Industrial DLP Projection Technology

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ABSTRACT

The Digital Light Processing (DLP) micro-mirror technology of Texas Instruments is commonly known for being used in digital cinema and data projectors. This paper provides a different view and shows that these unique MEMS offer significant potential beyond generating impressive movie screen pictures for human eyes. In a first section, the principle of operation of a digital micro-mirror device (DMD) is described when it is driven by the high-performance industrial control chipset. Explained is the architecture of a hardware/software co-design that puts the chipset capabilities into an industrial programming environment. Selected use cases will be highlighted, including 3D scanning and advanced manufacturing.

1 INTRODUCTION

The release to market of the first FPGA controlled chipset Discovery™1000 in 2000 formed the starting point for the successful use of DLP technology in new emerging industrial applications. Now, two decades later, DLP solutions have found their way into a wide variety of products. While standard projection is optimized for high-quality pictures for human perception, the industrial requirements are typically different with respect to both, optical performance and digital control of the micro-mirror array. Addressing the growing demand in industry, new DLP chipset and control modules have become available enabling highly productive solutions with enhanced resolution.

2 OPTICAL PERFORMANCE

The impressive application potential of DLP technology is based upon the fact that the incoming light wave is just reflected by the aluminum micro-mirrors independent upon its wavelength or polarization state. The DMD mirrors are bi-stable, switching between the two tilt angle states of ±12°, typically referred to as ON and OFF. The mirror size is in the range of several microns causing diffraction in the output channel according to the grid nature of the array. The DMD is operated under controlled gas pressure and the optical access is provided through a window.

2.1 Efficiency

One key parameter of the DMD mirror array is the fill factor, i.e. the fractional mirror coverage as viewed from the illumination direction when the mirrors are set in ON position. The ON-state *fill factor* depends upon the mirror size [1].

Table 1 DMD fill factor in ON position

DMD pitch [µm]	DMD fill factor, ON state
13.7	92%
10.8	92%
7.6	94%

The industrial DLP chipsets support a wide spectral range. The aluminum mirrors have 89% *reflectivity* in the visible range, they work well in the UVA range and reflect even better in the NIR above 1000 nm.

The *transmittance* of the window has impact on the total efficiency so that specific antireflective coatings are applied for industrial DLP chips optimized for UVA and NIR, respectively. The graph shows the typical transmittance for single pass normal incidence [2].

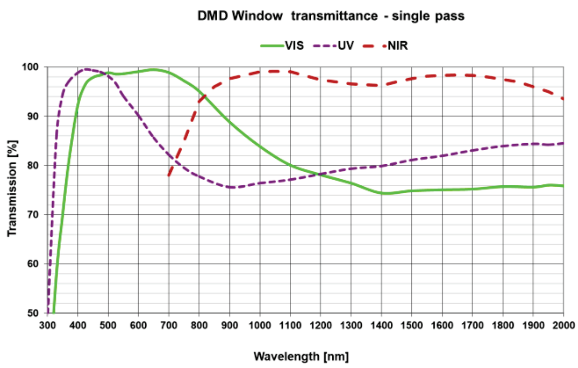

Fig. 1 DMD window transmittance

The DMD micro-mirror-array acts as a diffraction grating. The higher diffraction orders are clipped by the aperture as only the central part of the beam is collected by the projection lens. The resulting *diffraction efficiency* varies with mirror pitch, mirror tilt, and wavelength. Red light is clipped more than blue and the following table shows average diffraction efficiency values for the 420-680 nm range [1, 3]. The efficiency product of fill factor, mirror reflection, diffraction and (window transmittance)² yields the DMD total efficiency value.

Table 2 DMD efficiency

DMD pitch	Diffraction efficiency	Total efficiency
13.7 µm	89%	70%
10.8	87%	68%
7.6	84%	67%

2.2 Optical Power Transfer

The light lost by reflectivity and fill factor as well as some back-reflected light from the DMD window remains in the DLP chip. The upper limit for energy transfer is determined by the maximum allowable DMD array or pixel temperature and proper cooling is essential for high power applications. For continuous light sources, the array temperature shall not exceed the specifications limits of the respective DLP chip. The currently highest optical power of 150 W can be controlled by in the DLP650L NIR that allows local spots with power density up to 500 W/cm². Using pulsed laser illumination, the transient temperature of the pixels can no longer be ignored. It is desirable to keep pixel surface temperature below a critical temperature of 150°C and models are described to predict momentary temperature that the pixels reach during pulsed laser operation [4].

3 DIGITAL CONTROL

The FPGA controlled DLP chipsets facilitate precise pixel level control of high-resolution binary light patterns with millions of pixels at outstanding refresh rates in the 10^5 fps range. The bi-stable DMD mirrors of these industrial chipsets are kept in either +12° or -12° tilting position that is mechanically defined by landing pads and therefore highly reproducible. Mirrors may stay in that position for some extended time without any motion or they can be flipped to the opposite tilt state within a few microseconds.

The demanding timing and data rates combined with the high flexibility of industrial DLP chipsets call for dedicated FPGA logic implementation. PC programmable FPGA controller suites (Fig. 2) enable a rapid launch into that technology and offer the advantage of mature, industrially proven designs [5].

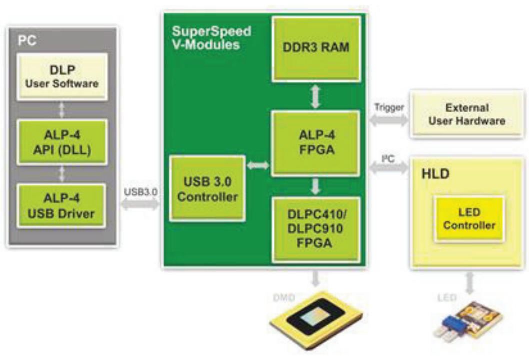

Fig. 2 Schematic of SuperSpeed V-Module family [5]

3.1 Switching Behavior

The refresh operation of the DMD array is split into two steps:

(1) Loading data for the next pattern in the pixel memory cells underneath each mirror.

(2) Transferring the previously memory pattern into the physical mirror positions, see Fig. 3.

The data rates implemented for step (1) are the essential parameter controlling the refresh rate to be achieved. The highly parallel data lines combined with 480 MHz clock rates for DLP9000X enable 60 Gbit/s data transfer to the DMD. For industrial applications, step (2) shall be precisely triggered and it is typically executed for all mirrors of the array simultaneously (Global Reset). Mirrors that do not change for the next pattern undergo only small tilt angles; that is optically compensated by a corresponding margin in the aperture of the projection lens. The mirrors cross over tilt operation takes about 4 µs (reset time) and the next frame can be loaded into the pixel memory as soon as the mirrors have reached their stable position (settling time).

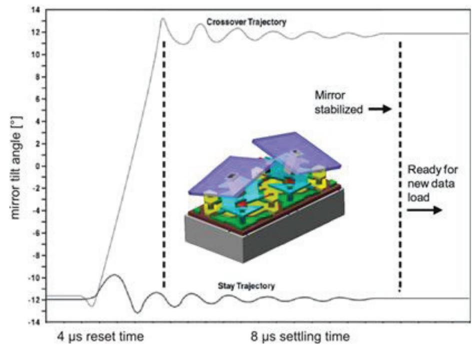

Fig. 3 DMD pattern refresh cycle

3.2 Pattern Rates

The DMD refresh rates depend upon the DMD bandwidth and the number of mirrors of the respective DLP system. It varies between 10 kHz and 23 kHz. Reducing the number of DMD lines used yields even higher rates up to 50 kHz at maximum. The table below summarizes the key parameters for binary patterns.

Table 3 DMD pattern rates with V-Modules

V-Module	DMD type	Mirror count	Frames / s
V-7001	DLP7000BFLP	0.8 Mio	22 727
V-9501	DLP9500BFLN	2.0 Mio	17 857
V-9601	.96 WUXGA	2.0 Mio	17 857
V-6501	DLP6500BFLQ	2.0 Mio	10 309
V-650L	DLP650LNIRFY	1.0 Mio	10 752
V-9001	DLP9000XBFLS	4.0 Mio	12 987

Time average during a certain time period is typically used for generating gray scale values for each pixel.

That way, the grayscale output is perfectly linear if a synchronized detector is being used. The frame rate for gray scale patterns depends upon the bit depth chosen, up to 12 bit are supported in the V-Modules. For the largest DMD array with 4.0 Mio mirrors, the grayscale frame rate is 1013 fps @ 6 bit and 20 fps @ 12 bit, respectively.

3.3 Advanced Control

V-Modules provide advanced control functions that facilitate reduced bandwidth requirement for the USB3.0 compared to the on-board streaming rate of data from RAM to DMD (Fig. 2). Data that are used repeatedly do not need to be transferred again.

- *Look-up table* operation is mapping the patterns stored in RAM to the output stream. That way, sequences of patterns can be freely composed from data already on board. Implementing a delta-sigma approach for grayscale generation is one good example for such approach.
- *Scrolling* describes a process where the pattern is shifted in the DMD display by N lines. The data to be displayed are organized in a long stripe in on-board memory and each new DMD pattern of L lines is read from a new, shifted position in the stripe. So, the bandwidth requirements for the PC transfer are reduced by the factor N/L.
- *Shear scrolling* is an extension that enables the N/L bandwidth reduction also for patterns that are to be shifted somehow inclined with respect to the DMD rows. Details of resolution enhancement by such an exposure technique are described in [6].

4 APPLICATIONS

This section is to highlight three applications that have developed rapidly over the past 2 decades using DLP technology as a typical solution. There are many other use cases and products in optical instrumentation, optical sensing, medicine, industrial exposure and recently also in automotive that cannot be addressed here.

4.1 3D Metrology

Full-field surface triangulation, also known as fringe projection, active stereo vision, structured light, etc., has taken substantial advantage of using DLP technology as a precise and reliable light pattern generator. High-speed 3D imaging has been demonstrated shortly after the availability of the FPGA based industrial DLP chipsets revealing the impressive potential of that technique [7]. Two frequently used solutions are based upon binary stripe patterns (Gray Code) and sinusoidal patterns (Phase shifting), respectively. While the Gray code is faster, the phase shifting approach yields better resolution and accuracy and has been widely adopted in metrology industry. A sequence of sinusoidal patterns is projected onto the 3D surface to be measured and (x,y,z) coordinates can be derived from corresponding camera images. The coordinates are directly calculated pixel by pixel from that camera intensity values. The schematics in Fig. 4 shows the recording process for an integrated sensor with DLP and image sensor tightly attached to the FPGA for high-speed data streaming and precise synchronization control. Current 3D metrology solutions based upon such sensor concept capture 20 Mio. (x,y,z) coordinates per second with an accuracy of 1/3000 FoV.

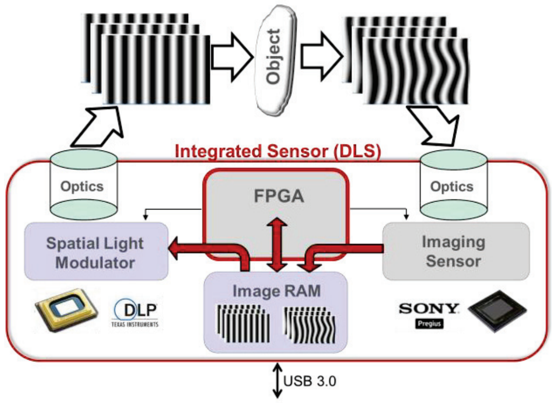

Fig. 4 Architecture of 3D measurement system [8]

One essential requirement for an accurate 3D measurement is the linearity of the projector output generating the sin-fringes. If proper synchronization of the camera is provided, DLP based projection has been verified to give outstanding precision in the gray values generated (Fig. 5).

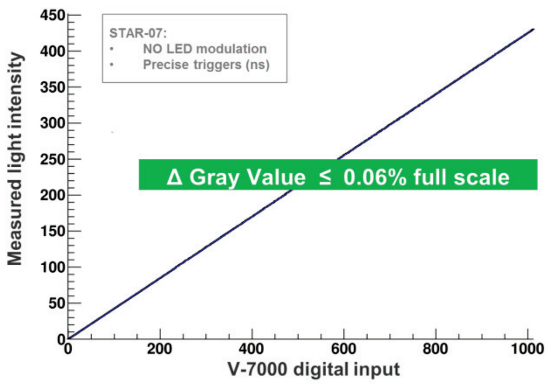

Fig. 5 Linearity of V-Module generated grayscale

4.2 Maskless Direct Imaging Lithography

DLP technology enables accurate digital exposure for high-speed, maskless lithography solutions used for high-resolution PCB patterning, solder masks, flat panel displays, laser marking, and other digital exposure systems requiring high speed and precision. In order to satisfy the speed and throughput requirements for exposure of an area as large as e.g. PCB, multiple identical projection channels are employed, with each operating in parallel to expose a portion of the overall area [9]. Each channel consists typically of a UV light source, illumination optics, one UV DMD, and a precise projection lens (Fig. 6).

The DMD array can be de-magnified to approximately 10:1 for increasing the spatial resolution of the projected pattern and subpixel technologies are applied in addition yielding structure sizes below 1 µm [10].

The maximum switching speed is achieved using the 13.7 µm and 10.8 µm DMD mirror arrays in V-7001 and V-9501 while the 7.6 µm pixel of V-9001 gives the highest resolution combined with the highest data rate.

Advanced control functions as described in 3.3 are essential for efficient system implementation with one or multiple DMD exposure heads moving across the working area and several such control schemes have become a well-proven component in industry.

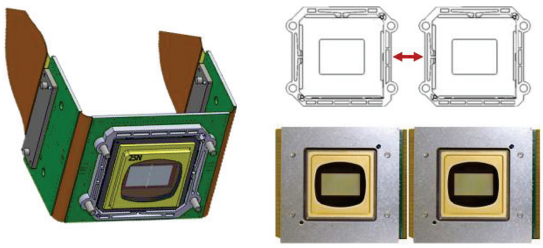

Fig. 6 V-Module design for multiple head exposure with minimal lateral distance

4.3 Additive Manufacturing

This new emerging branch in manufacturing technologies, frequently called "3D Print", has become very common, not only for rapid prototyping but also for industrial level products. The layer-by-layer exposure of liquid or powder material causes curing or melting processes and the exposed pattern correspond to the respective cross-section of the part to be generated.

The industrial DLP chipsets have found numerous applications in such new devices with different performance parameters according to the intended use case, from do-it-yourselfers up to personalized medical part producers.

Satisfying highest demands in both, working space and lateral resolution, the light structures are generated by one or multiple moving exposure heads and the advanced DLP controller technology of maskless lithography can be adopted in such applications [11]. Also the wavelengths used are in a similar UV range for systems based upon curing.

Recently, the high-power V-650L NIR module has been released supporting the DLP650L chipset that can transfer 150 W incoming light in total with a maximum local power density of 500 W/cm² [12]. That way, the melting of power by DLP patterns has become feasible and a new class of material will become available for additive manufacturing in near future.

5 CONCLUSIONS

The paper highlights the outstanding performance of digital micro-mirror devices for industrial use. The MEMS technology guarantees the reliability of millions of mirrors enabling powerful photonics technologies. New emerging products will take advantage of high switching rates, advanced control functions, and excellent optical efficiency of these spatial light modulators.

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