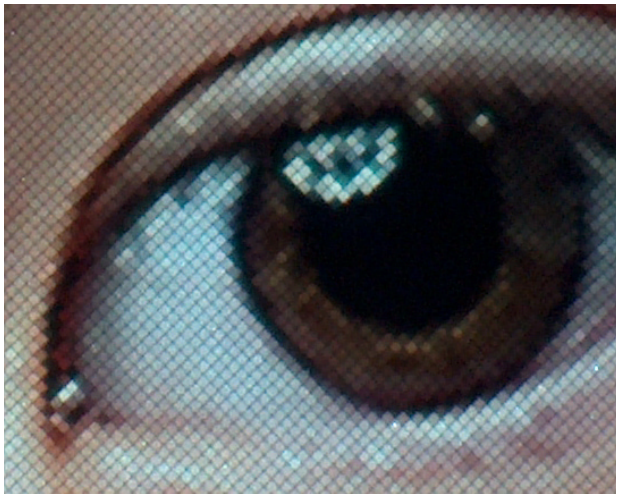
47.4: *Invited Paper:* Wobulation: Doubling the Addressed Resolution of Projection Displays

Will Allen
Digital Projection and Imaging, Hewlett-Packard, Corvallis, Oregon, USA

Robert Ulichney
HP Labs, Cambridge, Massachusetts, USA

Abstract

In this paper "wobulation" is presented. Wobulation is a cost-effective method of increasing the resolution of digital projection systems without changing the spatial light modulator (SLM). Multiple sub-frames of data are generated from each frame of image data. An optical image shifting mechanism displaces the projected image of each sub-frame by a fraction of a pixel. The sub-frames are projected in rapid succession, thereby appearing as if they were projected simultaneously and superimposed. The resulting image has significantly higher resolution than images produced by unwobulated systems having the same number of SLM pixels.



(a) unwobulated

(b) 2-position wobulated, vertical shift

Figure 1. Digital photos of projected images.

1. Introduction

Wobulation is applicable to various SLM technologies, but the first wobulated products use digital micromirror devices (DMDs) [1] from Texas Instruments (TI). In this short paper, only DMD-based projection systems are considered. Wobulation can be applied to front projection and rear projection systems. Figure 1 shows photographs of images produced on a testbed projection system imaging onto a reflective screen.

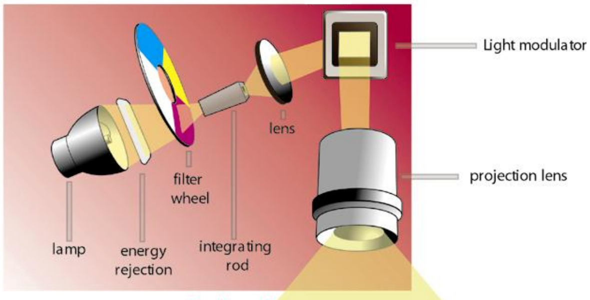


Figure 2. Single-chip DMD-based projection system

2. How a DMD-based Projector Works

Various optical configurations exist, but all share the same essential elements. Refer to figure 2. Light is generated in a lamp and focused to a point by an elliptical reflector. An energy rejection filter prevents unwanted ultraviolet and infrared radiation from propagating through the optical system. Light then passes through a spinning color filter wheel containing red, green, and blue segments. Downstream of the wheel, the light sequences through the colors on the wheel at least 2 times per frame. The colored beam passes through an integrating rod to make the intensity uniform, and then it is directed onto a DMD device. The DMD comprises an array of tiny (14 µm pitch) mirrors. Each mirror controls light for one pixel in an unwobulated image. The mirrors tilt between 2 positions: one that directs light into the projection lens and onto a screen, and one that directs light into a beam dump area where it is absorbed. The mirrors rapidly toggle between these positions to modulate pixel intensity. The intensity modulation is synchronized with the colors provided by the filter wheel. The system is capable of varying the intensity of each primary color for each pixel in the image.

3. How Wobulation Works

The basic idea for wobulation was taken from inkjet printing. Resolution of an image is increased when the resolution of the grid on which the pixels are addressed (placed) is increased. This is true, within limits, even if the size of the dots (pixels) is significantly

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larger than the pitch of the addressed grid. In a wobulated projector, for each frame of image data received, multiple sub-frames of data are generated. Each sub-frame contains unique image information, and is projected onto the screen in a slightly different position by means of an opto-mechanical image shifter. Subframe display is synchronized with the color wheel with at least one full color cycle occurring during the display period of each subframe. This increases the addressed resolution, but does not change the pixel size: pixels from distinct sub-frames overlap. The light modulator must have a switching speed fast enough to support the sub-frame display rate. Sub-frames are projected in rapid succession similar to individual frames in a movie. This rapid sequence is perceived as a continuous, flicker-free image. Detail in the resulting image is increased.

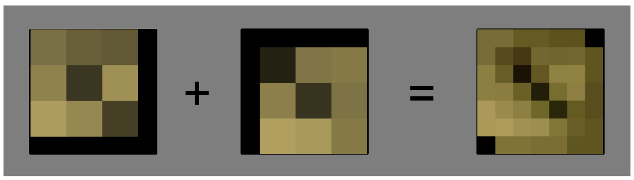
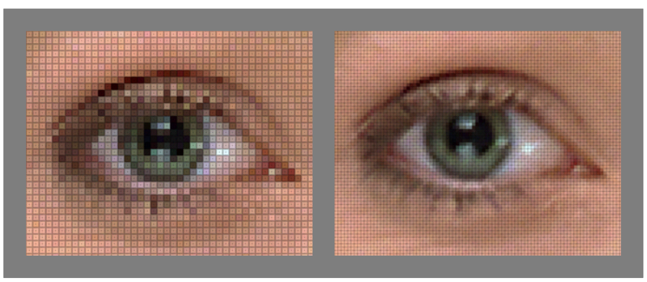


Figure 3. Superimposed sub-frames increase detail.

In the simplest case, 2 sub-frames are generated for each frame of image data. Figure 3 illustrates how 2 sub-frames, each composed of 9 large pixels, can be combined with a ½-pixel diagonal shift to produce a higher detail image. Smaller blocks are resolved in the combined image on the right.



(a) unwobulated **(b) wobulated**

Figure 4. Simulations of unwobulated and 2-position wobulated, diagonal shift, images from a DMD.

Figure 4 shows simulations of 2 images produced by projectors based on a DMD chip. The simulations depict a close-up view of a projected image. The form of individual DMD mirror elements is visible in figure 4 (a), a simulation of an unwobulated image. Under good conditions, the naked eye can resolve DMD mirror features in large, well-focused, projected images. If the same DMD chip is wobulated by producing and displaying 2 sub-frames with a ½-pixel horizontal shift, the image shown in figure 4 (b) is produced. Note the increased detail visible in figure 4 (b): eyelashes are easily distinguishable and the iris has a smooth circular edge instead of the jagged edge seen in the unwobulated image.

In addition to increasing resolution, wobulation has an extra benefit of hiding the screen door grid appearing between pixels in projected images. The grid is caused by gaps separating active pixel areas on the DMD. Due to shifting, pixels from sub-frames overlap, and the grid from one sub-frame is mostly covered by active pixel areas from the other sub-frame.

In many cases, wobulated images produced on a projector with an n-pixel SLM look better than images produced on similar projectors with $2n$ SLM pixels! Of course, the resolution of a digital projection system can be increased by increasing the number of pixels on the SLM, but SLM pixels are generally expensive and wobulation allows high quality displays to be built with a modest increase in total cost of components.

3.1 Positions and Pixel Arrangements

Wobulation is not restricted to 2 sub-frames per image data frame, nor is it restricted to a classic square array of pixels. Additional image quality can be attained when more than 2 sub-frames are generated for each image frame. This is computationally more complex, and the opto-mechanical image shifting mechanism must work at higher speed in order to shift the additional sub-frames to unique positions within the time allotted for display of the original frame of image data.

Figure 5. Simulations of projected images produced by a generic diamond-pixel SLM. (A) single sub-frame; (A+B) 2 sub-frames superimposed, horizontal shift.

Wobulation allows each pixel in the SLM to address multiple locations in the final image. 2-position wobulation addresses 2 locations with each SLM pixel. 4-position wobulation addresses 4 locations with each pixel: it fully doubles the addressable resolution of the device, compared to an unwobulated system using the same SLM, in both the horizontal and vertical axes.

Rotating the basic pixel array layout on an SLM by 45º produces a diamond pattern of pixels. Wobulation can easily be applied to this alternative layout. Simulations of images produced with a generic (perfect fill factor) diamond-pixel SLM are shown in figure 5. In these simulations, 2 sub-frames are generated for each frame of image data. The sub-frames are named A and B.

When a square array of SLM pixels is shifted to 2 positions diagonally, addressed positions form a diamond grid. When shifted though 4 positions, horizontally and vertically, the addressed positions form a rectangular grid at double the SLM pixel resolution in both axes. The number of addressed locations is 4 times the number of SLM pixels.

Shifting a diamond array of SLM pixels to 2 positions, horizontally *or* vertically, addresses a square grid. This configuration is convenient, because image data is typically supplied on a square grid. In this case, the number of addressed locations is double the number of pixels on the SLM.

3.2 Inverse Super-resolution

A well established area of image processing is that of super-resolution with an excellent overview presented by Park [2]. The goal of super-resolution algorithms is to capture a high resolution image with a lower resolution image detector array. Two or more frames are captured of the same scene with subpixel offsets. Key to the success of super-resolution approaches is the ability to accurately register overlapping frames with subpixel precision, and overcome low-pass filtering inherent in the low resolution detectors. The difficulty is compounded if the scene changes between sub-frame captures.

Wobulation is the inverse problem in that instead of capturing an image, low resolution sub-frames are used to display a higher resolution image. It is a much more controlled problem because the pixels in the high resolution input are naturally spatially registered.

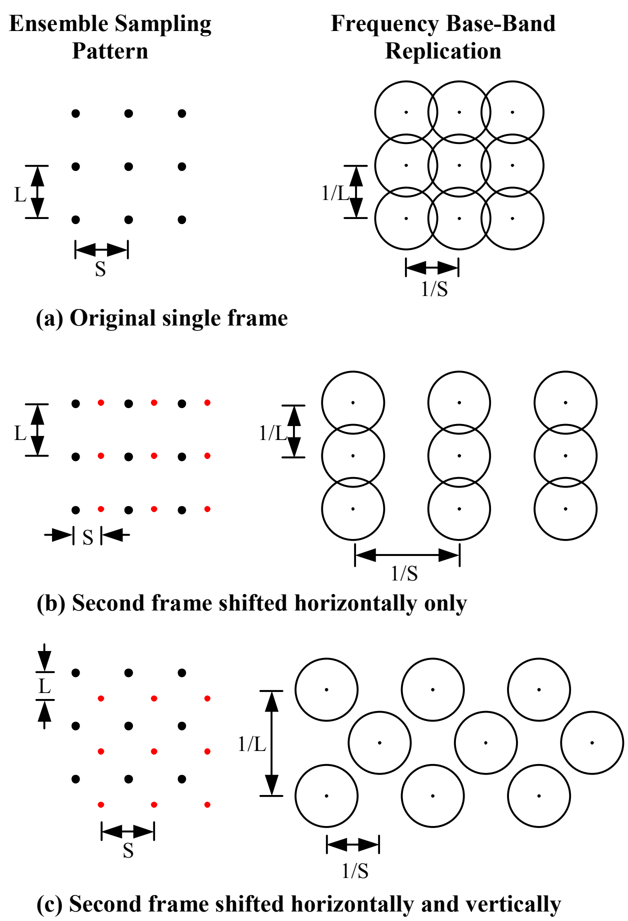


Figure 6. Frequency domain consequences of adding samples to an image with an offset frame. (b) and (c) have twice as many pixels as (a).

Generating a wobulated sub-frame is much like adding another set of spatial samples on an existing high resolution image. Figure 6 illustrates the process of doubling the samples used to render a wobulated image. The left side of the figure shows the samples in the spatial domain, and the right side shows the consequences of that sampling scheme in the frequency domain. Periodic sampling in the spatial domain corresponds to replicating the Fourier Transform representation of the image in the frequency domain. For the purpose of this illustration, assume that the patterns shown in both domains in figure 5 fill all of two-space. In the spatial domain, S is the sample period in horizontal direction, and L is the line period. The circles around the centers of the frequency base-bands depict the range of nonzero spectral energy in the image being sampled.

Part (a) shows the original low frequency sample pattern. In the frequency domain in this example aliasing occurs due to spectral overlap in both dimensions as is shown. In part (b) a second sub-frame is added by horizontally shifting the samples one-half period; the original spatial samples are shown in black (large dots) and the new samples are shown in red (small dots). This increase in horizontal resolution has a corresponding increased base-band separation in the frequency domain; however aliasing is not relieved in the vertical dimension. Offsetting the second frame as is shown in part (c) enjoys a more symmetric resolution increase. For multi-dimensional signal processing we know that base-band replication will be as shown in the frequency domain. No spectral overlap, or aliasing, would occur in this case.

The scheme shown in Figure 6 (c) is what is employed in two-position wobulation. For the case of the diamond-pixel SLM (as shown in figure 5), the patterns in figure 6 are turned 45º.

3.3 Image Processing

Image data should be supplied to a wobulated system at or above the addressed resolution to create the best quality images. Proper generation of sub-frame data is essential to producing high quality wobulated images. For example, if the same data are used for both sub-frames shown in figure 1 (b), shifting and superimposing the 2 identical sub-frames results in the blurry image shown in figure 7. Although the screen door is essentially eliminated, the vertical shift introduces artifacts that significantly degrade horizontal elements in the image.

Figure 7. Photo of projected image with two identical sub-frames (no sub-frame generation), vertical shift.

The set of sub-frames generated for a particular frame of image data are displayed during the regular time period allocated for the image data frame (typically about 1/60 s). Because the entire image frame period is used, wobulation does not inherently reduce bit depth or brightness of the resulting image.

4. Shifting the Image

A variety of alternative designs exist for shifting the image. Many rear projection systems based on DMD microdisplays have a fold mirror somewhere between the light modulator and the final element of the projection lens. Hewlett-Packard's 2005 rear projection (RP) products have such a mirror. They use voice coil actuators to rock the fold mirror back and forth, displacing the projected image between one of two positions. These RP devices have a diamond pixel arrangement on the SLM and function in a similar manner as figure 1's testbed projection system.

Image displacement, sub-frame display, and filter wheel position are synchronized.

5. Artifacts

We have observed wobulation has little effect on perceived field-sequential color artifacts [3].

Wobulated images do not carry as much high spatial frequency information as unwobulated images created by SLMs having pixel counts equal to the addressed resolution of the wobulated system. Wobulated images exhibit a slight softness relative to higher pixel count SLM images.

Wobulation essentially anti-aliases text and line art. In some cases, this slightly degrades image quality. In others, perceived quality is improved. Thin high contrast elements are affected the most.

If a static image is translated across a wobulated display at certain speeds (e.g., dragging a window), the screen door artifact can become visible. Pixels from the first sub-frame in a 2-position system predominately carry information from a particular set of original image pixels. The set is alternating rows and columns of pixels, such as the set of black squares on a checkerboard. The pixels in the second sub-frame predominately carry information from the non-black checkerboard positions.

When a window is translated, it's possible that the second sub-frame from frame *n* and the first sub-frame from frame *n*+1 will be derived from exactly the same set of original image data pixels. This essentially doubles the display time of the sub-frame, possibly allowing the screen door to be seen and causing the movement to appear less smooth than expected.

6. Summary

A novel and cost-effective method of increasing resolution and image quality of digital projection systems has been presented. The technique is based on generating sub-frames of data from each image data frame and projecting these sub-frames in rapid sequence. The sub-frames are spatially offset (shifted) slightly by an opto-mechanical image shifter synchronized with sub-frame projection. Resolution is improved and image artifacts related to pixel fill factor are reduced.

7. Acknowledgements

The authors would like to thank the dozens of HP colleagues that assisted in the development of wobulation.

8. References

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[3] T. Järvenpää, "Measuring Color Breakup of Stationary Images in Field-Sequential-Color Displays," Society of Information Display (SID), 7.2, Seattle, May 23-28, 2004.