Chapter 9

Conclusion

Diffraction-specific fringe computation has been designed, implemented, and used to generate complex holographic images for real-time display. The discretization of space and spatial frequency in a holographic pattern has yielded this faster, more direct method of computation. By treating a hologram as an array of hogels, the computational process is streamlined and generalized. Although it is a two-step process, diffraction-specific computation uses computing resources more efficiently than traditional interference-based methods. The intermediate diffraction specifications (hogel vectors) can be transmitted, stored, and manipulated analogous to 2-D image processing.

Early attempts to eliminate the four inherent problems of traditional interference-based computation led to the bipolar intensity method and the linear summation of precomputed basis fringes. As described in Chapter 3, the bipolar intensity method eliminated the noise components inherent to traditional interference-based computation, but did not provide a means for bandwidth compression. The use of precomputed fringes provided dramatic speed increases, and enabled the first-ever interactive computation of holographic images. But bipolar intensity computation was still fundamentally an interference-based approach. Computation followed an equation that is derived from the process of interference.

Diffraction-specific computation automatically eliminates the noise components found in traditional interference-based computation. It also provides a direct means of incorporating higher-level, non-analytical image elements. More important, it increases speed and allows for two diffraction-specific holographic encoding schemes. The two holographic encoding schemes born of diffraction-specific computation allow a bandwidth compression ratio of 16 times without severely degrading image fidelity. The use of diffraction-specific holographic encoding eliminates transmission bottlenecks caused by the enormous bandwidth requirements of traditionally computed holographic fringes.

Hogel-vector encoding and fringelet encoding are direct-encoding schemes. They generate the encoded fringe directly. As a result, the total time to compute them and to decode them was far less than the time to compute fringes directly. Therefore, not only are these methods useful for bandwidth compression, but they also provide a superior means of generating holographic fringes – even if no bandwidth bottleneck exists.

Computation speeds are increased, in the case of fringelet encoding and decoding, by a factor of over 100 due to the reduced number of calculations per fringe sample. Already, fringelet encoding allows for computation of complicated image scenes in under 10 s. The implementation of fringelet decoding in simple specialized hardware or in optical systems should allow for another order of magnitude increase in speed. Fringelet decoding is fast and easy, so it can be incorporated into an output framebuffer card. In such a case, there was no longer a bandwidth bottleneck in a holovideo display system. The full fringe pattern never exists until it was generated on-the-fly by the output module - each hololine as it is needed. This specialized fringelet decoding can be implemented in digital or analog electronic hardware. However, the most promising application of specialized fringelet decoding is an optical decoding scheme in which the holovideo display is specially constructed to perform the simple fringelet decoding step. Such a “fringelet display” may achieve an 8-fold increase in image volume size without increasing the requirements on computation or on electronics hardware.

Another important result of these novel holographic encoding techniques is the three-way trade-off between bandwidth, image resolution, and image depth. For example, given an upper limit on the amount of blur that is imperceptible by the viewer, a finite bandwidth limits the depth of the image. The conclusion is simply this: 3-D is more difficult than 2-D. This observation is expected, since a 3-D image contains more visual information than does a 2-D image. The bandwidth of an encoded holographic fringe representing a softball-sized image is still roughly a factor of 100 times larger than the equivalent size 2-D image. If holographic images need only to be flat, then higher achievable compression ratios reduce the bandwidth to be roughly equal to the 2-D image case. If the image must be very deep, then lower compression ratios must be used lest image quality should suffer. However, as long as a holovideo imaging system is not required to produce images with infinite depth, holographic encoding can provide bandwidth compression.

The engineering trade-off analysis of Section 7.3 is a powerful result. This is the first time that the analysis of a holographic system has resulted in a simple expression relating the fundamental system parameters of bandwidth, image resolution, maximum image depth, and viewing zone size. More significant is the result that diffraction-specific holographic encoding enables a reduction of bandwidth to roughly match the useful visual content of an image. This accomplishment makes diffraction-specific computation the first “visual-bandwidth holography.” Diffraction-specific holographic encoding has closed the gap between the amount of information the human visual system can utilize and the huge amount of information required to effect holographic diffraction. For the first time, holographic fringe patterns can be encoded and manipulated without being bound to the enormous bandwidths required by the physics of the diffraction of light. Instead, a stream of holographic information contains the same amount of visually useful information as does the image. Bandwidth is determined by the abilities of the human visual system, not by the physics of the diffraction of light.

By making holographic computation faster and more practical, diffraction-specific computation promises to create many applications for holovideo. The encoding schemes – particularly hogel-vector encoding – allows for the manipulation of encoded fringes using techniques that are similar to existing (2-D) image processing techniques. For the first time, encoded holographic fringes can be treated along with 2-D image data and other digital information. Diffraction-specific fringe computation has made holographic information more miscible with digital information from video, audio, images, text, etc. The new medium of electro-holography can be integrated into digital multimedia technologies. Holovideo is, after all, a genuinely digital medium. Unlike photography, video, or optical holography, which are essentially analog media, holovideo was invented as a digital medium. Its digital nature makes it an intensively computational medium; diffraction-specific computation minimizes the computation requirements and makes holovideo compatible with other digital media.

Diffraction-specific computation, though invented for real-time interactive holovideo, can be applied to other holographic applications. For example, fringes generated using diffraction-specific computation can be recorded onto film to produce static holographic images. (As part of the debugging process in this thesis research, computed fringes were often printed (using a 600 dots/inch laser printer) directly onto a transparency. These fringes created 3-D, sometimes full-parallax images.) The “fringe printer” approach to holographic hardcopy would require that large fringe patterns be computed on relatively standard computational platforms. In this case, diffraction-specific computation could provide the advantages of speed and bandwidth reduction. A type of holographic hardcopy called binary optics[39] records computed fringes in various optical materials using microlithography. Again, diffraction-specific computation provides a means for rapid, flexible fringe computation. Whether by printing, photoreduction, or binary optics techniques, hardcopy holograms can be used as holographic optical elements (HOEs) that can be used as complex optical components. Finally, the engineering trade-offs of a holographic memory system may require the use of diffraction-specific holographic encoding to make the most efficient use of system components. The same may be true in holographic metrology.

An important application of diffraction-specific holographic encoding is in the storage of holographic information. Already, HPO fringes have been reduced by a factor of 16, and full-parallax fringes can be encoded for a bandwidth compression of 256. Further “second-order” encoding, based on the statistical correlations among hogel-vector components should allow for additional reduction in required bandwidth. Sufficient compression may allow holographic movies to be recorded on digital media and transmitted over high-bandwidth networks or television cable.

One missing piece of the holovideo pipeline is an input device. To create a true “televisual” medium, holovideo displays must have a source of 3-D descriptions of real scenes. Work being performed at the MIT Media Lab involves developing an “intelligent camera” that sees not just patches of light and color but instead derives the 3-D structure of a scene[69], paralleling the behavior of the human visual system. Once a 3-D model of a scene is extracted it is well suited to be converted into holographic fringes for real-time display using diffraction-specific computation.

As computation power increases and as spatial light modulation technologies improve, holovideo is likely to find applications in visualization, education, design, entertainment, and communication. Most of these applications require interactivity. Holographic fringes must be computed in negligible time so that the user is only aware of the visible incarnation of the scene, and not the many layers of processing and calculation within the holovideo system. Diffraction-specific computation promises to provide increases in speed and manipulability as the size of the image volume increases and the variety of content grows.