DMD Display Systems: The Impact of an All-Digital Display

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While many advantages and the market potential of digital micromirror device (DMD) technology have been described **[1-3]** we intend to focus on the impact of a *fully* digital video display system. Redefining the architecture of an entire video system can dramatically decrease costs and increase performance from current display technologies (CRT and LCD). With recent disclosure of promising results relating to Texas Instruments DMD technology, the impact of that technology on the entire video system is presented.

Introduction

A brief overview of recent DMD progress in projection displays will provide a basis for discussion of the impact of the technology on the system. This paper focuses on the application of DMDs to video projection display systems. Significant progress has been made in the modeling, simulation, and prototyping of many video systems based on DMDs. We recently demonstrated compelling picture quality, rivaling the best competing technologies (CRT and LCD) with this "all" digital display technology. Video decoders, de-interlace, scaling, and other functions were evaluated. The key to providing competitive and compelling solutions rests on the optimization of video processing functions in the digital domain *with* digital display. We show that ignoring the display technology when developing the video system may actually result in a decreased advantage with respect to other display technologies. Texas Instruments has realized this potential, staffing a full system development strategy in terms of DMD development. Subsequent discussion of the impact of various system technologies on the DMD is presented.

Scope of Products and Solutions

Potential DMD video display systems in today's markets range from conventional consumer TVs to institutional high-end projectors and electronic cinema, as shown in **Figure 1**.

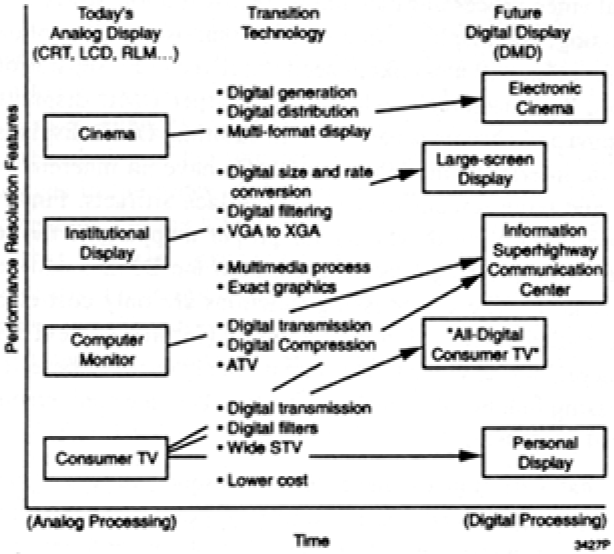

Fig. 1. Potential DMD video display systems.

Any application domain is possible; however, the inherent nature of a digital display tends toward high-performance applications, such as high-definition or high-quality displays. In addition, the digital nature of the technology matches well with today's surge in computer graphics display. In contrast, rapid integration of digital semiconductor technology could enable low-cost applications of the technology, such as consumer TV or personal viewers. While digital displays have inherent high performance, this can be traded for a cost advantage in these applications. Future displays will focus on the display of media from several sources, such as digital multimedia TVs or personal ports into the "information superhighway." In general, the scope of the DMD display application space is very large and seemingly ever-increasing high-definition or high-quality displays. In addition, the digitalnature of the technology matches well with today's surge in computer graphics display. In contrast, rapid integration of digital semiconductor technology could enable low-cost applications of the technology, such as consumer TV or personal viewers. While digital displays have inherent high performance, this can be traded for a cost advantage in these applications. Future displays will focus on the display of media from several sources, such as digital multimedia TVs or personal ports into the "information superhighway." In general, the scope of the DMD display application space is very large and seemingly ever-increasing.

Digital Processing Impact

The advantages of DMD technology for projection display have been described previously as:

- Exceptional visual quality display, free from limitations of other technologies:
    - High light throughput efficiency for very bright projection display.
    - Inherent convergence of single DMD systems.
    - Pure color fidelity with pixelated micromechanical mirrors.
    - Electromagnetic radiation-free.
    - High contrast ratio (with use of hidden hinge technology. **[4]**
    - No persistence, comet tails, or lag.
    - No warmup time.
- Inherently clean digitally generated graphics display.
- Flexible design for product differentiation:
    - Compact form (12 to 14 inch depths possible).
    - Rapid front and rear projection mode change.
    - Simpler optics solutions.
    - Less heat sensitivity for high-brightness applications (versus LCD).
- Semiconductor technologies:
    - Economies of scale enable new markets such as large-screen HDTV.
    - Reliability.

While these represent many compelling advantages of DMD and suggest true advantages for all video display applications, regardless of the nature of the video signals, the fact that we can now construct a *fully* digital video display system, with both digital video processing and display, has additional advantages. With the advent of this *truly* digital display, it seems intuitive to use digital video processing to create, transmit, and manipulate the video signals. Although it is difficult for a new display technology to change the infrastructure of an analog industry many decades old, several factors point to a convergence on digital processing in the video industry in the near future:

- Acceptance of the recently defined *all-digital* advanced television (ATV) standard for high-definition TV broadcast.

- Merging of computer graphics with television (i.e., Modular Windows™ on TVs and TV pictures in Windows™).

- The eventual coupling of digital cable and telephone networks.

- Evolution of billion-operation-per-second microprocessors and high-density memories.

- Increasing use of digital processing technology in TV and film production.

Only DMD technology permits digital processing *and* digital display of video. Images can be created, processed, distributed, stored, and displayed all in completely digital form. With DMD displays, the viewer sees extremely sharp and crisp digital images, a result of using time integration of bit images at rates exceeding human perception to create shades of gray (or color). To the system, the DMD appears as a digital memory. Redefining the architecture of the entire video system decreases costs and increases performance from current analog display technologies (CRT and LCD).

Advantages of Completely Digital Video Display

Using an integrated digital display in a projection system, rather than an analog display, maximizes the impact of the system's digital processing, yielding clean video images and reduced system cost. The advantages of implementing a completely digital video projection display system are:

- Inherent noise immunity.

- Stable, consistent operation, independent of temperature, signal, or component lifetime variations.

- Simple product differentiation (with performance and cost variations) by the selection of digital functions.

- Enhanced features and video quality with use of computer video algorithms.

- Unique new features only possible with digital video processing in the display.

With all-digital television sets or computer displays, users can watch without annoying ground-loop noise or electromagnetic interference from household appliances or local radiation sources. By maintaining digital processing throughout the video system, an architecture can be composed to add functionality without signal degradation. In some cases, the functionality can be altered by simple parametric or software changes. For example, by using programmable processors such as the scanline video processor (SVP)**[5]** or multimedia video processor (MVP)**[6]** from TI, we can alter the function of the video processor by simply changing the software loaded via disk, memory card, or networks (cable or telephone). Most algorithms (such as de-interlace, scaling, and sharpness) have functionality that is related to the complexity of the processing and, therefore, to the cost of performing those functions. This ability to optimize the algorithms to the product, including the type and mix of functions, is a feature of digital processing. Changes in analog systems are generally more complex and lead to component or board selection or removal. In addition, digital architectures can be made modular, enabling ease of "drop-in" additional functionality, leading to upgradable systems. This modular approach could be particularly attractive in today's fast changing video environment, since the customer would not need to commit to a single system.

Enhanced Features

Computer video algorithms that permit enhanced features and video quality in a digital system include the following:

- Nonlinear processing to remove distribution artifacts.
- Adaptive filters to improve perceived display resolution.
- Higher performance adaptive digital sharpness control (current sharpness controls are only horizontal).
- Dynamic range enhancement algorithms.
- Dithering to reduce number of bits/pixel transmitted or processed.
- Scene-adaptive histogram specification.
- De-interlace algorithms such as motion-adaptive or edge-interpolative.
- Simple de-interlace algorithms such as line-double or median filter.
- Digital scaling for resizing and aspect ratio conversion: bi-linear to custom-designed FIR filters.
- Vertical aperture correction.
- Features such as PIP, POP, freeze frame, zoom.
- Reduction of display artifacts such as cross-color, dot interference.
- Frame rate conversion.

In addition, the digital video display system uniquely opens new applications and features. These include:

- Interactive communication and advanced video games.
- Sophisticated computer-like interactive user interfaces.
- User video editing (program selection and commercial cuts).
- On-line user-customized video and audio.
- New uses such as video phones, Photo CDs™, and video printers. These features highlight the wide variation of performance and cost possible with digital video processing.

Direct Coupling DMD to Digital Video Systems

Eliminating the analog-to-digital and/or digital-to-analog conversion process for all digital systems and/or relocating analog functions to the digital domain for mixed analog/digital systems lowers the cost and increases the performance of DMD systems. In digital compressed video input systems, the added cost and noise injected by convening to analog signals is not needed for the digital display. Directly digital coupling of the display system to the digital transmission or digital storage media, such as when implementing MPEG-based cable decoders or MPEG-2- based ATV decoders, will remove a source of noise and cost. In particular, more bits per pixel or dynamic range will be available for less cost to the consumer since expensive high-precision ADCs will be in the studio rather than in the home receiver. In addition, direct decoding these digital bitstreams to formatted DMD video, rather than NTSC video, will improve those systems. In "mixed" analog and digital systems, moving functions such as sharpness and picture controls to the digital domain will yield more flexible and repeatable control of those operations.

Impact of DMD on the Display System Electronics

Use of the DMD greatly affects the entire video system electronics. Just as the characteristics of CRTs have influenced TV electronics, we must adapt the system electronics to realize the full benefits of the new features of the DMD display. Use of the DMD can require unique digital signal processing to prepare the data for display of video, including:

- Digital Video Processing — minimize distribution, storage, and display artifacts.
- DMD Data Formatting — spatial and temporal change of video for DMDs.
- De-Gamma and Artifact Concealment — picture linearizing manipulation and minimization of contours.
- Lower Frame Rate Display — without large-area flicker.
- Synchronization to Nonstandard Video — video sources vary widely in practice.

Avoiding the Hidden Costs — Use Digital Video Processing

Digital video processing can minimize distribution, storage, signal processing, and display artifacts. The composite video source decode function will most likely need improved color separation and reduced dot interference when using sharper DMD displays (via 3-D luma and chroma separation). In addition, DMD displays will use a de-interlace function since DMDs have no inherent persistence and large screens may show interlace artifacts. Finally, we can use resampling or scaling for proper mapping of the source image, with differing aspect ratios, onto the DMD's square-grid display array. These processing functions are only cost-effective when implemented with digital memory (for line or field delays). In general, digital video processing uniquely enables these vertical processing functions—analog techniques become cumbersome for vertical processing.

Note that variation of these "DMD-unique" functions and, as previously mentioned, the placement of other standard functions (such as sharpness) permit optimization of cost and performance for individual applications. The hidden costs of spatial light modulators (LCD and DMD) can inhibit products if not adequately handled by function integration or new algorithms. New integrated digital video chips are key to the long-term success of DMD technology over analog SLMs. For example, a very bright, large-screen DMD projection display designed for ATV will *expose* numerous visual artifacts that were not previously apparent when displaying lower-performance consumer video (via VHS tape and fringe-area reception). A new algorithm or method would be necessary to provide graceful degradation of visual quality to the user. Another example is the use of square pixels. Systems that require aspect ratio conversion (such as letter-box wide NTSC) or display of "non-square" pixel formats (such as NTSC video that has been decoded to integer multiples of the 3.58 MHz color burst) require unique digital filters to display on a square-grid, sampled array. If these functions were not evaluated, a cost disadvantage could result with the use of the DMD in some projection systems.

DMD Data Formatting

With DMDs, we use a common digital processing function, pulsewidth modulation (PWM), to create a unique display method **[1,2,7]**. In particular, the pixel (or byte) sequential data format used by most display systems must be convened to a bit-plane parallel data format for display on current DMDs. By use of electronic control signals and an integral memory array, the DMD's array of mirrors is time modulated with bit images or patterns that correspond to a desired "accumulated" image. Basically, the eye integrates a sequence of binary images with differing display times (although within the frame time). The display times of each binary image are weighted by the binary code (i.e., in an 8 bit system, 128 would require an "on" pixel for 8.3 ms and an "off" pixel for 8.3 ms of the 16.6 ms frame). Understanding this data formatting, the mechanism for concealing display artifacts, and the overall impact of processing for a sharp, linear display can lead to optimal systems for digital display. In effect, we have exploited the properties and limitations of the human visual system to develop optimized data formatting.

Display Artifact Concealment

DMDs can exhibit unique display artifacts, a problem associated with all video display technologies. We have developed methods to completely mitigate the new perceptual display artifacts associated with digital DMD displays. Without proper consideration for human perception, pulsewidth modulated display systems may exhibit annoying visual artifacts depending on the scene's temporal content (either object motion, intensity changes or chromatic changes) or viewer eye motion. These artifacts are produced by an imbalance of energy distribution (either monochrome or chromatic) during the eye's integration time. For stationary scenes and stationary eyes, changes in the temporal distribution of energy (i.e., the time ordering of the sequence of binary weighted bit images) or changes in the order of the colors displayed (for a sequential color system) will not affect one's perception of the image. However, this "stable" process can be interrupted by several mechanisms: (1) temporarily obstructing the display by waving one's hand or (2) quickly darting one's eye back and forth. In effect the integration time can be terminated early causing the eye to miss some bit images and leading to false contours. Another source of artifacts occurs when changing a pixel value over time because of object motion, noise, or changes in illumination (such as changing the camera's iris). With some bit coding patterns, such as at 127 and 128 in 8 bit systems, half the frame period is "on," either at the first or last of the frame (because of binary coding of "1000000" versus "0111111"). The problem occurs when the transition energy from one intensity to the next is lengthened by this extremely asymmetric display energy at the transition between 127 and 128. Obviously, recoding and weighting can remedy this problem. Finally, without attention to the frequency and order of colors, the use of sequential color display can create color separation, or chromatic "ghosting" of the display. This can result in blurring and color fringing of white text scrolling on a black background. Proper color sequencing and ordering of the PWM bit images has mitigated these artifacts.

Digital Display Contours

Balancing of the display's optical contrast ratio and number of bits processed dramatically influences the cost of a digital display system. Digital display systems, independent of the display methods can exhibit annoying visual contours and artifacts depending on the scene content and the number of bits per color displayed. In particular, pulsewidth modulated SLMs can have bandwidth constraints that limit the system's ability to display the number of bits necessary to eliminate these contours. This limit is set by the switching speed of the mirrors (nearly 18 microseconds) and the data input structure of the DMD. With the current input structure and memory-multi-plexed DMD architecture, the DMD can display 8 bits per color in a 60 Hz sequential color system. In three-DMD configurations, more than 10 bits are possible. One can only determine the number of bits or grayshades necessary when considering the resolution, brightness, and contrast ratio of the display.

Regardless of any of the DMD's bandwidth constraints for PWM, contours can be seen for all display technologies if the number of bits per pixel (dynamic range or precision) is too low with respect to the contrast ratio of the display **[8]**. The goal for any digital video system is not to perceive contour artifacts in the scene because of the quantization of pixels, ultimately correlating the number of bits processed to the contrast ratio of the display. Obviously, we must limit the number of bits per pixel to keep the cost of the system reasonable. In addition some component technology limitations can limit the choice of pixel precision, with 8 bit digital RGB used pervasively in the computer industry. The application and the video content determine the number of bits needed. Movies in a dark theater require more dynamic range than computer workstation monitors in a bright office.

The human eye is very good at detecting spatially local luminance variations down to 1%. At higher percentages, the steps are visible and below that point we cannot perceive them. The goal for obtaining a smooth ramp of luminance from dark to bright without contours or mach bands, would require each step to be less than 1 to 2% of luminance change. With a linear mapping of pixel codes to luminance and an ideal contrast ratio, one can see that below a digital number of 50 in an 8 bit system, we could exceed that threshold (i.e., 1 of 50, 1 of 49, ...). Theoretically, in a dark scene, where all the pixels are low intensity a change of 1 bit can correspond to as much as a 100% change in the illumination — clearly perceptible as a contour (assuming the display has greater than 100:1 optical contrast ratio). Fortunately, neither of these situations happens in practice. Most display systems are nonlinear (providing more precision in the dark regions) and the LSB does not normally double the light from nonideal optical contrast ratios. The existence of "off-state" light or background light reflecting from the screen all reduce the contrast ratio and the need for higher pixel dynamic ranges.

Any quantized video signal, including those used on analog displays such as computer video on a CRT, will exhibit this limitation in contrast ratio. For an 8 bit system, this may limit the usable contrast ratio. Another factor that alters this analysis is the nonlinear nature of the CRTs. For this reason, video contains a gamma function. The DMDs have exactly linear photo response, requiring the removal of gamma before display. Since the physics of perception remain the same, we need finer precision of bits in the dark and fewer in the bright to realize high usable contrast ratios.

Regardless of contour artifacts, it should be noted that the perceived contrast ratio of a system is also altered by the optical contrast ratio. A limited contrast ratio will also manifest itself as a "washing out" of the image. Digital processing techniques have been devised to minimize this effect with DMDs. DMD systems with hidden-hinge mirror technology **[4]** have an optical contrast ratio of 100:1 or better; however, as shown above, the usable contrast ratio may be less than that depending on the system electronics. Because of the preceding discussion, a linear signal would require more than 12 bits to meet the 100:1 optical limit. Higher brightness displays and applications will need a higher contrast ratio. However, with unique application of the PWM methods, we have demonstrated that only 8 bits are necessary to eliminate contours in most consumer video applications with contrast ratios at 100:1; however, applications such as institutional or cinema do require more bits.

De-Gamma Function Location

The contour artifacts associated with a digital video display are primarily in dark portions of the scene. Two methods for removal of video gamma have been evaluated: digital post-processing de-gamma and analog pre-digital processing de-gamma. With the first method, linearization of a digital video signal yields repeated output codes for multiple input codes at the dark end of the curve and missing codes at the bright end of the curve. In contrast, analog de-gamma followed by quantization (or use of nonuniform step-size ADCs) yields uniform incremental steps. At first, it appears that the analog de-gamma would have an advantage; however, Monte Carlo simulations of system and ADC noise show that the dark signals have more noise immunity for digital de-gamma. In addition, if digital video processing is performed in the nonlinear domain (as with post-processing de-gamma), then the precision is used where it is needed most in the dark portions of the image Finally we have developed several methods to minimize the perception of low-level contouring using spatial and temporal dithering at a given number of bits. Even more important the digital de-gamma permits quick nonlinear changes of contrast for context optimizations. Adaptive de-gamma permits the tuning of the bit weights to the particular applications. Depending on the scene content, such as night versus daylight scenes, the usable contrast ratio is altered to match the need. Conclusively, digital post-processing de-gamma is ideal for most applications.

Display Frame Rate

DMDs can display video frames at any rate up to the limit of the mirror switching speed and the input bandwidth structure (which is usually set to the mirror limiting speed). In addition, if one is willing to reduce electrical efficiency (or brightness) of the display or the number of bits per pixel displayed, the speed can be increased even further up to the limit of one bit plane displayed in one frame time (which is unrealistically high). Even though we could operate DMDs at very high frame rates, we have determined that it is pointless from a human perception standpoint. Studies have shown that DMDs do not exhibit the same flicker characteristics as CRTs (which are used predominantly in today's projection displays) in relation to frame rate. Operating between 50 and 60 Hz frame rates seems optimal for all applications; even standing 1 foot from a 13 foot diagonal screen, we do not see off-axis or large-area flicker at 50 Hz. Display of PAL-plus at 100 Hz, computer graphics at 78 Hz, and cinema at 72 Hz is not necessary with DMDs — a significant system cost advantage for DMD.

Synchronizing to Nonstandard Video

A display system must adapt to any of a wide range of video signals, both those that adhere to the NTSC timing standard and those that deviate from it. This is quite a challenge for a digital processing system, independent of the display method. Video tapes that stretch with age, weak transmission signals, and video games all lead to tremendous video timing variation. Sync separators insensitive to signal amplitude variations, line and pixel clock phase-locked loops with rapid recovery, and well-defined strategies for pixel location in the display with erratic source timing will be necessary to prevent "digital locking" problems. Without this attention to system timing, erratic display of portions of the video image become annoying to the viewer. Conventional control system methods can be used to develop the video system; however, the most effective solutions will recognize the fact that a digital display will be used when defining the source decoder timing rather than separate source interface and display timing.

Optics Versus Digital Electronic Processing

DMDs offer great flexibility in terms of the optimization of a system by trading optical and electronic processing to achieve the same function. Since the clear aperture of the DMD is quite small, with active areas near 1 square inch, projectors with compact form factors, including small projection lenses, result. Problems such as keystone correction can be resolved by displacement of the DMD with respect to the lens. This method is problematic for both large-area LCD and CRT projectors, requiring extremely large projection lenses. The cost and inconvenience of the complex setup procedure for alignment of a CRT system with deflection correction can be replaced with simple optics or spatial remapping of the image with digital signal processing techniques. This hidden-cost savings will help enable consumer application of projection displays.

Scaling of the image for letter-box applications or nonsquare pixel sources can also be implemented with either digital electronics or optical processing. Anamorphic optics will provide a rectilinear stretching of the image, however, without simple control of the scale factor. The frequent use of numerous letter-box aspect ratios in the industry supports the use of a digital scaling method (with parametric control of scale factors).

Many display applications require use of multiple scan formats (such as a conference room projector). With a digital DMD processor, the designer could choose to scale the image to fit onto the entire DMD or directly map the image pixel by pixel onto the DMD, using the projection zoom lens to fill the screen.

In comparison to CRTs, DMDs permit simple color balancing or adjustment of chromaticity. Not limited by the CRT's phosphors, we can change the displayed spectrum by selecting new filters or a lamp with a different spectrum. In contrast, electronic matrix operations can alter the color spectrum to the desired value. This wide assortment of choices permits rapid change of the system design.

In comparison to other SLMs, the only system parameter that creates difficulty for the optics designer is illumination of the DMD. The relatively small working aperture (limited by the small size and deflection angle of the DMD) restricts the design of the illumination system. However, these problems have been successfully resolved for numerous projection display applications.

System Impact of ATV and Digital Compressed Video

Within the decade, nearly *all* new projection televisions in the U.S. will adapt to support the currently proposed ATV high-definition television standard, with early entries in the middle of the 1990s, most likely supporting the 1996 Olympics. Digital high definition in the form of ATV appears to directly support the advantages of DMD technology. Sharp, clear, exact-color, stable, and noise-free the video will result, with a technology that is based on digital semiconductors.

Regardless of the final ATV distribution format, some DMD-critical issues have already been decided by the committees, and will not change. These decisions are important since they will also influence cable and DBS delivery of digital video bitstreams. The key ATV decisions that influence the DMD projection display include selection of MPEG-2 for digital compression, selection of square pixel formats (which was driven by computer manufacturers)—a key cost and performance differentiator since DMDs are limited to only square pixels, selection of progressive format distributions and selection of l6:9 display format (16:9 CRTs are deep and bulky). Future televisions could display at any format or frame rate; however, display of decompressed digital video at the "distribution resolution and rate" will result in higher performance and lower cost. Independent of the display technology, ATV signal conversion costs, including demodulation, decompression, decryption, and post-processing, will be quite expensive initially. Since the main formats chosen are square pixel and progressive format, DMD has a natural advantage. In addition, since the transmission resolutions were selected in two stages, 1280 x 720, followed by "full" 1920 x 1080 HD resolution, this permits simple staging of the introduction of HD to the market. In addition, the author believes that the higher quality of DMD displayed images over that of competing technologies will yield the appearance of "full" HD with use of the early 1280 x 720 ATV sets—delaying the higher-cost 1920 x 1080 ATV sets to later in the decade.

Another difference may be the system architecture. Whereas cable and DBS delivery may start with set-top box analog video interfaces, we believe the opportunity for all-digital inputs and subsequent integration of that functionality will occur with the introduction of ATV sets. The integration of the MPEG decode function with the digital display will enable a reduction of the overall system cost and add functionality. In addition, when considering closed systems, such as an interactive game network, if the sender knew that a digital display was connected to the network, unique digital functions could be added to the bitstream for selective use by the digital display (supported as ancillary data in the MPEG bitstream). In general, ultimate flexibility is attained with the digital display system.

Architectures

Figure 2 and **Figure 3** illustrate two possible system architectures for using DMDs in projection display applications. The functions generally fall into four categories: (1) source interface, (2) baseband video processing, (3) feature processing, and (4) DMD interface.

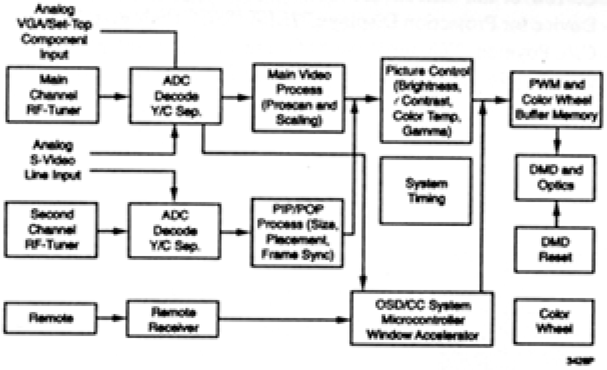

Fig. 2. Analog-Composite Video Input, "All-Digital" Processing and Display TV with Pipeline Architecture.

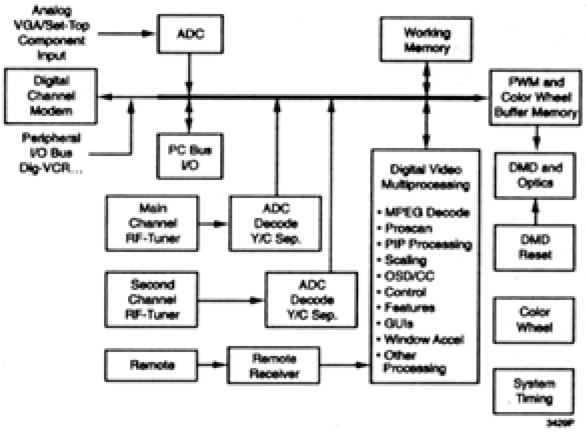

Fig. 3. "All-Digital" Compressed-Digital Video Input, "All-Digital" Processing and Display TV with Multi-Drop Highway Architecture.

These two architectures show a conversion from digital "pipeline" processing to digital "multidrop" highway processing. This migration reflects the change in use of video technology, from simple display of video (or bits) to the multifunction use of the display as a multimedia communication center.

Limitations in the availability of *digital* video commodity components restricts simple development of these architectures; most currently available chips have analog video inputs and outputs (although they may have digital video processing internally). As the market needs of digital video mature, the components will also. In addition, as digital signal processors continue to develop, the availability of billion operation per second processors and high-density memories will enable their implementation two such processors recently developed by Texas Instruments include the scan-line video processor (SVP) and multimedia video processor (MVP).

Another factor not discussed here is the processing of digital audio signals, other signals, and advanced user interfaces, such as Modular Windows™ or channel selection services. As these integrate into the display, they will play an increasing role in the integration of future display systems.

Optimization of the system requires careful analysis of the markets, functions, algorithms, and implementation methods. This wide range of choices illustrates the complexity of the architecture decision. We are performing these tradeoffs for a variety of DMD projection systems.

Simulations and Modeling

Another advantage of digital video systems lies with our ability to simulate the performance of any given system with readily available computer equipment. We have developed a digital video system that connects a multitude of digital video commercial equipment to programmable DMD projectors. The result is a system that permits flexibility in evaluating the performance of practically any DMD video system.

The system comprises several digital video recorders for buffering of long video sequences, with a direct digital connection to both one-DMD and three-DMD programmable projector systems. The digital recorders include a multigigabyte RAM array, magnetic disk, and digital tape (both studio-quality NTSC CCIR-601via Sony D1s, and studio-quality HD SMPTE-260 via Sony HDD-1000). Each video tape recorder is duplicated and synchronized to generate progressive format video signals from these interlaced sources. In addition, the multigigabyte RAM array can be programmed to generate virtually any video signal format, from NTSC to beyond HDTV. Digital video processing algorithms are processed in batch form on an array of Sun workstations, and then the results are transferred to the recordable media for "live" playback onto the DMD projector. Once the algorithms have been optimized in batch form, we use a programmable video system, based on the TI SVP to further evaluate the algorithms on a wider range of test images.

Within these simulation systems, the DMD interface also contains programmable features, such as the frequency and order of data loading and resetting. This feature permits optimization of DMD timing with particular video algorithms.

Remarkable performance assessment has been realized since the simulation and final form of processing are both digital. We can optimize a particular algorithm and accurately predict the performance within a particular implementation.

Conclusion

The exceptional flexibility offered by DMD digital display technology creates a tremendous opportunity to optimize applications in a wide range of display markets. The requirements of standard video, enhanced video, and high-definition TV systems were evaluated. In addition, as digital video input emerges, such as with MPEG-based digital video set-top cable/satellite/broadcast decoders, the advantages of digital display excel. Emerging component technologies, in the areas of parallel processors and new digital memory architectures, will enable this transition to full digital video systems.

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