Computation of Fresnel holograms and diffraction-specific coherent panoramagrams for full-color holographic displays based on anisotropic leaky-mode modulators

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ABSTRACT

We have previously introduced a computational architecture suitable for driving full-color holographic display systems based around anisotropic leaky-mode modulators; this architecture appropriately handles single-sideband modulation and frequency-division multiplexing of spectral bands that correspond to the independent red, green, and blue color channels in the display output. In this paper, we describe an implementation for driving the MIT/BYU Mark IV holographic display system with such a computational approach, in cases of both pre-computed Fresnel CGHs and real-time, GPU-based diffraction-specific coherent panoramagrams. Real-time holographic images of nearly VGA-resolution (468 lines) are generated via three dual-head NVIDIA GPUs via a CUDA-based implementation that encompasses the requisite orthographic view generation from 3-D data sources, parallel vector-based fringe computation per hogel and per color, single-sideband modulation, and frequency-division multiplexing. We present the first results of this scheme and review the resulting performance metrics.

Keywords: dynamic holographic displays, computational display holography, acousto-optic modulation, integrated optics, single-sideband modulation, wavelength-division multiplexing, GPU computation

1. INTRODUCTION

The MIT/BYU Mark IV holographic video system is a proof-of-concept system for horizontal-parallax only holographic display based upon a novel anisotropic leaky-mode acousto-optic light modulator implemented as a $LiNbO_3$ guided-wave device. This light modulator offers several significant advantages for holographic video displays, most notably the capacity for wavelength-division multiplexing for full-color displays.[1] The wavelength-division multiplexing scheme of the Mark IV display requires the generation of a single analog signal (per channel) containing holographic fringe information for all independent color channels in a frequency-division multiplexed manner.

We have previously introduced a computational architecture for generating fringe signals appropriate for input to anisotropic leaky-mode modulators and display on Mark IV-like displays that handles single-sideband modulation and frequency-division multiplexing of spectral bands corresponding to independent color channels in the display output.[2] In this paper, we describe implementations of this architecture in the generation of pre-computed Fresnel CGHs and real-time diffraction-specific coherent panoramagrams.

2. BACKGROUND

2.1 MIT/BYU Mark IV Holographic Display

The Mark IV holographic video display is built around a one-dimensional anisotropic leaky-mode spatial light modulator, implemented as a guided-wave device on a $LiNbO_3$ substrate. Fig. 1 depicts the structure and function of a single-channel anisotropic leaky-mode modulator. In this modulator, laser light of a particular linear polarization is coupled into an anisotropic waveguide via the use of a coupling prism, at which point the coupled light becomes a guided mode. A surface acoustic wave (SAW) transducer is patterned at one end of the device; when this transducer is excited by an RF signal containing holographic fringe information, it launches a surface acoustic wave along the waveguide. The guided laser

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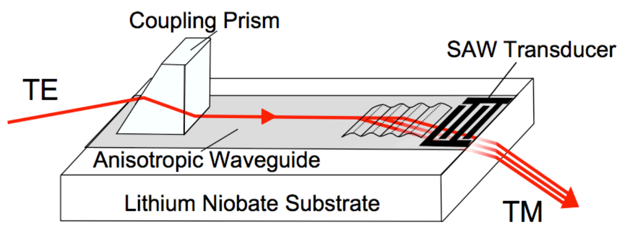

Figure 1. Structure and function of an anisotropic leaky-mode device, implemented as a guided-wave device on a $LiNbO_3$ substrate.

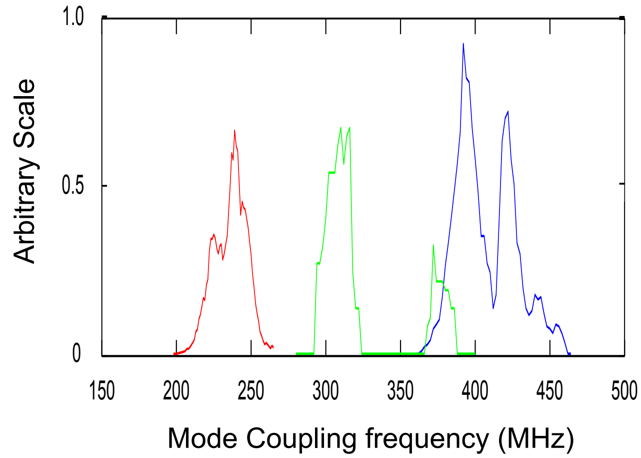

Figure 2. Typical mode-coupling frequency response of an anisotropic leaky-mode modulator, depicting nearly non-overlapping acoustic spectral bands that act exculsively and independently upon red, green, and blue light.

light is incident upon this surface acoustic wave at a nearly collinear angle and experiences Bragg-regime acousto-optic diffraction in accordance with the spatial frequencies present in the acoustic grating. The diffracted light is mode-converted into a leaky mode of an orthogonal polarization and exits the waveguide. Our current devices employed for spatial light modulation employ multiple independent channels, each comprised of an anisotropic waveguide and a SAW transducer. Each independent channel requires its own RF input signal to the SAW transducer. Details on the fabrication process of anisotropic leaky-mode modulator devices have been previously published.[1,3] Mark IV uses an 18-channel modulator.

With appropriate fabrication parameters, anisotropic leaky-mode modulators can be made to allow for the simultaneous and superimposed modulation of red, green, and blue light in a wavelength-division multiplexed fashion. A typical mode-coupling acoustic frequency response from such a modulator is shown in Fig. 2 and depicts nearly non-overlapping acoustic spectral bands that act independently and exclusively upon different wavelengths of incoming light, with the band acting exclusively upon red light at the lower end of the acoustic spectrum followed by those acting upon green and blue at higher acoustic frequency ranges.

The Mark IV display employs 26 discrete vertical steps per horizontal sync pulse; this translates directly into 26 horizontal-parallax only holographic lines per device channel. Viewed in aggregate, Mark IV is capable of delivering 468 total holographic lines in its display output.[4]

2.2 Frequency-Division Multiplexed Fringe Signal Generation

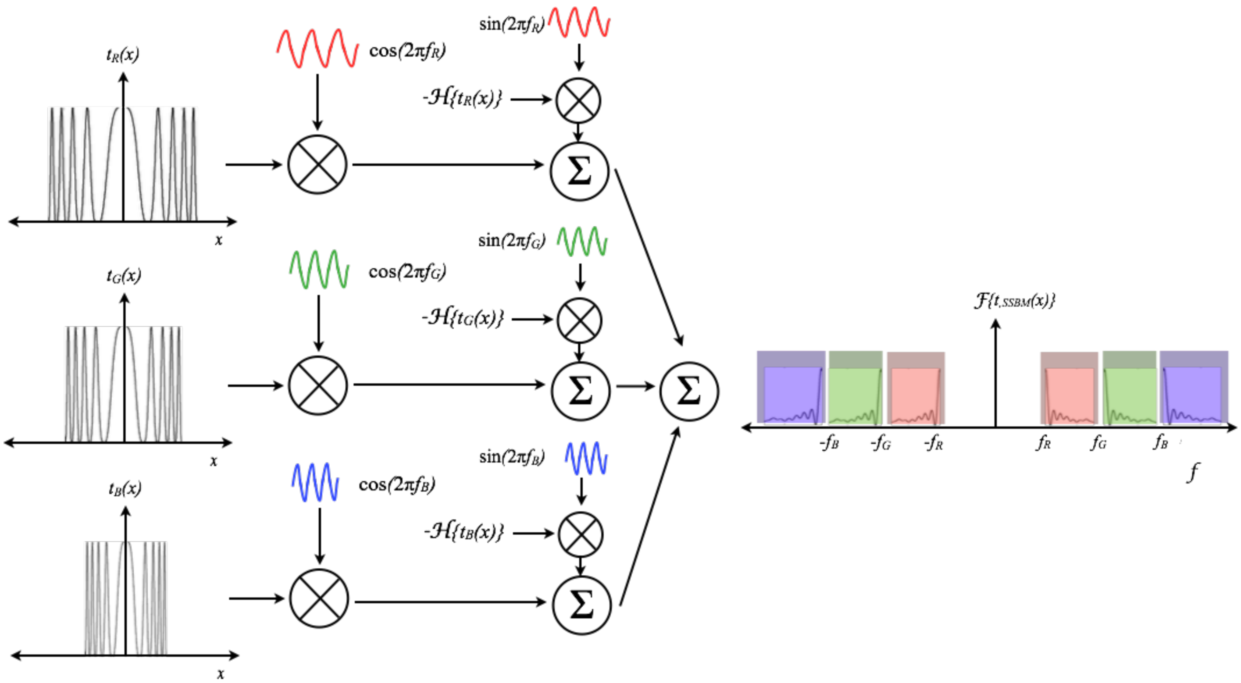

Figure 3. Depiction of single-sideband modulation process and frequency-division multiplexing scheme for generation of appropriate fringe signal for input to Mark IV electronics in the case of a general CGH.

Because of the frequency-division multiplexed nature of the light modulator, the goal in generating fringe signals for input to an anisotropic leaky-mode device is to spectrally match the multiplexed passbands in the mode-coupling frequency response of the device (Fig. 2).[2] With knowledge of the cutoff frequencies per passband, generating *frequency-division multiplexed* (FDM) fringe signals is possible entirely in the computational domain, without having to rely on a separate electronic subsystem. In the case of displaying a generalized full-color hologram, independent sub-holograms can be computed for each of the red, green, and blue color channels of a 3-D scene (i.e., $t_R(x)$, $t_G(x)$, and $t_B(x)$ in Fig. 3). Translating the spectra of these sub-holograms to match the passbands of the device mode-coupling frequency response is accomplished via *single-sideband modulation* (SSBM) as

$$t_{ssb}(x) = t(x)\cos(2\pi f_0 x) - \mathcal{H}\{t(x)\}\sin(2\pi f_0 x) \tag{1}$$

where $t(x)$ is the sub-hologram fringe pattern, $f_0 = N(f_T - f_{LO})/Pw$ is a spatial upconversion frequency (N being the number of pixels per holographic line, f_T the temporal upconversion frequency, f_{LO} is the local oscillator frequency, P the pixel clock rate, and w the width of the hologram plane), and $\mathcal{H}\{t(x)\} = \frac{1}{\pi}\,\text{p.v.}\int_{-\infty}^{\infty}\frac{t(x')}{x-x'}dx'$ is the Hilbert transform of the fringe pattern.[5] To form the composite FDM fringe signals, the SSBM signals for the red, green, and blue color channels are simply summed to generate a Fourier-domain characteristic similar to that in the right side of Fig. 3.

In the case of a diffraction-specific coherent panoramagram,[6,7] recasting the chirped basis functions used in wavefront element computation in a single-sideband modulated closed-form allows for simple computation of the FDM fringe signal.

3. COMPUTATIONAL METHODS

3.1 Frequency-Division Multiplexed Fresnel CGHs

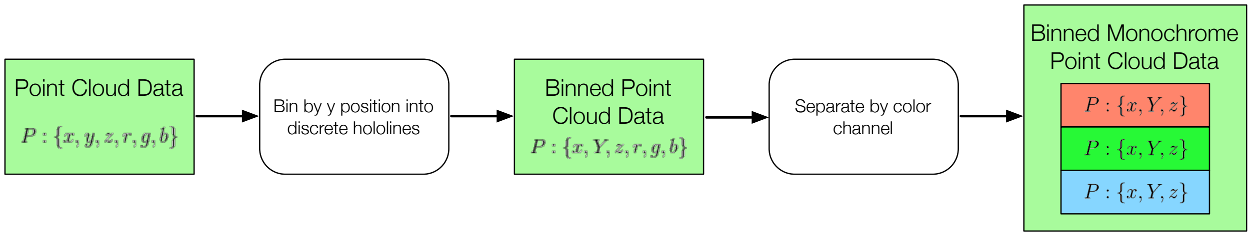

Figure 4. Process flow for generation of monochromatic, hololine-specific point cloud data from full-color, three-dimensional point cloud data. Beginning from 3-space coordinates and RGB information per point, points are binned into 468 discrete y-values. All points in each bin are then separated by color channel into constituent monochromatic points.

Beginning with RGB point cloud data, we depict a method for the generation of Fresnel CGHs for display on the MIT/BYU Mark IV display. Fig. 4 depicts pre-processing on the point cloud data. First, the point cloud data as a set of coordinates and color values $\{x, y, z, r, g, b\}$ is binned into 468 discrete y-values (each corresponding to an independent hololine on the HPO display). The binned point cloud data is a set of coordinates and color values $\{x, Y, z, r, g, b\}$, where Y is a discrete number $Y \in [1, 468]$. Then, this data is separated by color channel as $P_C : \{x, Y, z, c\}$, where C indicates one of the R, G, or B color channels and c is the corresponding color value. The vertically-binned and color-separated point cloud data per bin i can be expressed as $O_i(x, z) = \sum_{j=1}^{N_p} c_j \delta(x - x_j, z - z_j)$, where N_p is the number of points contained in that bin, c_j is the color value of the jth point, $\delta(x, z)$ is a two-dimensional Dirac delta function, and (x_j, z_j) are the coordinates of the jth point.

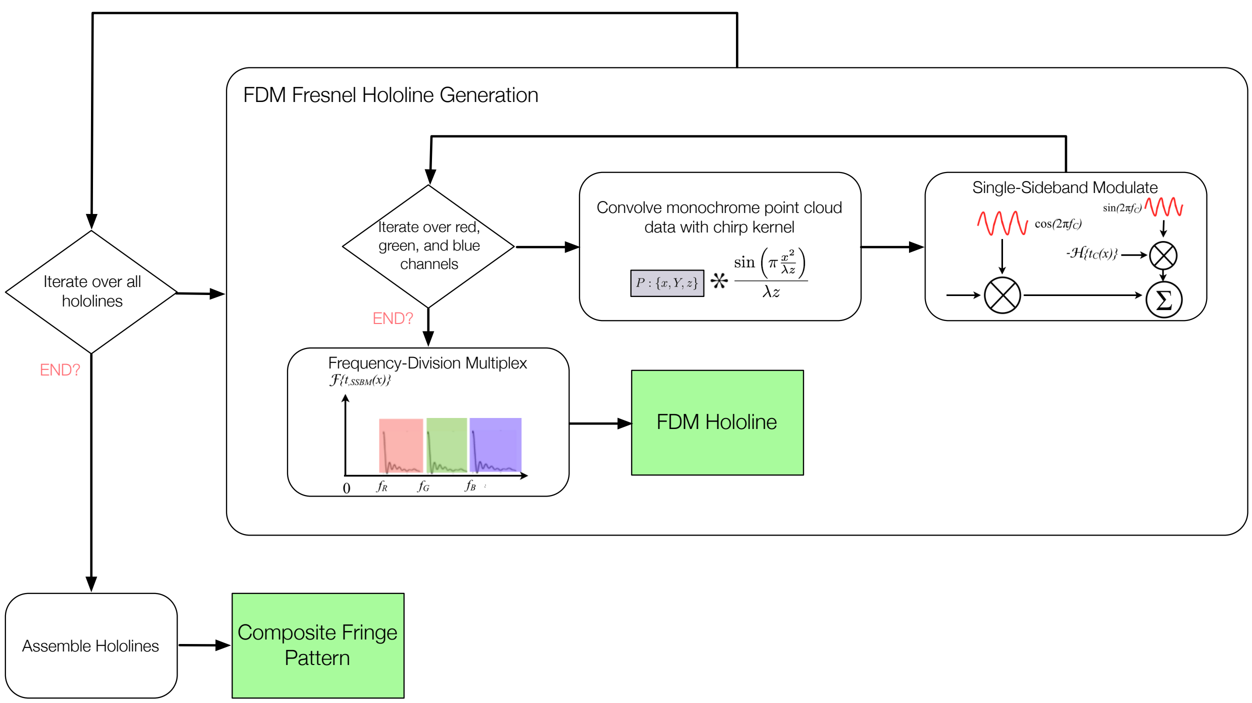

Figure 5. Computational pipeline for generation of Fresnel holograms appropriate for display on anisotropic leaky-mode modulators. Beginning with vertically-binned, color-separated point cloud data, hololines are independently computed via a convolution of all points per bin (i.e., a collection of Dirac delta functions in (x, z) space, each modulated by a brightness value), with a chirp kernel, $h(x) = \sin(\pi \frac{x^2}{\lambda z})/\lambda z$. The resulting convolution is then single-sideband modulated via a Hilbert transform method, and the single-sideband modulated hololines per color channel are summed together to form the composite frequency-division multiplexed hololine.

Fig. 5 depicts the pipeline for computation of the FDM Fresnel holographic fringe pattern. Beginning with the monochromatic, vertically-binned point cloud data corresponding to a color channel, a hololine is computed by:

1. Computing the holographic line resulting from point cloud data from a single vertical bin and a single color channel. This can be described as a convolution of the object point function $O_i(x, z)$ with the kernel

$$h(x) = \frac{\sin\left(\pi \frac{x^2}{\lambda z}\right)}{\lambda z} \tag{2}$$

where λ is the wavelength of the color channel as $t_{i,c}(x) = O_i(x, z) * h(x)$.

2. This color-specific hololine is single-sideband modulated with an upconversion frequency given by $f_0 = N f_T / P w$ via the Hilbert domain method (Eq. 1).

3. The SSBM hololines are generated for each of the three color channels.

4. Finally, the three SSBM hololines are summed to yield the ith FDM Fresnel hololine.

Once all 468 FDM hololines have been computed, they are assembled in sequence to form the composite fringe pattern.

3.2 Frequency-Division Multiplexed Diffraction-Specific Coherent Panoramagrams

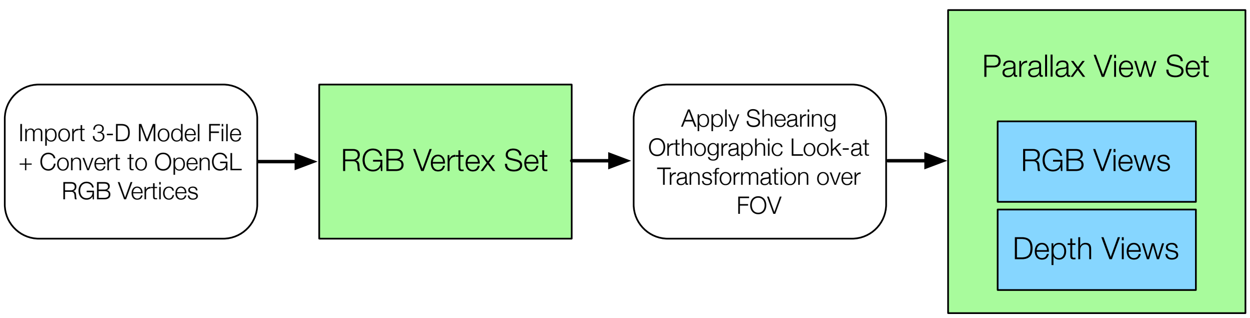

Figure 6. Process flow for generation of orthographic views from 3-D model input in an OpenGL context. 3-D model input is converted to a set of vertices with associated color values, upon which a look-at matrix (corresponding to viewing the scene with a double frustum camera geometry) acts over the desired field of view to generate a set of 16 orthographic RGB views and 16 orthographic depth views.

Beginning with a 3-D model file, Fig. 6 depicts a pipeline for pre-processing this information for generation of a composite FDM diffraction-specific coherent panoramagram fringe signal. First, the 3-D model is converted to a set of vertices with associated RGB values in an OpenGL context. Next, a set of 16 parallax views in both RGB color and depth are generated via a shearing orthographic look-at operation that employs a double-frustum camera geometry.[8]

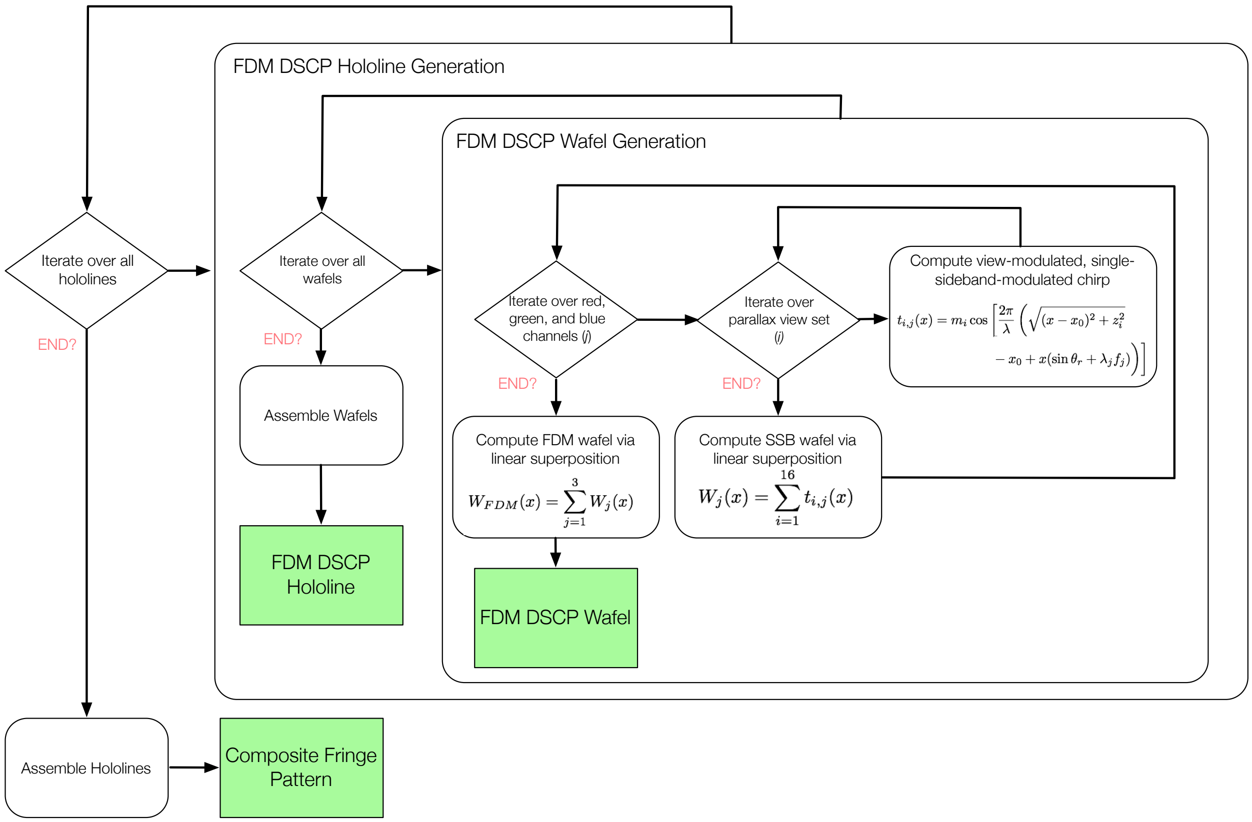

Figure 7. Computational pipeline for generation of diffraction-specific coherent panoramagrams appropriate for display on anisotropic leaky-mode modulators. Beginning with parallax 16-view sets for both color and depth, hololines are independently computed as assemblies of independent wavefront elements ("wafels"). Each wafel is computed via the linear superposition of 16 basis single-sideband modulated chirps, each of which is computed via depth data from one of 16 depth views and modulated by a color value from one of 16 RGB views. Composite FDM wafels are computed via the sum of the SSB wafels for each of the red, green, and blue color channels. FDM wafels are made to abut to form a hololine.

Fig. 7 depicts the pipeline for computation of the FDM DSCP composite holographic fringe pattern. Hololines are comprised of abutting wafels, and each wafel contains angular information corresponding to one spatial position in the hololine. Beginning with the set of parallax views in depth and color, a single wafel is computed by:

1. The process employs the pixels located at the coordinates within the parallax views corresponding to the wafel position within the composite fringe pattern in computing and modulating basis functions. For each color channel $j \in [1, 3]$ and view $i \in [1, 16]$, a view-modulated, single-sideband modulated basis chirp is computed as

$$t_{i,j}(x) = m_i \cos\left[\frac{2\pi}{\lambda}\left(\sqrt{(x-x_0)^2+z_i^2} - x_0 + x(\sin\theta_r + \lambda_j f_j)\right)\right] \tag{3}$$

where $f_j = N f_{jT}/Pw$ is the jth spatial upconversion frequency corresponding to the jth temporal upconversion frequency f_{jT}, x is the spatial position on the composite hololine, x_0 is the wafel center position on the composite hololine, θ_r is the angle of the reconstruction beam relative the hologram plane normal, λ_j is the wavelength of the jth color channel, and (m_i, z_i) are the color and depth values retrieved from the ith parallax views in RGB and depth.

2. After the computation of all 16 view-modulated, single-sideband modulated basis chirps, the SSB wafel per color channel is computed as

$$W_j(x) = \sum_{i=1}^{16} t_{i,j}(x). \tag{4}$$

3. After the computation of SSB wafels for all three color channels, the composite FDM wafel is computed as

$$W_{FDM}(x) = \sum_{j=1}^{3} W_j(x). \tag{5}$$

   Alternatively, the FDM wafel can be expressed as

$$W_{FDM}(x) = \sum_{j=1}^{3} \sum_{i=1}^{16} m_{ij} \cos\left[\frac{2\pi}{\lambda}\left(\sqrt{(x-x_0)^2 + z_i^2} - x_i + x(\sin\theta_r + \lambda_j f_j)\right)\right]. \tag{6}$$

4. After all FDM wafels per hololine are computed, they are assembled in an abutting fashion to form a composite FDM DSCP hololine.

5. After all 468 FDM DSCP hololines are computed, they are assembled to form the composite FDM DSCP fringe pattern.

3.3 GPU-Based Implementation of FDM DSCP

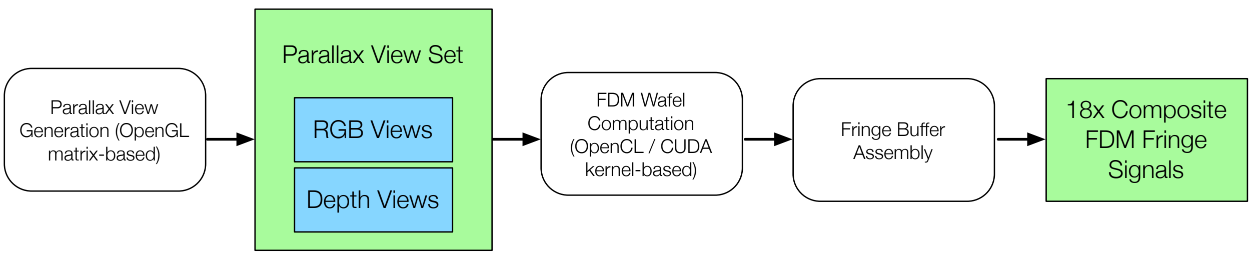

Figure 8. GPU-based pipeline for computation of frequency-division multiplexed fringe signals based on the diffraction-specific coherent panoramagram approach. Orthographic views in RGB and depth are generated in an OpenGL context as used as input for parallel wafel computation, implemented in either CUDA or OpenCL kernels.

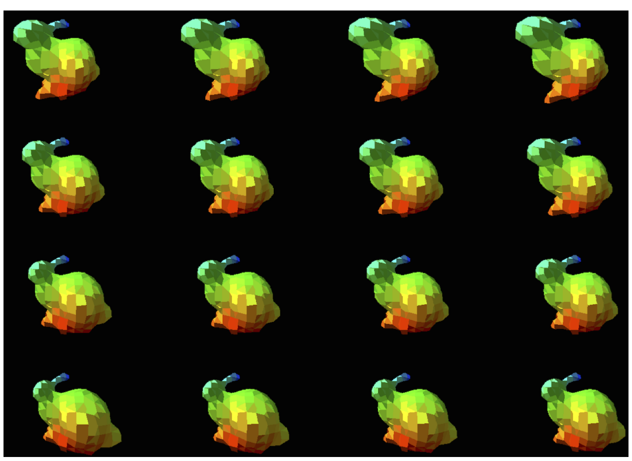

Figure 9. Set of 16 parallax views in RGB generated via a shearing orthographic camera.

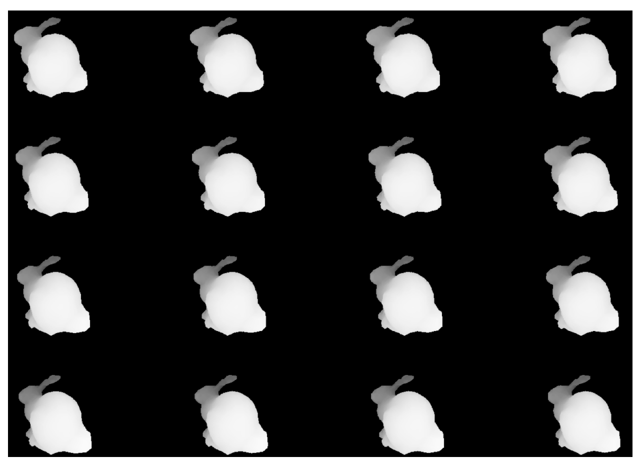

Figure 10. Set of 16 parallax views in depth generated via a shearing orthographic camera.

We have implemented the FDM DSCP algorithm on NVIDIA GPUs via an OpenGL context for orthographic view generation and CUDA/OpenCL kernels for parallel wafel computation and fringe pattern assembly (see Fig. 8). Figs. 9 and 10 depict 16 representative RGB and depth views generated via the shear orthographic look-at operation on a 3-D model of the Stanford Bunny for input to the wafel generation algorithm.

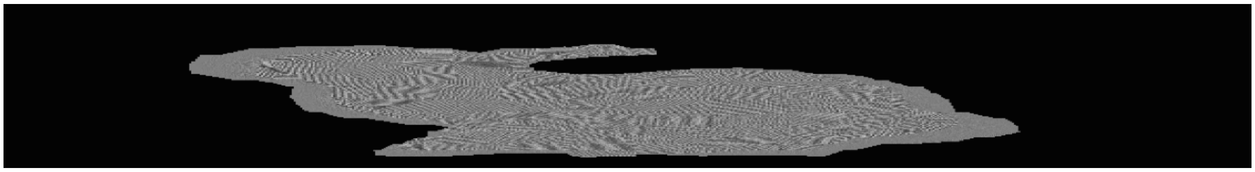

Figure 11. Composite frequency-division multiplexed HPO fringe pattern resulting from the application of the FDM DSCP algorithm on the Stanford Bunny input. The composite fringe pattern is formed via the assembly of 600 wafels per holographic line horizontally and 468 holographic lines vertically. Note that this image was scaled-down by a factor of 100 in the horizontal dimension in order to reveal its shape characteristics.

Employing the pipeline depicted in Fig. 7, an example composite FDM fringe pattern using the diffraction-specific coherent panoramagram algorithm on the input views depicted in Figs. 9 and 10 is shown in Fig. 11. Note the holographic line consisting of 355200 pixels is subdivided into 600 wafel apertures of length 592 pixels each. The composite fringe pattern has dimensions 355200 x 468 pixels, although the image shown in Fig. 11 is down-scaled by a factor of 100 in the horizontal dimension in order to reveal its shape characteristics.

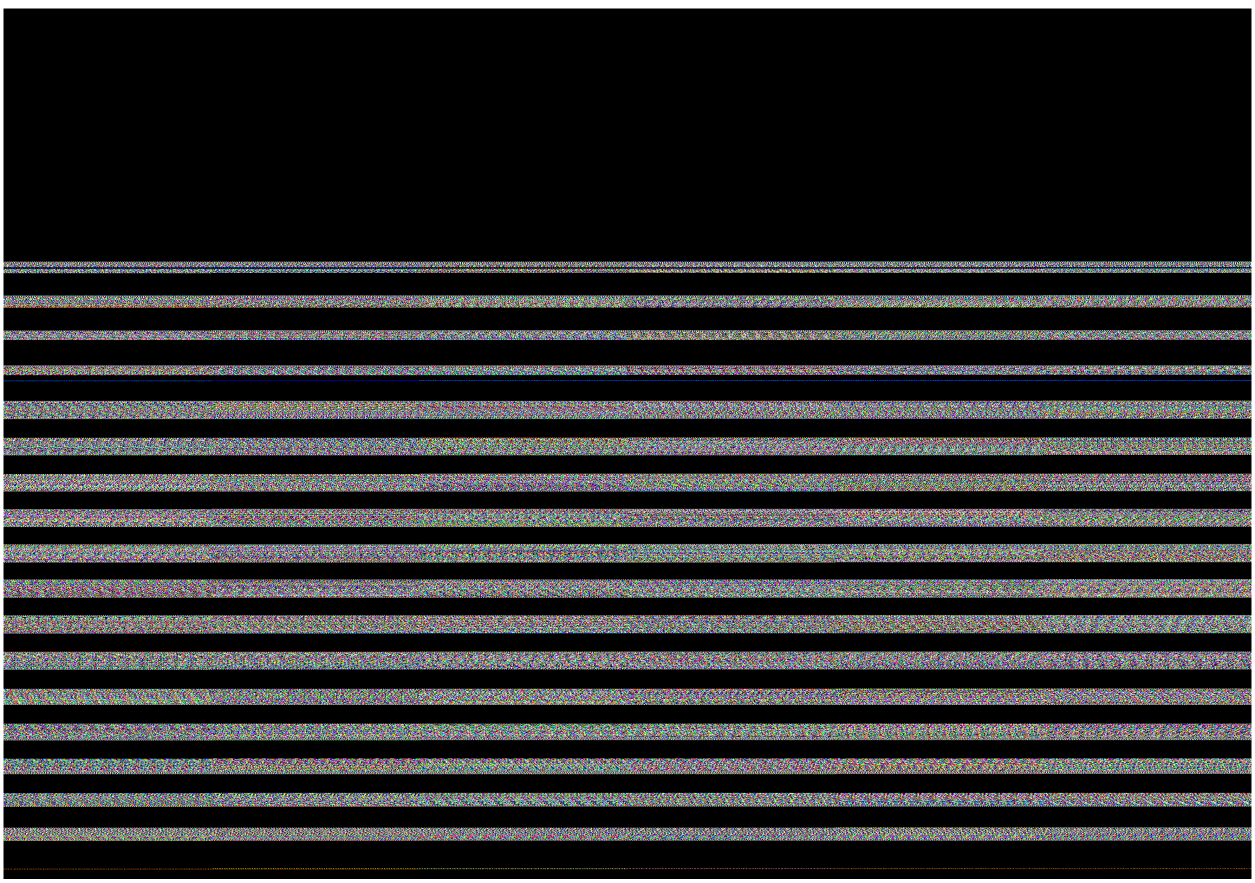

Figure 12. Fringe buffer displayed on the output of one GPU head, containing holographic information for 26 holographic lines for each of three analog channels (corresponding to the nominal red, green, and blue output channels of the GPU).

Fig. 12 depicts an example fringe buffer displayed on the output of one GPU head, comprised of holographic information for 26 holographic lines for each of three analog channels. These three analog channels per fringe buffer correspond to the nominal red, green, and blue output channels of the GPU. In the Mark IV data format, the overall framebuffer has dimensions 3552 x 2476 pixels; this format allows for 26 holographic lines to be displayed in each buffer per nominal GPU color channel (with each holographic line of length 355200 pixels occupying 100 frame lines). In our current computing architecture, 3x dual-head GPUs are used to provide fringe signals to each of the 18 channels in the Mark IV modulator leading to a total of 468 holographic lines in the overall display output.

As currently implemented at the time of this writing, we have demonstrated the generation of 600 wafels for each of the 468 holographic lines in the Mark IV display output from changing 3-D model input at 26 frames per second using a CUDA kernel for parallel FDM wafel generation on an NVIDIA K6000 GPU. The same fringe signal generation using an OpenCL kernel for parallel FDM wafel generation results in an output at 11 frames per second.

4. CONCLUSIONS

We have presented algorithms, offline implementations, and real-time implementations of fringe signal generation appropriate for driving the MIT/BYU Mark IV displays in full-color. We have also demonstrated GPU-based schemes for frequency-division multiplexed wafel generation via the use of OpenCL and CUDA kernels for parallelization. Real-time display of full-color images generated via the fringe signal generation schemes depicted in this paper on the Mark IV display will be depicted in a future publication.

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