2^{16} shades of gray: high bit-depth projection using light intensity control

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Abstract: Projectors create grayscale images by outputting a series of bitplanes or binary images within a short time period. While this technique works well for projecting low bit-depth (8-bit) images, it becomes infeasible for high bit-depth (say, 16-bit) projection — a capability that is increasingly desirable in many applications including cinemas and gaming. Existing designs for high bit-depth projection rely on multiple spatial light modulators and, as a consequence, their costs and complexities are usually far beyond the average consumer. In this paper, we describe a technique for high bit-depth projection using a single light modulator by adopting intensity-modulated light sources. With the proposed light intensity modulation, we show that the number of bitplanes required to achieve a desired bit-depth can be dramatically reduced — by marginally trading-off the brightness of the projected image. Hence, given a spatial light modulator of a fixed bandwidth for projecting bitplanes, the proposed projector design can achieve higher bit-depth as well as expanded color gamut while achieving the same video framerate as conventional projectors. The proposed design involves a minor modification to traditional projector designs, namely intensity modulation of the light sources, and hence, can be adopted widely by both traditional low bit-depth projectors and modern high dynamic-range projectors. Finally, we present a hardware prototype to showcase and validate the performance of the proposed design.

OCIS codes: (120.2040) Displays; (110.1758) Computational imaging; (110.2945) Illumination design.

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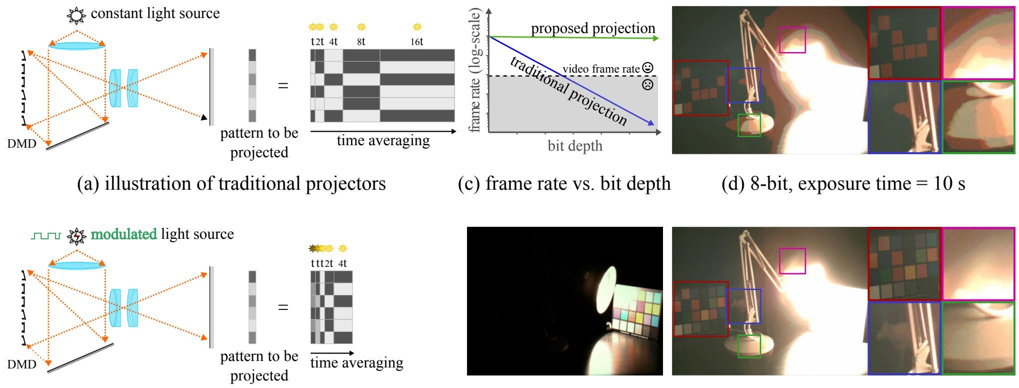
1. Introduction

Many projectors operate by spatially attenuating a light source using a digital micromirror device (DMD) or a liquid crystal-on silicon (LCoS) device. In a DMD-based projector, binary images or bitplanes are projected in rapid succession; these binary images are subsequently "averaged" by the human eye due the persistence of vision to create a grayscale image, as shown in Fig. 1(a). The intensity observed at a pixel in the projected image is simply proportional to number of bitplanes the pixel is illuminated in.

DMD-based projection at sufficiently high visual detail, in terms of bit-depth and color gamut, and frame rate, in terms of number of frames/images projected per second, requires a large bandwidth in terms of number of bitplanes per second. Yet, there are fundamental physical limitations that make high-bandwidth bitplane-projection difficult, if not impossible. One such limitation is the minimum time required to switch the micromirror array from one configuration to another. Suppose that the minimum switching time is 2 μs. To project a single RGB image at 8 bits per color channel (8-bit), we would require at least $(2^8-1)\times3\times2 = 1530$ μs; this allows for projection at 653 frames per second (fps). If we instead wanted to project a RGB image at high bit-depth, 16 bits per color channel (16-bit), then we would require at least 0.4 seconds to project a single image; this results in projection at 2.5 fps. The exponentially decreasing frame rate with respect to bit-depth, as shown in Fig. 1(c), clearly indicates a need for a design that can scale to the demands of modern applications.

In this paper, we propose a novel design for high bit-depth projection. Our key innovation is in the form of light intensity control, i.e., compared to traditional designs which use a light source with a constant intensity, our projector design utilizes a intensity-modulated light source with a co-designed light-intensity coding scheme. This additional degree of freedom in the light source enables a broader design space where grayscale intensities can be created not just by blocking light using a DMD but also via intensity control of the light source. As a consequence, the proposed design can achieve a desired intensity resolution using fewer projected bitplanes as compared to the traditional projectors, thereby enabling high bit-depth projection without a severe loss in the frame rate of the projector. We can also easily support the use of multiple color light sources to produce more vivid colors, wider color gamut, and higher brightness — all without sacrificing bit depth or frame rate. Finally, even when we are only interested in traditional



(a) illustration of traditional projectors (c) frame rate vs. bit depth (d) 8-bit, exposure time = 10 s

(b) illustration of the proposed projector (e) proposed, 16-bit, exposure time = 0.2 s (f) proposed, 16-bit, exposure time = 10 s

Fig. 1. The proposed high bit-depth projector (b) has 16 bits per color channel (16-bit). The proposed projector uses intensity-modulated light source instead of one with constant intensity as that used in traditional 8 bits per color channel (8-bit) projectors (a). (c) The additional degree of freedom allows the proposed projector to achieve high bit-depth without losing frame rate. (e) and (f) are the photographs with two different exposure times of the same image projected by proposed 16-bit projector. (d) is a photograph of the image projected in 8-bit. As can be seen, image details like the checkerboard and the bull in the dark are reproduced in the proposed 16-bit projection, and fewer quantization errors can be spotted in (f) than in (d). We denote the minimum DMD switching time by t.

levels of bit-depth projection, the proposed design reduces the operating speed of the DMD, which could potentially lower device costs.

Intensity modulation often raises the concern that the resulting projected image would be dimmer than what we would be able to achieve with the light source intensity set constant to its maximum value. This is because projectors often have to compete with ambient light sources and hence, any loss of brightness is undesirable. In part, this is one of the reasons that intensity-modulation is considered undesirable for achieving high bit-depth projection in prior literature [1]. In fact, a naive implementation of light-intensity modulation, as in [1], does result in severe reduction in the maximum brightness of the projected images. To address this, we propose a novel light-intensity coding scheme that provides high bit-depth projection with only a marginal reduction in maximum brightness; for the specifications relevant to this paper (16-bit RGB projection using current DMDs), the loss of brightness is typically 4%.

The proposed design requires a relatively small modification to existing projectors in the form of additional circuitry for enabling light intensity control. For LED sources, the intensity modulation can often be performed efficiently, without loss of energy, using pulse-width modulation. In all, this makes the proposed technology widely adoptable in most existing projector designs, including traditional 8-bit projectors and modern designs that enjoy high contrast ratio [2–4].

We make the following contributions.

- *Light intensity control.* We propose a novel approach to increasing the bit depth of a projector by introducing intensity coding at light source. This light intensity coding is easily achieved using pulse-width modulation with little loss of energy and little additional complexity to traditional projector designs.

- *Code design.* We chart out a design space that allows us to tradeoff the maximum brightness of the projected scene towards obtaining higher bit-depth, frame rate and/or wider color gamut. This design space is enabled by a novel hybrid code design that mixes light intensity control with traditional pulse-width modulation. A key observation is that for marginal loss in brightness (often, less than 4%) we can enable higher bit-depth and color gamut.

- *Hardware prototype.* We present a hardware prototype to showcase and validate the performance of our projector.

The benefit of high bit-depth is often only perceptible by the human visual system when the projector has high contrast ratio as well as a high-power light source. While the proposed design does not increase the contrast ratio of a projector, it can easily be incorporated into existing methods that increase contrast ratio using novel prism designs [2,3] or using a light modulator to spatially reallocate light [4].

2. Background

2.1. Bit depth and dynamic range

The output of a projector can be described by two factors — dynamic range and bit depth. Dynamic range determines the range of the projected light intensity and is measured by contrast ratio, which is the ratio between the highest possible light intensity and the lowest intensity, *e.g.*, $C:1$. Bit depth, on the other hand, describes the intensity resolution and is usually represented in bits. For example, a 8-bit color channel means that its intensity range is uniformly divided into $2^8 = 256$ levels.

For a projector with a contrast ratio of C and n-bit intensity resolution, if we denote the intensity of j-th level by I_j, where $j \in [0, 2^n - 1]$, we can represent the ratio between the j-th intensity level I_j and the highest intensity $I_{\max}$ (or I_{2^n-1}) as

$$\frac{I_j}{I_{\max}} = \frac{j}{2^n-1} + \frac{1}{C} \times \frac{2^n-1-j}{2^n-1}, \quad \forall j \in [0, 2^n-1], \tag{1}$$

where the first term represents the ratio of intended intensity outputs and the second term represents the undesired outputs due to limited contrast ratio. Therefore, the intensity difference between two adjacent levels is

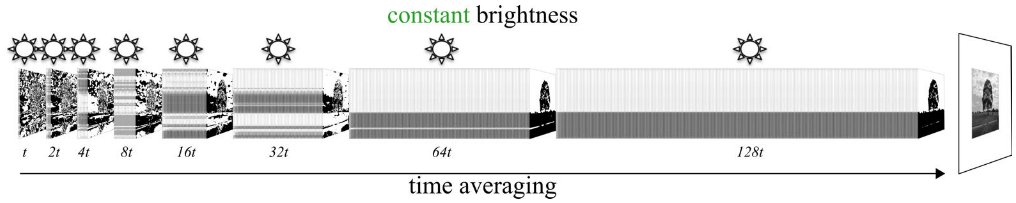
$$I_{j+1} - I_j = \frac{1}{2^n-1}\left(1 - \frac{1}{C}\right) I_{\max} := \frac{1}{2^n-1} I_{\text{eq}},\ \forall j \in [0, 2^n-2], \tag{2}$$

where $I_{\text{eq}} = (1-1/C)I_{\max}$ is the equivalent intensity range. It can be seen that larger C allows us to utilize larger portion of $I_{\max}$, and increasing n allows subtle intensity differences (*i.e.*, image details) to be reproduced.

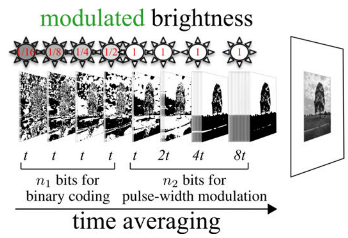
Contrast ratio of projectors is usually determined by their optical designs. For example, novel prism designs reduce stray light in the projectors and boost contrast ratio to $2^{15.5}:1$ [2, 3]; light reallocation methods [4–7] redistribute light energies from darker regions in the images to the brighter ones and thereby directly increase contrast ratio of the projected image. As these projector designs have achieved contrast ratios higher than $2^{15}:1$, in this paper, we propose a high bit-depth projection technique that can easily achieve bit depth of 16 bits, which fully utilizes the high dynamic-range of modern projector designs.

2.2. DMD-based projection

A DMD-based projector is typically composed of a light source, a DMD, and a projection lens. The light source constantly shines light onto the micromirrors on the DMD, and the projection lens maps each micromirror to a pixel on the screen. Each micromirror has two states — when turned on, it directs light toward its corresponding pixel; when turned off, it directs light away from the projection lens (usually toward a light collector in the projector.) Although the on-off operation allows simple micro-electromechanical design, the binary characteristic can only generate black-and-white images at any instance.



(a) An illustration for projecting a 8-bit, grayscale image with PWM projection.



(b) An illustration for projecting a 8-bit, grayscale image with the proposed HLM projection.

Fig. 2. Comparison between the PWM projection and proposed hybrid light modulated projection. By incorporating light intensity control, the proposed method greatly reduces frame time.

There are a few constraints underlying the operation of a DMD. There is a minimum amount of time required to transition from one micromirror configuration to another — a limitation that is imposed due to data transmission to the DMD. Typically, data transmission bus operates at 64 bits and at 400 MHz. Hence, for a DMD with 1024×768 micromirrors, it takes $\frac{1024\times768}{64\times400} = 30.72\ \mu$s to transmit a full frame binary image. The data transmission rates can be even larger for higher resolution DMDs. One approach to reduce the transmission time is to group micromirrors in blocks that are synchronized and change states jointly. This approach sacrifices spatial homogeneity within individual binary image similar to the trade-off between global and rolling shutters in cameras. Further, the electronics associated with block-based control is significantly complicated which makes the device expensive. However, the gains provided by this approach are often significant and it can reduce the latency between bitplanes to as little as 2 μs for a 1024×768 array. For simplicity of analysis, we adopt an ideal DMD model that sends out bitplanes with minimum exposure time of 2 μs.

2.3. Pulse-width modulated projection

DMD projectors uses pulse-width modulation (PWM) at each pixel (micromirror) to project a frame. Each micromirror encodes the binary representation of the desired intensity value at the corresponding pixel. Given a chosen minimum bitplane exposure time t ($t \geq 2\ \mu$s in our example), an n-bit grayscale image is produced by sequentially projecting n bitplanes (from the least significant bit (LSB) to the most significant bit), with exposure time $t, 2t, \ldots, 2^{n-1}t\ \mu$s. Hence, the total time required to project one image is $(2^n-1)t\ \mu$s. This concept is illustrated in Fig. 2(a) and the analytical formulas for frame rate and contrast ratio are listed in Fig. 3. One simple method to project color images is repeating this process for each color channel and, hence, for a three color image, the total time to project a single image is $3(2^n-1)t\ \mu$s. The exponential dependence on intensity resolution, given in terms of number of bits n, reflects the lack of scalability of traditional designs, as demonstrated by some examples in Fig. 4. It is worth mentioning that more sophisticated color projection can be achieved by the technique called gamut reshaping [8], which fully utilizes the wider color gamut of modern light sources like

	pulse-width modulation (PWM)	binary light modulation (BLM)	hybrid light modulation (HLM)
frame rate	$\frac{f}{2^n - 1}$	$\frac{f}{n}$	$\frac{f}{n_1 + 2^{n_2} - 1}$
rel. brightness	1	$\frac{2}{n}\left(1 - 2^{-n}\right)$	$\frac{1 - 2^{-n}}{1 + (n_1 - 1)\times 2^{-n_2}}$
contrast ratio	$C : 1$	$C : 1$	$C : 1$
power efficiency (avg. power to project the LSB)	$\frac{p}{2^n - 1}$	$\frac{p}{2^n - 1}$	$\frac{p}{2^n - 1}$

Fig. 3. Expressions of frame rate, relative brightness, contrast ratio, and power efficiency of n-bit grayscale projection. We denote the minimum bitplane switching time by $\frac{1}{f}$ and the power to project a frame with maximum brightness by p.

	PWM		BLM		HLM	
bit depth (bits)	frame rate	rel. brightness	frame rate	rel. brightness	frame rate	rel. brightness
12	40.7 fps	1	555 fps	0.17	50.5 fps	0.97
14	10 fps	1	476 fps	0.14	49.8 fps	0.96
16	2.5 fps	1	416 fps	0.12	49.0 fps	0.94

Fig. 4. Examples of frame rate and relative brightness of RGB projection. For PWM, we set $t = 2$ μs, which is achieved with the help of block-based micromirror control. For BLM and HLM, we set $t = 50$ μs as that used in our prototype (without the help of block-based micromirror control). We assign $n_2 = 7$ for HLM.

LEDs and lasers to increase color fidelity and maximum brightness of a projector. Since the gamut reshaping is achieved by temporally modulating the on-duration of the light sources, to increase the bit depth, the total frame exposure time still needs to be increased exponentially in term of n.

2.4. Light-intensity modulated projection

Intensity-modulated light sources can be used to break the exponential relationship between total frame exposure time and intensity resolution. One approach of light-modulated projection is to perform binary-coding on the light source *intensity* [1]. Suppose that we seek to project an n-bit grayscale image. We project n bitplanes, each of a fixed exposure period t. Each bitplane is associated with a different light source intensity; specifically, the i-th bitplane is illuminated with the light intensity set at $2^{-(n-i)}$ times its maximum intensity. Hence, the light source intensity takes the values $2^{-(n-1)}, 2^{-(n-2)}, \ldots, 2^{-1}, 1$. Each micromirror is coded with the n-bit binary representation of the intensity that we seek to project at its corresponding pixel. We refer to this scheme as binary light modulation (BLM).

A key feature of BLM is that it can project an n-bit image using n bitplanes with the same exposure time and hence, the total time to project an image is simply nt μs. This linear dependence of exposure time on n is in sharp contrast to traditional PWM projection whose exposure time is exponential in n, as compared in Fig. 3 and Fig. 4. Hence, we can achieve very high frame rate as well as intensity resolution in BLM. However, BLM has one critical disadvantage — a significant reduction in the brightness of the projected image. The maximum brightness of BLM can be derived by

$$L^b_{\max} = \frac{1}{n}\left(1 + \frac{1}{2} + \cdots + \frac{1}{2^{n-1}}\right) L = \frac{2}{n}\left(1 - \frac{1}{2^n}\right) L \approx \frac{2}{n} L, \tag{3}$$

where n is the number of bitplanes and L is the full intensity of the light source. For example, to achieve a bit depth of 16-bits, BLM can only output $1/8$ of the brightness achievable by PWM. This makes BLM rather impractical for most applications — a point noted in [1] as well.

2.5. High bit-depth projection techniques

Existing high bit-depth projectors utilize multiple spatial light modulators (SLM), *e.g.*, DMDs or liquid crystal displays (LCD), either in parallel or in series. Cinema projectors utilize three DMDs in parallel with each DMD associated with a single color channel, to achieve 15-bit projection at video rate [9]. Dual modulation techniques [10–15] are popularly used in high dynamic-range projectors, and they utilize two (or more) SLMs in series to modulate the outgoing light multiple times. For example, a LCD placed in front of a DMD-based projector can provide additional attenuation of the outgoing light intensity and thus reduces output minimum brightness and increases dynamic range. SLMs like analog micromirror array or liquid crystal on silicon (LCoS) can also be used to redistribute light energy from dark pixels to bright ones to increase both energy efficiency and dynamic range of the projectors [4–7].

In addition to the increased device costs, utilizing serial SLMs leads to the following three challenges. First, every stage of light modulation loses energy. For example, light efficiency for DMDs is 68% [16, 17] and those for LCDs and LCoSs are at most 50% (due to the polarization). To compensate the lost light energy, higher powered light sources are needed to achieve desirable brightness. Second, despite the increased dynamic range, serial modulations usually produce nonuniform intensity levels and thus require additional preprocessing algorithms from the typical linear intensity values. In addition, even with the preprocessing, the non-uniformity in pixel intensity reduces the overall bit depth of the projectors. For example, serial modulated projectors composed of two 8-bit LCDs can achieve at best intensity resolution of 13.3 bits. Third, utilizing multiple SLMs requires more sophisticated optical designs including subtle calibrations like careful positioning of the SLMs. Due to these factors, existing high bit-depth/high dynamic-range projectors are usually significantly more expensive than standard projectors. In contrast, our proposed projector requires only a single DMD and generates uniform intensity levels, and thereby no additional costs or calibration are needed. Besides, the system can be easily modified from commercial 8-bit DMD projectors or incorporated into existing high dynamic-range projectors.

2.6. Other types of high bit-depth displays and projectors

The principle of dual modulation has also been utilized in a variety of high dynamic-range displays [10, 18–20]. By coupling a second SLM with a traditional projector or a LED panel, local light intensity can be individually controlled to achieve high contrast ratio. Auto-iris technique used in some commercial projectors adaptively controls intensity of the light source based on the image content in each frame, but, unlike the proposed method which provides high bit-depth projection in every frame and requires no adaptation to the projected content, auto-iris can only increase bit depth across frames. Multi-projector systems [21–23] overlap the projected images to increase the maximum brightness as well as spatial resolution; however, this requires going beyond a single light modulator and hence, has the same benefits and limitations as multi-DMD systems.

3. Hybrid light modulation

Recall that while traditional PWM projection has the maximum brightness output, it suffers from low frame rate due to the exponential dependence between the exposure time of an image and the desired bit depth. As BLM projection significantly increases the frame rate, it sacrifices maximum brightness and therefore are not useful in practice. In this section, we propose *hybrid light modulation*, which solves the disadvantages of PWM and BLM by carefully incorporating PWM with BLM.

Observe that with PWM projection, the bitplane exposure time grows exponentially as the number of bits increase, while with BLM, the bitplane exposure time remains identical. If we apply BLM to the least significant bitplanes to decrease the number of bits assigned to PWM (as in Fig. 2(b)), we can dramatically reduce the total exposure time to project an image. Besides, if only a few bitplanes are assigned to BLM, the total exposure time of PWM will still be exponentially longer than that of BLM and thereby mitigate the loss of maximum of brightness due to BLM. We refer to this scheme as hybrid light modulation (HLM). In essence, in HLM, we use BLM for only the lesser significant bitplanes and use PWM on the rest (*i.e.*, more significant) bitplanes. As we will analyze next, HLM can provide significant reduction in exposure time associated with a frame without a commensurate reduction in brightness.

Suppose that we require an intensity resolution of n bits. We breakup the intensity resolution into two buckets: n_1 bits that are assigned to BLM and n_2 bits assigned to PWM, with $n_1 + n_2 = n$. Further, the PWM is performed with the light source intensity set to its maximum. The total exposure time per image is

$$(n_1+2^{n_2}-1)t,$$

and its maximum achievable brightness is

$$L^h_{\text{max}} = \frac{1}{n_1+2^{n_2}-1}\left(2^{n_2-1}+\ldots+1+\frac{1}{2}+\ldots+\frac{1}{2^{n_1}}\right)L = \frac{1-2^{-n}}{1+(n_1-1)\times 2^{-n_2}}L. \quad (4)$$

We can expect that 2^{n_2} is usually much larger than n_1, and hence, the maximum brightness $L^h_{\text{max}} \approx L$ for small n_1 and the frame time is approximately $2^{n_2}t$. Hence, by optimizing over n_1 and n_2 while keeping their sum equal to n, we can achieve the desired tradeoff between max-brightness and speed of operation, in terms of images per second. Besides, the contrast ratio of HLM can be computed as

$$C^h = \frac{L^h_{\text{max}}}{L^h_{\text{min}}} = \frac{\left(2^{n_2-1}+\ldots+1+\frac{1}{2}+\ldots+\frac{1}{2^{n_1}}\right)L}{\left(2^{n_2-1}+\ldots+1+\frac{1}{2}+\ldots+\frac{1}{2^{n_1}}\right)\frac{L}{C}} = C, \quad (5)$$

which remains the same as the contrast ratio of the original PWM projection. We compare the frame rate, brightness, contrast ratio, and power efficiency between PWM, BLM, and the proposed HLM in Fig. 3 and provide some example numbers in Fig. 4. For the numbers in Fig. 4, we allow for block-based micromirror control only for the PWM scheme. Yet, even without block-based control, HLM coding achieves 16-bit, RGB projection over 49 fps with only 6% of brightness reduction, when $n_2 = 7$. In contrast, traditional PWM with block-based control can only achieve 2.5 fps in spite of the efficiencies enabled by block-based control.

We illustrate the trade-offs among intensity resolution, frame rate, and maximum brightness of PWM, BLM, and the proposed HLM in Fig. 5. Note that when assigning all bitplanes to PWM (bottom right corner), HLM reduces to the traditional PWM, which has high brightness but low frame rate; on the other hand, when all bitplanes are assigned to use BLM, HLM becomes BLM and has high frame rate but low brightness. By designing the coding scheme (*i.e.*, judicious selection of n_1), HLM can achieve both high brightness and high frame rate for high bit-depth projection (upper-right corner).

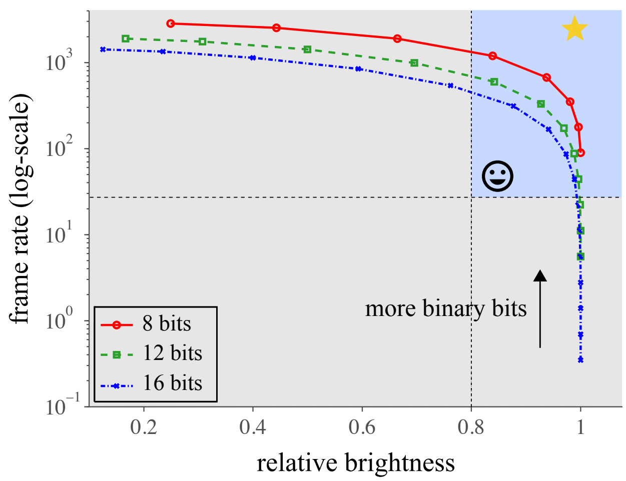


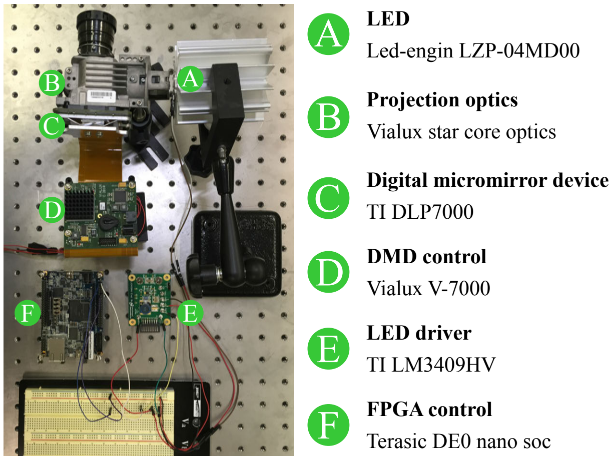
Fig. 5. Trade-off between brightness and frame rate of our proposed HLM with bit depth $n = 8, 12$, and 16 bits and $t = 50$ μs. The bottom-right corner assigns all the bits to PWM ($n_1 = 0$), and by increasing n_1, the frame rate increases rapidly without losing much of the brightness. When all bits are assigned to BLM (upper-left corner), the projection has the highest frame rate but lowest brightness. It can be seen that our HLM effectively achieves high frame rate and high brightness with high bit-depth (upper-right corner).

Enhancing color gamut and brightness. Recall that single DMD projectors use temporal dithering to achieve color perception and hence, the frame rate of projection is reduced by a factor equal to the number of colored light sources. For a small loss of brightness, we can exploit the efficiencies enabled by HLM to achieve greater color gamut without a commensurate loss in bit depth or frame rate. For example, Fig. 6(b) shows the typical color gamut of projectors with RGB LEDs; by adding cyan and yellow LEDs, we can potentially expand the color gamut to be a pentagon, and thereby project deeper colors that are unable to be produced by ordinary RGB projectors. Similarly, if we add an additional bright-white LED, we can boost the brightness on the brighter spots in the images and make them more vivid; here, we rely on the higher luminance output common to commercial white LEDs. The proposed HLM can also be incorporated into the gamut reshaping technique [8] to concurrently increase bit depth and utilize the extra color gamut to increase color fidelity and maximum brightness.

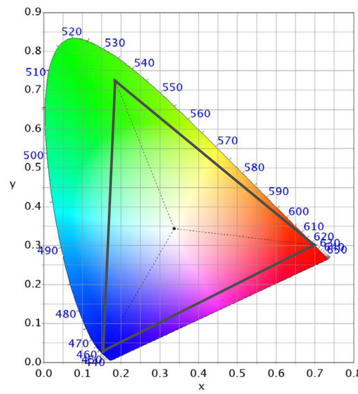
4. Prototype and Experimental Results

4.1. Light intensity control

In order to precisely control the intensity of the light source, we can use LEDs or laser diodes as light sources, both of which allow analog and digital controls of intensity at high frequencies. LEDs and laser diodes are also able to achieve high luminous flux output, *e.g.*, above 4000 lm for LEDs and 10000 lm for laser diodes, and have been popularly used in commercial projectors due to their high energy efficiency. While their current-driven characteristic allows us to continuously control intensity, we choose to modulate their intensity digitally by switching the LEDs on and off rapidly, *e.g.*, in MHz, with pulse-width modulation. By controlling the 'on' duration within the exposure time of each bitplane, we are able to adjust the (averaged) light intensity. While more efficient electrical designs may be used to switch the LEDs in high frequency, for simplicity we use a current controller [24] that requires no capacitor connected to the LEDs (thus minimizes delays), and we use a MOSFET to shunt the current from the LED inputs to turn off the LEDs. Since the MOSFET can be turned on and off within a few nanoseconds, we can easily switch



(a) System prototype.



(b) Color gamut.

Fig. 6. The prototype is composed of a LED, a DMD, and a projection optics. The color gamut of the prototype can be expanded by adding yellow or cyan LEDs to our system.

the LEDs in 20 MHz in our system prototype. This allows us to assign 10 bits to BLM with minimum bitplane exposure equal to 50 μs.

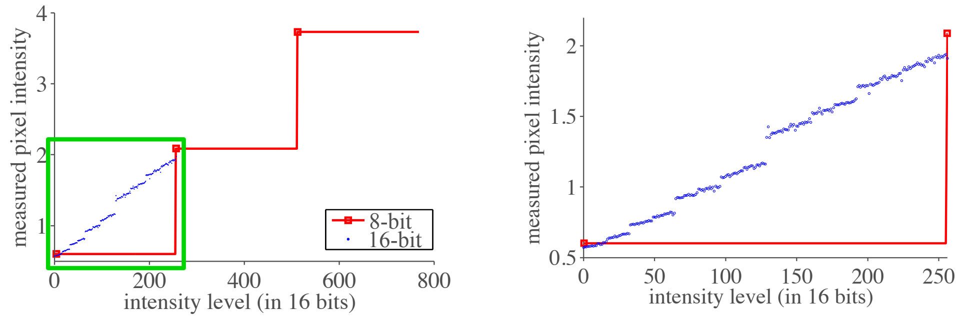
4.2. System prototype

Our system prototype is composed of three components — the projection optics, the DMD development kit, and the LED with associated circuit for intensity modulation (see Fig. 6(a)). For the projection optics, we use Vialux STAR-07 core [25], whose full on/full off contrast ratio is 2000 and aperture is $f/2.6$. The projection optics module has two ports, one connecting the DMD and the other connecting the light source. The light entering the module is first spatially smoothed by an integration rod, to create homogeneous lighting, and directed onto the DMD by relay optics. For further details, we refer to the application report provided by Texas Instruments [26]. We use Texas Instruments DLP7000 DMD, which has a spatial resolution of 1024×768 pixels. For the light source, we use the LED-ENGIN LZP-04MD00 — a RGBW LED system whose red, green, blue, and white LEDs output 330, 820, 35, and 1785 lumens, respectively. We use Texas Instruments LM3409HV chip to drive the LED and program an FPGA (Terasic DE0-Nano) to synchronize the LEDs and DMD. For the sake of simplicity, we update all micromirrors jointly with minimum bitplane switching time set to t=50 μs. With our system setup, we are able to modulate the LEDs with 20 MHz (with up to 10 bits of intensity control) and can achieve 16-bit, RGB projection at 49 fps and 6% loss of brightness (by assigning $n_1 = 9$ bits to BLM). We could also replace the FPGA and simply use a low-cost Arduino board to synchronize the LEDs and DMD, as shown in Code File 1 (Ref. [27]). With the speed of Arduino Uno board, we can easily achieve 12-bit projection ($n_1 = 4, n_2 = 8$).

4.3. Experimental results

To validate the performance of our prototype, we use a PointGray Grasshopper camera to analyze the projected photograph.

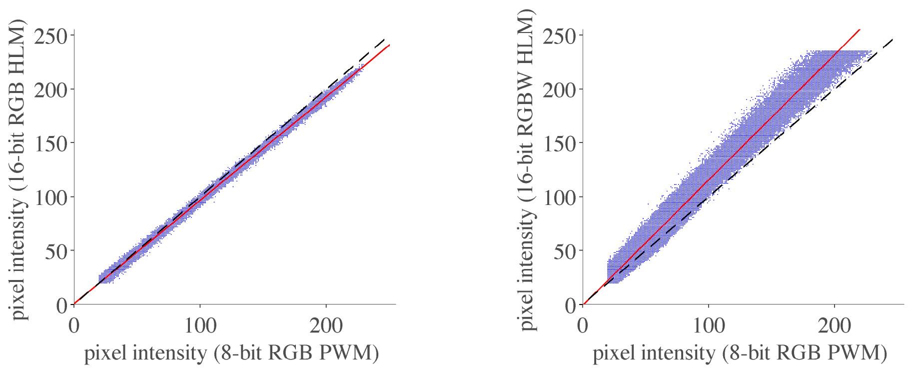
We first validate our claim that proposed HLM coding can achieve 16-bit high bit-depth projection at a small loss of brightness. We project images in which all pixels having the same grayscale value with HLM ($n_1 = 8$) and average the captured pixel intensities in each photograph. As can be seen in Fig. 7, the proposed 16-bit HLM successfully produce individual intensity



(a) Measured pixel intensities.

(b) Zoom in of the green region.

Fig. 7. Measured pixel intensities in grayscale projections of the traditional 8-bit PWM and the proposed 16-bit HLM.



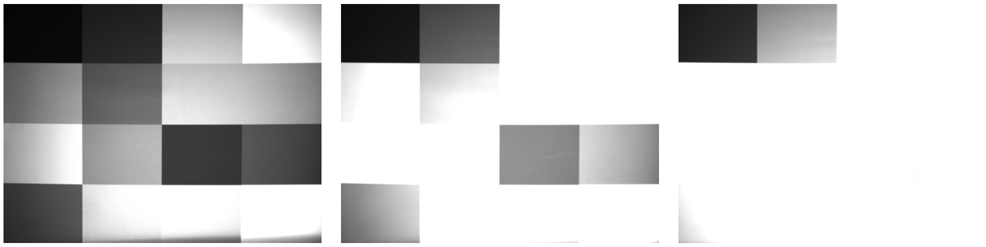
(a) RGB projection (n_1=9, n_2=7). The slope of the regression line is 0.96.

(b) RGBW projection (n_1=10, n_2=6). The slope of the regression line is 1.17.

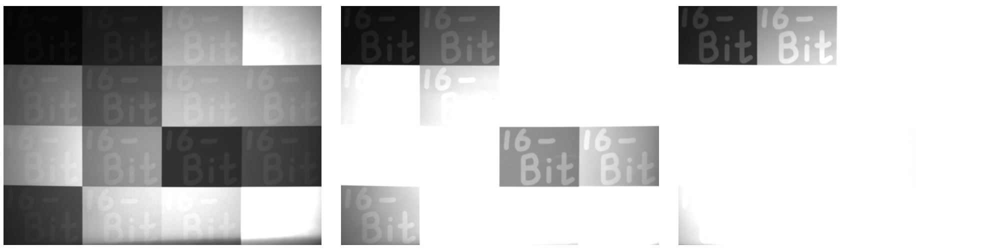
Fig. 8. Measured pixel intensities (blue dots) in RGB and RGBW projections of the traditional PWM and the proposed HLM. The dashed line represents the line $y = x$, and the red line represents the least-squares regression line of the measured pixel intensities.

levels which traditional 8-bit cannot produce. Note that the discontinuities of 16-bit HLM in Fig. 7 are caused by the natural delay in LED switching and can be removed by precisely adjusting the pulse-width of the 'on' duration of the LED in each binary bit. Next, we validate the claim that proposed HLM coding causes only a marginal loss in brightness. Fig. 8 compares the intensity observed at a pixel (of projected images shown in Fig. 9, Fig. 10, and Fig. 11) when we use the traditional 8-bit PWM to the intensity observed when we use HLM coding at 16-bits. We remove pixels that are either under-exposed or over-exposed. We observe that, on an average, HLM coding (RGB, n_1=9,n_2=7) loses only 4% of brightness. Next, we compare the traditional 8-bit coding to the 4-LED RGB+White (RGBW) system. Here, we observe that, in spite of using more LEDs and hence a 33% penalty in temporal dithering, HLM coding with 4 LEDs effectively increases brightness by 17%, compared to the traditional 8-bit RGB PWM. However, in the case of RGBW projection, the most benefit in brightness is at pixels which are gray-toned; this results in a higher variance of pixel intensities shown in Fig. 6(b).

Given a high dynamic-range radiance image, we perform primitive tone-mapping with exposure and contrast adjustment, then we quantize the radiance image to 16 bits and 8 bits per color



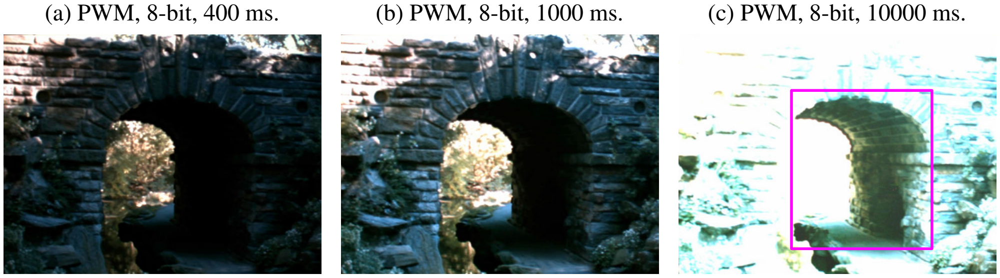
(a) PWM, 8-bit, 400 ms. (b) PWM, 8-bit, 1000 ms. (c) PWM, 8-bit, 2000 ms.



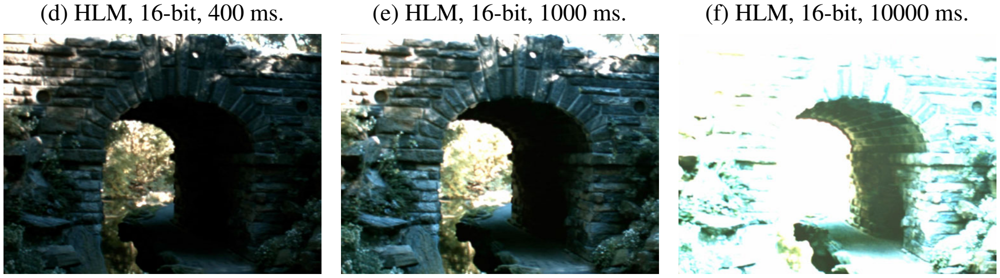
(d) HLM, 16-bit, 400 ms. (e) HLM, 16-bit, 1000 ms. (f) HLM, 16-bit, 2000 ms.

Fig. 9. Unprocessed photographs of grayscale projection results.

(a) PWM, 8-bit, 400 ms. (b) PWM, 8-bit, 1000 ms. (c) PWM, 8-bit, 10000 ms.

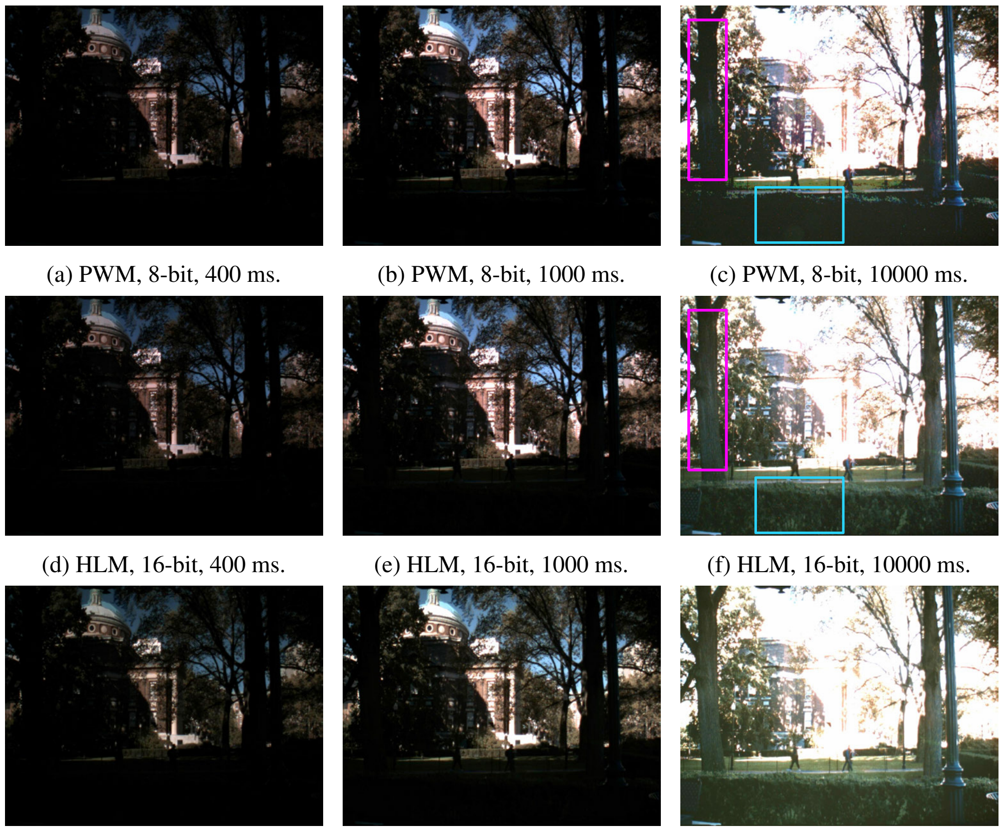


(d) HLM, 16-bit, 400 ms. (e) HLM, 16-bit, 1000 ms. (f) HLM, 16-bit, 10000 ms.



(g) HLM, 16-bit (RGBW), 0.4 s. (h) HLM, 16-bit (RGBW), 1 s. (i) HLM, 16-bit (RGBW), 10 s.

Fig. 10. Unprocessed photographs of color projection results.



(a) PWM, 8-bit, 400 ms. (b) PWM, 8-bit, 1000 ms. (c) PWM, 8-bit, 10000 ms.

(d) HLM, 16-bit, 400 ms. (e) HLM, 16-bit, 1000 ms. (f) HLM, 16-bit, 10000 ms.

(g) HLM, 16-bit (RGBW), 0.4 s. (h) HLM, 16-bit (RGBW), 1 s. (i) HLM, 16-bit (RGBW), 10 s.

Fig. 11. Unprocessed photographs of color projection results.

channel. As 16-bit images have 256× more intensity levels per color channel and 16-million times more RGB colors than the 8-bit ones, subtle details are preserved in 16-bit projection and less quantization noise (*e.g.*, banding effects) is observed. We demonstrate grayscale projection in Fig. 9, RGB and RGBW projection in Fig. 10 and Fig. 11. In the figures, we present unprocessed photographs of projected images under three different exposure time settings. We mark the regions where the difference between the 8-bit and the 16-bit projected results can be perceived in a dark environment. Due to the higher bit-depth, we are able to reproduce image details that are otherwise lost with traditional 8-bit projection, for example, the '*16-bit*' in Fig. 9, the inside of the bridge in Fig. 10, the checker board in the darker area of Fig. 1, and the bushes and tree trunks in Fig. 11. To convert the original RGB images to RGBW, for each pixel location, we set the white value to be the minimum in the three channels and subtract the value from the original channels. Based on the assumption that brighter objects tend to have lower-saturated colors, in the RGBW projection, we deliberately set the luminance output of the white LED to be higher than the RGB ones. This highlights the bright spots in the scene and makes the images more vivid, which can be seen from the brighter white regions in Figs. 10 and Fig. 11.

5. Conclusion

We propose hybrid light modulation, whose novel light intensity control introduces a new design space for high bit-depth projection with wider color gamut and higher frame rates. When applied to high bit-depth projection, hybrid light modulation avoids the significant drop of frame rate in pulse-width modulated projection as well as a drop in brightness in binary light-modulated projectors. Our projector prototype requires only a single DMD, projection optics, and a modulated LED light source — similar to most commercial DMD-based projectors; besides, no preprocessing algorithm is needed to adopt the proposed coding scheme. Thereby only few modifications and additional costs are needed in order to adopt this technology to existing projector designs. In addition, hybrid light modulation coding can also benefit existing high dynamic-range projection techniques, including novel prism designs and light reallocation projectors, to achieve higher bit depth and to expand color gamut. We hope that the proposed design can help popularize high bit-depth/high dynamic-range projectors and inspire next generation projector design to meet the ever increasing desire for better visual experience.

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