Advancements in the Micromirror Array Projector Technology II

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ABSTRACT

The Micromirror Array Projector System (MAPS) is a state-of-the-art dynamic scene projector developed by Optical Sciences Corporation (OSC) for Hardware-In-the-Loop (HWIL) simulation and sensor test applications. Since the introduction of the first MAPS in 2001, OSC has continued to improve the technology and develop systems for new projection and test applications. The MAPS is based upon the Texas Instruments Digital Micromirror Device (DMD) which has been modified to project high resolution, realistic imagery suitable for testing sensors and seekers operating in the UV, visible, NIR, and IR wavebands. This paper reviews the basic design and describes recent developments and new applications of the MAPS technology. Recent developments for the MAPS include increasing the format of the micromirror array to 1280x1024, increasing the video frame rate to >230 Hz, development of a DMD active cooling system, and development of a high-temperature illumination blackbody.

Keywords: Infrared, Scene Projection, Digital Micromirror Device, Simulation, FPA testing, Hardware-in-the-loop.

1.0 INTRODUCTION

The Micromirror Array Projector System (MAPS) is a state-of-the-art dynamic scene projector developed by Optical Sciences Corporation (OSC) for Hardware-In-the-Loop (HWIL) simulation and sensor test applications. Since the introduction of the first MAPS in 2001, OSC has continued to improve the technology and develop systems for new projection and test applications. The MAPS is based upon the Texas Instruments Digital Micromirror Device (DMD) which has been modified by OSC for sensor test applications. This projector technology is capable of producing very realistic dynamic scenes in the UV, visible, NIR, and IR wavebands. The projector technology offers several attractive features including high spatial resolution, high frame rates, no dead pixels, and excellent uniformity. OSC now offers a family of commercial projector products including projectors, test-sets, and projector engines. In addition, the projector may be customized in a variety of configurations which are tailored to specific applications.

2.0 DMD BACKGROUND

The DMD is a micro-electromechanical system (MEMS) which has a 2-D array of individually controlled aluminum micro-mirrors. The DMD is the spatial light modulator in TI's Digital Light Processing™ (DLP™) system. DLP engines are manufactured by TI and sold to OEMs for use in display products such as business projection systems, cinema, and High Definition Televisions (HDTVs). DMDs are currently commercially available in a variety of formats with resolutions up to 2048x1024. The latest generation of DMDs contains micromirrors on a 13.6 μm pitch which tilt ±12.5° mechanically. However, we are still utilizing DMDs which have micromirrors on a 17.0 μm pitch and tilt ±10.0° mechanically. Figure 1 shows a 1024x768 DMD package, and Figure 2 is an SEM image of the micromirrors with a grain of salt on the surface of the device.

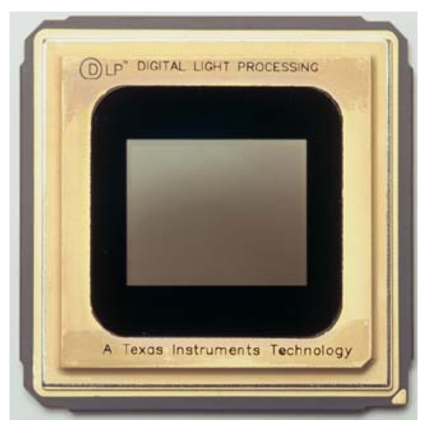

Figure 1: DMD Package

As depicted in Figure 3, each micromirror in the DMD can tilt in one of two directions (±20° or ±25° optical) depending upon the state of the underlying SRAM memory cell. With proper illumination, each mirror will reflect light into the pupil of the optical system when a one is written to its SRAM and out of the optical system when a zero is written to its SRAM. The device is therefore binary in nature. The switching speed on the individual mirrors is approximately 10 usec. The binary image on the array can be updated at rates in excess of 10,000 Hz (for the XGA format devices), and a global reset allows the entire image to be cleared in less than 20 usec. Intensity control is typically achieved using binary Pulse Width Modulation (PWM). OSC developed the technique of synchronized PWM which allows the DMD to be used in sensor testing applications.

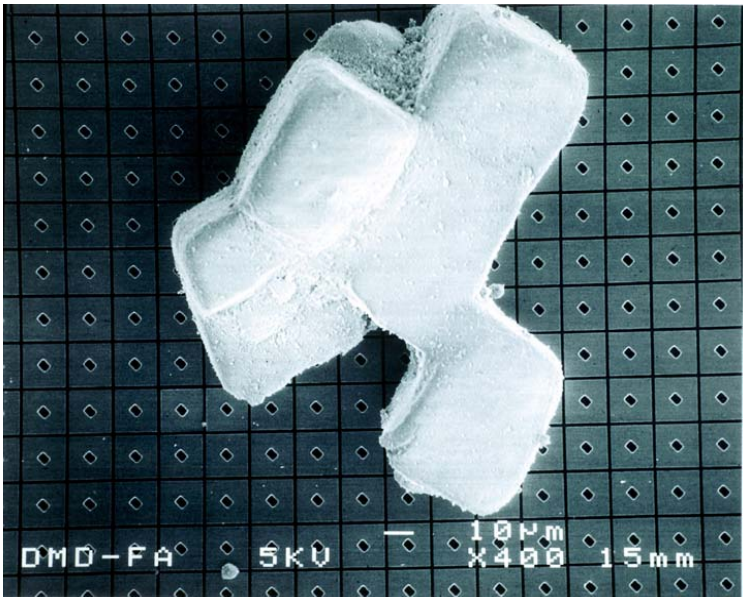

Figure 2: DMD with Grain of Salt on Surface

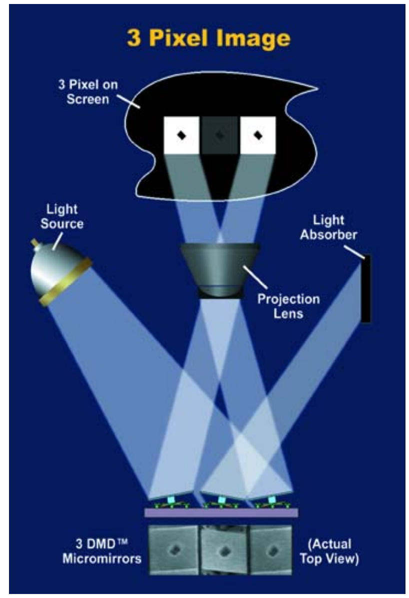

Figure 3: DMD Illumination

3.0 MAPS DESIGN OVERVIEW

3.1 System Block Diagram

Figure 4 shows the system level block diagram and interconnections for the MAPS. As shown in the figure, the complete projector system consists of three major components - the projector head, the support electronics, and the control PC. The projector head contains the DMD, DMD drive electronics, illumination source(s), illumination source controller, and collimator lens. The support electronics chassis contains the video converter electronics, sync signal processor, and power supplies. The control PC is not required for standard operations, but can be used to monitor the status of the projector system and to set the illumination source temperature and other operational parameters of the projector system. The control PC communicates with the support electronics via an RS 232 interface.

The preferred input video format for the MAPS is the Digital Visual Interface (DVI). The DVI standard was developed by the Digital Display Working Group and has become the standard within the computer industry for flat panel displays. The DVI interface will support 24-bit video at up to 165 megapixels per second for each Transition Minimized Differential Signaling (T.M.D.S.) link. Thus, the DVI standard can support video at rates up to 330 megapixels per second which equates to frame rates of 398 Hz for XGA format and 239 Hz for SXGA format (assuming 5% blanking). The MAPS utilizes a single TMDS link for each input video port, and up to two input video ports are available for the XGA and SXGA MAPS projector systems. The SXGA format MAPS can support incoming video at this maximum DVI bandwidth for an effective 239 Hz of uncompressed video. However, the XGA format MAPS currently only supports pixel rates of up to 190 megapixels per second which results in a 230Hz effective uncompressed frame rate. Frame rates for the MAPS can be increased if necessary through re-packing of the video to utilize all 24 bits of video. The MAPS also accepts other video formats including DVP2, RGB-HV, NTSC/PAL, and S-Video. These video formats are converted to DVI within the support electronics prior to being sent to the projector head.

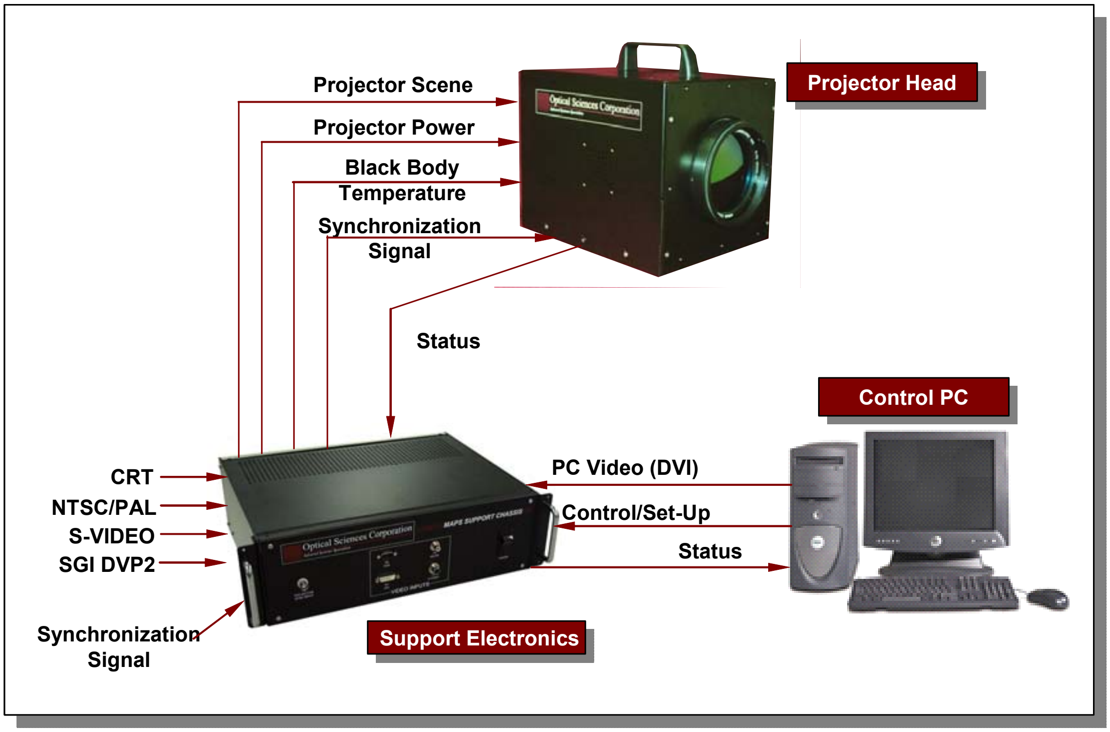

Figure 4: MAPS Block Diagram

3.2 MAPS Projector Head

The projector head contains the DMD, DMD drive electronics, illumination source(s), illumination source controller, and collimator lens. The design of several of these subsystems is discussed in the following sections.

3.2.1 Modified DMD

The window material used in the commercially available DMDs will not transmit wavelengths significantly outside the visible band. Therefore, one of the major design issues that had to be addressed in the development of the MAPS technology was the replacement of the DMD window. OSC has developed the techniques for removing the visible window and installing a window which will transmit in the customer's waveband of choice while maintaining 100% mirror operability. Figure 5 shows the array formats offered by OSC. The smallest array is an SVGA (800x600) format, the mid-sized array is an XGA (1024x768) format, and the largest array is an SXGA (1280x1024) format. OSC has successfully replaced the windows on numerous DMDs with a variety of window materials and anti-reflection coatings, while maintaining 100% operability of the mirrors.

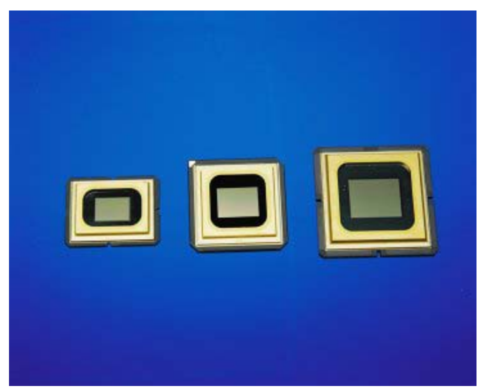

Figure 5: SVGA, XGA, and SXGA DMD Packages

3.2.2 DMD Drive Electronics

The DMD drive electronics are located in the projector head assembly at the rear of the DMD. Figure 6 is a photograph of and XGA format DMD drive electronics board with the DMD mounted on the board. The functions of the drive electronics include:

- Receive the digital video from the support electronics

- Reformat the video for loading into the DMD and store in dual-port RAM
- Load video bit planes into the DMD in sync with the input sync signal
- Generate all required analog signals for the DMD
- Transmit status and receive control commands via the serial interface

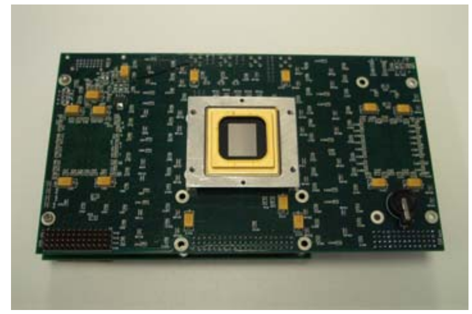

Figure 6 : XGA Drive Electronics Board

In its most basic mode, the DMD can be operated in a single-bit flickerless manner. In this mode, binary images can be generated at high frame rates and there is no minimum integration time required for the UUT. In binary mode the MAPS is projecting the scene for ~97% of the frame time. During the remaining 3% of the frame time the mirrors are allowed to go to a rest state to prevent hinge memory. The timing of this rest event can be synchronized to the UUT so that it occurs during a time when the sensor is not integrating or during the flyback time of a scanning sensor. The rest time can actually be eliminated if necessary, however the lifetime of the device may be reduced. Give the reported MTBF lifetimes of greater than 100,000 hours for these devices, this would probably not be a problem for most applications. OSC is currently under contract to develop a system with this no-rest mode of operation and will determine if there is any degradation to the DMD from operating in this mode for short lengths of time.

Because the DMD is a binary device, gray scale intensities must be generated by Pulse Width Modulation (PWM) or some other technique such as half-toning. The PWM technique controls the intensity of each pixel by setting the percentage of time each mirror is in the ON position within a given duration of time. Commercial (DLP) projectors utilize sequential PWM to generate 8-bit intensity values for three colors. The standard electronics in the DLP projector systems are designed to generate three 8-bit colors at a 60-85 Hz frame rate using PWM. Thus, it takes approximately 5.5 msec to generate an 8-bit image.

For sensor test applications, temporal aliasing will occur if the PWM is not synchronized properly with the sensor integration. OSC has developed the technique of synchronized PWM to address this issue. The synchronized PWM technique was implemented in MAPS by designing custom DMD drive electronics to drive the DMD in synchronization with the FPA integration (input sync signal). Figure 7 shows the basic technique of PWM where the entire PWM sequence occurs during the sensor integration time. The DMD supports latching of the image such that the new image can be written to memory while the previous image is displayed. The Least Significant Bit (LSB) display time is typically ~15 usec and it takes ~100 usec to write a binary image into the DMD SRAM for the XGA device. Thus, for the LSBs there is some dead time where the scene is not displayed while waiting for the next binary image to be loaded into memory. This dead time can be effectively eliminated when displaying 6-bits or more, but increases the PWM sequence time when less than 6-bits are displayed. For most applications, the LSB display time of ~15 usec is the limiting factor in the number of bits that can be displayed.

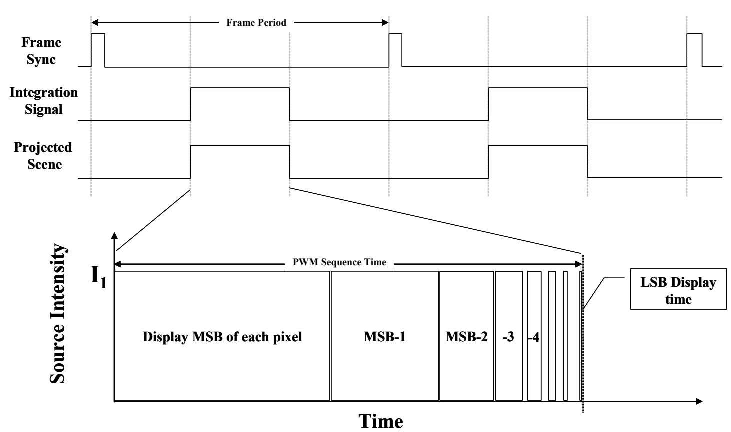

Figure 7: Synchronized PWM Timing

The length of the sensor integration time determines the maximum number of bits of resolution which can be generated. Longer sensor integration times allow more intensity levels to be achieved. Figure 8 shows the minimum integration time required to generate N bits of resolution. As an example, a typical integration time for an InSb FPA camera is 3 msec. With this integration time, the DMD can generate 128 (7-bits) intensity levels. The MAPS electronics are capable of monitoring the input sync signal and adjusting the PWM sequence timing automatically to match the integration time and maximize the bit resolution with only one sync period of lag. Because of the DMD's binary nature and the stability of the master clock, the intensity levels are very accurate and linear. Figure 8 also shows the maximum DMD, video input, and system frame rates as a function of the number of bits displayed. As shown in the table the frame rate can be limited by either the DMD sequence time or the video clock rates depending upon the number of bits displayed. Figure 9 plots the number of bits which can be generated vs. DMD frame rate for a single DMD system.

1024x768 DMD Display Timing

		Max Frame Rate (Hz)		
Image Mode	*Min. Sequence Time (us)*	*DMD Display*	*Video Input*	*Total System*
1bit	128.0	7812.5	4800.0	4800.0
2bit	236.8	4223.0	2400.0	2400.0
3bit	390.4	2561.5	1600.0	1600.0
4bit	585.6	1707.7	1200.0	1200.0
5bit	841.6	1188.2	960.0	960.0
6bit	1353.6	738.8	800.0	738.8
7bit	2377.6	420.6	685.0	420.6
8bit	4425.6	226.0	600.0	226.0
9bit	8521.6	117.3	533.0	117.3
10bit	16796.8	59.5	480.0	59.5
11bit	33347.2	30.0	436.0	30.0
12bit	66444.8	15.1	400.0	15.1
13bit	132643.2	7.5	369.0	7.5
14bit	265036.8	3.8	343.0	3.8
15bit	529824.0	1.9	320.0	1.9
16bit	1059395.2	0.9	300.0	0.9

Figure 8: Integration Time vs. #Bits

3.2.3 Illumination Source

The DMD is illuminated by a source which emits radiation in the waveband of interest. Because the DMD is capable of generating scenes in any waveband from the UV to LWIR the illumination source may be one of several types of sources. For IR applications, extended area blackbody sources are typically used to illuminate the DMD. In addition to the single illumination source configuration, OSC has developed a dual-blackbody configuration for IR applications. In the dual-blackbody configuration a cold blackbody is used to illuminate the off-side of the DMD, which improves the contrast and reduces the minimum apparent temperature. In addition to improving the minimum apparent temperature, the dual-blackbody configuration also allows differential control of the blackbodies which is useful for precision testing of IR sensors. For visible and NIR applications a halogen bulb source is typically used. For visible color applications a metal halide lamp and color wheel are used to illuminate the DMD with three sequential colors of light.

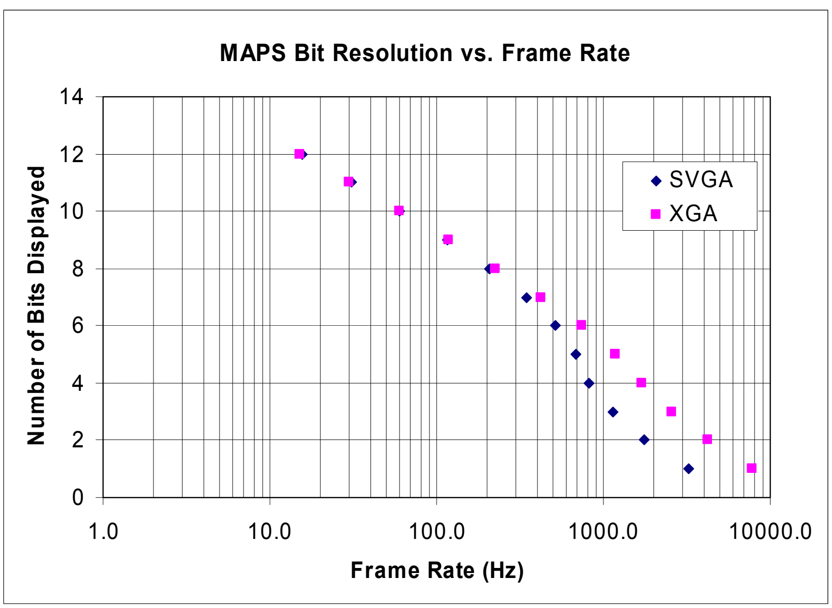

Figure 9: MAPS Bit Resolution vs. Frame Rate for Single DMD

3.3 Support Electronics

The MAPS support electronics are housed in a standard 3U 19 inch rack mount chassis. Figure 10 is a photograph of the standard support electronics chassis. The functions of the support electronics include:

- Receive the video from either a DVP2, DVI, RS-170/PAL, RGB-HV (CRT), or S-video source
- Convert/digitize the video and send to the DMD drive electronics
- Receive the input sync signal and modify as commanded by the user via software
- House the power supplies for the electronics and illumination sources
- Transmit status and receive control commands to/from the computer via the serial interface

Figure 10: MAPS Support Electronics Chassis

3.4 Control PC

The control PC allows the user to modify the projector operational parameters and monitor the status of the projector. The PC communicates with the support electronics via an RS232 serial port.

3.4.1 Control Software

The MAPS includes control software which will run on any Microsoft Windows-based PC. This software allows the user to control and monitor the projector operational parameters via the computer's serial interface. Figure 11 shows one of the windows from the control software. The top-half of this window allows the user to set the dual-blackbody source temperatures and load a calibration file which will set the blackbody temperature required to generate the desired apparent temperature. The bottom half of the window displays the status of the blackbody sources and the other parameters of the projector system. The control software also includes a video setup screen and a synchronization setup screen. The video setup screen will allow the user to perform a variety of functions on the incoming video such as image flips and intensity scaling. The synchronization setup screen will allow the user to generate a sync signal or modify an incoming sync signal as necessary to synchronize to the UUT.

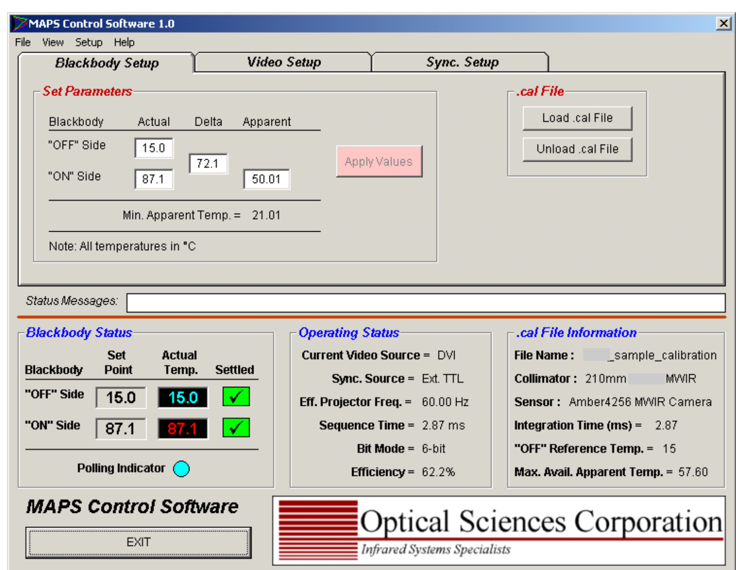

Figure 11: MAPS Control Software

4.0 RECENT DEVELOPMENTS AND CURRENT STATUS

The following sections discuss recent developments in the MAPS technology, examples of systems manufactured to-date, and the current status of the various array formats.

4.1 SVGA (800x600) MAPS

The SVGA format MAPS projector was commercially introduced in April 2001. It is now in full-production and available in various wavebands and configurations. The SVGA MAPS has demonstrated outstanding system reliability and performance. With some systems now operating for more than four years, there has not been a single mirror or electronics failure on any of more than 10 systems delivered to-date.

4.2 XGA (1024x768) MAPS

Development of the XGA format (1024x768) MAPS was completed in early 2003. It is now in full-production and available in various wavebands and configurations. The XGA DMD has more than 786,000 individually controllable micromirrors which is a 33.33% increase in the number of mirrors from the SVGA version. In addition to the increased resolution, this projector format also offers an improved binary frame rate. OSC has demonstrated a binary frame rate in excess of 10KHz for this DMD compared to 4065 Hz for the SVGA format. The XGA MAPS has also demonstrated outstanding system reliability and performance. With some systems now operating for more than two years, there has not been a single mirror or electronics failure on any of more than 5 systems delivered to-date.

In addition to the high-efficiency binary and synchronized PWM modes, the XGA MAPS also offers special operating modes including color mode, modulated source mode, and laser binary mode. These modes were developed such that the DMD could be used in other test applications. The color mode allows the DMD to be used with a color wheel for visible color scene projection. In the modulated source mode, the DMD will modulate a binary scene at a user defined frame rate similar to an optical chopper modulating a source. The laser binary mode allows the DMD to project a scene when illuminated by a pulsed laser system.

4.3 XGA High Frame Rate Electronics

To meet the requirements of a high frame rate application, a second DVI video pipe was added to the XGA drive electronics. This increased the unpacked 24-bit video frame rate to 230 Hz and allowed the scene generation computer system to split the rendering process into two pipes for increased frame rates. Figure 12 shows the architecture for the two pipe video input where each video pipe feeds one horizontal half of the DMD. The two-pipe video was implemented using a daughter card on the existing drive electronics, thereby making previous versions of the drive electronics upgradeable.

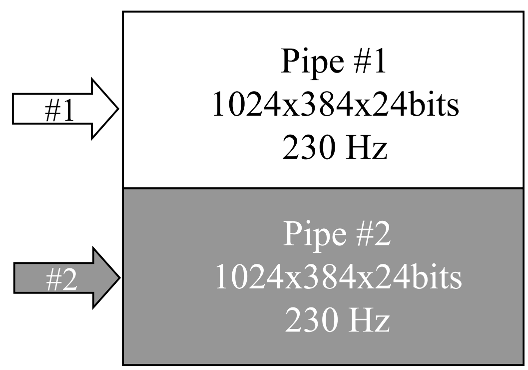

Figure 12: XGA Two-Pipe Video Architecture

It should be noted that higher frame rates can be achieved by packing the video into the unused bits of the video stream. For example, three 8-bit pixels can be packed into one DVI pixel by the scene generation computer then unpacked by the MAPS to support a 1024x768x8-bit scene at 690 Hz.

4.4 XGA (1280x1024) MAPS

OSC is has recently completed development of the SXGA format (1280x1024) MAPS. This DMD has more than 1.3 million individually controllable micromirrors, which is more than 2.7 times the number of mirrors in the SVGA MAPS and 5 times the number of pixels in a 512x512 format projector. Figure 13 is a photograph of the SXGA drive electronics with the DMD, and Figure 14 is a close-up photograph of the DMD chip displaying an image. The SXGA

MAPS will operate at a binary frame rate of approximately 7.5KHz and has a 24-bit video frame rate of >230 Hz. This system also has a two-pipe input video architecture as shown in Figure 15.

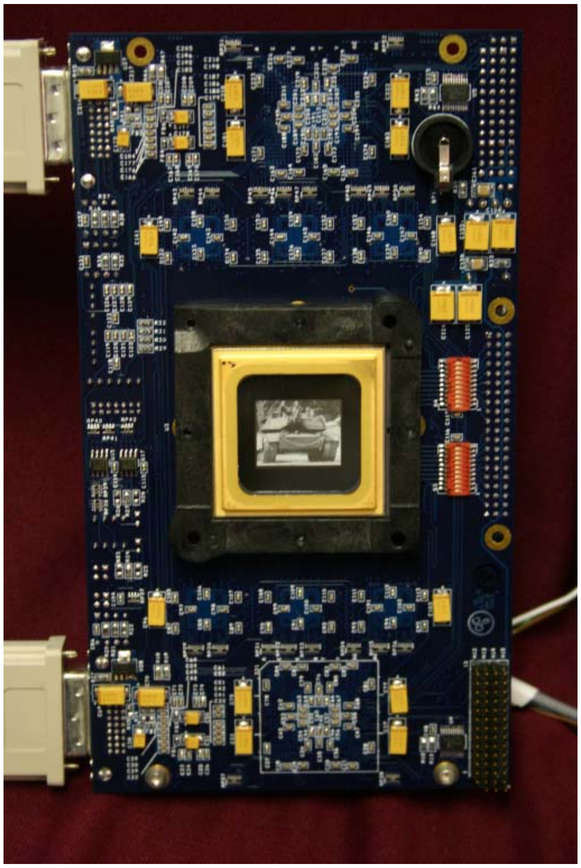

Figure 13: SXGA Drive Electronics & DMD

Figure 14: SXGA DMD Displaying an Image

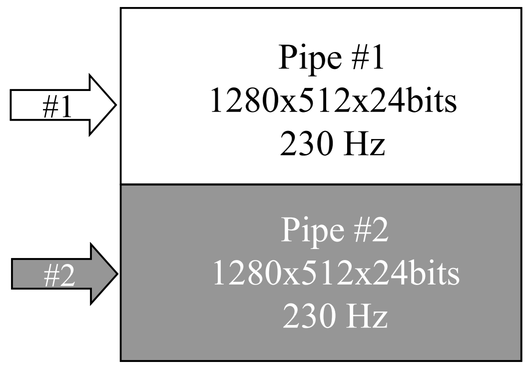

Figure 15: SXGA Two-Pipe Video Architecture

4.5 DMD Cooling System

In order to reduce and stabilize the minimum apparent temperature of the MAPS, OSC has developed an active DMD cooling system. The DMD cooling system consists of a thermo-electric cooler, heat sink, and closed-loop temperature controller. The user can control the DMD operating temperature via the MAPS control software.

4.5 High Temperature Illumination Blackbodies

OSC has developed a custom high-temperature modular blackbody for illuminating the DMD in the MWIR and LWIR wavebands. Figure 16 is a photograph of the high-temperature blackbody. It is an extended area, resistive-heated blackbody which is capable of temperatures up to 800°C (1073 K) with a 0.1°C set-point resolution, 0.2°C stability, and <1 hour warm-up time to 800°C. It features an integrated temperature controller, high efficiency insulation, and a grooved emitter surface for improved emissivity. The blackbody was developed to provide high temperature illumination of the DMD in a

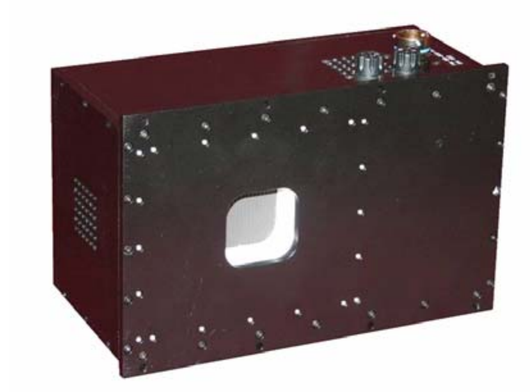

Figure 16: High Temperature Blackbody

more compact package than could be obtained from a commercial blackbody. Using this blackbody, the MAPS can project maximum apparent temperatures in excess of 800K in the MWIR.

5.0 MAPS PERFORMANCE

5.1 Performance Summary

Table 1 below summarizes the performance characteristics of the MAPS.

Parameter	Performance
Spectral Range	UV to LWIR available. Determined by illumination source and optics.
Format	800x600 (SVGA) 1024x768 (XGA) 1280x1024 (SXGA)
Pixel Pitch	17 um
Maximum Binary Frame Rate	4065 Hz. (SVGA) 10,000 Hz. (XGA) 7,500 Hz. (SXGA)
Address Mode	Snapshot
Max. Duty Factor	~97%
Amplitude Resolution	1-24 bit programmable.
Contrast Ratio	400:1 Visible ~250:1 MWIR 15:1 LWIR (Normal Mode) 110:1 (Special Mode)
Max Apparent Temperature	>800K (Dependent upon source selected)
Pixel Operability	100%
Spatial Uniformity	>99.8%
Video Interfaces	PC (CRT), DVI, NTSC, PAL, S-Video, DVP2
Max 24-bit Video Frame Rate (unpacked)	100 Hz. (SVGA) 230 Hz. (XGA) >230 Hz. (SXGA)

Table 1: Micromirror Array Projector System Performance Summary

5.2 Apparent Temperatures

The maximum and minimum apparent temperatures of the IR-MAPS are dependent upon the illumination source temperature. OSC has collected apparent temperature data on numerous systems, and it has remained very consistent. Figure 17 shows the maximum and minimum apparent temperature of a MAPS operating in the MWIR band as a function of illumination source temperature.

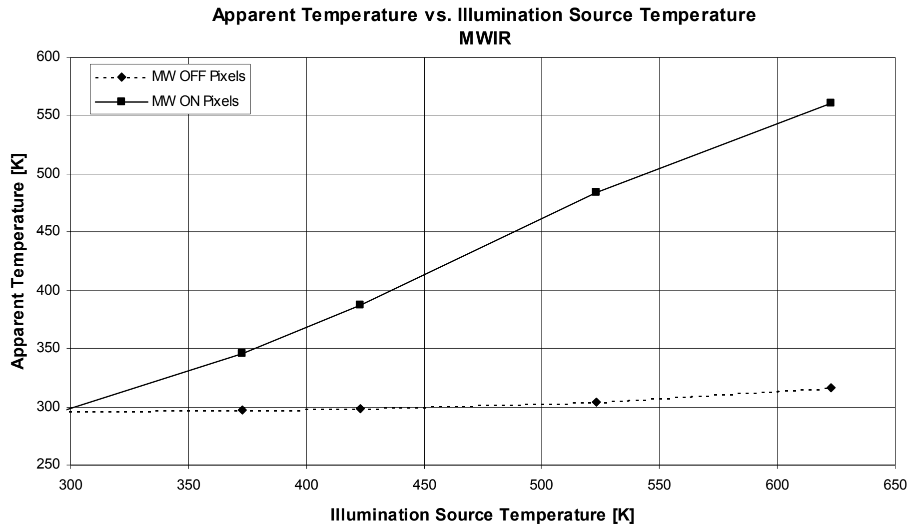

Figure 17: MWIR Apparent Temperature vs. Illumination Source Temperature

Figure 18 shows the maximum and minimum apparent temperature of a MAPS operating in the LWIR band as a function of illumination source temperature. Note that the data is shown for two modes of operation - normal mode (NM) and special mode (SM). The special mode of operation is a proprietary technique of operating the DMD which can be used to significantly enhance the contrast in the LWIR band under certain conditions.

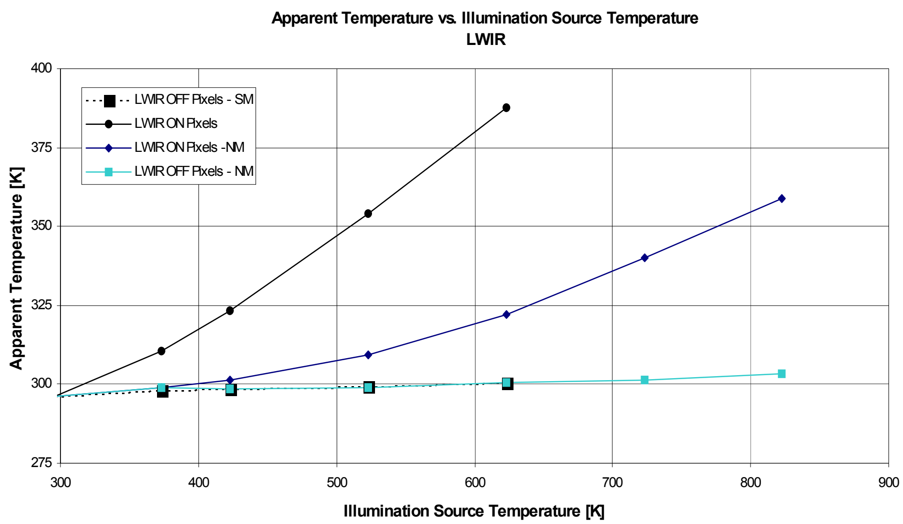

Figure 18: LWIR Apparent Temperature vs. Illumination Source Temperature

5.3 Contrast

Contrast ratio is an important performance parameter for any type of spatial light modulator. It is defined as the ratio of the ON and OFF state difference radiances, each obtained by subtracting the surrounding's radiance from the relevant projected radiance. By definition, the contrast ratio is unity when the projector is OFF, and may assume an infinite value provided that the OFF state projected radiance matches that from the designated surroundings. [1] The equation for contrast ratio is:

$$ContrastRatio = \frac{L_{on} - L_{Background}}{L_{Off} - L_{Background}}$$

The contrast ratio of the MAPS in the MWIR has been consistently tested to be >250:1. The contrast ratio of the MAPS in the LWIR has been consistently tested to be >15:1 in normal mode and >110:1 in special mode.

5.4 Sample Images

Three sample images collected from two MWIR MAPS and one LWIR MAPS are shown in Figures 19, 20, and 21. The image in Figure 19 was projected by a SVGA MWIR MAPS operating at 6 bits of amplitude resolution and collected by a 320x240 InSb FPA camera. The image in Figure 20 was projected by an XGA MWIR MAPS operating at 7 bits of amplitude resolution and collected by a 256x256 InSb FPA camera. The image in Figure 21 was projected by a SVGA LWIR MAPS operating at 8 bits of amplitude resolution and collected by a 320x240 uncooled bolometer array camera.

Figure 19: MWIR SVGA Collected by 320x256 InSb FPA camera

Figure 20: MWIR XGA Collected by 256x256 InSb FPA camera

Figure 21: LWIR SVGA Collected by 320x240 Uncooled Bolometer Array Camera

7.0 ACKNOWLEDGMENTS

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8.0 REFERENCES

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9.0 TRADEMARKS