53.1: Real-time Binary Hologram Generation for High-quality Video Projection Applications

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Abstract

Presenting visual information using binary-phase holography has a number of advantages over conventional video projection techniques. However, acceptable image quality for video applications has yet to be realised. In addition, the computational complexity of hologram generation has precluded real-time operation. The authors present a new approach to hologram generation and display which allows high-quality images to be projected holographically, in real time.

1. Introduction

Conventional video projectors frequently employ an amplitude-modulating liquid crystal (LC) device as the image display element. A bright white light source is used to illuminate the display, and associated optics are used to magnify and project the image.

Such an architecture has been demonstrated to produce high quality, bright images. However, at least 50% of the incident illumination is absorbed by the front polariser on the LC device. Furthermore, the device forms images by blocking light, resulting in an additional efficiency penalty. The low efficiency of this approach necessitates illumination by an extremely bright source such a halogen bulb, which itself may be less than 10% efficient. As a result, such devices exhibit a wallplug efficiency of at most a few percent. The bulky optics required for projection of large, distortion-free images also make miniaturisation difficult.

The challenges associated with such display architectures have motivated the investigation of an alternative approach, which utilises a phase-modulating holographic display element in combination with a coherent light source to produce images by diffraction rather than projection. As this approach requires no polarisers and forms images by routing, rather than blocking light, substantial efficiency gains can be realised. Furthermore, a holographic display architecture readily lends itself to miniaturisation as the requirement for large projection lenses is potentially obviated.

2. Computer-generated holography for display applications

Figure 1 shows a dynamically-addressable display element with pixel size Δ, placed behind a lens of focal length f and illuminated with coherent light of wavelength λ. Such a display device is termed a spatial light modulator (SLM). A standard result from Fourier optics states that the image formed in the focal plane of the lens - termed the replay field (RPF) - will be the Fourier transform of the pattern on the display [1], with size $f\lambda/\Delta$.

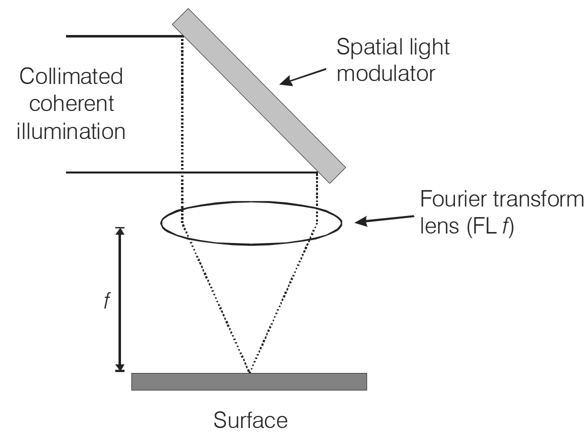

Figure 1 - A simple holographic display architecture

The basis of computational holography is the calculation of a suitable hologram pattern to display on the SLM that, when illuminated by coherent light, forms a desired RPF image in the focal plane. For our application, we utilise a ferroelectric liquid crystal on silicon (LCOS) device, chosen for its high frame rate operation (greater than 10,000 frames/sec), excellent contrast, and high fill factor. Such a device is inherently binary and phase-only, due to the nature of the electro-optic effect of the ferroelectric material. As a result, the problem is that of the calculation of suitable binary-phase-only holograms to form desired structure in the RPF.

3. Issues with conventional approaches

Algorithms to calculate appropriate binary-phase holograms for the generation of desired structure in the RPF are well-established, and include direct binary search (DBS) and simulated annealing (SA) [2]. While such approaches are suitable for production of very simple RPF structure such as routing patterns for optical telecommunications switches [3], the algorithms are orders of magnitude too slow to produce video-resolution holograms in real time. In addition, the images they generate are of inadequate quality for video applications. Gerchberg-Saxton (G-S) [4] represents an alternative approach which is substantially faster, but poor resultant image quality renders it of little use in this application.

To date, the authors are not aware of any approach to holographic display that generates, in real time, high-resolution binary-phase holograms that form images of sufficient quality for video projection.

4. A novel approach to hologram generation and display

The limitations of the algorithms discussed in the previous section have motivated the development of a lateral approach to hologram generation and display that fulfils the dual requirement of high

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quality resultant images formed by holograms that are calculated in real time. The first of these points is addressed by determining the precise correlation between the statistical parameters of noise encountered in holographically-generated images and the human perception thereof.

4.1 Perception of noise in holographically-generated images

The factors governing human subjective perception of noise in images are too numerous and detailed to cover in this paper. Instead, we concentrate on the relative perceptual importance of the statistical parameters of additive noise encountered specifically in binary-phase holographic replay. We have shown that the probability density function of such noise has a Rician distribution, specified by parameters V and S^2 which relate to mean μ and variance σ^2 respectively. In order to characterise the perceptual degradation of image quality with respect to variation in these noise parameters, we constructed a suitable psychometric test.

The test consisted of the sequential presentation to the subject of 300 stimuli, each consisting of pairs of images. Each image in the pair is formed from the same base image, which is generated randomly from a set of basis shapes at random positions with random intensities. Independent additive Rician noise fields were added to the left and right images, with each field in the pair having different distribution parameters. Such an example stimulus is shown in Figure 2. To give the subject the impression of a video image, the stimulus is updated with newly-generated noise fields 20 times a second, although the distribution parameters are kept the same.

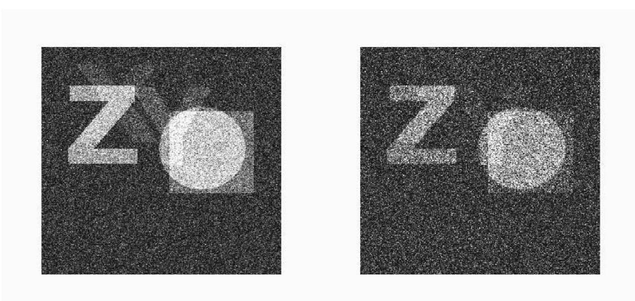

Figure 2 - Example psychometric test stimulus

The test format used was that of the three-alternative forced choice (3AFC) paradigm [5], in which the subject is instructed to express a preference for the left or the right field based on their own subjective interpretation of quality, but is also offered a third option to indicate if they have no preference. Although the user clearly needs time to make a decision and indicate their choice, a time limit of 4 seconds per sample was imposed to ensure that the choice was made instinctively, as it would be when observing a typical video stream with regularly changing content. In our initial test, we obtained 2400 samples.

The results were analysed by constructing a scatter plot (Figure 3) indicating, for each sample, the user's preference. Each sample was plotted on axes of mean difference and variance difference between the left and right fields, showing the positions of the "left preferred", "right preferred" and "cannot tell" regions in mean-variance space. Boundaries of best fit between these three regions were then constructed using a linear least-squares measure.

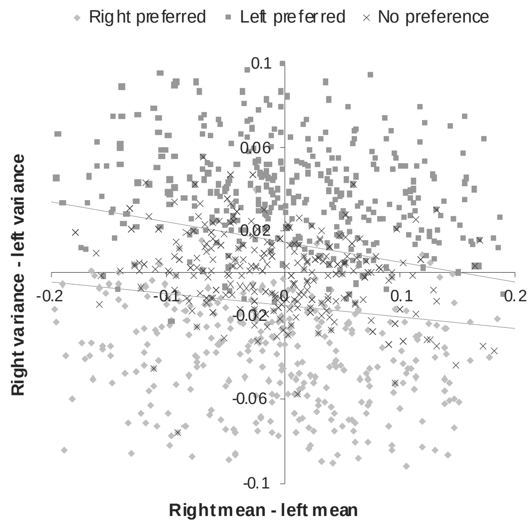

Figure 3 - Psychometric test results

We conclude from the dominant horizontal component in the boundary lines that noise variance is far more significant than noise mean as a determinant of the perceptual significance of noise. This experiment therefore suggests that a hologram generation approach optimised for video-style images must produce replay fields with minimal noise variance σ^2. By contrast, conventional algorithms can be shown to attempt to minimise noise energy $\mu^2 + \sigma^2$.

4.2 The one-step phase retrieval approach

We have developed a novel approach to hologram generation and display which allows the rapid (better than real time) computation of holograms with the required noise properties. Our algorithm – one-step phase retrieval (OSPR) – requires specification of a parameter N which controls the extent of variance minimisation at the expense of computation time. From the results of the psychometric test, we expect perceived image quality to increase concomitantly with N.

In order to implement the design in hardware, an FPGA (field-programmable gate array) board was chosen as this was deemed to be the most easily customisable solution that would allow maximum parallelisation. FPGA implementations also lend themselves to the future development of an ASIC (application-specific integrated circuit) device that can be produced easily in bulk.

We have found that the best compromise between video quality and speed of operation occurs with N = 32. Such holograms for full frames of size 512x512 could be generated in around 41ms, thereby delivering a frame rate of 24.4 fps and giving excellent reproduction quality for video applications. While acceptable for a monochrome demonstrator, for full-colour video, two more of these machines would have to be placed in parallel. Work is currently being done to fit these in the Virtex-II device.

Such an approach has been found to yield holograms approximately 10^6 times faster than a standard implementation of DBS on a 2 GHz Athlon PC.

4.3 Experimental results

As an initial demonstration of the efficacy of this approach in comparison with DBS, we employed a 320 x 320 pixel transmissive ferroelectric SLM device (with 80µm pixel pitch) from CRL Opto. A low-resolution device was utilised initially as computation of higher-resolution holograms using DBS is prohibitively slow.

Coherent illumination at 646nm from a 1mW laser diode was employed in our demonstration system. A Fourier transform lens of focal length f = 250mm was used to form the replay field, and a CMOS camera of active area 25mm × 25mm, with exposure time set to 40ms to mimic the 25 Hz temporal bandwidth of the eye, was used to image the replay fields produced. Since the viewing angle of the hologram is small due to the large pixels on the device (around 0.5 degrees, corresponding to an RPF size of only 2mm × 2mm), an objective lens was used to magnify the Fourier image plane onto the CMOS sensor element. Results are given in Figure 4.

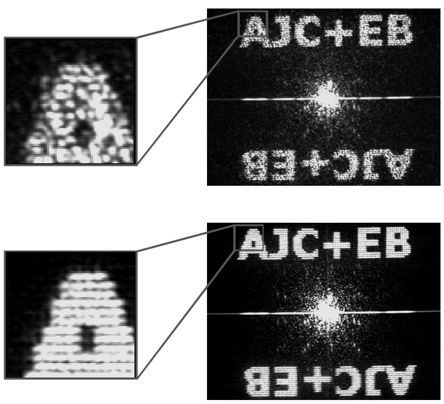

Figure 4 - Experimental comparison of replay fields generated by DBS (top) and OSPR with *N* = 32 (bottom)

As can be seen, OSPR offers a substantial improvement in pixel definition, image uniformity and perceived noise level compared to an image generated by a single hologram calculated using DBS.

A further experiment was carried to demonstrate real-time holographic replay of high-resolution video. In this case, DBS cannot be used for performance and quality reasons. Instead, OSPR was employed with N = 24.

A 1280 x 1024 pixel binary-phase ferroelectric LCOS SLM with a pixel pitch of 13.62µm, also manufactured by CRL Opto, was used in the reflective-geometry set-up of Figure 1. The reduced pixel size of this device obviates the need for an objective lens. The replay fields formed were recorded with a Casio EX-Z3 digital camera. Figure 5 shows an example replay field produced by this set-up, demonstrating high-fidelity reproduction of continuous-tone images using binary-phase holograms. Note that the apparent graininess in the image is caused by the long exposure time necessary to record the image in low light conditions. The actual image quality is better than the photograph suggests.

Figure 5 - Example replay field produced using 1280 x 1024 binary holograms using OSPR (*N* = 24)

5. Conclusion

The authors have developed and implemented a new approach, termed OSPR, for the generation of 2D binary-phase Fourier holograms that is based on a metric, determined psychometrically, that is far more suited to human vision than the conventional mean-squared error measure. We have demonstrated experimentally that the RPFs produced by the holograms generated by OSPR exhibit a substantial improvement in quality, and a reduction in computation time on the scale of orders of magnitude, compared to other commonly utilised algorithms such as DBS.

6. Acknowledgments

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