Locally Switchable 2D and 3D Displays

In a 2D/3D switchable display, the 2D and 3D regions can be defined independently on screen on a per-pixel, per-timeframe basis.

by **Sung Lee, Abe Mammen, Xiaojun Zhang, Andre Krebbers, and David Fattal**

AS THE 3D CONTENT CREATION ECOSYSTEM MATURES, it is causing a resurgence of autostereoscopic (glasses-free) 3D displays.[1] They represent a compelling alternative to head-mounted displays, delivering immersive 3D experiences without the encumbrance of eyewear. Recently, they have been adopted in a host of familiar devices, including tablets,[2] laptops,[3,4] and monitors. A key feature of these new-generation displays is 2D/3D switchability,[5] enabling the device to function in its original "2D" state with negligible performance degradation, especially resolution. People can deploy the device in this normal 2D mode for routine functions (such as checking emails or browsing the web) or the 3D mode for watching 3D movies or engaging in 3D immersive games.

To date, 2D/3D switchability in these commercial devices has been "global" in the sense that the whole display switches from one state to another. A known shortcoming of this method is the poor rendering of text or high-resolution graphics in 3D mode, precluding the embedding of 3D content in normal web pages or making flat user-interface (UI) elements in 3D games look pixelated. Many original equipment manufacturers consider local switchability a must in their future roadmap. Local segmented switchability is another option,[6,7] but it frequently adds significant complexity and only partially addresses the problem.

Thus here, we demonstrate (to our knowledge) the first fully "local" 2D/3D switchable display, where the 2D and 3D region can be independently defined on screen on a per-pixel, per-timeframe basis. The approach is based on Leia Inc.'s core Diffractive Lightfield Backlight (DLB) technology and consists of lighting up an LCD display with a temporally multiplexed dual 2D/3D backlighting system.

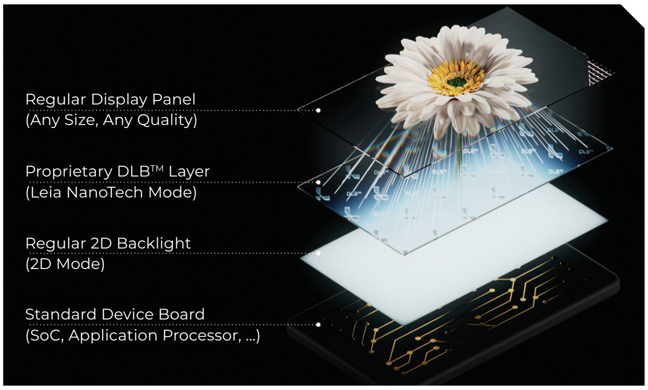


Fig. 1. Diffractive Lightfield Backlight configuration for a switchable 2D/3D display.

Diffractive Lightfield Backlight

DLB is a technique developed at HP Labs[8] and commercialized by Leia Inc. A nanostructured light-guiding DLB layer is introduced in a regular LCD display stack between the standard backlight (BL) unit (such as edge-lit, backlit, or miniLED) and the active panel (**Fig. 1**).

In 2D operation, the regular BL illuminates the LCD panel through the inert DLB layer, resulting in a full-resolution, full-brightness image. Residual reflections and diffractions from the DLB layer are typically between 5 to 10 percent.

In 3D operation, the DLB layer is edge-lit by a dedicated LED system and scatters guided light upward only, resulting in highly directional light to propagate through each LCD pixel.

Switching between 2D and 3D modes is as fast as turning on and off an array of LEDs, typically a few microseconds. The system is compatible with a scheme where a fast LCD panel would display a

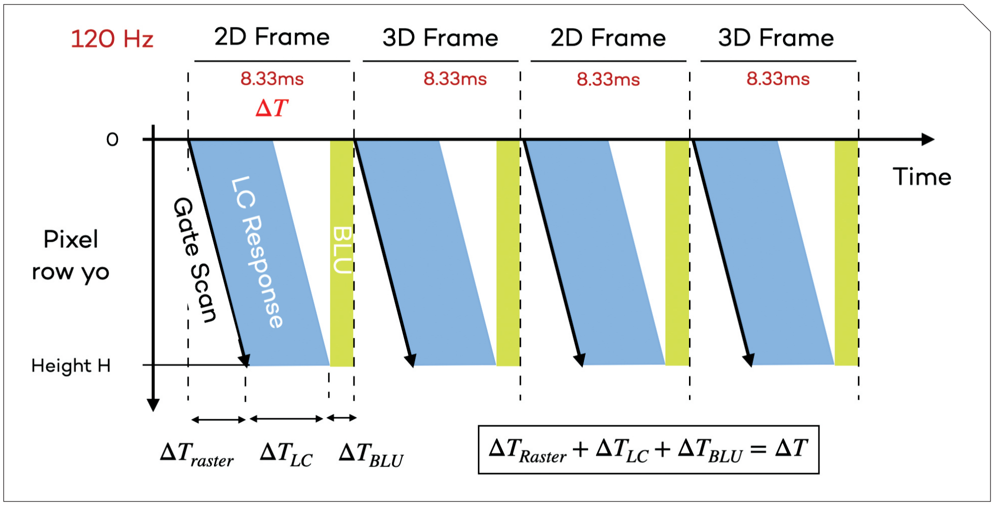


Fig. 2.

Timing diagram for a temporally multiplexed DLB 2D/3D system.

sequence of 2D and 3D images in synchronization with an alternating 2D/3D illumination scheme.

Temporally Multiplexed DLB

In designing a temporally multiplexed DLB system, controlled timing between the dual BL and the LCD 2D/3D image sequence is critical. Note that the response time of the liquid crystal is finite, and the pixels are updated in a rasterizing fashion. If not careful, a mismatch between illumination and images will occur, resulting in regions of the screen with blurry 3D or low-resolution 2D.

Fig. 2 shows a proper timing sequence for BL and LCD assuming a refresh rate of 120 Hz (with a cycle time of ΔT~8.33 ms). Once the LCD finishes a raster cycle (ΔT_{raster}) for the 2D image and the liquid crystal of the last row of pixels settles (ΔT_{LC}), the 2D BL flashes for a short duration (ΔT_{BLU}). The sequence repeats, but this time the LCD rasterizes the 3D image and the 3D BL flashes. The diagram shows the straightforward process, and no 2D/3D cross-contamination will occur as long as:

$$\Delta T_{raster} + \Delta T_{LC} + \Delta T_{BLU} < \Delta T. \quad (1)$$

The scheme would work flawlessly with timings listed in the first row of **Table 1**, which is well within commercially available current LC technology.[9] For this proof of concept, we use off-the-shelf technology with slightly slower timings, which still demonstrates the local 2D/3D feature in a wide (and adjustable) portion of the screen.

Switching Things Up: Experimental System

For the experimental demonstration, we used an off-the-shelf 4K ultrahigh definition (UHD), 15.6-inch, 120-Hz LCD display from AUO with a head-tracked DLB 2D/3D system, providing 2D images at a resolution of 3,840 × 2,160 and 3D images at an effective resolution of about 1,920 × 1,080. **Table 1** (second row) shows the relevant timings. Even though the display raster time is on the long side, we still operate the BL and display sequences at a rate of 120 Hz and are able to define a very wide portion of the screen with clean synchronization between the BL and image.

The combined 2D/3D cycle takes 16.67 ms to complete, so the local 2D/3D content is experienced at an effective refresh rate of 60 Hz.

Our default timing for the LED strobe is during the vertical black (VB) period immediately following the end of the display raster for both 2D and 3D images. To achieve this timing, the time control (TCON) 120-Hz STV1 test point output is connected to the BL driving board. After displaying a 2D image, the 2D LED is strobed; after a 3D image, the 3D LED is strobed, creating a temporally multiplexed hybrid 2D/3D image at 60 Hz.

For the 15.6-inch panel, the vertical sync (VS) period is ~430 us, which is ~5 percent of the 120-Hz frame cycle and 2.5 percent of the 60-Hz combined image cycle (**Fig. 3**). To conserve the same brightness as the normal display, the peak current of the strobing LEDs ideally should be boosted by a factor of 40, from 30 mA to ~1,200 mA.

For the purpose of this demo, we modified the BL driving scheme to drive the LEDs close to their maximum current spec of 200 mA using a TI LP8866 200 mA device, with the maximum duty cycles set at 10 percent. The microcontroller unit (MCU) includes a BL safety control function to protect the LED in the event of an overcurrent issue.

Selecting an LED driving device that can support 60-Hz pulse width modulation (PWM) presents a challenge, as most LED driver devices do not support frequencies below 100 Hz. The direct PWM mode with a 60-Hz PWM is used, which is below the minimum PWM requirement specification of 100 Hz for the timing Texas Instrument device. However, this did not result in any significant failure on the LED power line, and there was no LED flickering observed when driving 60 Hz for 2D and 3D LED strobes. To address the observed 2D/3D frame timing offset in the software, a field

ΔT	RASTER	LC	BLU	RASTER + LC + BLU
Ideal case	3.93	4.0	0.4	8.33
Experiment	7.9	6.6	0.5	15

Table 1.

Time-multiplexed DLB system timings (in milliseconds).*
*BLU: backlight unit; LC: liquid crystal.

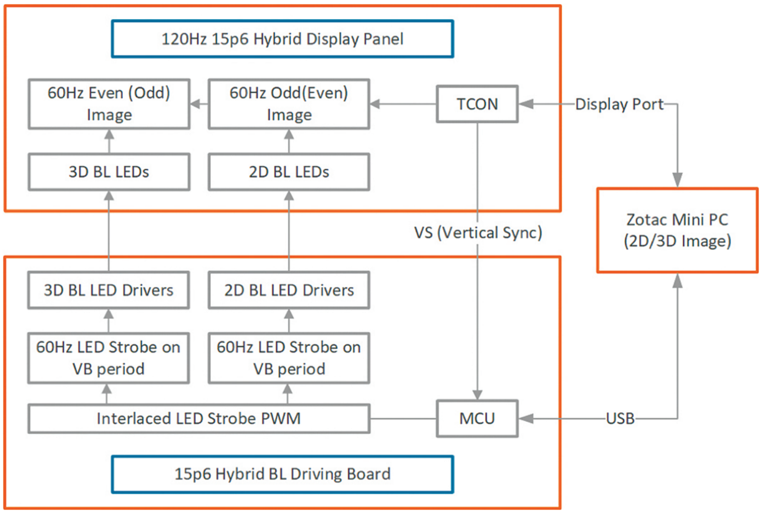


Fig. 3.

A 15.6-inch hybrid 2D/3D system. BL: backlight; TCON: time control; VB: vertical black.

programmable gate array (FPGA; as either a single or two display port [1DP to 2DP]) was built for the experiment to confirm a hardware 2D/3D frame sync, with a confirmation of no offset issue with the FPGA.

Content Driving and Co-existence

In the system, we want 2D and 3D content to co-exist within the same display frame. Furthermore, we do not want to enforce restrictions with respect to placement of 2D and 3D regions, to account for both cases where they might intersect each other or be independent. This provides maximum flexibility from a content authoring perspective while preserving image fidelity. Our goal was to render high-quality 2D text within overlapped 3D regions as well as in independent regions, such as window toolbars, buttons, and hover regions.

To match the switching DLB technology interleaving independent 2D and 3D frames at a 120-Hz refresh rate, a content rendering system was developed to precisely deliver alternating 2D and 3D rendered frames every 16.33 milliseconds.

SWITCHING AS A SOFTWARE MODEL

A hybrid application supports two rendering threads that operate autonomously; a presentation manager (PM) joins their respective outputs so the interleaved switching drives either a single display port or two display ports. Each thread uses a set of back buffers to render into, and the PM sequences these for precise switching. In addition, each rendering thread can parallelize and balance its workload through the allocated set of back buffers. From a software perspective, the PM manages the switching in the background, while the main application focuses on the task of rendering—UI control. The PM exposes a set of methods for buffer management and synchronization for application conformation.

Table 2.

Buffer allocation for hybrid displays.*
*B: buffer; F: frame.

	B0	B1	B2	B3	B4	B5	B6	B7
F0	2D F0							
F1					3D F0			
F2		2D F1						
F3						3D F1		
F4			2D F2					
F5							3D F2	
F6				2D F3				
F7								3D F3

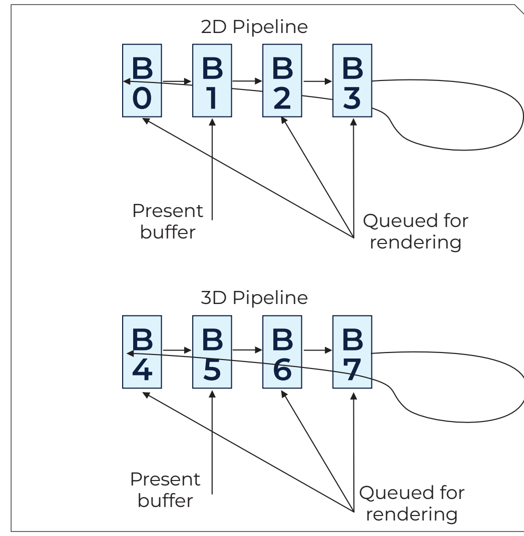


Fig. 4.

Swap buffer chain.

SWAPPING VIA AN INTERLEAVING APPROACH

To prevent screen tearing and decouple rendering from the display scan, graphics systems use back buffers and its associated set of application program interfaces (APIs) to control the output of high-performance rendering applications. For this hybrid system, we allocate a pool of back buffers that are assigned to the respective 2D/3D renderers. When a "swap" request is made, these buffers are advanced in an interleaved fashion (**Table 2**). For a four back buffer organization, 2D is allocated buffers B0, B1, B2, and B3, while 3D receives buffers B4, B5, B6, and B7. The interleaving sequence swaps buffers in this order: B0, B4, B1, B5, B2, B6, B3, B7, and so on. **Table 2** describes the allocation of buffers for hybrid displays.

To achieve maximum overlap and parallelism for this example of four back buffers per rendering channel, while one buffer is being used to drive the output display, the other buffers are available to render into. To precisely present buffers to the respective panel BL control, the 2D/3D renderers have a maximum of 16.33 milliseconds to complete its task. By having additional buffers, each pipe-

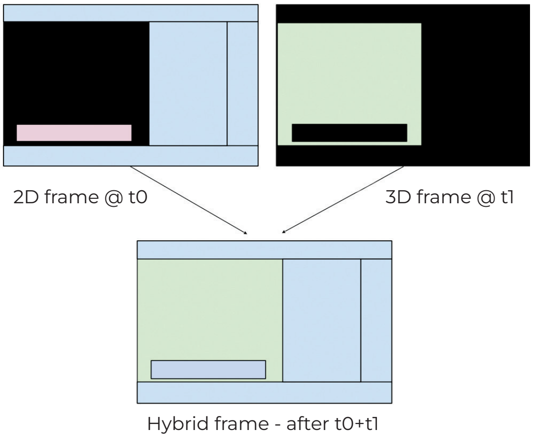


Fig. 5.

Interleaved image composition with arbitrary 2D/3D pixel assignment.

line can locally maximize its time slot. **Fig. 4** shows B2 (frame 2) can complete in 10 milliseconds, thus allowing B3 (frame 3) to now have 16.33 + (16.33-10) = 22.33 milliseconds to complete.

If a back buffer has not completed rendering before it is needed for a switch, the previous buffer in the chain continues as the "current present buffer." In **Fig. 4**, if B2 is not ready in time, the display is scanned out of buffer B1. While this is normal behavior for a single pipeline swap buffer system, there is added complexity in this interleaved system, as we have two independent sets of buffers within a single swap chain layout.

BUFFER PIXEL LAYOUT

In support of Leia's dual BL system, the 2D/3D frame buffer contents have their respective regions set to black, which is rendered by the other buffer. In **Fig. 5**, 2D content is present on the top, right, and bottom. The 3D content is present in the middle left, with a shared region of 2D (e.g., text, banner, and ticker) overlaid on top of the 3D.

Results

Fig. 6 shows a photograph of the display screen in local 2D/3D mode. The 3D video content is shown from YouTube in a small window with a "clean" 2D UI around it. Both the 3D effect of the content in the window and the legibility of the small font text in the UI region are excellent.

To showcase the obvious gain of resolution in the 2D zone, **Fig. 7** shows the same small font text content rendered in the 2D region and 3D region, respectively. The text is indecipherable in the 3D zone but perfectly legible in the 2D zone.

Fig. 6.

Local 2D/3D display unit featuring a page from YouTube with 3D video and 2D user interface. The 3D portion is rendered in head-tracked stereo.

To further quantify the performance of the display in hybrid mode, we performed the following luminance measurements in nine locations on the screen (top, middle, bottom and left, center, right):

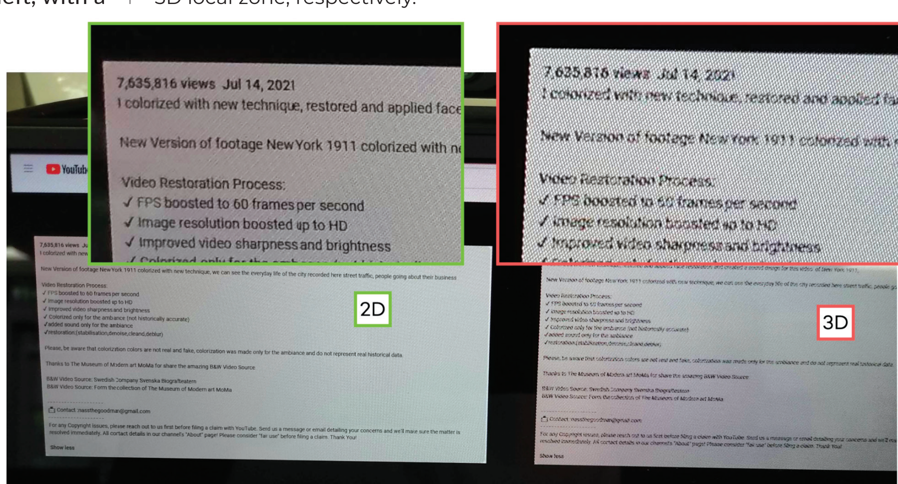
(L_{2D2D}) 2D BL strobing, 3D BL off, white 2D image, black 3D image
(L_{3D3D}) 2D BL off, 3D BL strobing, black 2D image, white 3D image
(L_{3D2D}) 2D BL off, 3D BL strobing, white 2D image, black 3D image
(L_{2D3D}) 2D BL strobing, 3D BL off, black 2D image, white 3D image

We first adjusted the BL driving currents to equalize L_{2D2D}, and L_{3D3D} then defines 2D-to-3D and 3D-to-2D cross-talk metrics as $C_{2D3D} = L_{2D3D}/L_{3D3D}$ and $C_{3D2D} = L_{3D2D}/L_{2D2D}$, respectively.

The results, reported in **Table 3**, show that good separation between

Fig. 7.

Local 2D/3D unit displaying the same small font text in the 2D local zone and 3D local zone, respectively.



	LEFT	CENTER	RIGHT
Top	4%/7%	4%/7%	4%/7%
Middle	5%/8%	5%/8%	5%/8%
Bottom	45%/50%	45%/50%	45%/50%

Table 3.

Cross-talk metrics C_{2D3D}/C_{3D2D}*
*The metrics are measured at different locations of the display under the backlight strobing timing of Fig. 2.

image and cross-illumination are achieved in the top and middle part of the display and start degrading toward the bottom because of the limited raster speed of the display.

By adjusting the strobing timing to be earlier or later than that of **Fig. 2**, the "good" hybrid region could be adjusted at will (to cover a wide middle portion of the display or the bottom of the display).

Summary

As we usher in a seamless era of 3D content creation, 2D/3D switchability is the chief mechanism to enable this technology to flourish. With that in mind, we used a dual BL Leia display operated in strobing mode to demonstrate per pixel, per temporal frame control over 2D or 3D display output. A liquid crystal response time below a 4-ms LED strobing time of half a millisecond and a display raster rate below 4 ms would lead to good hybrid performance across the display. Although the display's raster time was slower (~8 ms), it still showed good performance with hybrid operation in approximately two-thirds of the display area. This work paves the way to fully local 2D/3D displays using widely available LCD technology on the market today.

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Andre Krebbers is the chief operations officer at Leia and has been instrumental in leading the industrialization and supply chain management of the company's 3D lightfield displays. Over the years, he has worked across the consumer electronics, automotive, and mobile display markets. He received a BSC in chemical engineering from NHL Hogeschool. He can be reached at *andre.krebbers@leiainc.com*.

David Fattal co-founded Leia in 2014 and currently serves as the company's CTO. Fattal has over 200 granted patents and was featured on the 2013 list of MIT Technology Review's Innovators under 35. His pioneering work on diffractive lightfield backlighting earned him the French National Order of Merit in 2014. He received a PhD in physics from Stanford University. He can be reached at *david.fattal@leiainc.com*.