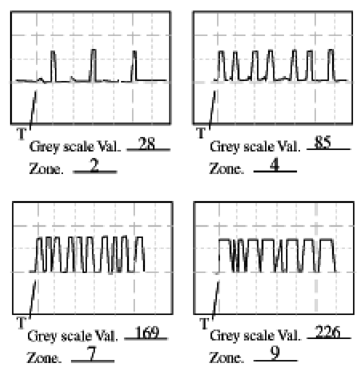

Figure 4. Switching by development kit

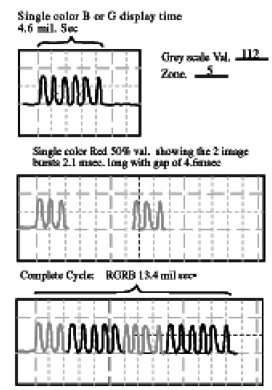

Figure 5. Projector timing and sequence

2.2.2 Display characteristics observed.

The two DLP systems were fed a 24-bit color image at 60Hz. The projector had a 13.6ms total display time for the RGB sequence. The Red, Green and Blue values of the image are sequentially displayed as 4 sets of data, matching four segments of the color wheel (Red, Green, Red, Blue). Red channel light is displayed twice for each RGB sequence (Figure 5) in the one-chip projector system to compensate for the human eye's lower sensitivity to red light. Red display time is 4.4ms (2.2msx2), Green and Blue channels have 4.6ms duration. Display timing of this sequence is locked to the rotational frequency of the color wheel by a small reflective stripe on the inside of the color wheel, read by an infrared optical device.

The development kit had a 16.8ms display time for the RGB sequence. Individual channel display times measured were 5.6 ms each. Red channel light is not repeated twice. The development kit is configured without a color wheel so color synchronization is not necessary.

If only one color channel of a 24-bit color image is fed to these one-chip DLP systems, they will only display image data for one segment of the RGB timing sequence--reducing the output light by one-third. Monochromatic 8-bit images are automatically distributed by the DLP system, as if they were a "Y" channel, to completely filling the RGB timing sequence.

2.2.3 Differences in optical switching between the development kit and projector

The development kit has ~1 ms longer segments per RGB color channel than the projector. 3.4 ms longer for the total RGB sequence. However, the total light throughput is about the same for both systems tested. The measured difference in timing is compensated for by modulating the "on" time of the mirrors. Referring to Figures Three and Four, we see that while the sequence length is longer and there are more pulses observed from the development kit, the "plateaus" of the pulses ("on" time) are narrower than that of the projector. Hence, the “on” time is adjusted so as to be nearly the same for both systems. Note that RGB sequencing and segment timing may vary from system to system.

2.3 Configuration for holographic recording

Analyses of the light output timing from the development kit and the projector system revealed no fundamental differences between their light output. The projector system is found to be somewhat more useful because it allows more flexible image input and output control.

Here we outline the procedure for converting the InFocus projector for holographic use (n.b.: care must be taken when removing components, as some of them must remain connected to the system): Remove the light source, and bend back the interlock switch. Remove the rotating color wheel and motor assembly from the input optical path, retaining its electrical attachment to the DMD processor board with both wires (Note: the ribbon cable is very fragile and the wheel is very sharp). The DLP control pad must also remain attached to the system. The power supply and DMD component boards should be separated to reduce vibration transmitted from the power supply fan (Figure 8). Remove optics upstream and downstream of the DMD chip (see below).

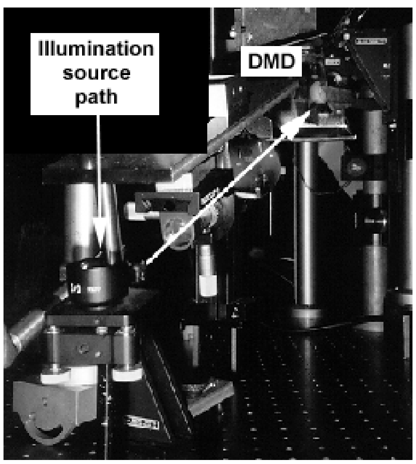

Figure 7. DMD illumination (viewed from diffuser)

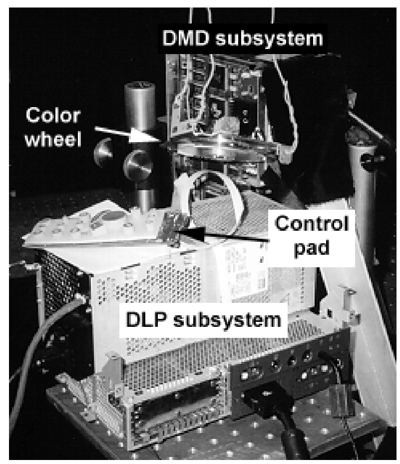

Figure 8. DLP components (viewed from backside)

Tests were performed with and without the various optical components that came with the InFocus projector. It is necessary to leave the color wheel active and attached, in as vibrationally-damped a manner as possible (Figure 8). It is possible to feed the optical sensor at the frequency of the reflective strip and have the projector display the image. Without this signal the projector will not display any image data. However, the motor must still remain attached and operating or the DLP system will not display images. We encountered no problems leaving the color wheel attached and operating during holographic recording.

The output lens was discarded because it has too long a focal length for our purposes, and its special modifications for incoherent-light use are not needed. The input optical components can provide a handy and compact DMD illumination scheme, but are vulnerable to dust accumulation, do not entirely correct for keystone distortion, and slightly reduce the optical power throughput. One illumination geometry used for our two-step holographic stereogram printer system is simply a lens/pinhole spatial filter and condensing lens arrangement (Figure 7). The input light is directed to evenly illuminate the DMD chip at 20° to the chip’s perpendicular, offset along the chip’s diagonal. This allows light reflected from the “on” micromirrors to exit perpendicularly to the chip, minimizing problems of keystone distortion. The DMD chip and component board produce some heat, so precautions must be taken to redirect heat flow away from the optical path of the illumination source and object-beam.

2.4 Comparison of SLM types:

As background information, we recall that both DMD and LCD types of SLMs are quite dynamic. The pixels of the LCD are constantly being refreshed by a scanning voltage, and their effective optical distances may thereby fluctuate. The pixels of the DMD are constantly being "flipped" to avoid sticking, and the optical path length of the reflected beams may thereby fluctuate. And the grayscale modulation schemes are very different: the LCD modulates by absorption of the "rotated polarization" light, while the DMD transmits all of the light but only for a fraction of the time. Thus, although their performance as incoherent light projectors may be comparable, by design, their performances as coherent light SLMs are quite different.

3. EXPERIMENTAL METHOD

The first task was to compare the image transmission qualities of the DMD system, as to a typical LCD SLM previously used in our systems. We chose a Kopin liquid crystal display evaluation system, which is a monochromatic transmission unit (no color filters) with VGA resolution and about the same size as the DMD. Both systems were evaluated in their "boot-up" state for these tests. We were primarily interested in understanding: 1) the maximum optical power throughput, 2) the maximum diffraction efficiency available, 3) the maximum contrast of the recorded images, and 4) the "toe" and "shoulder" grayscale transfer characteristics of the devices.

3.1 Setup

The standard off-axis transmission recording setup shown in Figure Nine was used for testing. 24- and 8-bit TIFF images consisting of black & white zones, ten specific grayscale value zones (encompassing gray values 0-255, with 25 step separation), and continuous color ramps were projected by the SLMs, focused onto a ground-glass diffuser and recorded. Each SLM was positioned in the same location, relative to the projection lens and diffuser, for each test. The same objective lens in the lens/pinhole spatial filter (LPSF) and was used throughout. Prior to exposure, the projection beam intensity across the image area was equalized to within ± 10% or better.

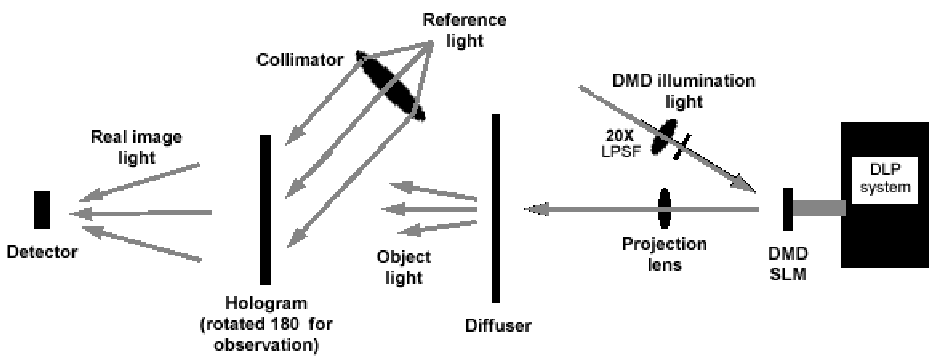

Figure 9. DMD holographic recording and projection setup (Not shown: LCD in rear-lit configuration)

Agfa 8E56 silver-halide plates from the same production batch were exposed to 600 ergs/cm^2 (60 mW-sec/cm^2) of $\lambda = 532$ nm (Coherent Inc. doubled-YAG with ~100mW output) light, at a beam ratio (K) of 20:1. We developed in Ilford (Wood) developer, stopped, fixed, and bleached with dilute bromine water.

3.2 Methods

3.2.1 Throughput

Flux intensity was measured 2 cm upstream of each device, and at the diffuser surface. A white "open gate" image was displayed by the SLM for diffuser measurements. The ratio of input to output irradiance was taken for both the DMD and the LCD.

3.2.2 Diffraction efficiency (DE)

A white "open gate" image was projected onto the diffuser by both devices. Light illuminating the DMD was attenuated so as to bring the output irradiance to the same value as that of the LCD. Holograms of the same area were recorded using the same beam ratio and exposure time. The holograms were evaluated using conjugate illumination to project the real images of the test patterns onto the power meter probe ("Detector" in Figure 9).

3.2.3 Contrast ratio

Irradiance was measured at black and white image zones as imaged on the diffuser, and as presented as projected real images of the diffuser.

3.2.4 Grayscale characteristics:

Images containing of a range of grayscale value zones were displayed and recorded using the computer graphic files described above. Again, measurements of irradiance at the diffuser, and at projected real holographic image were recorded.

3.2.5 Optical clarity

The visual image qualities observed at the diffuser and in the projected real image of the diffuser were recorded for subjective comparison.

3.3 Recording Materials

Images were recorded using DuPont pan-chromatic photopolymer and the Bierenheid (HRT series BB-Pan) silver-halide plates for general interest.

4. RESULTS

4.1 Throughput

The DMD projected 6.6 times more object light to the diffuser than the LCD. The most important effect of this difference was in the exposure time needed to achieve a 20:1 beam ratio (*K*). Typical exposure times obtained using the DMD were 10 seconds, while the LCD would require a 57 second exposure under the same circumstances.

The reasons for this large difference in throughput are related to the very nature of the devices—the LCD is transmissive, the DMD reflective. The LCD's structure has a number of surface interfaces which back-reflect and absorb light, while the DMD is essentially a mirrored surface with a protective glass cover piece (with an anti-reflective coating). The DMD's 90% fill factor (compared to ~70% for the LCD) is another reason for its superior performance in this area.

4.2 Diffraction efficiency (DE)

Even when the system was adjusted to compensate for the large difference in optical throughput, so that the beam ratio, *K* (20:1; exposure times were much different as mentioned above), and the exposure time was the same, the brightness of the reconstructed images were quite different for the LCD and the DMD SLMs. The DMD images typically diffracted twice as much light as the LCD image. The DMD image was approximately as bright as for a flat mirror "reference SLM," which indicates that mirror motion was not a cause of degradation of coherence of the object beam, and thus a loss of diffraction efficiency.

The loss of diffraction efficiency for the LCD SLM, on the other hand, is not understood in detail. We presume that it is due to a small residual "twitching" of each pixel as the array is electrically scanned 30 times per second, although this is surprising in a TFT-type array. Different LCD types would be expected to vary greatly in this "de-cohering" effect.

4.3 Contrast ratio

Measurements of the ratio of maximum to minimum flux at the diffuser was ~321:1 for the DMD, and ~29:1 for the LCD. That is, the DMD had 11 times the contrast of the LCD in projection. However, measurements of the holographic images were less impressive: ~30:1 for the DMD, and ~9:1 for the LCD. That is, the DMD images had approximately 3.3 times the contrast of the LCD images.

We attribute the low overall contrast to a number of factors: 1) the presence of intermodulation noise (characteristic of the large-grained Afga 8E-56 materials), which suggests that the beam ratio, *K*, should have been even higher; and 2), the time-averaged exposure characteristics of pulse-width modulation. For example, black (grayscale value "0"), while darker than the LCD's "black", is not completely absent of light. This is because each the mirrors switch "on" every 19 ms--introducing a bit of noise each time. Although, not measured by the detector, this noise adds up over time in the holographic recording.

4.4 Grayscale characteristics

The intensity transmittance of an SLM is expected to be roughly a linear function of the digital value sent to each pixel, in order to present a good photographic-style image. In the DMD, there may be small (and proprietary) "tweaks" to the "D-to-I" transfer curve (especially in the "toe" and "shoulder" regions) to try to improve the visual quality of the images, and perhaps some "gamma un-correction" in an effort to better simulate the appearance of the images seen on CRTs (which typically have a contrast or gamma greater than unity that is anticipated in the imaging chain).

Both the LCD and DMD SLMs exhibited "normal" transfer curves when measured in the usual way. However, the holographic reconstruction brightness curves for the two SLMs differ considerably. The "D-to-H" transfer curve for the DMD shows a marked "sag" in the mid-tone regions that is not observed in the images made by the LCD (Figure 10). Where one would expect to find a relative brightness of 50%, based on the intensity during exposure, we find instead a relative brightness of only 25%.

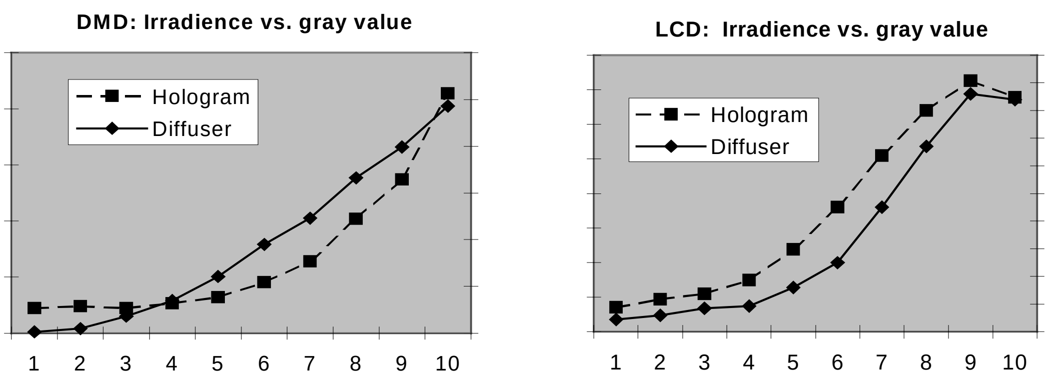

Figure 10. Irradiance measured at diffuser and projected real image plane for ten grayscale steps for DMD and LCD

We attribute this effect to a peculiarity of the pulse-width modulation scheme used by DMD SLMs. When the intensity of an LCD-modulated beam is reduced to 0.50 by adjusting the pixel drive voltage, the (constant) electric field magnitude is reduced to 0.71, and so is the corresponding hologram fringe contrast, so that the intensity of the diffracted beam is reduced to 0.50 as expected. But when the intensity of a DMD-modulated beam is reduced to 0.50, it is "on" only 50% of the time, and the time-averaged electric field magnitude is reduced to 0.50, and so is the corresponding fringe contrast. The intensity of the diffracted beam is then reduced to 25%, as observed. That is, the intensity of the modulated beam is the time-average of the squared-magnitude of the electric field, whereas the diffraction efficiency it produces varies with the square of the time-average of the magnitude of the electric field. Measurements of irradiance measured by the detector at the diffuser, show that the two curves track as expected, but for pulsed object-beam exposures, they differ considerably in the mid-values where there is more delay time between the "on" and "off" state of the DMD mirrors (Figure 10).

This non-linear "gamma-like" effect is not direly noticeable in the final hologram, but can readily be compensated for to render a more satisfying grayscale image. Figure Eleven shows the results of adjusting the input image's grayscale histogram to compensate for the affects of time-averaging to straighten the holographic grayscale curve. Figure Twelve shows a comparison of the holographic grayscales achieved from input images utilizing the standard tonal range, and a pre-adjusted tonal range. Essentially, this pre-adjustment involves modifying the input image's grayscale histogram to send more light, i.e., assign higher grayscale values, to the mid-tone regions.

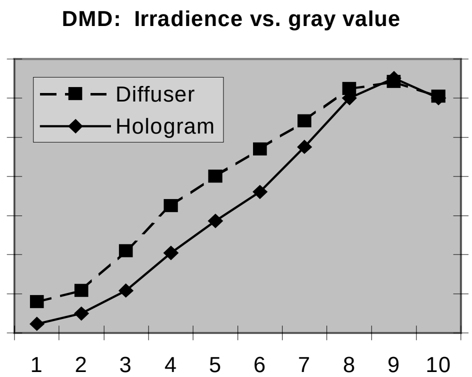

Figure 11. Adjusted input image histogram

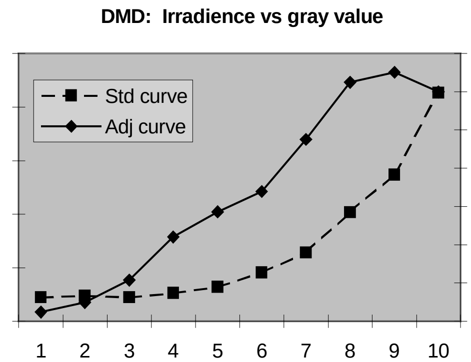

Figure 12. Holograms of standard and adjusted input images

4.5 Optical clarity

Figures Thirteen and Fourteen are photographs of the holographic images produced by the DMD and LCD as projected onto a diffuser. Arrows indicate the location of image artifacts. The LCD image as displayed on the screen, and projected holographic image (Figure 14) had noticeable woodgrain-texture appearance, apparently due to interference between reflections from the various LCD/glass and glass/air interfaces. The DMD had a slight concentric artifact (Figure 13), but it was much less noticeable than the LCD's artifacts in the final holographic images.

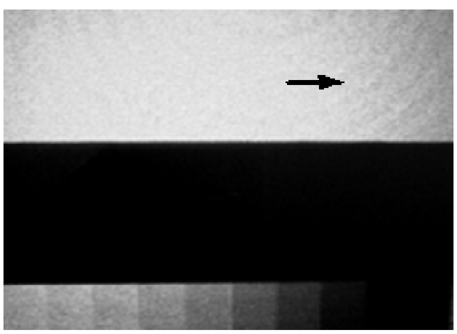

Figure 13. DMD image clarity

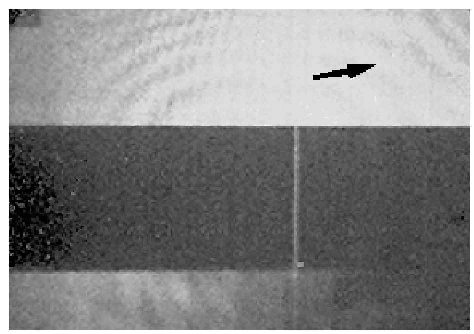

Figure 14. LCD image clarity

4.6 Recording materials

The also DMD performed normally with materials requiring lengthy exposure times. Exposures of over two minutes were made using photopolymer materials in the transmission testing setup. Two-color reflection holograms were also made of diffusers using the BB-Pan materials. However, no comprehensive testing or evaluation was undertaken.

5. CONCLUSIONS

We conclude that the diffraction efficiency of holograms made with DMD spatial light modulators was not degraded by mirror motion or other effects. On the other hand, minor fluctuations of the LCD pixels seemed to markedly degrade the diffraction efficiency of holograms made with the same beam ratios.

The major advantage of DMD SLMs is the efficiency of light use or throughput. About 90% of the incident light can be made available for recording. The contrast of the resulting images is also high, providing deep shadows in images, and they are free from the woodgrain-texture artifacts often produced by SLM optical structures. Furthermore, the DMD provides a wider dynamic range of grayscale values.

An important and non-intuitive finding is that the brightness of the holographic image does not accurately track the visual brightness of the pulse-width-modulated object beam. An apparent intensity of 50% produces a relative diffraction efficiency of only 25%, for example. This shift of the grayscale transfer function is readily compensated for by applying a simple lookup table to modify the input image's grayscale histogram curve during image processing.

The DMD has proven to be a valuable tool for the production of holographic stereograms in our work. Typical production time of our full-parallax one-step printer system is now one-third of what it was when using a LCD SLM. Furthermore, image quality and contrast ratio of our images has also been improved dramatically. The promise of higher resolution DMD chips arriving on the market will enable the production of even higher quality imagery.

ACKNOWLEDGEMENTS

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