Digital Optics Tool for Multi-Purpose Experimental Applications

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ABSTRACT

This work presents the results concerning the application of a Discrete Fresnel Transform algorithm (DFT), which was upgraded for modeling and experimenting with scalar diffraction fields, whose characteristics are analyzed. The MATLAB® software environment was used to implement this algorithm, which allows the user to set the initial conditions, corresponding to the optical information at the input plane, by using a graphic friendly user interface (GUI). Then, by using the DFT algorithm, light propagation from the input to the output plane is achieved. The outputs of the algorithm are the maps corresponding to the 2-D distributions amplitude and phase-modulo 2π, or equivalently, the corresponding real and imaginary parts of the complex analytical field. Also, to assist the analysis, line profiles for these maps are provided. Results allow the user synthesizing Fresnel diffraction in presence of multiple components, like lenses, prisms, diffractive gratings, and holographic elements. Indeed, by implementing a series of successive steps, applications like image forming and spatial filtering can be demonstrated. The basis of the algorithm’s architecture and some typical results, which closely resemble those from the experiments, are presented.

Keywords: Diffraction, Discrete Fresnel Transform, Fast Fourier Transform, GUI, Propagation, Digital Optics.

1. INTRODUCTION

The developments in the different knowledge areas are related with computation. In optics, the computation has led to improved sensitivity devices and progressively more effective systems for processing and transmitting information, which implies more efficient optical processes with better quality, in both analogical and digital experimental settings. The conjunction of optics and computation unifies the theory, methodology, and technical means of the optical signal processing, by computational methods, approaching to the optical phenomena in a flexible, simple and natural way. This discipline is known as digital optics [1].

As early as the beginning of the 1920s, the first applications in digital optics, including a wired transmission system across the Atlantic Ocean developed by H. Bartholomew and M. McFarlane were reported [2]. But it took two decades to fund the link between optics and computation, in particular, when the Marechal’s optical spatial filtering, the application of the Fourier methods by Duffieux, and the Gabor’s holography invention [3] led to many applications in this field. Since then the digital optics have progressed significantly, turning into an interesting knowledge area.

As far the computational processing speed and data storage have incremented through last decades, the digital optics development has grown in quantity and quality, and a better computing performance has led to more efficient techniques. Similarly, the pixel size reduction and discretization refinement have allowed the resolution of optical systems improvement. Also more accurate mathematical solutions for the models have been achieved.

In the digital optics field, the numerical simulation of optical phenomena is a major study area, which intends to reproduce experimental behavior based on a set of given data. The computational predictions allow obtaining estimate results, emulating the “real-world” experiments and going further than the analog-alone setups, due the combined digital information processing and storage capacity. One of these phenomena to be simulated is the light propagation through different optical elements.

There are several computational platforms for light propagation simulation which are available in the market. Nevertheless, due the specificity of the experimental optics applications, some of these computational tools are intended to fit relatively narrow application spectra, and the multi-purpose platforms are quite expensive.

The purpose of this paper is to present an own computational tool, based on the light propagation phenomena, to obtain a multi-purpose platform, user friendly and properly calibrated for real scale experiments.

The MATLAB software environment was used to implement this algorithm. It allows the user setting the initial conditions onto the input plane, by using a graphic user interface (GUI). A monochromatic plane wave, whose wavelength is settled by the user, impinges onto the input plane. At this plane, a set of optical elements including different apertures, wedges, lenses, diffractive gratings and different holographic elements could be defined. Afterwards, the propagation from the input to the output plane, through an arbitrary chosen propagation distance, is achieved. The amplitude and phase-modulo 2π maps with the corresponding profiles are the algorithm outputs. Also the real and imaginary parts of the analytical signal at the output plane can be displayed.
2. THEORETICAL APPROACH

The light diffraction phenomena for many applications can be achieved by using the Fresnel Integral Transformation, as a consequence of the Huygens-Fresnel principle [4].

Fresnel Transform

The light propagation, from the input plane to the output plane, through an arbitrary distance in free space, is represented by equation (1), where the field amplitude at a given point on the output plane stands for the superposition of all spherical waves coming from different point sources located at the input plane.

\[
E(x_h, y_h, z) = \frac{i E_0 e^{-ikz}}{\lambda z} \int \int h(x_i, y_i) e^{i \frac{2\pi}{\lambda z}} (x_h, y_h, z) dx_i dy_i.
\]

In Cartesian coordinates, this integral transform is called the Fresnel Transform, where \(\lambda\) is the wavelength, \(k\) is the wave number, \(h(x_i, y_i)\) is the complex function representing the transmittance at the input plane, \(z\) is the distance the light is going to be propagated from the input plane to the output plane, \((x_h, y_h)\) and \((x_i, y_i)\) represent a generic point of the input and the output plane, respectively, as shown in Figure 1.

![Figure 1. Input and output plane setup in Fresnel Transform.](image)

A discrete version of the Fresnel Transform for computational simulations is achieved by means of a discretization of the entrance signal and the corresponding output, by defining the pixel physical dimensions to be employed when mapping each of these surfaces. Then the complex amplitude at each pixel onto the output plane is computed by adding the complex amplitudes corresponding to all the contributions from pixels representing individual radiators onto the input plane. This results in the discrete form presented in equation (2).

\[
E_d(m, n, z) = \frac{i E_0 e^{-ikz}}{\lambda z} \left[ i \frac{\pi}{\lambda z} \left( x_i^2 + y_i^2 \right) \right] \text{FFT}[H(k, l)]
\]

where

\[
H(k, l) = h(k, l) e^{-\frac{\pi}{\lambda z} \left( x_i^2 + y_i^2 \right)}
\]

In this equation, \(m\) and \(n\) are the row and column position, \(N_x\) and \(N_y\) are the amount of pixels in the \(x\) and \(y\) axis respectively, \(\Delta x_h\) and \(\Delta y_h\) are the pixel's size in both input and output plane and \(FFT[H(k, l)]\) is the 2-D Fast Fourier Transform, operating over the product of the transmittance function and a quadratic phase term.

3. COMPUTATIONAL APPROACH

The simulation of the field propagation in the MATLAB® environment was done using the graphic user interface (GUI), as an integrating platform. All related phenomena were implemented as satellite algorithms adding versatility to the tool.

The development of a user-friendly platform implies the implementation of a visual interface, where all menus are located in the experimental setup logic. The first step is to introduce the variables related to lighting, to allow the user choosing the wavelength, transmittance window size, the illuminating beam profile (plane, spherical, uniform intensity or Gaussian). Whenever the spherical beam profile is chosen, the user should specify its convergence or divergence, and its radius.

The second step for setting up the simulation of an optical experiment is to define the pixel dimension, and choose the optical elements that will be needed when running the first routine of propagation. In this step the user can choose the implementation of one or multiple diffracting apertures or obstacles, diffractive gratings, spherical and cylindrical lenses, random phase diffusers, optical wedges, or saved images, which could be interpreted both as real-amplitude and pure-phase transmittances.

Each selected element enables a window where the parameters are set. In the window "aperture and obstacle", the user can choose between a circular mask or drawing a free geometry, and if the circular geometry is chosen, there are three options to setup the mask: entering the coordinates, generating the mask based on two points to be picked by using the mouse, and picking the center by using the mouse and entering the radius.

The diffractive grating allows the user to pick between phase and amplitude gratings, and in each of these cases, the user can choose Ronchi, triangular, saw tooth, and cosine profiles, both in \(x\) and \(y\) axis. The period in pixels and the modulation can be set individually.
If the lens option is chosen, the user can pick between spherical and cylindrical lenses, in which the focus and inclination for the cylindrical case can be settled.

The optical wedge is simulated, with the dihedral angle, the inclination of dihedral axis and the refractive index as parameters input. Finally, the diffuser and the loaded image can be located onto the transmittance plane just by clicking on the option button.

In a schematic way, the all associated physical phenomena are called by the GUI when required, and this allows the implementation of new simulations of optical propagation related phenomena, for example add to the platform more optical elements, making this tool a fully upgradeable for different experimental setups.

In Figure 2, the basic computational elements of the algorithm and its relation with the associated physical phenomena are schematized.

![Diagram](image)

**Figure 2.** Scheme for related physical phenomena

On the other hand Figure 3 presents a scheme of the data usage by the platform. Particularly the algorithm inputs and outputs are apparent, showing a general sight of the user tunable options.

![Diagram](image)

**Figure 3.** Scheme of the input to the output cycle

### 4. SIMULATED RESULTS

In Figures 4 to 6 some representative results for the real amplitude and phase distributions of diffracted fields are depicted. In Figure 4, a Fraunhofer diffraction experiment by using a circular aperture is shown.

![Fraunhofer Diffraction](image)

**Figure 4.** Fraunhofer diffraction field associated with a circular aperture. a) The real amplitude distribution, b) the line profile (arbitrary units) corresponding to a), c) the 2-D map for the phase, and in d) the line profile for c).
aperture was simulated, being presented the corresponding
real amplitude and its line profile (arbitrary units) in a) and b),
and the phase distribution map and its line profile in c) and d),
respectively. In this experiment, the aperture diameter and the
propagation distance were set to 100µm and 23cm,
respectively.

In Figure 5, the classical Young interference experiment is
presented. The aperture dimensions and the propagation
distance are the same than in Figure 4, and the distance
between the apertures centers is 200µm. As in Figure 4 the
real amplitude, the phase map and the associated line profiles
are shown.

Figure 5. Young’s experiment with circular apertures. In a)
the real amplitude distribution, in b) the line profile (arbitrary
units) corresponding to a), in c) the 2-D map for the phase,
and in d) the line profile for c).

The platform also allows the user to make multiple
propagation processes, by saving the previous results, and by
resetting to a default state the platform. In consequence, the
saved data from amplitude and phase obtained in the previous
process are the starting point for a new propagation step, and a
new configuration for all the optical elements that were
available in the previous steps can be set again.
The platform iterative behavior allows the user to perform almost any experiment related with scalar fields propagation, as is the case in image formation. In Figure 6, an image reconstruction example by using a 4f optical system is depicted. The saved image (10,024 mm side) is entered as a transmittance input (Figure 6 a). Then, diffracted light is propagated 15 cm through free space (Figure 6 b.), and a lens with focal distance of 15 cm is placed there. Light passing by the lens is propagated through 30cm distance, where a similar lens is located to form the final image 15cm behind the second lens (Figure 6 c.). Note that also this setup could be used for filtering applications, by properly locating a mask at the intermediate plane.

5. CONCLUSION

We implemented a functional and versatile platform by employing the MATLAB® environment to simulate the light propagation, which allows the easy adaptation to many applications of high technological impact.

This platform supports the development of future projects, by aiding to save time in the experiments design allowing the user to obtain simulated results in short time. Also the platform becomes into a multipurpose tool, which allows the development of image processing, synthetic digital holography, synthesis of speckle fields, evaluation of vortex network, among other applications.

Due to its simplicity, all users interested in optical applications can use the platform. At its present state, the platform allows the user to perform a wide range of experimental setups by using the basic optical elements, providing accurate solutions of the simulated optical systems.

Currently we are working on the implementation of a novel module to be added to the platform built-in the Data Acquisition Toolbox from MATLAB®, which will link the data processing available tools with a digital imaging capture system such as a frame grabber and a CCD camera. Also we are conducting research activities in the fields of digital holography, speckle interferometry and vortex metrology by using this platform.

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6. BIBLIOGRAPHY