Efficient compression of digital holograms for Internet transmission of three-dimensional images

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Digital holography[1,2] is one of several possible techniques for three-dimensional (3D) imaging.[3] Multiple perspectives of a 3D object can be recorded optically, in parallel, and stored together as a single complex-valued digital hologram. Although the capabilities of holography have been known for many decades, digital holography has seen renewed interest with the recent development of megapixel digital sensors with high spatial resolution and dynamic range. We record digital holograms using a technique called phase-shift interferometry.[1,4] Each hologram encodes multiple views of the object from a small range of angles. As with conventional holography,[5] a particular view of the object can be reconstructed by extracting the appropriate window of pixels from the hologram and applying a numerical propagation technique.[1,2] A real-time optical reconstruction technique has also been demonstrated.[6]

Our holograms have dimensions 2028×2044 pixels and in their native format require 16 bytes for each real-imaginary pair. We would like to compress these holograms for more efficient storage and transmission. Hologram compression differs to image compression principally because our holograms store 3D information in complex-valued pixels, and secondly because of the inherent speckle content, which gives the holograms a white-noise appearance. It is not a straightforward procedure to remove the holographic speckle because it actually carries 3D information. The noisy appearance of digital holograms causes lossless data compression techniques to perform poorly.[7] The use of lossy compression techniques seems essential. This introduces a third reason why compression of digital holograms differs to compression of digital images; a change locally in a digital hologram will, in theory, affect the whole reconstructed object. Furthermore, compression losses introduced into the hologram itself might not be significant. We are interested instead in how compression losses affect subsequent object reconstruction, range of viewing angles, and so on.

In these experiments we quantize the holograms. By reducing the number of possible values available to each pixel we reduce the number of bits required to describe it. Compression will permit digital holograms to be stored more efficiently. However, in order to be useful for a real-time 3D object reconstruction system, the compression strategies must be shown to admit efficient algorithms that make it advantageous to spend time compressing and decompressing rather than simply transmitting the original data. A client-server application was developed to quantify the gains in transmission time due to compression. The application and compression algorithms were written with Java™ (Sun Microsystems, Inc). This allowed us to develop a platform-independent environment for experimentation over the Internet. For the experiments, the web server was deployed on a Sparc Ultra in Maynooth, Ireland, and was accessed by a client machine in Connecticut, USA. For several degrees of quantization, and several hologram window sizes, the client made requests to the server. The server extracted the appropriate window from the hologram, compressed the pixels, and transmitted the compressed data along with timing information (see Fig. 1). The client decompressed the data. Speedup s was calculated from $s = t_{\mathrm{u}}/(c + t_{\mathrm{c}} + d)$, where t_{u} and t_{c} are the uncompressed and compressed transmission times, respectively, and c and d are the times to compress and decompress, respectively. The results are shown in Fig. 2(a). For windows of size 64×64 pixels, or greater, there is significant speedup (over 2.5) for quantizations of 8 bits or lower. This speedup rises to over 20 for 512×512 pixel windows.

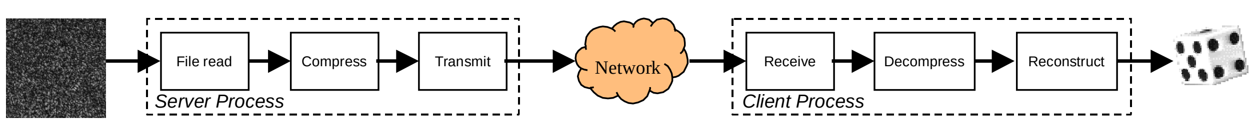
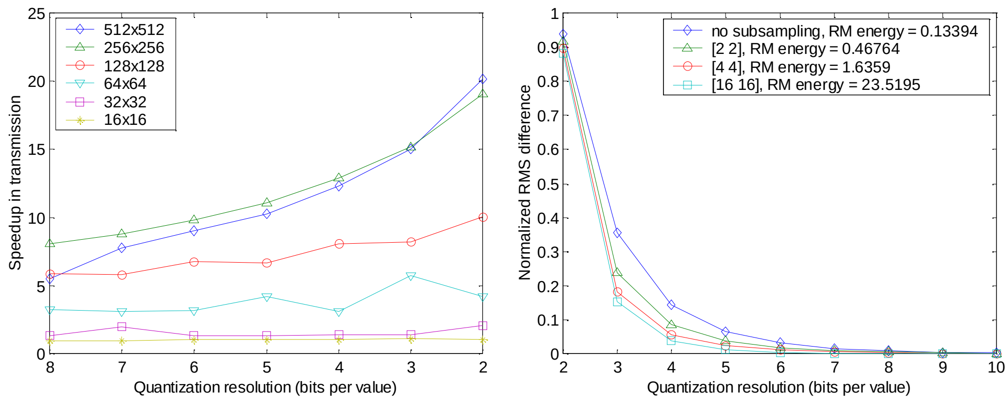
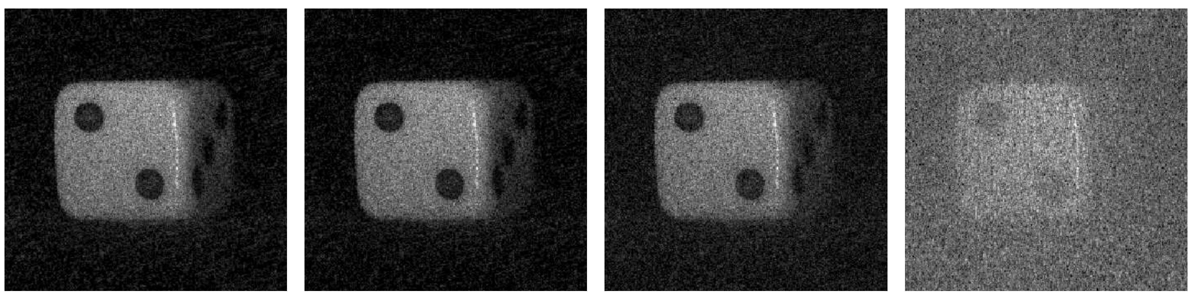


Fig. 1: Sequence of operations from server-side hologram storage to client-side object reconstruction.



(a) (b)

Fig. 2: Quantization experiments: (a) speedup relative to the uncompressed hologram, for various hologram window sizes, and (b) NRMS difference in the reconstructed intensity plotted against number of bits in each of the hologram's real and imaginary values, for various degrees of subsampling.



(a) (b) (c) (d)

Fig. 3: Reconstructed views (with 4×4 subsampling) from a 1024×1024 pixel hologram stored with different quantization resolutions: (a) no quantization, (b) 4 bits, (c) 3 bits, (d) 2 bits of resolution in each real and imaginary value.

The objects were then reconstructed from the hologram data and evaluated in terms of normalized RMS (NRMS) difference. In order to lessen the effects of speckle we examine only intensity in the reconstruction plane and apply a subsampling operation. Here, $n \times n$ subsampling means that nonoverlapping blocks of $n \times n$ intensity values are integrated to a single value. Figure 2(b) shows a plot of NRMS difference against number of bits per data value for a hologram of a die, for various degrees of subsampling. Figure 3 shows reconstructed object intensities of the die for selected quantization resolutions. Note that quantization at 4 bits (with 4×4 subsampling) reveals little visible loss in image quality, and a moderate NRMS error of 0.056. This level of quantization corresponds to a compression rate of 16. Incorporating the compression/decompression delays we still observe a speedup of over 12 for window sizes of 256×256 pixels or greater.

Our testing environment can be accessed at `http://hologram.cs.may.ie/leos2002/hologram.html` . The first two authors acknowledge support from Enterprise Ireland, Department of Electrical and Computer Engineering at University of Connecticut, and Department of Computer Science at N.U.I. Maynooth.

References

[1] I. Yamaguchi and T. Zhang, "Phase-shifting digital holography," *Opt. Lett.* **22**, 1268–1270, 1997.

[2] B. Javidi and E. Tajahuerce, "Three-dimensional object recognition by use of digital holography," *Opt. Lett.* **25**, 610–612, 2000.

[3] B. Javidi and F. Okano, eds., *Three-Dimensional Television, Video, and Display Technology*, Springer, 2002.

[4] J. H. Bruning, D. R. Herriott, J. E. Gallagher, D. P. Rosenfeld, A. D. White, and D. J. Brangaccio, "Digital wavefront measuring interferometer for testing optical surfaces and lenses," *Appl. Opt.* **13**, 2693–2703, 1974.

[5] H. J. Caulfield, ed., *Handbook of Optical Holography*, Academic Press, New York, 1979.

[6] O. Matoba, T. J. Naughton, Y. Frauel, N. Bertaux, and B. Javidi, "Real-time three-dimensional object reconstruction using a phase-encoded digital hologram," *Appl. Opt.* To appear.

[7] T. J. Naughton, Y. Frauel, B. Javidi, and E. Tajahuerce, "Compression of digital holograms for three-dimensional object reconstruction and recognition," *Appl. Opt.* **41**, 4124–4132, 2002.