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ALP: universal DMD controller for metrology and testing

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ABSTRACT

The paper presents a current development in the field of high-speed spatial light modulators. The Digital Micromirror Device (DMD) developed and produced by Texas Instruments Inc. (TI) stimulated new approaches in photonics. Recently, TI introduced the *Discovery* general purpose chipset to support new business areas in addition to the mainstream application of DMD technology in digital projection. ViALUX developed the *ALP* parallel interface controller board as a *Discovery 1100* accessory for high speed micromirror operation. *ALP (Accessory Light Modulator Package)* has been designed for use in optical metrology but is widely open for numerous applications. It allows for rapid launch into new DMD applications and can be integrated instantly into existing systems or may initiate new developments. The paper describes both, the general hardware architecture and the software concept of the new high-speed controller solution. Binary and gray-value patterns of variable bit-depth can be pre-loaded to on-board SDRAM via USB and transferred to DMD at high speed (up to 6900 XGA frames per second). Three examples are to illustrate how the approach enables advanced applications of DMD technology in metrology, testing and beyond.

Keywords: spatial light modulator, digital micromirror device, DMD, DLP, optical 3D measurement, fringe projection, confocal microscopy, Shack-Hartmann sensor

1. INTRODUCTION

Spatial light modulators are opto-electronic systems that consist in a number of independently controlled elements used to generate defined spatial modulations of the light field. Providing both, high number of elements and low switching time, they have become an important new element for the design of optical systems in general and of optical measuring systems in particular. So-called microdisplays are produced by two main technologies: liquid-crystal arrays (LCD) or micro-electro-mechanical systems (MEMS). The LCD technology is not preferred for high-speed applications because of the limited response time of the liquid-crystal elements. The most successful MEMS solution in the field of microdisplays is the Digital Micromirror Device[1] (DMD) built by Texas Instruments Inc. (TI). In the past, DMD applications were focused on large sales volume devices as business projectors and home cinema. Recently, however, TI introduced the *Discovery* general purpose DMD light modulator chipset for the development of new business opportunities[2]. *Discovery* provides to the user direct control of the micromirror array by a high-speed parallel interface so that the potential of the Double Data Rate DMD can be exhausted for any application. However, cost and time consuming development of a corresponding high-speed control unit has been required.

In the following sections, a controller solution is described that simplifies the *Discovery 1100* integration significantly maintaining flexibility and performance for a certain class of applications, many of them are typical for optical metrology. After an introduction into the hard- and software architecture that was chosen to meet the objectives of high-speed operation, the paper is to highlight some of the applications in optical metrology the authors can imagine, three examples are described. Various improvements are expected in 3D shape measurement using fringe projection. Confocal microscopy will benefit from the high frame rate that can be achieved. Flexible diffraction gratings are immediately available serving for a variety of applications, e.g. a Shack-Hartmann sensor that can be adapted to the given wavefront.

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2. OBJECTIVES

The system design was driven by a typical need in metrology: displaying and recording a sequence of patterns in a short time for further evaluation on a PC. In the past, graphic display electronics (DVI or analog RGB) has been frequently adopted as DMD interface for optical metrology due to the availability of commercial components[3,4]. The pattern recording device is usually a high-speed CCD or CMOS camera and consequently the PCI bus of the PC is mainly occupied by the frame grabber or digital camera adapter (typically CameraLink or FireWire). Therefore, to reduce the PCI load, the microdisplay should not be simultaneously controlled via the PC graphics interface. Also high frame rates (> 60 fps) and variable bit-depths are not feasible with a standard graphics controller. On the other hand, metrology applications are frequently based upon a fixed sequence of patterns that has to be loaded into the microdisplay for each measurement. Correspondingly, the following objectives have been set for the development of the new *ALP* interface board:

- sequences of patterns (binary or gray) can be pre-loaded and stored on the DMD controller board
- on-board sequences can be transferred to the micromirror array and displayed at maximum DMD speed
- DMD and camera operation can be exactly synchronized
- time-average gray level patterns of various bit-depths can be generated
- pulse-width modulation (PWM) is implemented with a minimum of micromirror movements
- standard PC interface enables mobile laptop solutions

3. SYSTEM ARCHITECTURE

3.1 Hardware concept

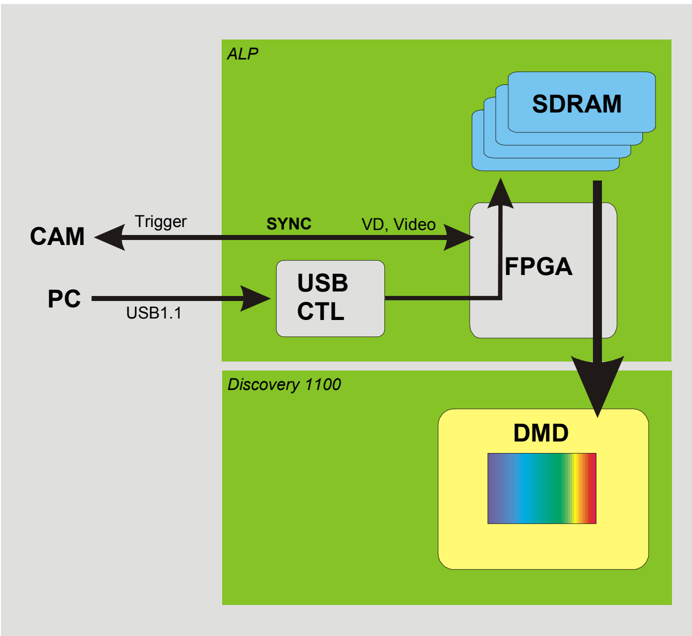

Fig. 1: Components and data flow in the ALP system

The hardware concept chosen is based upon the universal serial bus USB on the PC side and the parallel interface on the DMD side.

A turnkey *ALP* package for DMD applications consists of a *Discovery 1100* board and an *ALP* board. The *Discovery* board carries the digital micromirror device and the driver electronics for mirror motion control. *Discovery* provides a high-speed parallel data interface to the *ALP* board that is plugged on.

The main *ALP* components are sketched in Figure 1:

- USB controller as PC link
- on-board SDRAM for data storage
- FPGA for high-speed data control

The DMD data access is organized in *sequences* of XGA frames. Each sequence is a series of patterns that is to be displayed at high rates, all patterns in a sequence have the same bit-depth and different sequences may be defined and loaded at the same time. The SDRAM on-board memory stores the XGA pattern sequences that are pre-loaded for subsequent high-speed display. An USB controller realizes the PC connection for both, data transfer and sequence display control. The maximum storage capacity is 2 GBit, the pattern sequence memory is not mapped to the PC.

The heart of the *ALP* controller board is a *Virtex-II* FPGA linking the on-board SDRAM pattern sequence memory with the DMD data lines of the *Discovery* parallel interface. In addition, the FPGA logic design includes all the timing and control facilities necessary to load and switch the DMD according to the user-defined properties of the sequence selected for display. The FPGA has been programmed to realize the PWM display of gray level images with flexible bit-depth. Both, sequence pre-loading from PC to SDRAM and sequence display from SDRAM to DMD are implemented to run in parallel for two different sequences, i.e. a new sequence may be loaded while another sequence is displaying.

Comprehensive trigger opportunities yield precise synchronization between the DMD operation and external devices (recording camera, light source etc.). The *ALP* can be set-up to run as master or slave and corresponding TTL triggers are generated or accepted depending on the *ALP* mode. An additional signal extraction circuit is implemented that simplifies synchronization with any analogue CCD camera, the composite video signal (Video + HD/VD) can directly serve as trigger input in this operation mode. This synchronisation is supported on picture level within the sequence. When running in slave mode, the *ALP* will wait for the first trigger or VD to start with the first picture of a sequence display, and after the picture is completed *ALP* waits for the next trigger to display the second picture etc.

The *ALP* timing is controlled by a set of parameters in such a way that high flexibility results for the specific user application without degradation of the high-speed operation of the whole system. The main timing parameters that can be chosen by the user are summarized in Table 1.

Table 1: Selected ALP timing control parameters

IlluminateTime	duration of the display of one picture in the sequence
PictureTime	time between the start of two consecutive pictures according to the following relation: < *PictureTime* > = < *IlluminateTime* > + < *DarkTime* >

ALPTriggerMode	master mode	The ALP operation is controlled by internal timing, a trigger signal is sent out for any picture displayed
	slave mode	The ALP operation is controlled by external trigger, the next picture in a sequence is displayed after the detection of an external input trigger (TTL, VD or composite-video) signal

TriggerDelay	delay of the display with respect to the trigger output (*master mode*)
TriggerPulsewidth	length of the TTL trigger signal, the maximum value is < *PictureTime* >
VdDelay	delay of the display with respect to the VD input signal (*slave mode*)

Table 2: ALP image formats (all XGA)

bitplanes per picture	gray values generated	single image on-board RAM size [kbyte]
1	binary	96
2	4	192
3	8	288
4	16	384
5	32	480
6	64	576
7	128	672
8	256	768
9	512	864
10	1024	960
11	2048	1056
12	4096	1152
13	8192	1248
14	16384	1344
15	32768	1440
16	65536	1536

The *ALP* supports a series of image formats. While the frame size is fixed to the 1024x768 XGA format of the *Discovery 1100* DMD, the bit-depth can be freely chosen for any individual *ALP* sequence. To cover the needs in optical metrology and beyond, the system accepts all formats in the range of 1...16 bits per pixel, i.e. from a binary pattern up to an image with 65536 gray levels. A complete list of gray resolution and corresponding memory consumption is given in Table 2. The impact of image format on the maximum display rate will be discussed in section 4.

It is worth mentioning, that the precise synchronization of the DMD PWM sequence display with a time-averaging detector device, e.g. the camera, guarantees a perfect linear generation of light intensity distributions with up to 16 bit resolution. To the author's knowledge, a comparable spatial light modulator system has not been available so far.

3.2 Software concept

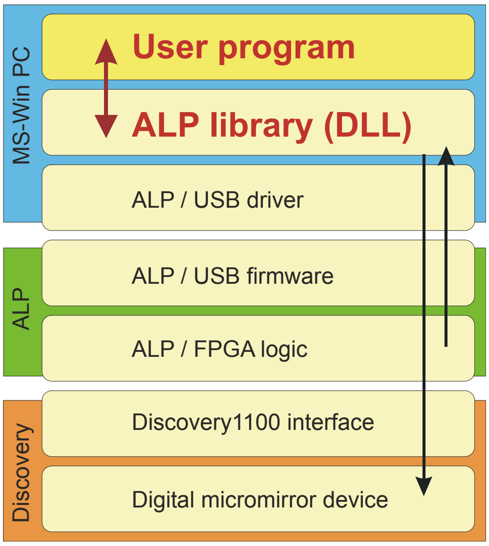

Figure 2: ALP programming interface

The aim of the *ALP* software concept is to provide the user a maximum of flexibility at a minimum of effort that is required for the implementation of an application or for setting up just an experiment. Therefore, the whole DMD programming interface is brought to PC level and is put into a DLL library that can be involved in any C/C++ application running under *Microsoft Windows® 2000 or Windows® XP* operating systems.

In general terms, the desired high-speed DMD operations are coded as a pattern sequence with certain timing parameters added. The patterns can be generated by the user program or loaded from disk on PC level and the sequences are then pre-loaded to the on-board *ALP* memory. The display process can be finally initiated either by software or by a trigger signal put directly onto an FPGA line of the *ALP* for highest timing accuracy. Figure 2 shows the complete control flow in the *ALP* system from the user code to the micromirrors.

The ALP function library encapsulates all functionality required to control the pattern sequence data loading and the high-speed display of the sequences. It communicates with the *ALP* driver to transfer image sequence data via the USB interface into the on-board SRDAM or to read and write control registers in the FPGA controller section. Finally, the FPGA logic controls the communication with the Discovery 1100 chip set and thus the DMD mirrors. All layers below the library are of increasing complexity (driver/firmware/logic). However, they are transparent to the user so that DMD programming is significantly simplified and application development is accelerated.

4. PERFORMANCE ACHIEVED

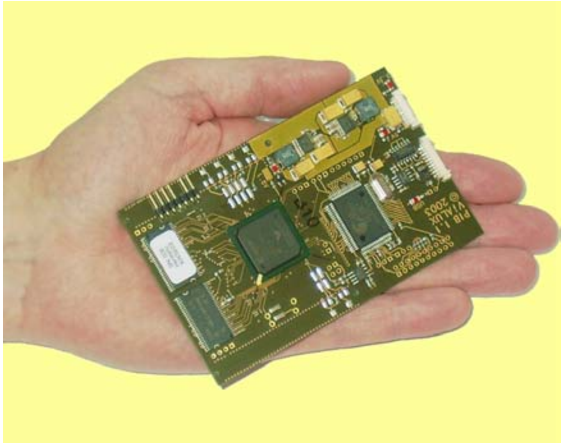

Figure 3: ALP controller board

The hard- and software concept described in the previous section has been implemented in a controller board shown in Figure 3. Care was taken to minimize the overall footprint of the system and four signal layers with a 1 mm line pitch provide the density needed for the high-speed section of the board. The *ALP* PCB measures 110×71 mm and plugs directly on the *Discovery 1100* board.

The SDRAM capacity installed may vary from 64 to 256 Mbyte. The corresponding number of XGA patterns that can be stored in the on-board memory depends upon the gray value resolution that is chosen for the sequence. Table 3 gives an overview for selected image formats. The number of biplanes can be different for any of the sequences loaded to the *ALP*.

The pre-loading of patterns via the USB1.1 interface takes 80 ms per binary XGA frame or biplane, respectively. The high-speed display of the on-board sequences takes advantage of the parallel interface provided by the Double Data Rate DMD *Discovery 1100* chipset. According to the concept described in Section 3.1, the user can freely control the display timing due to the individual requirements. Also, the timing may vary between different pattern sequences. Of course, there are upper limits of the frame rates that can be achieved; the maximum *ALP* ratings are shown in Table 3.

Table 3: ALP parameters

bitplanes per picture	max. # of on-board pictures	max. display rate XGA frames / s
1	2730	6918
2	1365	3334
3	910	2215
4	682	1451
5	546	936
6	455	557
7	390	308
8	341	162
10	273	145
12	227	38
14	195	9
16	170	2

It might be important to note that the PWM algorithm implemented is optimized for time-averaging detectors rather than for human eyes, i.e. that the mirror movement (duty cycle) is minimized increasing the overall efficiency of the micromirror device. High linearity of the output and low noise are key objectives that have been met. Also, if required, the pattern in the digital micromirror device can be „frozen“ for up to 10 seconds by defining a binary pattern sequence and a very low frame rate. This may improve the performance of DMD applications that need a longer illumination time with a completely stable optical system at maximum efficiency and at maximum contrast. At this point it becomes very clear that the solution described differs significantly from any DMD control via standard graphic interfaces.

5. APPLICATION POTENTIAL IN METROLOGY

5.1 Three-dimensional shape measurement

There are various techniques for the measurement of three-dimensional shape by optical means [5]. One method with a high potential for industrial use is the full-field triangulation by structured light projection, also well-known as fringe projection technique. The basic principle is the identification of object points by a pattern projected onto the surface and observed by a camera under a different perspective view, see Fig.4 (left). A number of practical approaches for the implementation of this principle have been investigated in detail during the last decade and there is a clear trend towards the multiple frame methods where not a single picture but a *series of patterns* is taken to obtain any 3D shape with high reliability and accuracy. To give a number, about 10 frames are typical and well-enough for the automatic evaluation of any 3D shape [6,7], for specific in-line testing applications with a priori knowledge of the shape, three frames might be sufficient.

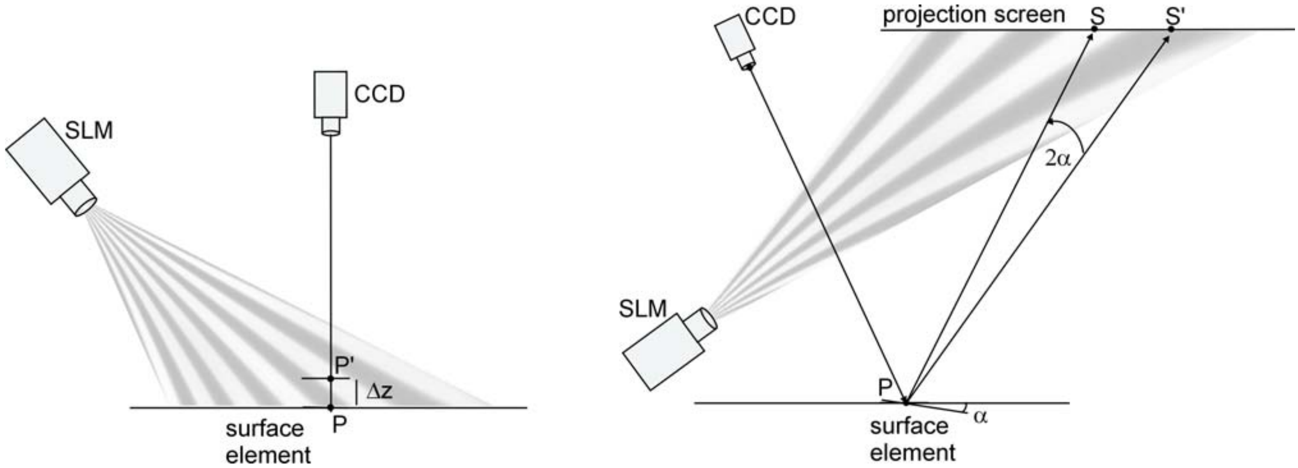

Figure 4: 3D testing arrangements: fringe projection (left) and reflective technique (right)

The pictures recorded belong to different projected patterns for the same object at the same view, i.e. the object is not allowed to move with respect to camera or projector device during measurement. This might cause trouble for a certain class of tasks, especially with living objects, if e.g. the human face is to be recorded three-dimensionally. Also industrial in-line inspection frequently calls for „snap-shot“ measuring systems that do not require objects to be still and enable very short recording time. Finally, the range of application for 3D metrology can be significantly increased if powerful hand-held measuring devices become reality.

Similar equipment is used in reflective arrangements where the shiny object acts as a mirror and the series of patterns produced on a flat screen is seen by the camera after reflection from the object surface [8].

Measuring time is the crucial point in all that cases, i.e. the time needed to project a series of patterns and to record it by the camera. High-speed cameras are available in general. In particular, affordable CMOS devices are on the market now that realize 200-500 full frames per second or even more at reduced resolution. In other words, a full sequence of 10 patterns can be acquired within 1/50 s – a convenient time for hand-held systems or living objects. In comparison, the standard graphic interface for DMD control provides 10 frames in 1/6 s [9]. Color-encoding is proposed [10] to accelerate the measurement by a factor of three; however, the object surface color has to be taken into account for this method. Obviously, the bottleneck up to now was the lack of high-speed, precisely synchronized pattern projection. *Discovery 1100* and *ALP* are powerful tools to overcome these current limitations [11].

5.2 Wavefront sensing

The Shack-Hartmann sensor principle is widely used for characterizing optical wave-fronts in laser technology, astronomical equipment or non-contacting surface measurements. Basically, the sensor consists of a microlens array and a camera, where the lens array divides the wavefront in sub-apertures that are focused according to the individual angle of incidence of the wavefront at each sub-aperture. An array of focused spots is detected by the camera and the wavefront shape can be reconstructed from the position of each spot.

Diffractive optical elements (Fresnel lenses) are frequently used to form the microlens array. Recently, flexible and adaptive arrangements have been introduced in order to improve the sensor performance for steep slopes and strong curvatures of the wavefront [12,13,14]. The authors improved the dynamic range as well as the measurement accuracy of Shack-Hartmann sensors using LCD-based spatial light modulators to realize the diffractive lens patterns. The digital micromirror device offers additional opportunities with respect to the wide range of wavelengths, from UV to IR, and the high contrast of the diffractive lens lets.

5.3 Confocal Microscopy

The method of confocal imaging through a z-scanning microscope yields 3D surface topography data and a very effective version of this principle is realized in camera based devices. A spinning Nipkow disc is frequently used there in order to do the time-multiplexing for the pin-holes that cover the field of view during a camera frame. Recent work has been reported that introduces the digital micromirror device as a well suited and flexible alternative for the Nipkow disk [15,16,17]. The spinning aperture disk can be replaced by a dynamic pattern of sub-apertures that change rapidly. Up to now, the performance of the proposed DMD-based confocal microscope suffers from the low switching time of a microdisplay controlled via standard graphics adapters. The *ALP* performance is likely to eliminate this drawback. The binary patterns that represent the „moving“ subapertures are well know a priori, they can be loaded into the *ALP* SDRAM and then switched by high-speed control, the camera recording is not affected by this operation because the PCI bus is kept completely free.

CONCLUSIONS

Aiming at use in optical metrology, a new accessory component, the *ALP* controller board, has been built for the high-speed control of the TI Digital Micromirror Device. Any *Windows*® application program can define and pre-load sequences of XGA patterns (binary or up to 16-bit gray) to the *ALP* board using the C/C++ library. The on-board sequences are then transferred to the micromirror array via FPGA logic and displayed at maximum DMD speed (up to 6900 fps) realizing a minimum of mirror switches in the PWM mode. DMD and optional camera operation is exactly synchronized so that the time-average gray level patterns are perfectly linear. The USB interface simplifies DMD applications and enables mobile laptop solutions.

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