Available online at www.sciencedirect.com
ScienceDirect
Signal Processing: *Image Communication* 22 (2007) 169–177
SIGNAL PROCESSING: IMAGE COMMUNICATION
www.elsevier.com/locate/image

Signal processing issues in diffraction and holographic 3DTV

Levent Onural*, Haldun M. Ozaktas

Department of Electrical and Electronics Engineering, Bilkent University, TR-06800 Bilkent, Ankara, Turkey

Received 18 November 2006; accepted 29 November 2006

Abstract

Image capture and image display will most likely be decoupled in future 3DTV systems. Due to the need to convert abstract representations of 3D images to display driver signals, and to explicitly consider optical diffraction and propagation effects, it is expected that signal processing issues will be of fundamental importance in 3DTV systems. Since diffraction between two parallel planes can be represented as a 2D linear shift-invariant system, various signal processing techniques naturally play an important role. Diffraction between tilted planes can also be modeled as a relatively simple system, leading to efficient discrete computations. Two fundamental problems are digital computation of the optical field arising from a 3D object, and finding the driver signals for a given optical display device which will then generate a desired optical field in space. The discretization of optical signals leads to several interesting issues; for example, it is possible to violate the Nyquist rate while sampling, but still achieve full reconstruction. The fractional Fourier transform is another signal processing tool which finds applications in optical wave propagation.

Keywords: Diffraction; Holography; 3DTV; Sampling; Fractional Fourier transform

1. Introduction

Regardless of the algorithmic, representational, and technological choices made for the acquisition, transmission, and display of three-dimensional (3D) visual signals, optics is expected to play a more important role in holographic 3D television (3DTV) than it does in conventional display technologies such as cathode ray tubes and liquid crystal displays, or cinematic projection. This is because the creation of a 3D image, or the illusion of it, depends on the manipulation of light for the purpose of synthesizing desired spatial light distributions. The analyses of the underlying processes will almost certainly involve explicit consideration of diffraction and related phenomena.

The image capture and image display steps will most likely be decoupled in future 3DTV systems. The captured 3D scene and object information will be stored or transmitted in convenient forms. Then the viewer at the display-end will access the abstract 3D information in an interactive fashion. Finally, the abstract data will be converted to signals that will drive the optical display.

As a consequence of this decoupled approach and the need to convert abstract representations to driver signals, as well as the need to explicitly consider diffraction and propagation effects, it is expected that signal processing issues will play a fundamental role in 3DTV systems. The purpose of this paper is to identify and revisit some of the key

*Corresponding author.
E-mail address: onural@bilkent.edu.tr (L. Onural).

0923-5965/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.image.2006.11.010

signal processing issues in holographic 3DTV. The formulation of diffraction phenomena, forward and inverse problems in holographic 3DTV, discretization issues, and the use of the fractional Fourier transform are the main subjects covered in this paper.

2. Relationships between diffraction and basic signal processing tools

2.1. Review of diffraction from a systems point of view

It is well known that scalar monochromatic diffraction in homogeneous media can be exactly represented as a linear shift-invariant (LSI) system [7]. Based on the well-established plane-wave decomposition technique, which is equivalent to Fourier decomposition, we can write

$$\psi_{2D_Z}(x,y) \triangleq \psi(x,y,Z) = \frac{1}{4\pi^2}\iint_{k_x^2+k_y^2\leqslant k^2} T(k_x,k_y) \times \exp[jZ(k^2-k_x^2-k_y^2)^{1/2}] \times \exp[j(k_x x + k_y y)]\,dk_x\,dk_y, \quad (1)$$

where $\psi(x,y,z)$ is the 3D coherent optical field, and $\psi_{2D_Z}(x,y)$ is its 2D cross section at $z=Z$. Since only the positive square-root is included in the superposition above, it is implied that the plane-wave components are propagating along the positive z-direction. Furthermore, only the propagating waves are included in the superposition, and therefore, the evanescent wave components are assumed to be zero. The output function $\psi_{2D_Z}(x,y)$ is the diffraction pattern over a planar 2D surface, arising from an input object transparency mask $t(x,y)$ located at $z=0$. $T(k_x,k_y)$ is the Fourier transform of $t(x,y)$. Restriction of the superposition only to propagating waves and the corresponding restriction of the domain of integration to the indicated circle imply that the mask $t(x,y)$ is a low-pass function, and therefore, does not generate any evanescent wave components. Incidentally, this is always the case when there is no physical mask, but the 2D field $t(x,y)$ is obtained simply by taking the cross section of a 3D field which is composed of propagating waves. k_x and k_y are the spatial frequencies along the x and y axes, respectively. The monochromatic light wavelength is λ, and $k=2\pi/\lambda$. Therefore, the transfer function of the 2D LSI system is $\exp[jZ(k^2-k_x^2-k_y^2)^{1/2}]$. Surprisingly, it is quite difficult to find the inverse Fourier transform of this function in texts or tables. However, it has been proven by Sherman [29] that the inverse Fourier transform (i.e., the impulse response of the system representing the diffraction of light) is the kernel of the well-known first Rayleigh–Sommerfeld solution [7]. For distances Z, which are large compared to the wavelength, the impulse response reduces to the well-known kernel associated with a spherical wave emanating from a point source:

$$h_Z(x,y) \approx \frac{Z}{j\lambda(x^2+y^2+Z^2)}\exp\left[j\frac{2\pi}{\lambda}(x^2+y^2+Z^2)^{1/2}\right]. \quad (2)$$

We can rewrite Eq. (1) compactly as

$$\psi_{2D_Z}(x,y) = \mathscr{F}^{-1}\left\{\mathscr{F}\{t(x,y)\} \times \exp[jZ(k^2-k_x^2-k_y^2)^{1/2}]\right\}. \quad (3)$$

A simulation of the diffracted field as a function of Z, based on the exact formula given by Eq. (1)

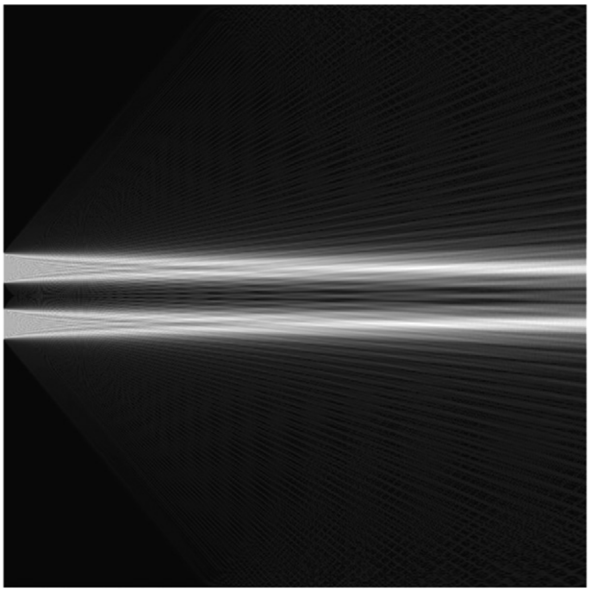

Fig. 1. Simulation of diffraction for a 1D double slit object. We chose $X = 8\lambda$, which is the physical size of a pixel along the transversal (vertical) direction, with $N = 2048$ pixels in both directions. The slit widths are equal and 105 pixels wide, with a slit separation of 90 pixels. The physical size of a pixel along the longitudinal (horizontal) direction is 20 times greater than that in the transversal direction. Therefore, the physical horizontal axis is visualized 20 times compressed compared to the vertical axis, for better viewing. The authors thank G.B. Esmer for conducting the simulation.