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MULTIFOCAL NEAR-EYE DISPLAY: TIMING OF OPTICAL DIFFUSER ELEMENTS AND SYNCHRONIZATION TO DLP-BASED PROJECTION MICROUNIT

R. Ruskuls[1], K. Slics[1], R. Ozolins[2], R. Fenuks[3],
E. Linina[3*], K. Osmanis[1], I. Osmanis[1]

[1] Hansamatrix Innovations Ltd., 1 Ziedleju Str., Marupe, LV-2167, LATVIA
[2] Hansamatrix Ventspils Ltd., 1 Ventspils Augsto tehnoloģiju parks,
Ventspils, LV-3602, LATVIA
[3] LightSpace Technologies, 1 Ziedleju Str., Marupe, LV-2167, LATVIA
*e-mail: elza.linina@lightspace3d.com

The paper present the key technical details of a multifocal near-eye display concept. Along with an overview of the basic architecture, a particular implementation that utilises a digital light processing (DLP®) based spatial light modulator as the image source is provided in the study. The investigated approach involves the utilisation of a small-scale volumetric screen formed by a stack of fast-switching optical diffuser elements based on liquid crystal technology. The volumetric screen is illuminated by a rear image projector. To make the whole system functional and small, the challenge lies within the development of integrated control board for the projection modules as well as the synchronization of the DLP® projector image output to the optical diffuser element switching-cycle.

The main difficulty of the development process is accounting for the peculiarities of in-house developed diffuser elements and the off-the-shelf DLP®, which is the main focus of this paper. There is no direct control over the full set of DLP® operational parameters, an indirect method for adjusting frame dead time is proposed, showing that an increase in dead time close to 0.3 ms (from 0.3 ms to 0.6 ms in the particular setup) can be achieved without significantly sacrificing image colour depth or quality. Tuneable dead time mitigates the limitations set by the non-instantaneous switching of liquid crystal diffuser elements as longer dead times allow for the removal of image bleeding between frames.

Keywords*: Digital light processing, digital micromirror device, liquid crystal diffuser, multifocal display, near-eye display.*

1. INTRODUCTION

For decades it has been claimed that virtual reality (VR) and augmented reality (AR) are slowly but surely entering everyday life. Even though its use in everyday life is currently far from what had been imagined in the 1980s, in 2020 AR was removed from the Gartner hype cycle as, according to Gartner, AR has matured so rapidly that it is no longer considered an "emerging technology" [1].

Currently the predominant form of AR is achieved through the use of various smart device-based applications. Through the camera of a smartphone or a tablet, one can visualize interior and exterior design, virtually try on clothing, explore different hairstyle options and make-up products. In the professional front – a medical professional can overlay x-ray or tomography imaging data directly onto a patient's body to more easily interpret visual information. While useful, looking though a screen of a handheld smart device is not convenient nor is it immersive. An alternative to handheld video see-through devices is an optical see-through head-mounted display (OST HMD) commonly referred to as smart glasses [2]. OST HMDs present additional challenges in creating an immersive experience, but improvements in electronic components and computing power over the past years have made such devices more feasible.

For certain applications it is important to be able to view content close-up, but the conventional way of creating a 3D image is relaying on binocular disparity – providing each eye with a different 2D image that is processed together by the brain into a 3D scene [3]. For objects close to the viewer (up to 1 m from the viewer) this presents a problem – the human visual system relies on both vergence and accommodation to determine the distance to an object. In the case of a near-eye display with a single focal plane these cues do not match and this gives rise to a phenomenon known as the vergence-accommodation conflict (VAC) that can cause blurred vision (out-of-focus image), eyestrain, visual fatigue and in some cases even nausea [4], [5]. A straight-forward approach to mitigating the adverse effects of VAC is providing the eye with additional focal planes for content at different depths. This is the type of OST HMD architecture pursued and developed at *LightSpace Technologies* [6].

This paper examines the challenges of integrating the operation of a custom method for creating virtual focal planes (by using liquid crystal switchable diffusers) and an off-the-shelf solution for projecting an image (a DLP microprojection unit provided by *Texas Instruments Inc.*).

2. MATERIALS AND METHODS

Instead of showing image on a single focal plane, multifocal display architecture approximates depth with multiple focal planes, for which either multiple displays are required or a single display can be, for example, mechanically swept. This allows for the splitting of a 3D scene into "slices" of which each is shown on a corresponding focal plane. Consequently, the utilization of even just a few focal planes can substantially mitigate the VAC.

In the case of the proposed display

architecture by *LightSpace Technologies*, it is formed by a stack of liquid-crystal (LC) based optical diffuser elements and a rear microprojector. Essentially it is a tiny volumetric display which is imaged through an eyepiece – thus resulting in multiple virtual focus planes. The optical diffuser elements forming the stack have two distinct optical states – highly transparent and highly scattering. The transparent state virtually does not interfere with the incident visible light due to very low haze values (<0.2 %). In the highly light-scattering state, the LC element acts as an image receiving screen. Thus, a single projection unit (considering image-forming module for one eye) is sufficient to address all image planes time-sequentially. Essentially, the architecture is entirely solid-state and the "scanning" of the projection volume is executed electronically. Key optical characteristics of optical diffuser elements for applications in HMDs have been described previously [7].

Rapid diffuser element switching (<0.8 ms) has been shown previously on a direct-view volumetric display having 20 discrete depth planes [8]. Thus, the challenging component concerning a near-eye display is a microprojector that is as small as possible but with a high enough image refresh rate to support multiple focal planes. For this purpose, the digital light processing (DLP) technology from *Texas Instruments Inc.* was found to be the most fitting. In particular, the *DLP2010* digital micromirror device (DMD) was chosen as the spatial light modulator. This DMD offers an 854×480-pixel resolution within a 0.2" diagonal active region and with a small overall package. The issue design-wise in relation to the high level of integration and overall miniaturization is the bounding condition of dedicated digital light processing controllers (DLPCs) – in particular we chose DLPC3435 due to support of a 240 Hz frame rate. With a 240 Hz overall frame rate it is clear that the highest number of focal planes attainable is four, due to the requirement of at least a 60 Hz volumetric image refresh rate (which for most people should not result in noticeable achromatic flicker [9], [10]).

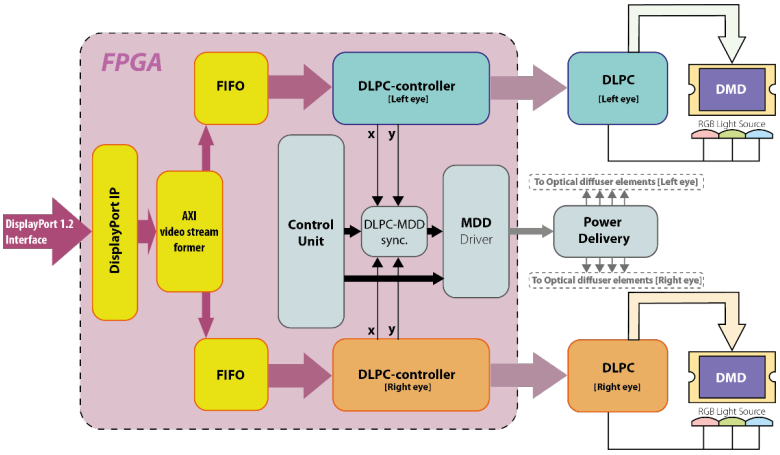

Fig. 1. Simplified block diagram of the integrated control module developed for an OST HMD produced at LightSpace Technologies.

The DLPC3435 is a proprietary DLP controller; thus, there is virtually no control options over internal processes or the way it interacts with the spatial light modulator (a digital micromirror device). The only freedom accessible by the designer is con-

figuration of the frame rate, white balance adjustments and image orientation. Thus, it is of crucial importance, when tuning the multifocal prototype near-eye display device, to take into account specifics of the DLPC3435 operation and ensure the image output is well synchronized with the operation and switching of the optical diffuser elements.

The simplified block diagram of the integrated control module is depicted in Fig. 1. The data processing and main functionality are ensured by a *field-programmable gate array* (FPGA). The data host is a connected computer device, which interfaces through a USB-C and uses a DisplayPort 1.2 interface. The FPGA handles DisplayPort data stream decoding and formation of an *advanced extensible interface* (AXI) video stream. The DisplayPort data are split into two AXI video streams for each eye, which are buffered within a *First In-First Out* (FIFO) buffer of low capacity. Further the FIFO buffer is connected to a DLPC controller (symmetrical for both eyes). The DLPC controller reformats data to feed a steady video stream over digital video graphics array (VGA) to DLPC (more precisely the DLPC3435), which takes in a 240 Hz video feed. Furthermore, the DLPC controller incorporates a counter – to identify the image row and the pixel in each row transmitted. These X-Y coordinates are sent to DLPC-*multi diffuser driver* (MDD) synchronization module. The DLPC-MDD sync module calculates the order of diffuser elements to be activated from the received X-Y coordinates. The DLPC-MDD sync. module further is coupled to the MDD driver and sends the diffuser ID (to be activated) and enable pulse, whereas MDD driver then configures the diffuser driving circuitry to energize or discharge the given diffuser element. In parallel to switching of diffuser elements, a constant 240 Hz video feed is provided to corresponding DLPC modules, which by proprietary inner workings then output this information to DMD spatial light modulator as well as synchronously control the RGB light-source of the micro projection unit. The image output by DLPC-DMD obviously is carried out field-sequentially.

The DLPC controller was modelled to provide coordinates of the pixel row and number to enable synchronization between the DLPC driven projector images and switching of diffuser elements.

To know the synchronization constants, a test setup was assembled (Fig. 4). Two channels of a multi-channel oscilloscope were used to register output from the microprojector and optical switching of optical diffuser element. The switching of optical diffuser element was monitored by a photodetector, which captured light from a constant white LED emitter. In contrast, the second photodetector monitors projector output directly.

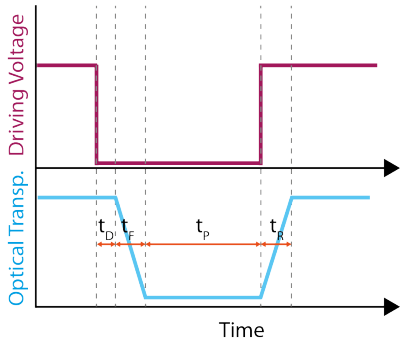

Fig. 2. Optical transparency of an optical diffuser element in response to an electric driving signal Transparency shown over visible spectrum (420 nm –700 nm). Distinct response times – t_D (delay time); t_F (fall time); t_P (projection time); t_R (rise time).

It must be noted that the switching cycle of an optical diffuser element has four distinct segments (Fig. 2). In the energized state, the diffuser element is transparent and does not interact with the incident light (Fig. 3a). Upon the removal of voltage, the first segment t_D is when the optical transparency remains unchanged. Typically, this period is in the range of 200–400 microseconds [11]. Then, the local field starts to collapse and the diffuser enters a transition from transparent to light-scattering state. This period is denoted by a fall time t_F, which is followed by the highly light-scattering state, in which the diffuser enters "screen-mode" – this is denoted by t_P and corresponds to a period, in which the projected image can be visualized (Fig. 3b). After the projection period t_p, an external electric field is applied again, the diffuser is energized and in response to the electric field undergoes transition from screen-mode to transparent mode – this is denoted as t_R or rise time.

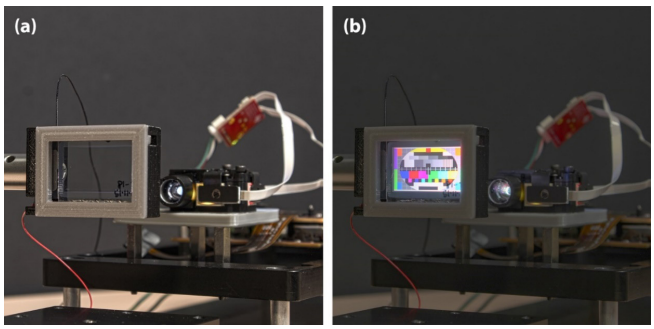

Fig. 3. Electrically driven optical diffuser element (acting as a switchable screen) in the transparent (a) and diffuse (b) state.

When considering image output, it is necessary to show the whole frame within the projection period of a diffuser element when it is in the highly light-scattering state. In case of utilised DLPC controller, it can be hard to achieve precise alignment of the projection and switching of diffuser element. Partly, this is also associated to the transitional periods – t_F and t_R, which are not instantaneous, and inability to explicitly control dead time of the projection unit, as this is predetermined.

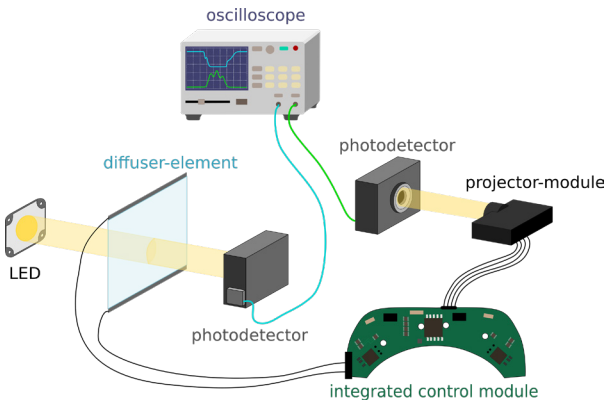

Fig. 4. Experimental setup for determining the frame output timeslot with respect to diffuser switching.

With the setup of Fig. 4, different colour frames were projected by the projector – white –, and primary-coloured frames (red, green, blue). Thus, it was established how the DLPC deals with image output. In the first part, we looked only at the output of the projector, which was receiving a feed of 240 Hz video stream, which contained a pattern of repeating white screen for a duration of one frame followed by three black-screen (blank) frames. Similar pattern was repeated using primary colours – red, green and blue.

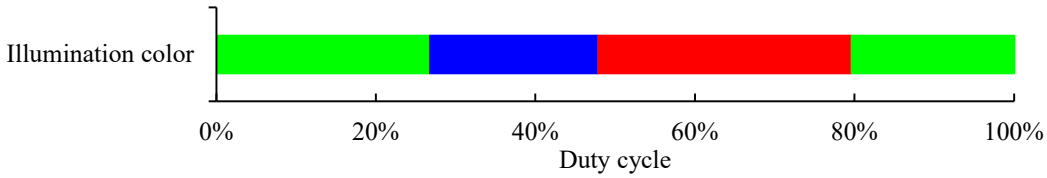

Fig. 5. DMD matrix illumination colour during one frame (dead time excluded) for a neutral white-point (zero offsets).

To reduce the appearance of colour artefacts, the DLPC3435 does not simply allocate one timeslot for displaying each colour. Even though the duty cycles are retained close to the nominal RGB 30,50,20 for a neutral white-point, the green LED imaging period is split into two sub-periods and displayed at the beginning and end of each frame (Fig. 5).

Typically, the different shades of a colour with a DMD are achieved by some combination of pulse width modulation (PWM) and light source intensity modulation (LSIM) [12]. This is due to the physical limitations of how fast a micromirror can switch from one state to another and be addressed again (usually about 20–30 μs [13]); thus, a true 8-bit colour depth at a 60 Hz volumetric refresh rate (corresponding to 240 Hz projector refresh rate) cannot be achieved by PWM alone, as this provides only about 4.1 ms for all three colours that each need to be further split into 255 shade gradations. However, the particular implementation of how shades are achieved is quite complex, as peculiarities of human visual system are often exploited to achieve a better perceived image, such as adjusting the colour output through colour dithering (this can be executed both spatially and temporally).

As previously mentioned, the dead time of an imaging period cannot be tuned directly; however, it could be expected that changing the green encoded bit value might provide an indirect approach – if the bit-planes on either end of the green imaging period can be identified and later removed by adjusting the input image, this might allow for longer dead time (however, at the cost of colour depth). With the increased dead time, the synchronization of diffuser elements to the imaging period can then be more easily adjusted by tuning the operation of the MDD.

3. RESULTS AND DISCUSSION

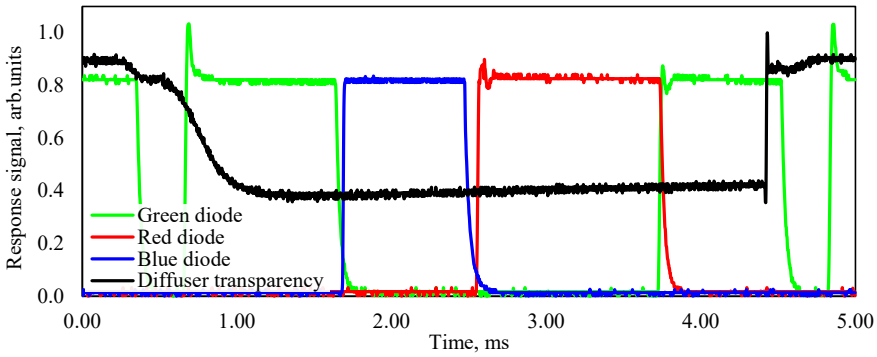

Fig. 6. Detector diode response to light reflected from the micromirror matrix, combined from primary colour (RGB) measurements, with diffuser element transparency as a reference.

In order to fine-tune the timings for switching the optical diffuser elements, a simple experimental setup was used to probe the operation of the DLPC3435 and DLP2010 combination.

First, it can be noted that the DLP2010 does not utilise LSIM – a purely white frame RGB(255;255;255) does not show any periods associated with lower light emitting diode intensity (Fig. 6). The required colour for low luminance shades that cannot be obtained through PWM alone is achieved through colour dithering.

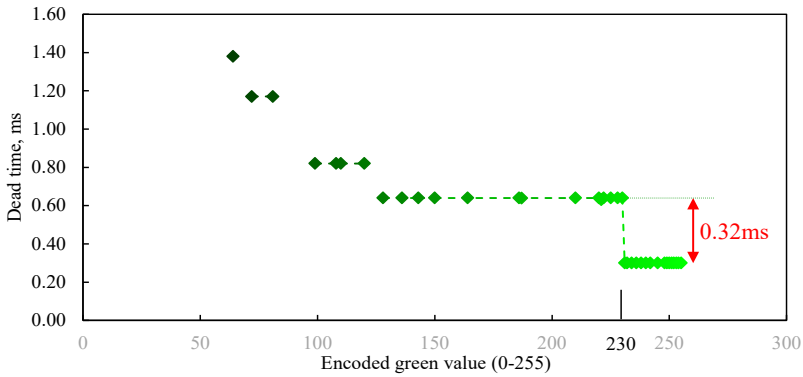

Fig. 7. Dependence of dead time on encoded green value passed to the DMD. A sharp step-wise decrease can be observed below encoded value of 230.

Next, as can be seen in Fig. 7, the total dead time increases in a step-wise fashion as the green encoded value is decreased to 230. Below this value the dead time plateaus – the illumination timeslots associated with these bits lay somewhere in the middle part of green illumination period (Fig. 8). Thus, the dead time remains unchanged until a significant decrease in green value is necessary and the illumination timeslots directly before or after the dead time are removed.

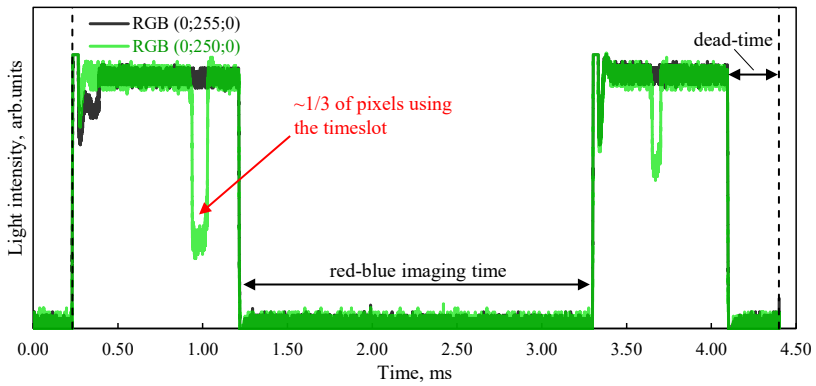

Fig. 8. Comparison of RGB(0;255;0) and RGB(0;250;0) encoded colour outputs from the DMD as detected by the setup in Fig. 4. Dashed lines indicate the beginning and end of one frame.

Notably, the illumination timeslots at the beginning and end of a frame imaging period are not used ever if the green value is below 230. This implies a non-straightforward bit mapping that is not a simple least-significant-bit placed at the beginning or end of an imaging period. What is more – often a given timeslot is used by some fraction of the pixels as can be seen by reduction in light intensity measured by the photodetector (Fig. 8); this, once again, hints that spatial colour dithering is applied to an image before it is displayed by the DMD.

The dead time required for feasibly switching the existing diffuser elements is about 0.6 ms (limited by the rise and fall times of a single diffuser element). As can be seen – by decreasing the encoded green value of each pixel below 230 on the software side, the obtained dead time is increased from 0.3 ms to about 0.64 ms, which is just enough to successfully project images without having to rework the available hardware.

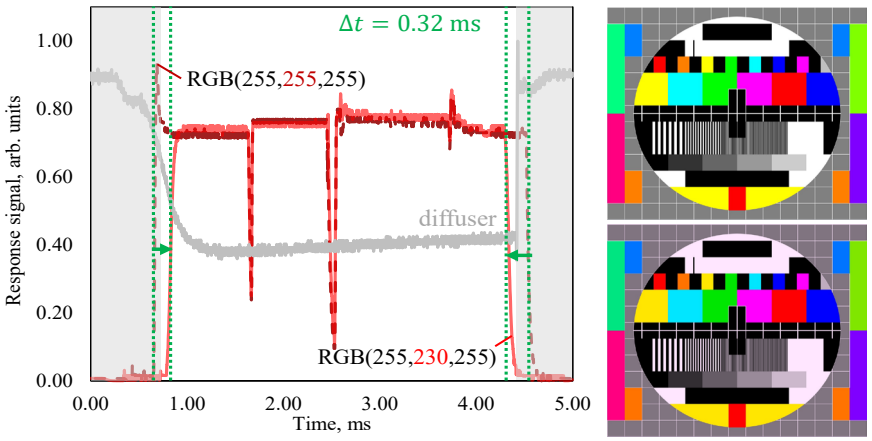

Fig. 9. Left: detector diode response to light reflected from the micromirror matrix, comparison of different green components. Diffuser transparency as a timing reference. An increase in dead time can be observed, achieved through removing green illumination timeslots at both the beginning and the end of a frame. Right: two colour calibration test patterns with full green component (top) and adjusted green component (bottom). A characteristic red tint can be seen.

Whilst the image output on a single diffuser element is well-behaved and reduction of encoded green value allows for the removal of colour bleeding between different image depth planes through increased dead time, the addition of multiple focal planes produces a visual artefact similar to laser speckling. We speculate that this unwanted visual effect, which becomes evident in the case of a multifocal display architecture, is associated with temporal dithering produced internally by the DLPC chipset.

4. CONCLUSIONS

In the paper, we have demonstrated the possible application of DLP technology in creating a multifocal OST HMD. The limited tunability of off-the-shelf DLPCs can be overcome by adjusting the input parameters of an image (namely, the encoded bit value for the green colour channel); however, this comes at a cost of reduced colour depth. One of the major advantages of DMD-based projection systems is the elimination of colour switching artefacts. However, colour dithering for accurate colour perception becomes a challenge. When the images are output time-sequentially on different image depth planes at a lower frame rate, the image quality suffers due to visual artefacts similar to speckling.

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