Time-multiplexed tiled projection system with improved pixel and spatial resolution

Hagen Seifert
Nicola Ranieri
Quinn Smithwick (SID Member)
Markus Gross

Abstract — We propose two methods to increase the pixel and spatial resolution of Digital Micromirror Devices (DMD)-based projectors by utilizing the large bandwidth provided by their high pattern rates. By varying the intensity of the illumination for each binary pattern displayed on the DMD, the time required to display an 8-bit grayscale image can be reduced by up to factor 32 compared to using constant illumination and binary pulse-width modulation (BPWM). The high image rate projection is then spatially separated by either using a galvanometer scanner or sequentially illuminating the DMD from different directions, thus creating multiple independently addressable projections which are then tiled to form a larger, higher resolution image.

Keywords — *time-multiplexing, improved resolution.*

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1 Introduction

The bandwidth of displays – displayed image information by unit time – is a prominent feature of 2D and 3D displays. In the consumer market, manufacturers push the development of higher resolution televisions and projectors, starting from standard-definition (<0.5 MP) to high-definition (~2 MP) and now to 4 k (~8 MP). Even 8-k (~32 MP) displays have been showcased.

Extremely high bandwidth is required for light-field displays, which not only control the spatial but also the angular distribution of light, allowing an observer to see a three-dimensional image without the need of wearing glasses (autostereoscopic) and providing motion parallax without tracking the observer. Various sacrifices can be made to achieve the desired number of views without increasing the bandwidth: In integral imaging the spatial resolution is divided by the number of views[1]; in systems using a rotating screen and a high-speed projector, the color and bit depth are decreased.[2–4] Alternatively, the required high bandwidth can be achieved by using multiple projectors.[5–7]

Digital Micromirror Devices (DMD) from the Texas Instruments Digital Light Processing (DLP) technology have an inherently high bandwidth with their high switching speeds of tens of kilohertz. However, when used in conventional projectors this high bandwidth is usually wasted, as the displayed content rarely exceeds 60 or even 30 Hz. Taking advantage of that high bandwidth, we propose ways to increase the displayed image pixel resolution without having to manufacture any additional pixels, while at the same time maintaining full color 24-bit images.

In DLP projectors, different gray levels are traditionally created using binary pulse-width modulation (BPWM), where light from a constant light source is modulated by the DMD and the gray level results solely from the ratio of time the micromirror spends in the on and off positions. By also modulating the intensity of the light source, the time required to show an 8-bit grayscale image can be reduced by approximately factor 32 with the same binary pattern rate. A full 24-bit image can then be displayed in as low as 1 ms.

We propose two methods to spatially separate these high frame rate images into individually addressable projections, and to merge them into a single, higher pixel resolution image. Two prototypes were built to showcase their feasibility and the images' increased pixel and spatial resolution.

In the first prototype, the DMD is illuminated by red, green, and blue LEDs. The image is focused and then redirected by a galvanometer, a high-speed, high-precision radial motor with a small mirror mounted to the shaft that directs the image among a number of defined positions during each frame. A set of fixed mirrors aligns the images to form a larger combined image, as seen in the concept drawing in Fig. 1a. In the second prototype, the DMD is sequentially illuminated by laser light sources from different directions, therefore throwing the projection in different directions (Fig. 1b). In either case, a full frame is composed of multiple temporally separate tiles. The frame rates are sufficiently high, so that the human eye cannot distinguish that the tiles appear sequentially.

In both prototypes, in order to merge the tiles into a single projection, a calibration is applied that uses a digital camera and computer vision to find the mappings from the tiles to the combined projection. The calibration also creates masks that are multiplied with each image to correct

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Hagen Seifert, Quinn Smithwick and Markus Gross are with the Disney Research, USA; e-mail: hagen.seifert@disneyresearch.com.
Hagen Seifert, Nicola Ranieri and Markus Gross are with the ETH Zürich, Computer Graphics Laboratory, Switzerland

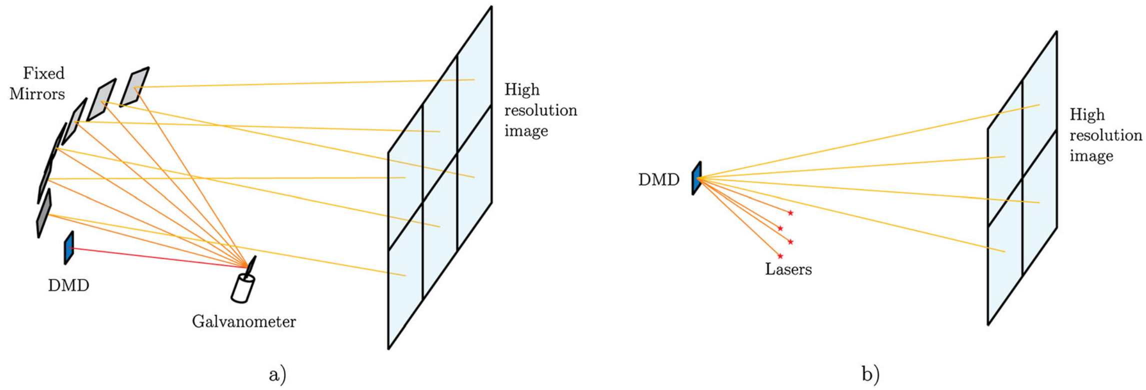


FIGURE 1 — Concept drawings of two methods to improve spatial resolution of DMD-based projectors. a) The high image rate from the DMD is split into multiple directions using a galvanometer scanner. The split images are redirected by fixed mirrors and tiled into a high-resolution image. b) The DMD is alternately illuminated by different laser light sources, thus projecting the resulting images into different directions.

the brightness and color distribution and apply a smooth blending between them.

2 Related work

Various other projection systems have taken advantage of the DMD's high pattern rate for a variety of applications.

As mentioned earlier, systems based on a high speed projector with a rotating screen generate a high number of views.[2–4] However in all three works, each view has only a 1-bit depth; gray levels can only be achieved by using dithering.

Eichenlaub et al. increased the spatial resolution of a DMD-based projector by factor nine by using a light source that jumps between nine spots in a 3×3 array every 1/540th second.[8] A fly's eye lenslet array was then used to focus these spots on different locations on each micromirror of the DMD. The jumping light source was realized by deflecting a laser beam with two galvanometers.

Time-multiplexing has been used to double the vertical resolution of LC-based projectors by adding a wobbling device, which can dynamically shift the image by half a pixel for every second frame.[9,10] The sharpness in these systems is slightly reduced compared to a natively doubled resolution by the overlap of the shifted and non-shifted pixels.

Jang et al. used a galvanometer to sequentially tile projections created by an LCD projector onto a lenslet array to create a high-resolution integral imaging display.[11] Because of limitations of the used technology, it took a full second to display six tiles.

Similar to the second method proposed in this paper, Kanebako et al.[12] and Bogaert et al.[13] proposed the use of time-multiplexed directional illumination of DMDs. However, in both systems a common projection lens was used to focus light of all directions on an anisotropic rear projection screen to create multiple views for an autostereoscopic display. Furthermore, the system of Kanebako et al. produced only single color 5-bit grayscale images, and no prototype was built by Bogaert et al.

3 Image generation

The image in a DLP projector is created by a DMD, where an array of microelectromechanical systems (MEMS)-based micromirrors controls the brightness of each pixel. Because these micromirrors only have two states, *on* (+12°) or *off* (−12°), different shades of gray are achieved by controlling the ratio of the times spent in those states. This technique is called BPWM.[14]

For each pixel's 8-bit word input, leading to 256 brightness levels, the simplest control sequence is dividing the total field time into eight divisions, each of which is half as long as the previous one. After each division the memory array is updated with the next bit of the input word, from the most significant bit (MSB) to the least significant bit (LSB). This timing is repeated at a high speed so that the observer cannot distinguish the separate on and off states and instead perceives the output as a constant brightness value. For a 4-bit word, the timing is illustrated in Fig. 2a.

The downside to BPWM however is the long field time $t_{f,bpwm}$ which is limited by the minimum time between two mirror switches t_{LSB}. For an 8-bit word, single channel:

$$t_{f,bpwm} = \sum_{i=0}^{7} 2^i t_{LSB} = \left(2^8 - 1\right) t_{LSB} = 255 t_{LSB} \qquad (1)$$

If instead of halving the time for each successive bit plane the brightness of the illumination is halved, the same amount of time can be used for every bit in the input word (Fig. 2b). We call this *light intensity modulation* (LIM). The resulting minimum field time is

$$t_{f,LIM} = 8 t_{LSB} \qquad (2)$$

which is an improvement of nearly factor 32. For higher bit depths this factor becomes even larger, because $t_{f,bpwm}$ rises exponentially, while $t_{f,LIM}$ only rises linearly.

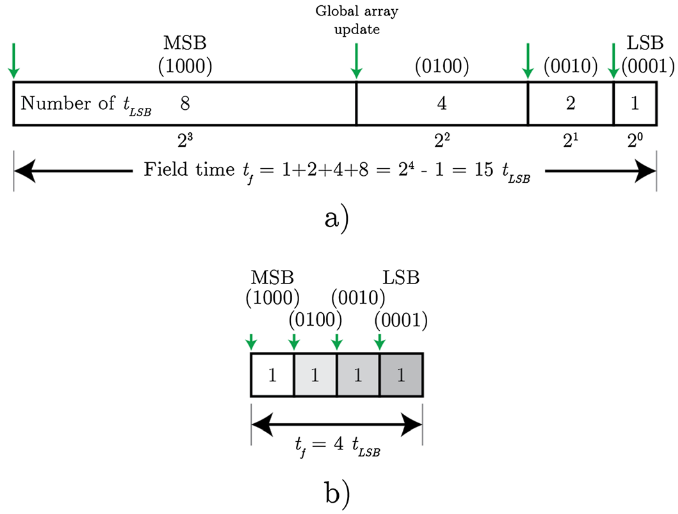


FIGURE 2 — Comparison of binary pulse-width modulation (BPWM) and light intensity modulation (LIM). a) In binary pulse-width modulation, the output brightness is determined solely by the ratio between on and off-time of the micromirror. Higher bit planes require exponentially longer illumination times. b) When using light intensity modulation, the brightness of the light source is modulated, so that each bit plane can be displayed for the same amount of time. This leads to much faster field times compared to BPWM.

The downside of LIM however is the overall decrease of the light intensity. In BPWM, a white pixel gets the full intensity the full time. With 8-bit LIM the average intensity is

$$I_{LIM,avg} = \frac{1}{8}\sum_{i=0}^{7}\frac{I_{max}}{2^i} = \frac{255}{1024}I_{max} \tag{3}$$

which about a quarter of what could be achieved using BPWM. It is possible to combine some of the benefits of both control schemes by using BPWM for the more significant bits and LIM for the less significant bits.

4 Hardware setups

We built two prototypes to validate the proposed concepts and demonstrate the improved spatial resolution. The first prototype uses single RGB LEDs as a light source and divides the high frame rate images generated by the DMD into multiple directions using a galvanometer scanner. The second prototype uses multiple sets of RGB laser diodes to illuminate the DMD from different directions, therefore creating multiple projections.

4.1 Galvanometer prototype

The galvanometer prototype can be seen in Fig. 3.

4.1.1 DMD

This prototype uses a ViALUX V-7000 module, which incorporates the DLP7000 0.7 XGA (1024 × 768) DMD. This relatively low resolution DMD currently has the highest binary pattern rate in the Texas Instruments portfolio, with 22 727 Hz or 44 µs per binary pattern. Using LIM, exactly one binary pattern is required per bit plane; therefore a 24-bit RGB image can be displayed in just 1.06 ms or at 947 Hz.

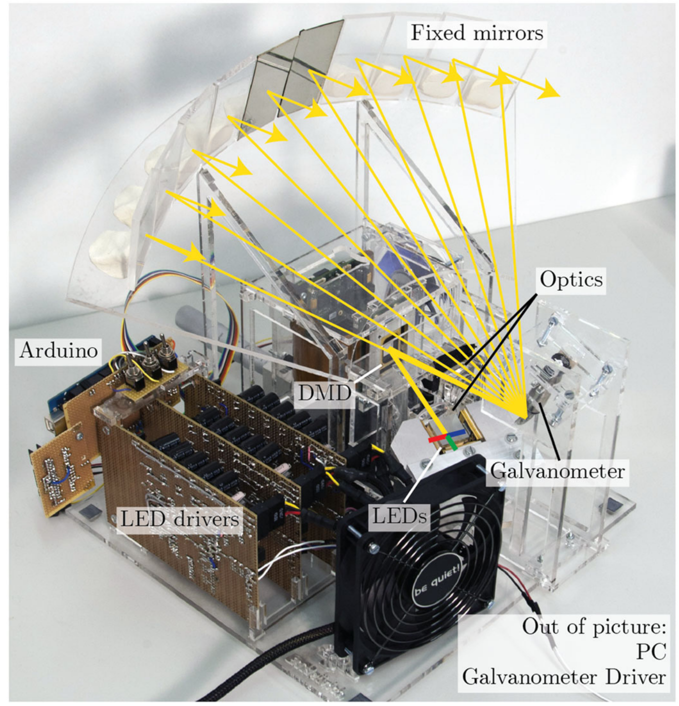


FIGURE 3 — Photo of the first prototype, which uses a galvanometer scanner to split the high image rate into spatially separate images. The most important components of the projector are labeled, and the path of the light is highlighted.

The module is connected to a computer using a USB 2.0 interface through which images have to be uploaded to the onboard RAM before they can be displayed. A maximum of 43 690 binary patterns can be stored, which, if played back continuously at maximum speed, is equivalent to just below two seconds of video.

4.1.2 Image composition

We aimed to get close to a UHD (3840 × 2160) resolution with the combined projection; hence a 5 × 2 tiling of portrait orientation projections was used, leading to a theoretical pixel resolution of $5 \cdot 768 = 3840$ in width and $2 \cdot 1024 = 2048$ in height, as seen in Fig. 4. In reality, each of the projections has to overlap slightly; therefore some resolution is lost.

4.1.3 Galvanometer

The galvanometer scanner (a high speed, high precision rotary motor with a shaft-mounted mirror) is needed to spatially separate the so far only temporary separate images. For this, it has to discretely rotate between a set of defined angular positions that are evenly spread across its range during each frame. At each position, it should remain stationary for the

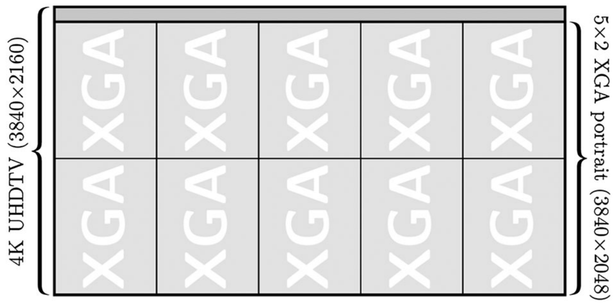


FIGURE 4 — Comparison of a tiling of 10 XGA (1024 × 768) projections in portrait orientation with no overlaps to 4K UHDTV.

time it takes to display the tile. The angular position of the mirror during one frame consisting of 10 tiles is plotted against time in Fig. 5. This abrupt stop and go motion at a very high speed requires a high torque, small moment of inertia galvanometer, which limits the available mirror size to below 10-mm aperture. The fastest step response times and highest precisions in galvanometers are achieved with digital servo drivers; however, these are considerably more expensive than systems using analog drivers. Among analog-driven galvanometers, we chose the model 6220H from Cambridge Technologies with a low inertia beryllium 10-mm y-mirror and 671XX-HP servo, as it was the only galvanometer whose written specifications could meet the timing requirements for 60 fps and the required optical range of ±40°.

4.1.4 Timing

The frame rate should be sufficiently high, so that the separate fields cannot be distinguished and no flickering appears. We therefore aim for either 60 or 48 frames per second, which results in frame times of 16.7 ms or 20.8 ms, respectively. After deducting the time for the 10 tiles (10.6 ms), this leaves 6.1 ms/10.6 ms for the galvanometer to perform the nine smaller steps of 8.9° between each position and the large step back over the whole range of 80° (optical).

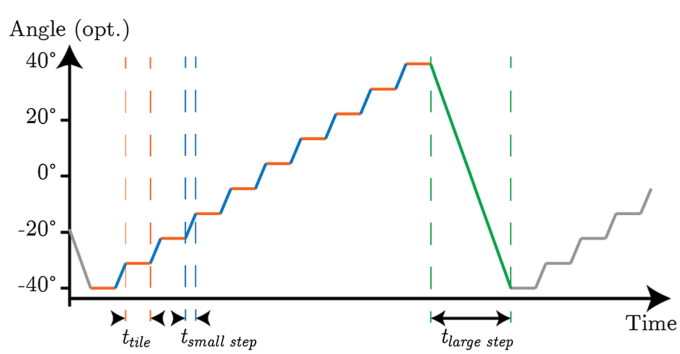


FIGURE 5 — Angular position of the galvanometer mirror over time during one frame. The galvanometer performs nine small steps between ten fixed positions, at each of which it stays for the time required to display one tile, and one large step (flyback) over the full range back to the initial position.

4.1.5 Light engine

The light source for the projector should be able to modulate the brightness of each color for every binary frame, which cannot be achieved with traditional high intensity discharge (HID) lamps. Instead, Luminus PhlatLight LEDs were used, which are specifically designed to replace discharge lamps in projectors. Additionally to being able to quickly change their brightness, their advantages are a much higher lifetime of 60 000 h, and a wider color gamut because of narrower frequency spectra. The red, green, and blue PT-121 LEDs used for this prototype offer a combined white luminance of up to 3575 lumens with an emitting area of 4 mm × 3 mm.

Custom LED drivers based on the buck converter were designed with switchable output currents of 30 A, 15 A, 3.8 A, or 0.9 A. The remaining four brightness levels for the LIM were achieved by varying the on-time of the LEDs.

4.1.6 Optics

The light of the three LEDs is combined into a single optical path using a dichroic x-cube prism and converged onto the DMD using a single biconvex spherical lens. The image is then focused to the projection screen using a pair of spherical lenses, one convex and one concave. The galvanometer is placed about 6 cm in front of the focusing lenses, where a real image of the LEDs is formed, as it represents the narrowest beam diameter.

The optical range of the galvanometer of ±40° limits the width of each of the 10 tiles to a throw ratio of at least

$$r_{th} = \frac{projection\ \ distance}{projection\ \ width} = \frac{1}{2\ \tan\left(\frac{80^{\circ}}{2\cdot 9}\right)} = 6.43 \qquad (4)$$

Finally, a set of 10 fixed mirrors redirect the projections onto the projection screen.

4.1.7 Synchronization

The DMD board outputs a synchronization signal for each binary frame, which is read by an Arduino Mega 2560 microcontroller board. The microcontroller in turn controls the output currents of the LED driver and sets the desired galvanometer position via the 6757 digital to analog converter on the 671XX-HP servo driver.

4.2 Directional illumination prototype

4.2.1 DMD

The core element of the second prototype visible in Fig.6 is the Dli4130 Developer Kit. Like the ViALUX V-7000, images are uploaded to the onboard RAM via USB before they can be displayed. However, instead of the DLP7000, it uses the DLP9500 0.95″ 1080p (1920 × 1080) DMD, which has an around 2.6 times higher resolution. On the other hand, it has a

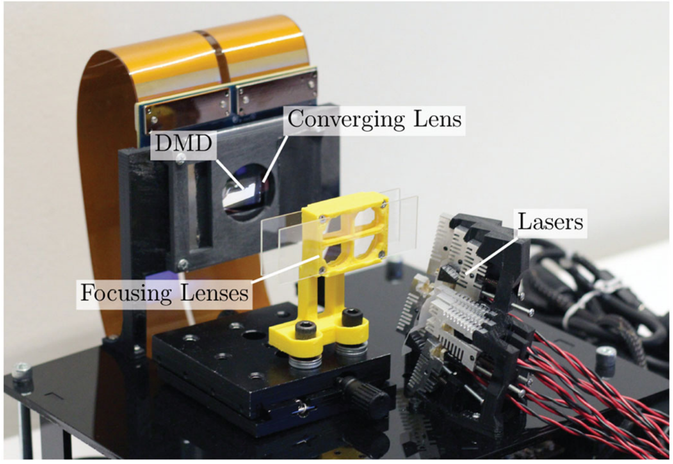


FIGURE 6 — Photo of the second prototype, which sequentially illuminates the DMD from different directions using four sets of RGB lasers. Each of the four focusing lenses captures the light coming from one set of lasers, thus projecting four spatially separate, independent images.

lower binary pattern rate of 10 638 Hz (2.14 times lower compared to the V-7000). Overall it therefore has a 23% higher bandwidth.

4.2.2 Image composition

Thanks to the 1080p resolution of the DMD, an UHD (3840 × 2160) image can be achieved by simply tiling four images in a 2 × 2 array.

4.2.3 Timing

Each binary pattern is displayed a minimum of 94 µs, leading to a full color image time of 2.256 ms and an image rate of 443 Hz. Unlike in the galvanometer prototype, no additional time is wasted on moving parts; therefore the maximum frame rate is exactly a quarter of the image rate (111 Hz). A part of that frame rate can be traded for a higher brightness. By using 16 binary frames instead of 8 per 8-bit grayscale field, the average brightness can be tripled. To achieve this, the MSB is displayed for six binary frames instead of only one and, as before, the amount of light for each successive bit plane is halved (see Fig. 7).

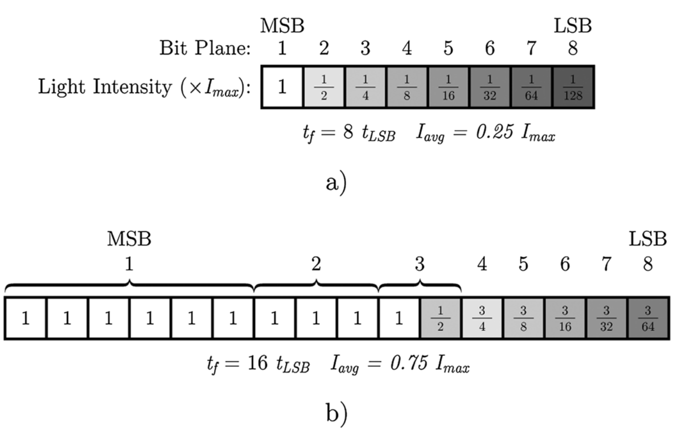


FIGURE 7 — a) As described in section 3, an 8-bit grayscale field can be displayed in eight binary patterns (one for each bit plane) of equal length by halving the light intensity for every successive pattern, which leads to the fastest field time, but also a low average light intensity. b) By using 16 binary patterns, the most significant bit plane can be shown at full intensity for six binary patterns. As before, the amount of light for each successive bit plane is halved. The average light intensity is about three times as high as when using only eight binary patterns.

4.2.4 Light engine

Four sets of red (Oclaro L638P700M, 638 nm, 700 mW), green (Osram PLP 520, 520 nm, 120 mW), and blue (Osram PL TB450B, 450 nm, 1.6 W) laser diodes are used to illuminate the DMD from different directions. They are again driven by three custom buck converter drivers (one for each color), but other than the LED drivers from the first prototype, they have only one constant output current. The constant current of a driver is either redirected to one of the lasers at a time, or the output is shorted, therefore always maintaining the constant current in the buck inductor. This allows to switch the lasers on and off instantly, with virtually no rise and fall time. Different brightness levels for the LIM are then achieved solely through control of the on-time of the lasers.

4.2.5 Optics

Because of the coherence of laser light, the diodes can essentially be considered as point light sources. With a point light source, an image of the DMD could theoretically be created without the need for any focusing optics.

FIGURE 8 — Projection of the DMD using a single laser diode without focusing optics. Clearly visible is diffractive ringing around edges as well as multiple shadow images caused by diffraction on the periodic micromirror structure of the DMD.

However, as seen in Fig. 8, in reality this approach resulted in diffractive ringing around edges as well as multiple shadow images. We assume that the shadow images are created because the micromirror array with a pitch of 10.8 μm acts as a diffraction grating. The grating equation[15] suggests that light with a wavelength λ that is diffracted on a grating with spacing d will result in maxima of the diffracted light at angles θ_m to the central line:

$$d \sin(\theta_m) = m\lambda \tag{5}$$

This equation suggests, that shadow images should be expected about

$$\theta_1 = arcsin\left(\frac{\lambda}{d}\right) = \begin{cases} 3.7^\circ (red) \\ 2.7^\circ (green) \\ 2.4^\circ (blue) \end{cases} \tag{6}$$

apart. This corresponds well with the observed distance of the shadow images.

To avoid the multiple diffraction images using point projection, we use one achromatic doublet focusing lens for each of the four projections as reimaging optics. All the light coming from the DMD collected by the lens is focused to the same spot on the projection screen, regardless of the direction it leaves the DMD. The positions of the focusing lenses determine the direction of the projections. They were chosen in a way, that the projections overlap by 20% in the center, which is necessary to combine them to a single, larger projection.

In order for the directional light from the DMD to be collected by the relatively small focusing lenses, the light needs to be converging on the lenses. For this purpose, a plano-convex lens is placed directly in front of the DMD. The lasers are placed, so that the green light converges directly in the center of the focusing lenses, and the red and blue light 4.25 mm to the left and right. By using the focusing lens to combine the colors, we can avoid using dichroic beam combiners, which would increase the cost and complexity of the projector. A ray tracing of this setup can be seen in Fig. 9.

4.2.6 Synchronization

Because the laser drivers cannot vary the output current and different brightness levels can only be achieved by controlling the on-time, it has to be controlled with sub-microsecond accuracy. We chose a CESYS EFM-1 embedded FPGA module for this task. It reads two input signals from the DMD board, the frame synchronization signal, and a sequence change signal. The binary frames are ordered to minimize flickering, visual tearing, and rainbow effect. To achieve this, the tiles and color channels are built up in an interleaved order. It starts by displaying the first binary frame of the first channel of the first tile, looping first through the image tiles, then the color channels, and finally the binary patterns.

5 Calibration and image blending

Because the tiles never line up perfectly, their mappings to the combined image have to be found and a smooth blending has to be applied. Furthermore, the brightness and color distribution of both prototypes is improved using a brightness calibration.

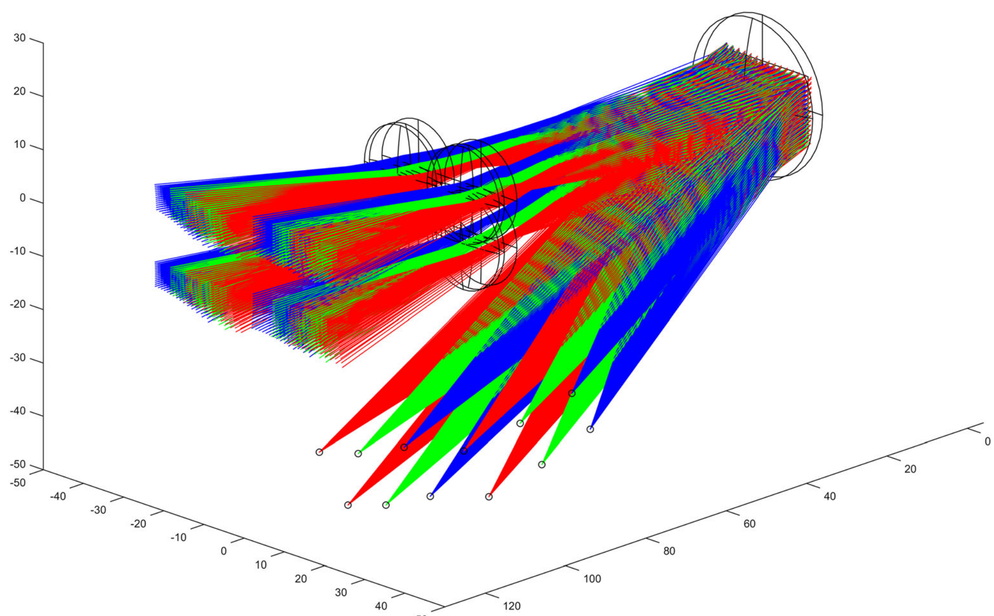


FIGURE 9 — Ray tracing of the path of light in Matlab. Starting from the 12 laser sources (four for every color) the light is reflected by the DMD and converged onto the focusing lenses by a plano-convex lens directly on the DMD. Each of the focusing lenses captures the light of three different colored lasers, focusing them to the same spot on the projection screen, thus rendering the use of dichroic beam combiners unnecessary.

The calibration process uses a digital camera that is remotely controlled from a computer to take photos of test patterns on the projector. Computer vision is used to identify those patterns and create the calibration files.

All calibration steps are performed for each color channel separately to achieve higher accuracy and to prevent color fringing caused by chromatic aberrations in the lenses and a slightly out-of-focus projection.

A photo of an image on the uncalibrated directional illumination prototype can be seen in Fig. 10a.

5.1 Mapping

To find the mapping from the combined projection to the single tiles, first the mapping from the camera to each tile is found. For this purpose, a checkerboard pattern is displayed on a single tile. OpenCV is used to find the checkerboard corners and refine them to subpixel accuracy.

The mapping we used consists of a first-order radial distortion and a homography. The first-order radial distortion is applied to the checkerboard corner coordinates in the tile image space, by using a simplified Brown distortion model:[16]

$$x' = x_0 + (1 + k(x - x_0)^2)\cdot(x - x_0) \tag{7}$$

where x is the undistorted image point, x' the distorted image point, x_0 the center of distortion, and k the first order radial distortion coefficient.

Then, a homography is found from the found checkerboard corners in camera space to the distorted corners in tile space. The parameters k and x_0 are found iteratively by minimizing the mean square reprojection error after applying the homography.

The inverse radial distortion can be applied to an image by remapping it using an undistortion map, which for each pixel contains the coordinates of its distorted counterpart.

The combined projection in camera space is chosen as the quad defined by the outermost corners of the tiles, scaled down around its center by 5%. Its homography to the camera is found. The homography from the combined projection to the distorted tiles is a multiplication of the homography from the combined projection to the camera with the homography from the camera to the distorted tiles. Then, for the complete mapping first the homography and then the undistortion map are applied. The result of the mappings on the directional illumination prototype can be seen in Fig. 10b.

5.2 Blending masks

To eliminate the bright areas where the tiles overlap, a mask is multiplied to each of them. Based on the borders of each tile transformed into the combined image space, the combined image is divided along the centers of the overlapping areas, so that each pixel belongs exactly to one tile. The masks are then blurred, to allow for small inaccuracies in the mappings without visible seams. The respective masks are multiplied with the combined image for each tile, before the mapping is applied.

The blending masks, as well as the updated projection on the second prototype, are shown in Fig. 10c.

5.3 Brightness distribution

In both prototypes, the DMD is not illuminated uniformly by the light sources (LEDs/lasers), because no homogenizing elements such as light pipes or diffusers were used. This leads to uneven color and brightness distributions across the projection. To correct this, masks that are inverse to the brightness distributions are multiplied with each tile. To create a mask, a full brightness single channel image is shown in one tile at a time. A photo is taken, and the previously found mapping from camera to tile is applied. The brightness value (0–255) in every pixel corresponds to the actual brightness achieved by the projector at that location. A first brightness mask is then created by dividing the desired brightness by the achieved brightness and multiplying by 255 for each pixel.

a) b) c) d)

FIGURE 10 — Successive application of calibration steps on the directional illumination prototype. a) A quarter of the image is shown on each tile without any calibration. b) With an applied mapping consisting of a homography and a first order radial distortion, the images align correctly. c) Masks (top) are applied to each tile to smoothly blend between them (bottom). d) Finally, brightness masks (top) are applied, which improve color and brightness uniformity (bottom). Still images from Frozen are provided courtesy of Walt Disney Animation Studios for demonstration purposes. (Neither the authors nor projection prototype was involved with the production of the motion picture.)

The choice of the desired brightness is a tradeoff, because a lower brightness means better uniformity, we chose the brightness to be approximately half of the peak brightness of the image.

The brightness mask is further refined by displaying it on the projector, creating another inverse mask, and multiplying the two. This second step can be executed multiple times. However, the quality of the mask is limited by the accuracy of the mapping. Examples of the resulting brightness masks and their effect on the projected image can be seen in Fig. 10d.

6 Results and discussion

Both prototypes are able to verifiably increase the usable pixel and spatial resolution of the DMD. The directional illumination prototype was designed as a follow-up to the galvanometer prototype and offers the overall better image quality, while at the same time being mechanically more simple and robust.

6.1 Galvanometer prototype

The galvanometer prototype in theory offers up to 10 times the resolution of the used XGA (1024 × 768) DMD, providing a resolution of up to 3840 × 2048. In reality, the visible resolution is reduced by the homographies and required overlap of the tiles, as well as image blur because of aberrations in the focusing lenses. To reduce the blur, an aperture had to be introduced in the system, which in return led to strong vignetting. A resolution test pattern was shown on the prototype, once at the XGA resolution of the DMD and once at 3840 × 2048. The results are compared in Fig. 11. Figure 12 shows a color image displayed over the ten tiles on the prototype, with all calibrations applied.

As can be seen, one of the biggest problems of the system is the inhomogeneous light distribution and strong vignetting of each tile that even the brightness distribution calibration can only correct partially. However, these problems could be fixed by using additional optical elements such as a light pipe homogenizing rod and better focusing lenses.

A further problem is the low brightness of the projector. With the Luminus PT-121, we used the brightest LEDs available on the market at the end of 2013. As of 2015, Luminus increased the brightness with their PT-121-TE by approximately 50%. Because the smallest beam diameter, and therefore the required size of the galvanometer mirror, is related directly to the emitting area of the LED, brightness cannot be increased by using a bigger LED. Therefore we conclude that with LEDs the brightness of the projector can currently not be improved by the orders of magnitude that would be necessary for a commercial product. By using lasers that can be focused to extremely small spots, the brightness could potentially be increased, and a smaller and faster galvanometer could be used.

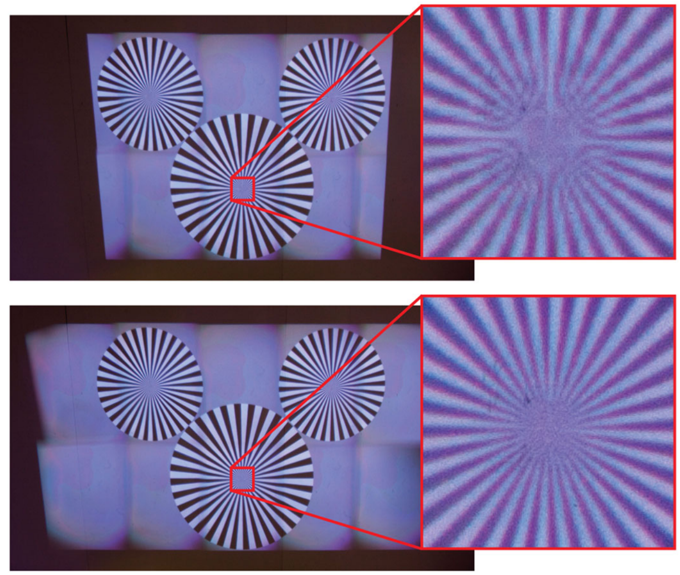


FIGURE 11 — Comparison of a resolution test pattern shown at XGA (1024 × 768, top) and 3840 × 2048 resolution (bottom), with all calibrations applied. In the enlargement on the right, jagged, pixelated edges can clearly be seen in the top image, while they seem completely smooth in the bottom, and lines remain distinguishable further towards the center. In both cases, sharpness is limited by aberrations of the focusing lenses of the projector. The color and brightness distribution cannot completely be corrected by the calibration, which is clearly visible in the uniform background; the strong vignetting makes the seams between the tiles visible.

FIGURE 12 — A color image is displayed on the projector, with all calibrations applied. Still images from Frozen are provided courtesy of Walt Disney Animation Studios for demonstration purposes. (Neither the authors nor projection prototype was involved with the production of the motion picture.)

The galvanometer was the source of multiple problems in the projector. As the only macroscopic moving part in the projector, it is susceptible to damage (it had to be sent in for repair once for unknown reasons) and makes clearly audible noise. Furthermore, during operation of the prototype, the controller becomes unstable after approximately 30 s, which causes the mirror to hit its physical constraint and the controller to reset.

6.2 Directional illumination prototype

The directional illumination prototype addresses the issue of the galvanometer and removes all moving parts as well as the fixed mirrors. It tiles the 1080p image of the DMD four times to reach up to an UHD (3840×2160) pixel resolution.

As before, part of the resolution is lost because of the overlap and the homographies. However, thanks to the better optical properties of the achromatic doublet lenses compared to the combination of spherical lenses used in the galvanometer prototype, and because the laser light hits the focusing lens mainly in one small spot, therefore attenuating the effect of aberrations, there is no blur visible in the directional illumination prototype. The improvement of the resolution can be seen in the resolution test pattern in Fig. 13, as well as in the color image in Fig. 14, which shows remarkable detail.

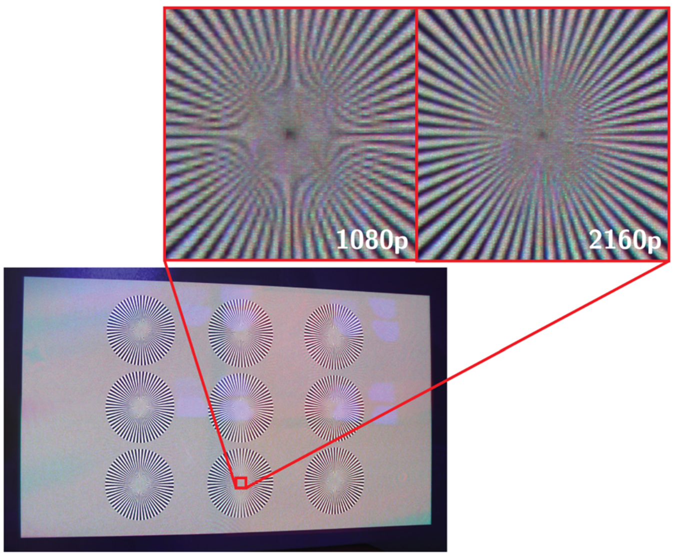


FIGURE 13 — Comparison of a resolution test pattern displayed on the calibrated directional illumination prototype at 1920×1080 and 3840×2160 resolution. Just like in the first prototype (see Fig. 11), lines can be distinguished significantly further towards the center of the pattern in the higher resolution image, while pixelated edges are visible in the lower resolution image. Furthermore, the second prototype has an overall better sharpness and more uniform brightness distribution.

Because the optics also does not introduce any vignetting, the brightness and color distribution is much more even. After the calibration, the different tiles blend perfectly and are virtually indistinguishable.

The projector has a low brightness of approximately 5 lumens. However, as opposed to the first prototype, which used LEDs as a light source, the use of laser light means that higher power lasers could be used without increasing the optical extent of the light, and therefore without the need to change the optics.

A problem that needs to be addressed in laser projectors is speckle, which is created when coherent light is scattered from a rough surface, and is visible as a fine-grained noise. As this is merely a first prototype, no methods of speckle reduction are applied. However, in future prototypes, a time-varying diffuser,[17,18] could be introduced in the optical path between the laser diodes and the DMD. The effectiveness of this approach and its impact on the optics of the system remain to be seen.

Thanks to the focusing lenses, diffractions caused by the periodic structure of the DMD are focused to the same spot on the screen, as long as they are collected by the same lens. This removes the ghost images seen in Fig. 8. However, because the diffraction pattern of each laser spreads further than one lens (Fig. 15a), a portion of it is picked up by the wrong focusing lenses and appears on the projection as crosstalk between the tiles (Fig. 15b).

The crosstalk could be eliminated by positioning ferroelectric shutters in front of each focusing lens, and only opening the shutter belonging to the tile that is currently displayed. However, this would reduce the brightness of the projection and increase the complexity and cost of the system.

Because the diffraction pattern spreads mainly along the horizontal and vertical axes, crosstalk is observed only between the directly neighboring tiles, but not between the diagonally opposite ones. Taking advantage of that fact, crosstalk can be eliminated using polarization filters in front of the focusing lenses, where directly neighboring tiles have an orthogonal polarization. Because laser light is inherently polarized, this can be done with close to no loss of brightness, and because only passive components are needed the complexity of the system

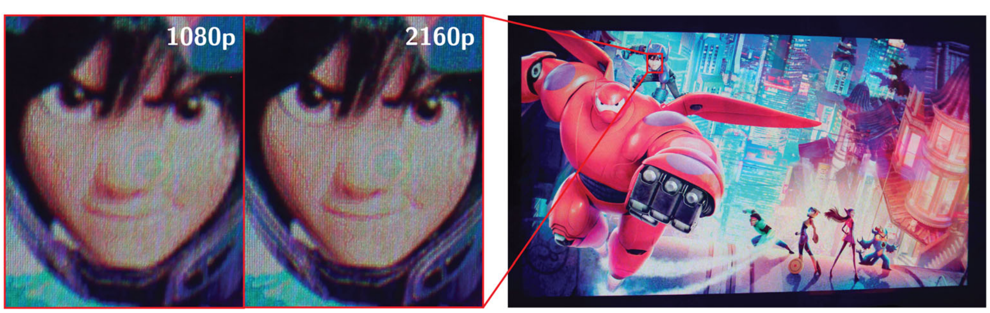


FIGURE 14 — Comparison of a color image displayed on the directional illumination prototype at 1920×1080 and 3840×2160 resolution. Note the increased detail in 2160p compared to 1080p in the structure of the character's face in the enlargement on the right. Still images from Big Hero 6 are provided courtesy of Walt Disney Animation Studios for demonstration purposes. (Neither the authors nor projection prototype was involved with the production of the motion picture.)

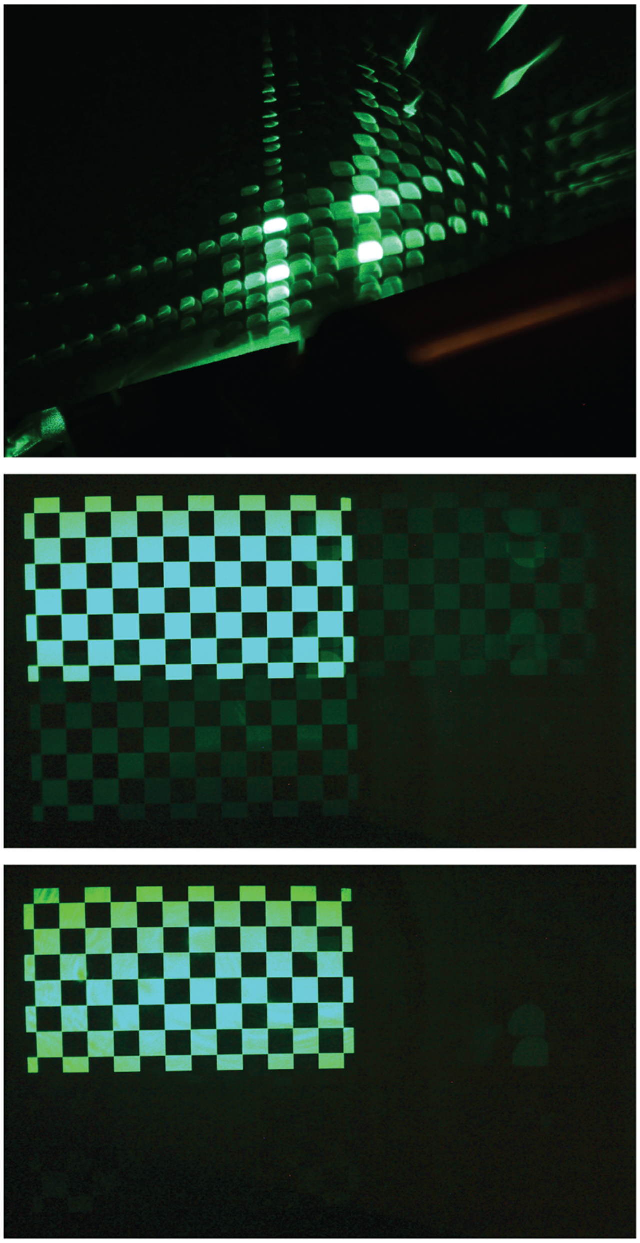
a)
b)
c)


FIGURE 15 — Investigation of crosstalk between the tiles because of diffraction of the lasers on the DMD. a) Overlapping diffraction patterns of the four green lasers in the plane of the focusing lenses. Crosstalk is created because the patterns extend into the neighboring focusing lenses. b) A checkerboard pattern is displayed on the upper left tile; crosstalk can be seen in the directly neighboring tiles. c) Putting orthogonal polarization filters in front of neighboring focusing lenses efficiently eliminates crosstalk.

is not increased unnecessarily. Figure 15b shows that the polarization filters effectively eliminate all visible crosstalk.

7 Conclusion

We demonstrated two methods to use the bandwidth provided by the high switching speeds of DMDs to increase the pixel and spatial resolution of a projector without having to manufacture additional pixels and while maintaining full 24-bit color depth. To achieve this, multiple tiles that are projected time-sequentially are merged to one larger, high-resolution projection. LIM allows us to display images at an up to 32 times higher rate than when using binary pulse-width modulation. The first prototype uses a galvanometer scanner to spatially separate the projection into multiple tiles, while the second prototype sequentially illuminates the DMD from different directions. In both cases a superior resolution compared to the utilized DMD could be demonstrated.

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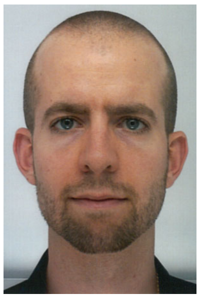
Hagen Seifert received his BSc and MSc in Electrical Engineering and Information Technology from the Swiss Federal Institute of Technology Zürich (ETH) in 2013 and 2014. He currently works as a Project-Hire Research Associate at Disney Research in Los Angeles, California, following his interests researching 2D and 3D display technologies and applications.



Nicola Ranieri received his Master from the Swiss Federal Institute of Technology Zürich (ETH) in 2011 and was PhD candidate in the Computer Graphics Laboratory at the Institute for Visual Computing, where he defended in June 2015. His research interests include computer graphics, computer vision, 3D display technology, and interaction with such devices as well as augmented reality.

Quinn Smithwick is a senior research scientist at Disney Research in Los Angeles, California. His main research area at Disney Research Los Angeles is novel display technologies with particular emphasis on autostereoscopic displays and augmented reality environments. He received his PhD in Aeronautics and Astronautics from the University of Washington for his dissertation on the nonlinear modeling and control of a miniature scanning endoscope. His postdoctoral research at Harvard Medical School was on the development of a transportable scanning laser ophthalmoscope. His postdoctoral research at the MIT Media Lab was on the development of MIT's next generation holographic video display. He joined Disney Research in 2010.

Markus Gross is a professor of computer science at the Swiss Federal Institute of Technology Zurich (ETH), head of the Computer Graphics Laboratory, and the Director of Disney Research, Zurich. He joined the ETH Computer Science faculty in 1994. His research interests include physically based modeling, computer animation, immersive displays, and video technology. Before joining Disney, Gross was director of the Institute of Computational Sciences at ETH. He received a master of science in electrical and computer engineering and a PhD in computer graphics and image analysis, both from Saarland University in Germany in 1986 and 1989. Gross serves on the boards of numerous international research institutes, societies, and governmental organizations. He received the Technical Achievement Award from EUROGRAPHICS in 2010 and the Swiss ICT Champions Award in 2011. He is a fellow of the ACM and of the EUROGRAPHICS Association and a member of the German Academy of Sciences Leopoldina as well as the Berlin-Brandenburg Academy of Sciences and Humanities. In 2013 he received a Technical Achievement Award from the Academy of Motion Picture Arts and Sciences, the Konrad Zuse Medal of GI, and the Karl Heinz Beckurts price. He cofounded Cyfex AG, Novodex AG, LiberoVision AG, Dybuster AG, and Gimalon AG.