DLP Cinema™ Technology: Color Management and Signal Processing

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Abstract

In June 1999, Texas Instruments partnered with Lucasfilm to premier the first fully digital release of a major motion picture. *"Star Wars: Episode 1 - The Phantom Menace"* was shown at two theaters with DLP Cinema™ projection technology. Subsequently, field trials of DLP Cinema™ prototype projectors have been conducted in over 40 theaters in the U.S., Canada, Europe and Japan, with an audience of over 2.5 million. Results of these field trials are currently being incorporated into designs for volume production.

Key to the performance of DLP Cinema™ projection systems is the linearity and stability of the DMD. The DMD's method of accurate digital data display is described and in-theater measurement data is presented. The system stability and linearity are then utilized in the development of a color management methodology for the distribution and playback of content. This paper provides an overview of DLP Cinema™ projection technology, with emphasis on color management and signal processing.

Introduction

Texas Instruments (TI) has worked closely with the movie studios and industry to develop a digital cinema projection and distribution solution. A field demonstration program was developed to understand and define these requirements. TI has currently deployed over 40 prototype projectors into postproduction facilities and theaters around the world. This demonstration project encompassed not only the display of material in theaters, but also production and digital mastering, the delivery of the digital material to theaters, and the storage and playback of this material.

The field trials have been utilized in the presentation of over 32 films, including *Toy Story II, Jurassic Park III, The Perfect Storm,* and *Shrek.* The DLP Cinema™ field trial systems have operated on the regular show schedule, (between 5 to 7 shows per day), using existing theater personnel. To date over 33,000 showings have been presented to more than 2.5 million theater patrons.

The DMD

The heart of the DLP Cinema™ projection system is the DMD chip. The DMD is an electromechanical device containing over one million individually addressable mirrors that operate in a bi-stable mode to switch light on and off. The structure of two mirrors is shown in Figure 1.

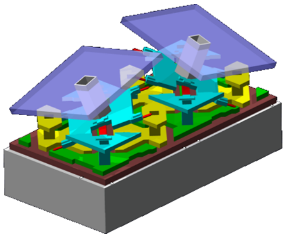

Figure 1. Structure of 2 mirrors on the DMD.

The bi-stable mode of each individual pixel is controlled using underlying conventional 5-volt CMOS circuitry. The superstructure of each pixel is built over the CMOS circuitry using conventional semiconductor processes. This CMOS circuitry provides one simple function: the fast and precise rotation of each micromirror through angles of +10 and -10 degrees.

Figure 2 illustrates the optical switching action of the mirrors. When the mirror rotates to its on state (+10 degrees), light from a light source is directed into the pupil of the projection lens and the pixel appears bright on a projection screen. When the mirror rotates to its off state (-10 degrees), light is directed out of the pupil of the projection lens to a light absorber and the pixel appears dark. Thus, the optical switching function is simply the rapid directing of light into or out of the pupil of the projection lens.

This bi-stable switching of light into or out of the pupil of the projection lens by the DMD is then used to produce the appearance of grayshades by modulating the light using pulse width modulation (PWM) techniques. The use of PWM techniques results in the transfer function of the device, (from input signal to light output), to be linear.

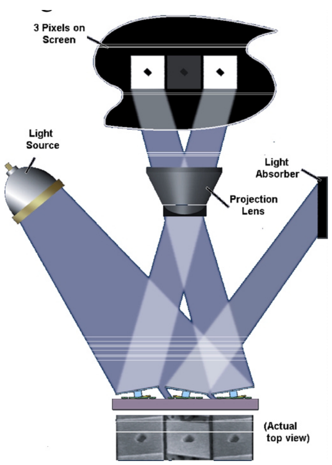

Figure 2. Optical switching characteristics of the DMD pixels.

Prototype Projector

The prototype projectors were designed to utilize existing equipment wherever possible in order to minimize the impact to theater installations. The projection head was designed to mount on a standard theater lamp housing. The DLP Cinema™ projection head simply takes the place of the existing film projector. Figure 3 is a photograph of a typical prototype projector configuration.

Figure 3. DLP Cinema™ prototype projector

For the projection head to be mounted on a standard lamp housing, the light path into the projector must be designed to be inline with the output light path of the projection lens. To accomplish this, the light is directed inside the projection head using fold mirrors and total internal reflection (TIR) prisms. An optical integrator is included in the light path to provide a highly uniform image display.

The TIR prism is also used to split the light into the three component colors: red, green, and blue, which are then individually modulated by three 1280x1024 DMD's. This color splitting TIR prism assembly was modified to increase its thermal stability to insure its performance at high illuminance levels over extended periods of time.

In order to produce the wide image aspect ratios of cinematic presentations using 5:4 aspect ratio DMD's, new anamorphic projection lenses were developed by TI. For the academy standard flat 1.85:1 presentations, a 1.5:1 anamorphic lens was developed. For CinemaScope™ presentations of 2.35:1, a 1.9:1 anamorphic lens is used.

The DMD has been used in applications requiring from 1000 lumens to over 15,000 lumens. The DMD has not been the limiting factor in increased power handling capability. Other optical elements, such as lenses, typically limit usable power levels.

The DMD at 1280x1024 has been compared to film in terms of resolution and sharpness of the produced pictures. Several side-by-side comparisons of the DLP Cinema™ projector and film have been conducted. Observers are surprised at the level of sharpness exhibited by the DMD-based system. An explanation for this phenomenon can be seen in a comparison of the modulation transfer functions (MTF) of the DLP Cinema™ projector and film. Figure 4 shows a comparison of typical MTF data from a release print, (MTF only, not projected), and the DLP Cinema™ projector. For this comparison, the lp/mm are normalized to film at 0.825” x 0.446” frame (flat) and both the vertical and horizontal DMD resolutions are shown. The vertical MTF is higher than the horizontal resolution due to the anamorphic lens used in the system. It can be seen that in the 10 to 30 lp/mm region, the DMD-based system outperforms the print film.

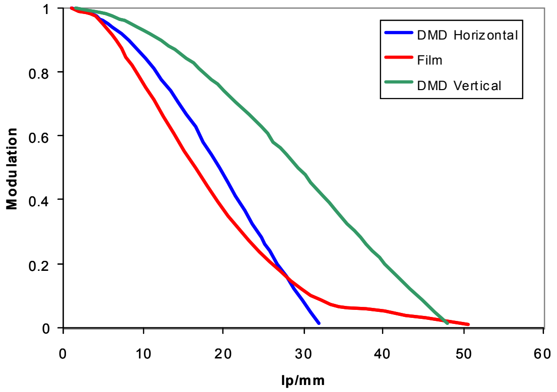

Figure 4. MTF Comparison of DLP Cinema™ and film

An expanded color gamut, compared to standard DLP™ products, was needed to achieve the colors required by a theatrical motion picture. An additional yellow notch dichroic filter was inserted into the optical path.

The expanded color gamut of the DLP Cinema™ prototype projector was determined through the analysis of the color of real-world objects and the gamut of film. This expanded color gamut, as shown in Figure 5, compares closely with the color gamut of film (END = 2.5).

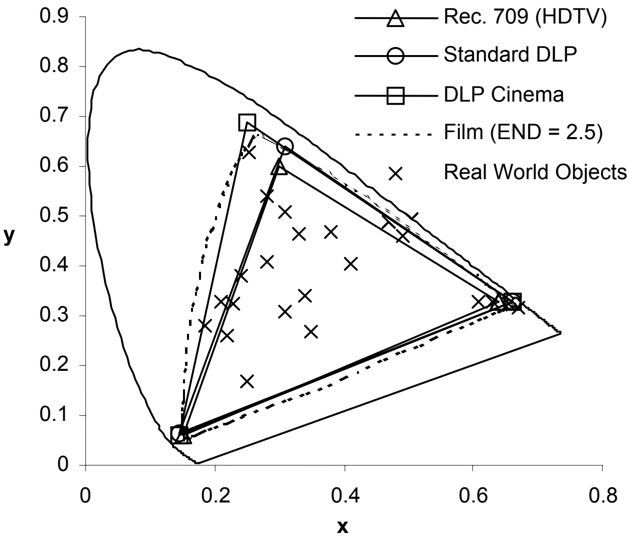

Figure 5. Color gamut comparison of real-world objects with color gamut of various technologies.

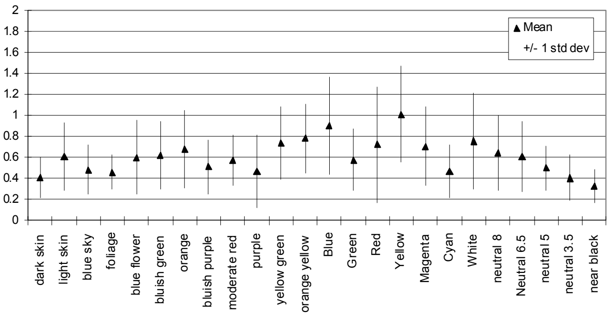

Figure 6. Measured □(Lab) range vs. reference color (in theater measurement over 20 day period).

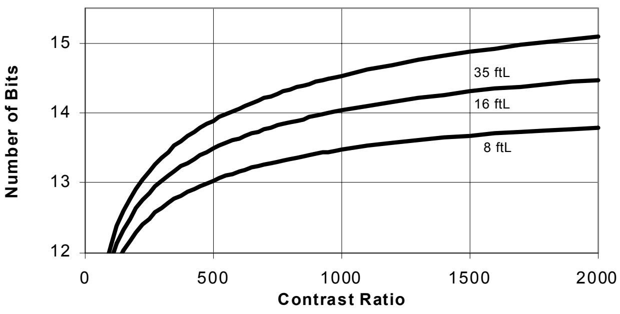

Figure 7. Number of bits needed for contour mitigation vs. contrast ratio and luminance level (fL).

The theatrical release of *Star Wars: Episode 1 – The Phantom Menace* into theaters provided the first opportunity to measure the projector's color stability over time in the theater operating environment. A modified MacBeth color chart was used for testing. The chart contained a set of 12 real-world colors, 6 colors on the color gamut of the projector, and 6 shades of gray. Colorimetric data in CIELAB color space[8] was collected over a twenty-day period for the 24 colors. For each color, the color difference ΔE_{CIELAB} was calculated as the difference between the normalized daily measurement, (normalized for lamp intensity variations), and the average color over the twenty days. The range of the ΔE_{CIELAB} color difference for each color is shown in Figure 6. The results demonstrate that the system performed to less than 2.0 ΔE's over the 20-day period. The DLP Cinema™ projection system provides remarkable color stability over time, a direct result of its linear digital light output.

The DMD chip is inherently a linear device, and as such requires more input bit depth than do most other display technologies. The bit depth requirement for a DMD-based system, such as the DLP Cinema™ projector, can be determined using results obtained from luminance difference studies.[8] Utilizing the percent differences derived in these studies, the bit-depth requirements can be plotted against contrast ratio and screen luminance (in footlamberts (fL)). Figure 7 shows the results of the study for a range of luminances from 8 fL (minimum theatrical), to 16 fL (typical film open gate requirement), to 35 fL (studio monitor). At 1000:1 contrast ratio, the required number of bits in a theatrical showing is 14 bits per primary color (42 bits total). If the requirements were to use the DLP Cinema™ projector in a studio monitor application, then the requirement would rise to 14½ bits. The current DLP Cinema™ prototype projector provides 14 bits of bit depth to the DMD ensuring artifact free performance. In the future, as the contrast ratio is further increased, the bit depth will be correspondingly increased.

Signal Processing

The DLP Cinema™ signal processing architecture, shown in Figure 8, provides the capabilities necessary for accurate display of digital cinema material. The architecture has been designed to support the current prototype delivery and projection system as well as supporting future standards and upgrades.

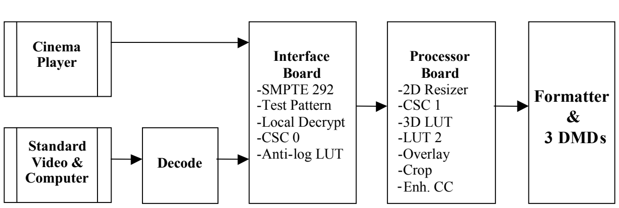

Figure 8. DLP Cinema™ Signal Processing

The primary input signal from the cinema player provides 24 Hz progressive image data across dual SMPTE 292 links. The dual link 292 supports 10 or 12 bit data in either 4:2:2 or 4:4:4 data formats. At 24Hz, the link can deliver up to 5 megapixels per frame. Support for ancillary data and metadata have also been included.

To guarantee signal integrity and processing options, TI carefully controls the signal path from the cinema data input to the generation of light. Non-linear or gamma corrected processing uses a 12 bit signal path. This signal path includes all functions up to lookup table 2 (LUT2). The remaining signal processing operates in a linear signal domain and has 16-bit resolution.

The color space converter 0 (CSC0) and anti-log LUT are used to decode signals that use colorimetric ratios and logarithmic encoding. This allows the system to adapt to evolving digital cinema delivery and mastering standards.

A two dimensional resizer provides horizontal and vertical scaling using polyphase FIR filters. The filter coefficients have been optimized for DLP Cinema™ projection to avoid filter ringing, thus avoiding the 'video' look. The CSC1 converts the input data from a luma/chroma representation into an RGB signal format, if required.

A 3D-LUT offers capabilities of gamut mapping, film emulation, and special looks. A 12-bit signal path is maintained from input to output, with support for multiple lattice sizes.

The overlay provides the projection system with the ability to overlay up to 2 planes of 8-bit RGB and alpha images at the full DMD resolution (1280 x 1024). The overlay function supports the full Porter-Duff compositing operators along with fade and priority select. Inputs of TGA and PNG bitmap formats are supported into the overlay planes, and a TI DSP can additionally render anti-aliased text characters into these overlay planes, allowing for real-time sub-title insertion.

The crop function allows the operator to adjust the image extent to match the screen geometries in each theater. The function provides independent adjustment of the four sides, including offset, tilt, and curvature.

LUT2 converts the gamma corrected signal into a linear 16-bit signal. Currently, the lookup table is loaded with a simple power law function with a gamma of 2.6. It has been found through analysis and testing that this provides excellent color and gray level tracking.

The inherent linear nature of the DMD requires that the input signal to the device be a linear encoded signal. This linear signal encoding provides additional signal processing opportunities. The most obvious area is in color signal processing and management. To avoid projector specific 3-D LUTs, an additional color processing algorithm was developed. It was determined that the use of a traditional 3x3 color correction matrix approach was too restrictive in manipulating the color gamut of the projector, so a more versatile, yet compact linear color correction method was needed. The new algorithm allows for the x,y chromaticity coordinates and luminance level of the primaries (RGB), secondaries (CMY), and white (W) to be set independently. Each projector can be adjusted in the field to meet a common color gamut and white standard, thus making the 3D-LUT contents projector independent. Figure 9 shows one example of enhanced color correction that has been utilized. In addition to common color correction of the projectors, the algorithm can also be used to provide very good emulation of CRT colors through the precise mapping of the colors in linear light space.

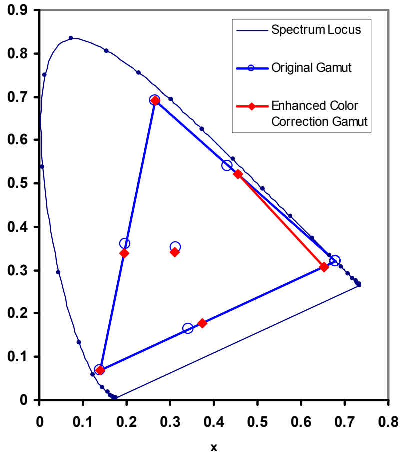

Figure 9. Enhanced Color Correction Processing

The grayshade light intensities are produced using PWM modulation. Altering the duty cycle of the DMD on a pixel-by-pixel basis produces the required varying light intensities. The input digital signal is first converted into a PWM format. This can be accomplished by assigning each bit plane of video data to a segment of time within the frame time. Figure 10 shows the frame time divided into bit segments. In this figure, the two examples are given where individual bit planes are turned on (shaded regions) to create different intensities. For simplicity, only 4 bit signals are shown.

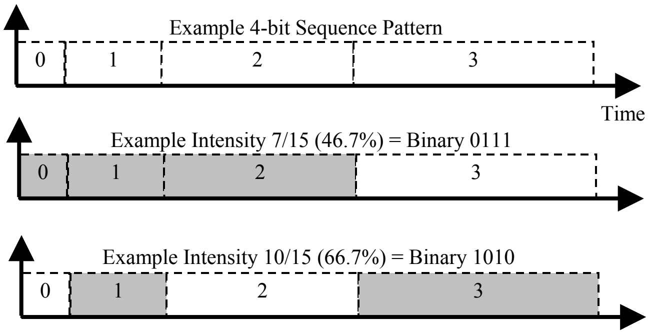

Figure 10. Example single frame time 4 bit PWM sequence

In the binary PWM case, the least significant bit (LSB), bit 0, consumes 1/(2^n-1) of the total frame time. The LSB+1, bit 1, would consume twice the LSB time, LSB+2 would consume double the LSB+1 time; and so on. The duration of a given bit, b, is:

$$\tau_b = \frac{2^b}{F \cdot n \cdot (2^B - 1)} \tag{1}$$

where F is the input source frame rate (Hz), n is the number of occurrences of bit b during the frame period, and B is the total number of bits. The DLP Cinema™ technology refreshes the input bit planes 4 times per the 24Hz input frame rate. The effective refresh rate is then 96Hz, which eliminates the perception of flicker from the image.[4]

As was shown earlier, at a contrast ratio of 1000:1, a system would need approximately 14 linear bits per primary to display image data without producing contouring. The smallest bit length to produce a 14 bit PWM sequence would require bit durations that are below the timing threshold of the current DMD's to ensure reliable image creation. To compensate, the DLP Cinema™ technology utilizes proprietary error diffusion technology and temporal bit modulation techniques to produce 15 bits of resolution.

Color Management

In order for the deployment of digital cinema to be successful, the control and adjustment of the color information throughout the delivery chain must be carefully controlled. The desire to maintain a single digital master for various venues, provide compatibility with future projection systems, while maintaining creative flexibility were all considered in the design of the DLP Cinema™ projection system. These requirements, along with psychophysical phenomenon that were present in high contrast, large gamut additive color projection designs, lead to the current system design.

Digital Delivery

Figure 11 provides an overview of the digital delivery process. The current process uses existing HDTV post-production equipment for digital mastering of movies to be exhibited in the DLP Cinema™ projector field trials. This equipment has been adapted to match the extended color gamut, contrast ratio, and bit depth of the DLP Cinema™ projector.

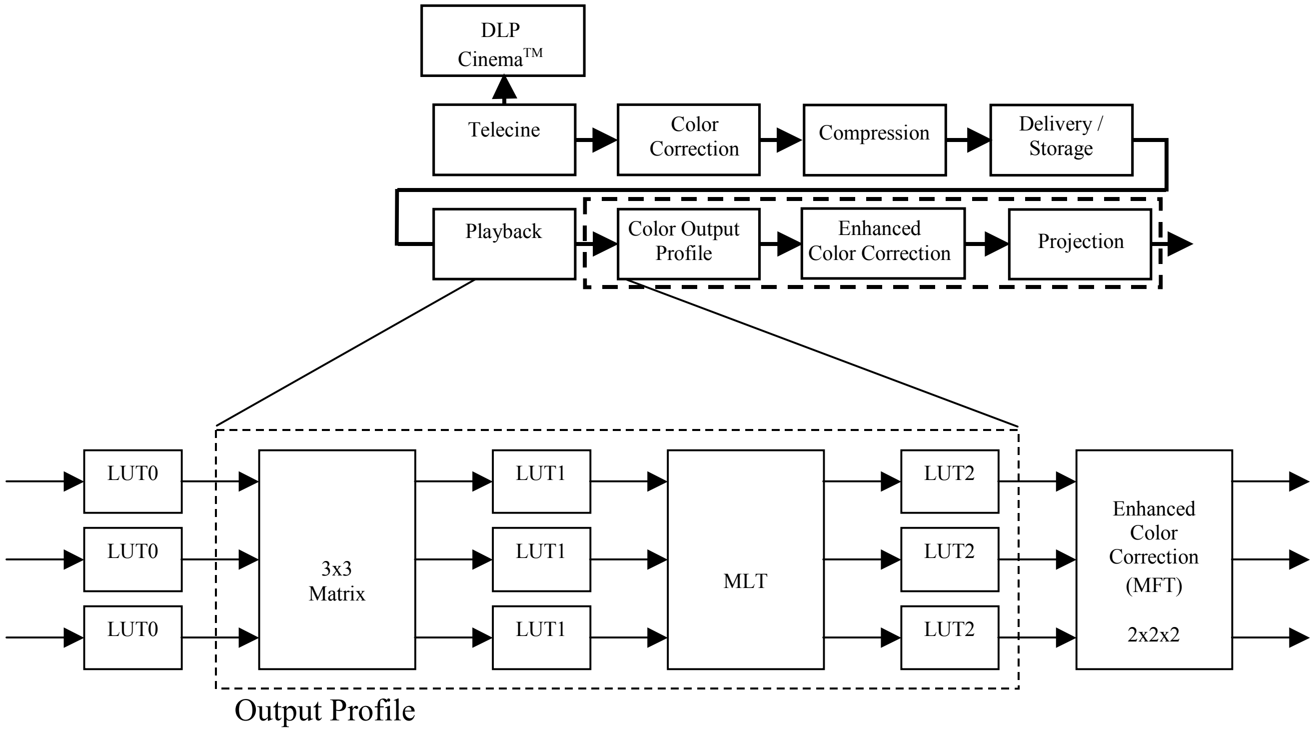

Figure 11. DLP Cinema™ on Projector Color Management Output Profile Processing

The original camera negative is edited as in a conventional motion picture. Both a color-timed answer print and a color-timed interpositive are created from the negative. The interpositive is scanned in real-time using a telecine, which digitizes the image by making dye density measurements of each pixel of each frame of film. This produces a digital data stream, usually 10 bits per color component (nonlinearly encoded) that is further processed by a color correction system. The color corrector allows specific colors and areas of the scene to be isolated and adjusted independently as required to get a visual match to the reference medium (the answer print). All color decisions are made while viewing the image on a DLP Cinema™ projector in a properly darkened screening room. Luminance and chromaticity of the primaries and white-point are carefully controlled to guarantee consistent results.

After the images have been digitized and color-corrected, the digital image data may be compressed, to minimize storage requirements. Both DCT-based and wavelet-based compression systems are in use with very good results. No visible artifacts are generated by the compressions systems used in the DLP Cinema™ field trials. The data rates used are typically in excess of 40Mbits/second, which is significantly higher than those used in HDTV broadcast equipment.

The actual delivery of the digital movie to the theater and its playback at show time have been in the form of: a) multiple DVD data disks subsequently loaded onto a magnetic hard disk drive-based server system, or b) multiple magnetic hard disk drives, or c) high-definition videotape for field playback. The latter option is only used for special events, due to the cost and maximum play time limits of videotape decks.

Industry standardization of this delivery process will require that a single digital master be produced and used to create digital content for various venues, including DVD, VHS, broadcast television, and digital cinema.

Color Management Hardware

Early in the development, it was discovered that the red primary of the projection system was not producing a hue consistent with film. Study of the problem revealed that the differences were due to the Abney Effect.[10] The red filter cut-off had been moved to a longer wavelength to move the hue of the red primary away from an 'orange-ish' hue. The chromaticity coordinate of the red primary was already on the spectrum locus, (this can be seen in Figure 9), and remained on this line. In examining models of the hue lines in this region,[11] it was found that hue lines that would produce the 'orange-ish' red were highly non-linear. The enhanced color correction initially was developed to correct this problem by moving the red primary toward blue, thus moving onto a reddish hue line. The addition of the 3D-LUT provides additional flexibility in overcoming this aspect of the human visual system's response.

The additional requirements of compatibility and flexibility are also provided by the 3D-LUT and were enhanced to provide a general-purpose hardware solution. The structure of the color management hardware additionally matches the ICC output profile definition at a conceptual level with a 3x3 matrix followed by a multi-function lookup table (MLT or 3D LUT), followed by a standard lookup table.

This hardware can be configured to address the Abney effect, map to other projection system gamuts, emulate film's subtractive characteristics, as well as provide creative means for achieving 'special looks'. These might include a high contrast look emulating a 'skip-bleach' film process, a low-con print, or high color saturation. These are possible using the defined architecture, and each of these looks can be embedded in the meta-data of the digital movie material. The movie can thus change the 'look' of the projector as needed to achieve the desired effect.

Conclusion

The DLP Cinema™ technology is advancing the move from traditional film based movie delivery, to a flexible digital delivery system. The system is designed using the DMD technology that is capable of delivering precise digital pictures to the screen. This precise delivery, along with the signal processing and color management systems provides a digital system that rivals or surpasses film's delivered quality.

Acknowledgements

DLP Cinema™ projection display technology is the result of numerous individual contributions from within DLP™ Products at Texas Instruments. Some of the key contributors are Douglas Darrow, Scott Dewald, Matt Fritz, Ira Goldstein, Greg Hewlett, Frank Poradish, and Bill Werner.

References

1. Hewlett, G., and Werner, W., "Analysis of Electronic Cinema Projection with the Texas Instruments Digital Micromirror DeviceTM Display System," Proc. 137th SMPTE Tech. Conf., September 1995.
2. Werner, W., and Dewald, S., "Application of DLP™ Technology to Digital Electronic Cinema – A Progress Report," Proc. 140th SMPTE Tech. Conf., pp. 406-412, October 1998.
3. Hornbeck, L.J., "DLP Cinema™: The All-Digital Movie Experience," Keynote, 1999 Intl. Symposium, Seminar, and Exhibition, May 18, 1999. (Keynote included a demonstration of a DLP Cinema™ prototype).
4. Hewlett, G., Pettitt, G., "DLP Cinema™ Projection: A Hybrid Frame Rate Technique for Flicker-Free Performance," Proc. Special Issue of the Journal of the SID on Microdisplays, September 2001.
5. Doherty, D., and Hewlett, G., "Pulsewidth Modulation Control in DLP Projectors," Texas Instruments Technical Journal, July-September 1998.
6. Van Kessel, P. F., Bartlett, T. A., Dewald, D.S., and Pettitt, G.S., "A Comparison of Alternative High-Definition Display Technologies to CRT," Proc. 141st SMPTE Tech. Conf. and Exhib., New York, NY, 1999

7. Van Kessel, P. F., Bartlett, T.A., Dewald, D.S., and Pettitt, G.S., “A Comparison of Alternative High-Definition Display Technologies to CRT,” Proc. 141st SMPTE Tech. Conf. and Exhib., New York, NY, 1999
8. Wysezecki, G., Stiles, W.S., "Color Science: Concepts and methods, Quantitative Data and Formulae", John Wiley & Sons, Inc., 1982, p. 168, p. 569.
9. Van Kessel, P. F, Hornbeck, L. J., Meier, R. E., and Douglass, M. R., “A MEMS-Based Projection Display,” Proc. IEEE, 86, No. 8, pp. 1687-1704, 1998.
10. Fairchild, M., “Color Appearance Models,” Addison Wesley Longman, Inc., 1997, p.140.
11. Ebner, F., Fairchild, M., “Development and Testing of a Color Space (IPT) with Improved Hue Uniformity,” Sixth Color Imaging Conference, p.8-13, 1998.

Biography

Mr. Pettitt received his BSEE and MSEE from Oklahoma State University in 1982 and 1983, respectively. In 1994, Mr. Pettitt joined Texas Instruments, working in the areas of target tracking, system modeling, and simulation. In 1993, he joined the DLP™ Products group at Texas Instruments, where he has worked in video signal processing algorithm development, projection display modeling, color management, and electronic cinema.

Mr. Walker received a BSEE from Rice University in 1983. He has over 18 years experience in video and film post-production, equipment design, and manufacturing. He has worked with various manufacturers and post-production companies on a wide range of film and video products. In 1998, Mr. Walker joined the Texas Instruments DLP Cinema™ team, and has developed a number of key elements and features in signal processing and color management, including the overall system architecture. He currently leads the DLP Cinema™ Systems Engineering team.

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