

Research Article

Enhancing Real-Time Pyramid Holographic Display Through Iterative Algorithm Optimization for 3D Image Reconstruction

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Abstract

Holography, a crucial technology for 3D visualization, strives to create realistic relief images. This research aims to enhance hologram quality and viewer experience by optimizing the image-processing pipeline. Conventional holographic displays face challenges due to their bulkiness and limited viewing angles. To overcome these limitations, this study proposes a novel approach that integrates digital holography with holographic pyramid technology. Digital holography uses computer algorithms for hologram generation, while holographic pyramid technology projects images onto a reflective pyramid for 3D display. The drawback of holographic pyramid displays in low-light environments is addressed through increased diffraction to enhance image resolution. This integrated approach involves comprehensive research, including an examination of existing methods. The anticipated outcome is holograms with improved visibility and resolution from multiple angles. The research presents an initial image preprocessing phase, succeeded by sophisticated processing employing iterative algorithms. This aims to diminish the image size while upholding its quality, thereby achieving an image suitable for pyramidal display. The fusion of digital holography and holographic pyramid display shows promise for immersive visual experiences. However, advancements in processing techniques may lead to increased material complexity, posing a challenge. Through this research, the system aims to unlock creative potentials and pave the way for enhanced holographic displays in various applications.

Keywords

Hologram Computation, Iterative, Image Processing, CGH, Pyramid, Detour, Diffraction

1. Introduction

In the past, holograms were created by Denis Gabor on semi-transparent flat surfaces to reflect the image, constituting the principle of analog holography [1, 2]. However, in recent years, digital holography has emerged. On the other hand, pyramid holographic display is a technique that projects an image above the projection screen [3-5], offering the main

advantage of viewing a hologram from multiple angles. Thus, how can we improve the viewing angle and visibility of digital holograms while respecting the holographic principle?

Therefore, the new system aims to merge digital holographic technology with pyramid display. This aims to enhance the process of reconstructing digital images, analyze

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Received: 24 March 2024; **Accepted:** 11 April 2024; **Published:** 29 April 2024



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and implement imaging systems for 3D rendering, and achieve a hologram visible from various viewing angles. Consequently, it is crucial to delve into the fundamental studies of digital image construction principles and the main hologram generation methods, to be applied to pyramid projection systems.

This project will first address the fundamentals of projection, focusing on the importance of preprocessing. Then, it will explore relevant methods and algorithms based on pre-processing techniques, image processing, and finally, simulation using MATLAB. These techniques aim to improve image resolution and quality to achieve the defined objectives.

2. Methodology

2.1. Global Architecture

This project involved the integration of digital holographic display with the pyramid display system. Indeed, the involvement of the hologram generation system was necessary, as well as obtaining a hologram seen from multiple angles. Figure 1 shows the general scheme of this system, enhanced from [6].

This system is modified from digital holography CGH or "Computer Generated Holography" [7, 8]. Thus, the

flowchart in Figure 2 illustrates the processing from the formation of 3D image data to relief display, through hologram calculation and the use of SLM or "Spatial Light Modulation" [9, 10]. With the digital holography technique, digital images are processed using corresponding software and then their hologram is calculated.

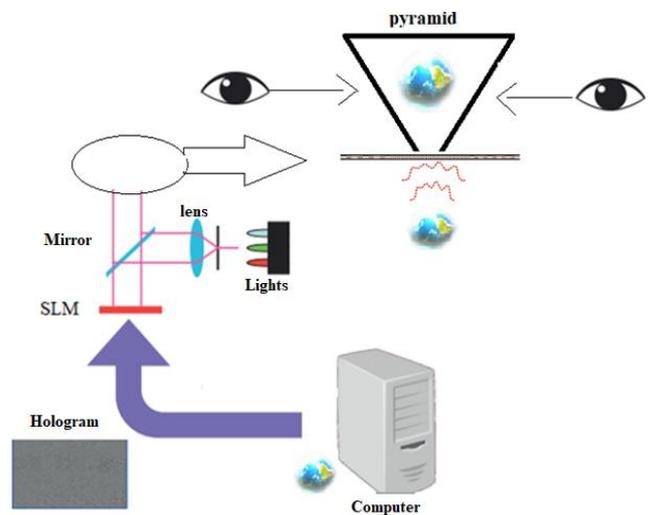


Figure 1. Illustration of the CGH System with implementation of pyramid Display.

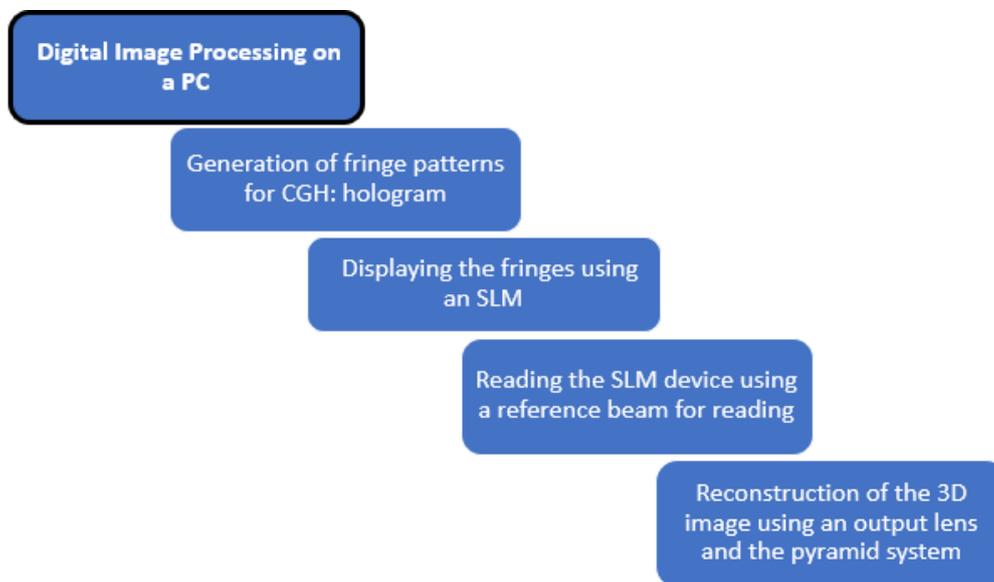


Figure 2. Process of the digital holographic system with implementation of the pyramid display.

Since the pyramid display requires four images to be projected onto a single screen in order to achieve the same image simultaneously from all viewing angles, the algorithm must divide the image into four equal parts along the diagonal. Each part thus forms an identical portion of the triangle con-

taining the object. Before calculating the hologram, this step was necessary to ensure consistent and accurate visualization of the object from each viewing angle. The diagram in Figure 3 illustrates the various stages of this enhancement.

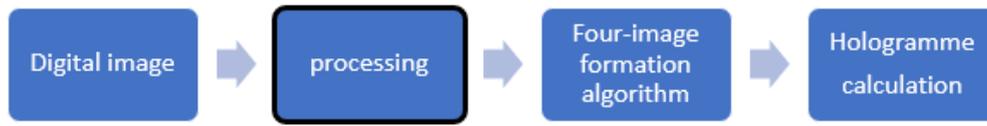


Figure 3. Image processing process until hologram calculation.

Therefore, the introduction of the algorithm for generating four images is essential with the holographic pyramid display system. All tools of display with CGH such as Fourier transform, Fresnel algorithms, 3D image generation, and processing are enhanced. It is thus the assembly of the detour method, kinoform, and iterative to achieve maximum resolution.

2.2. Image Preprocessing Process

2.2.1. Object Initialization

The Object Initialization involves applying a series of operations as follows [11, 12]:

- 1) Filtering to reduce noise, provided from the averaging filter and the Gaussian filter

$$I_{av}(x, y) = \frac{1}{n^2} \sum_{i=0}^{n-1} \sum_{j=0}^{n-1} I(x+i-\frac{n-1}{2}, y+j-\frac{n-1}{2}) \quad (1)$$

Where $I_{av}(x, y)$ is the filtered pixel value at position (x, y) , $I(x, y)$ is the original pixel value at position (x, y) , and n is the filter size.

$$I_{fil}(x, y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} * I_{av}(x, y) \quad (2)$$

Where $*$ is the Operator of convolution, the advantage of the Gaussian filter is that one can easily adjust the degree of filtering through the parameter σ .

- 2) Contrast enhancement to improve detail visibility:

$$I_{cor}(x, y) = \text{clip}(a \cdot I_{origin}(x, y) + b, 0, 255) \quad (3)$$

Where,

$I_{cor}(x, y)$ is the corrected pixel value at position (x, y) in the resulting image,

$I_{origin}(x, y)$ is the original pixel value at position (x, y) in the input image, a is the slope coefficient of the transformation, adjusting the contrast,

b is the offset of the transformation, adjusting the brightness,

$\text{clip}(x, \min, \max)$ is a clipping function that limits the value x to the interval $[\min, \max]$. For more details on [13].

2.2.2. Detour

The detouring process involves precise contouring technique and background cleaning for enhancement, using contour arrays and algorithms such as Bernstein and Bézier curves. Figure 4 provides an overview of the algorithm for

precise contouring.

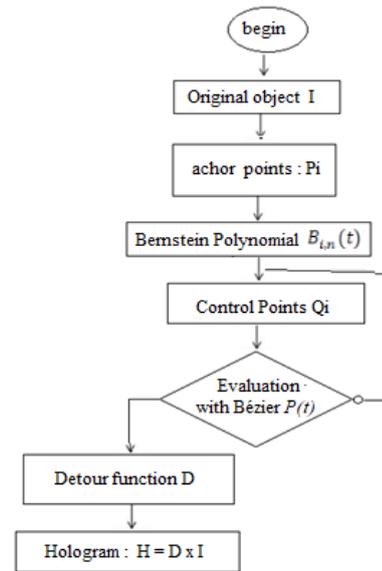


Figure 4. flowchart of contouring technique

Indeed, an image $I(x, y)$ was represented as a contour cell array [14], as shown in Figure 5.

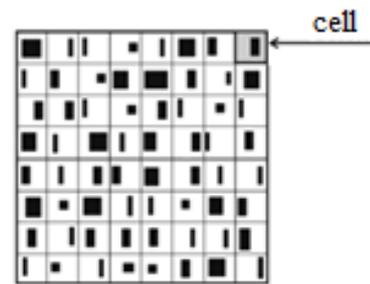


Figure 5. Detour cell array.

The algorithm is inspired by [15]. On this array, contours to improve should be selected, then the Bernstein algorithm from equation (4) is applied,

$$B_{i,n}(t) = \binom{n}{i} t^i (1-t)^{n-i} \quad (4)$$

(4) is the i -th Bernstein polynomial of degree n evaluated at t , n is the degree of the detour curve. Then, the calculation of control points is used to define the characteristics and be-

havior of curves or surfaces, given by (5). In summary, this allows for precisely controlling the geometry of the object.

$$Q_i = \sum_{i=0}^n B_{i,n}(t) \cdot P_i \quad (5)$$

(5) represents the control points defined for the Bézier curve, and P_i are the anchor points defining the detour curve.

Finally, Bezier curve evaluation allows for determining the coordinates of points on the curve given by (6),

$$P(t) = \sum_{i=0}^n B_{i,n}(t) \cdot Q_i \quad (6)$$

Concerning the detour function $D(x, y)$, where $D(x, y) = 1$ in regions where the hologram is detoured and $D(x, y) = 0$ otherwise, and $H(x, y)$ the resulting hologram described by the relation (7),

$$H(x, y) = I(x, y) \cdot D(x, y) \quad (7)$$

2.3. Image Processing Process

2.3.1. Iterative Algorithm to Reduce the Image While Maintaining Its Quality

Although the resolution needs to be reduced to fit into the pyramid, the iterative algorithm maintains the resolution, sharpness, and clarity of objects through repeated image processing steps, including sampling, quality enhancement, and resampling. Figure 6 illustrates the algorithm to achieve this objective.

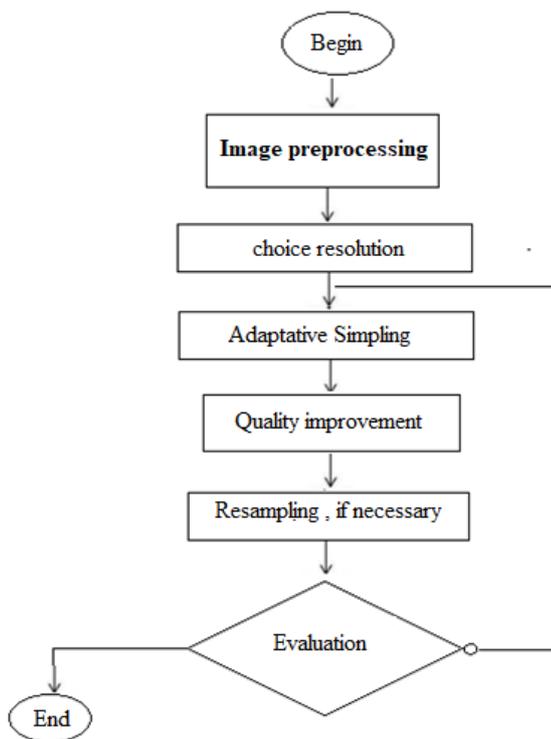


Figure 6. Iterative algorithm.

Therefore, preprocessing is succeeded by resolution selection (to accommodate pyramid display), followed by a loop for sampling, enhancement, and resampling. The loop concludes upon meeting the necessary evaluation condition.

Indeed, image sampling is a technique used to reduce the size or resolution of an image while preserving its essential visual characteristics as much as possible. Moreover, adaptive sampling employs adaptive methods to select samples based on the characteristics of the image. Thus, it is a technique grounded in edge detection. It aims to intelligently select samples based on the characteristics of the image, in order to enhance representation quality, reduce the number of required samples, optimize the utilization of computing resources, and enhance the robustness of image processing algorithms.

Sampling is the process of spatial discretization of an image, and under sampling refers to when the image is already discretized, as illustrated in Figure 7. That's why discretization is used.

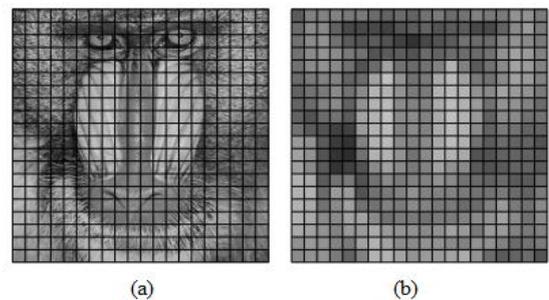


Figure 7. (a) digital image (b) Sampling.

Sampling and resampling involve discretization, as coordinates (n_1, m_1) and (n_2, m_2) take continuous values, [16] hence discretization is necessary, as indicated in Figure 8.

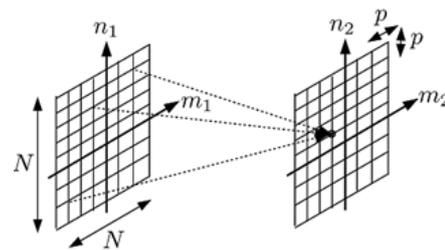


Figure 8. Discretization of Fresnel Diffraction.

If the source and destination planes are sampled with $N \times N$ pixels, the coordinates can be written using equations (8),

$$x_1 = pm_1, y_1 = pn_1, x_2 = pm_2, y_2 = pn_2 \quad (8)$$

Where p is the sampling step, and m_1, n_1, m_2, n_2 are discretized coordinates given by (9),

$$-\frac{N}{2} \leq m_1 \leq \frac{N}{2} - 1, -\frac{N}{2} \leq n_1 \leq \frac{N}{2} - 1$$

$$-\frac{N}{2} \leq m_2 \leq \frac{N}{2} - 1, -\frac{N}{2} \leq n_2 \leq \frac{N}{2} - 1 \quad (9)$$

Discretization is expressed as (10),

$$A_2(m_2, n_2) = \frac{p^2 \exp(i\frac{2\pi}{\lambda}z)}{i\lambda z} \sum_{n_1=-\frac{N}{2}}^{\frac{N}{2}-1} \sum_{m_1=-\frac{N}{2}}^{\frac{N}{2}-1} A_1(m_1, n_1) \times e^{[i\frac{2\pi p^2}{\lambda}((m_2-m_1)^2+(n_2-n_1)^2)]} \quad (10)$$

A_1 A_2 designate the source and destination planes, z is the distance between source and destination, and λ is the wavelength.

In order to compute a point (m_2, n_2) in the destination plane, it is necessary to add all the light emitted from each sampling point in the source plane. To monitor the quality of the resulting reconstructed image from the hologram, the root mean square error (RMSE) is measured and defined as (11),

$$RMSE = \sqrt{\frac{1}{MN} \sum_{m,n} [|\psi(m,n)| - I(m,n)]^2} \quad (11)$$

Where $I(m,n)$ is the target image, $\psi(m,n)$ is the evaluated field, (m,n) are the sampling indices, and M and N are the numbers of sampling along the x and y axes.

2.3.2. The Holographic Plane

This plane is determined by the dimension of the projection screen and the tilt of the memory. Figure 9 illustrates the calculation method for determining the volume of the plane.

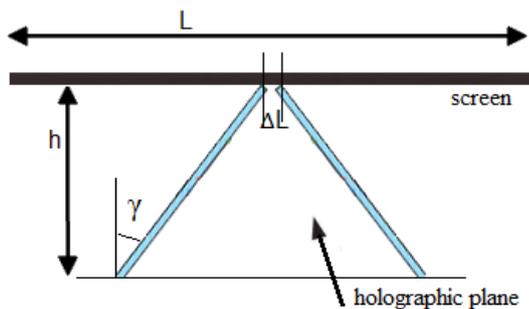


Figure 9. Holographic plane.

Indeed, half of the plane is similar to the surface of a triangle, defined by (12),

$$s = h \cdot h \cdot \tan(\gamma) \quad (12)$$

With s representing the surface area of the triangle on the half-plane and h denoting the height of the plane, the surface area of the plane, denoted as S , is then given by (13),

$$S = 2h^2 \tan(\gamma) + h \Delta L \quad (13)$$

Where L represents the length of the projection screen.

Now, every screen has its length L and its width l , thus the volume of the plane is given by (14),

$$V_p = h \cdot l (2h \tan(\gamma) + \Delta L) \quad (14)$$

3. Presentation of Results

3.1. Result of Initialization

Figure 10 illustrates the results obtained on the initial object following the application of the averaging and Gaussian filters, using MATLAB. For the Gaussian filter, three trials were conducted with σ values of 1.5, 5, and 10.

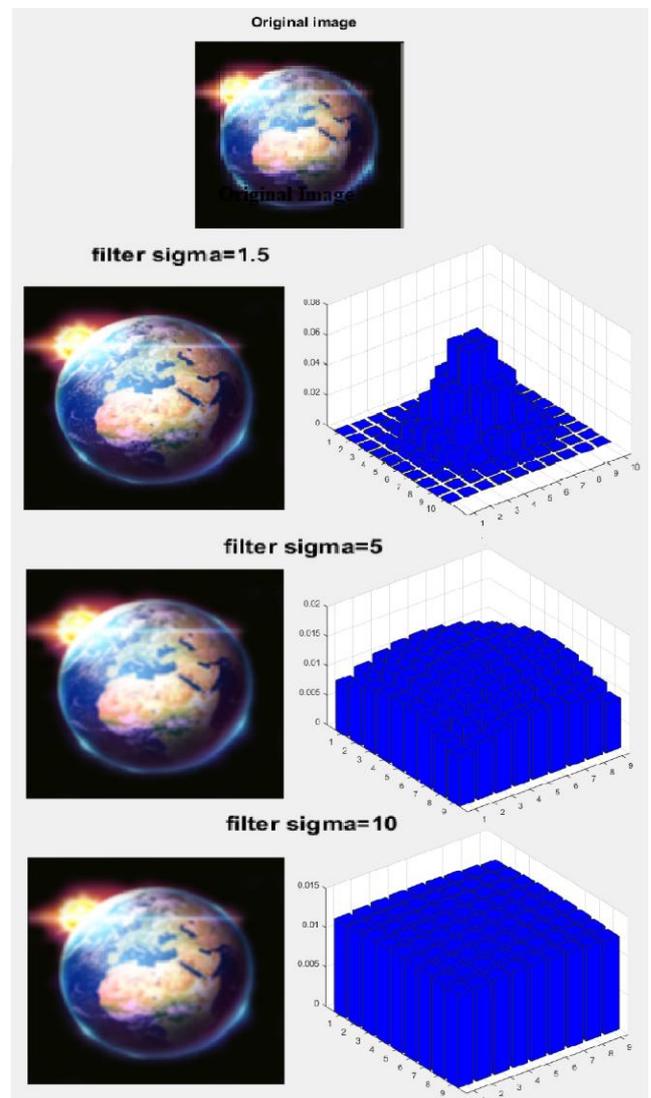


Figure 10. Result obtained from MATLAB using the averaging filter and the Gaussian filter.

The consequence of applying the Gaussian filter with sigma values of 1.5, 5, and 10 is as follows:

1. With a sigma of 1.5, the Gaussian filter will produce a slight attenuation of fine details in the image while retaining some sharpness.
2. With a sigma of 5, the Gaussian filter will further attenuate the details of the image, resulting in a more pronounced blur effect.
3. With a sigma of 10, the Gaussian filter will cause even greater attenuation of the details in the image, resulting in more significant blur and a notable decrease in sharpness.

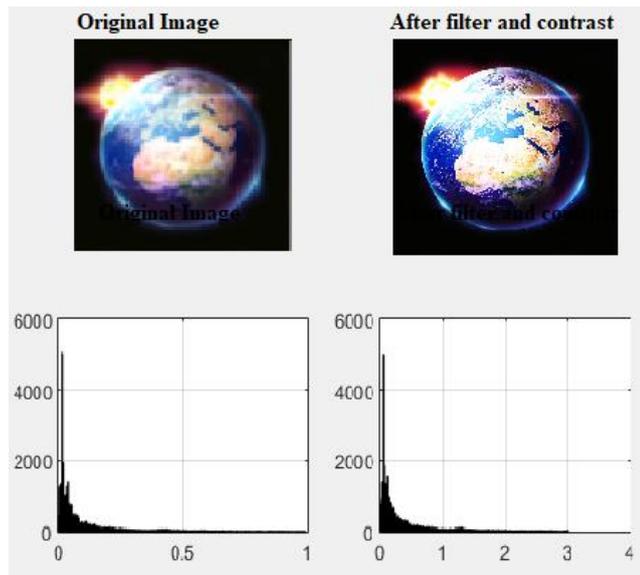


Figure 11. Result obtained from MATLAB using the contrast enhancement as well as its histograms.

Then, the result obtained on contrast enhancement is depicted in Figure 11. In this case, the values of a and b are 3 and 300. However, b can be left as an adjustable parameter to control both the amplitude and shift of the transformation, aiming to achieve the best possible result based on the characteristics of the image. For histograms, it is essential to plot both the histogram of the original image and that of the transformed image in order to assess the distribution of grayscale levels and achieve improved contrast.

3.2. Result of Edges Detection

To enhance the edges of an image, edge detection is performed using the edge detection technique described in Section 2.2.2, resulting in the outcome depicted in Figure 12.



Figure 12. Result obtained from MATLAB for edges detection.

Finally, Figure 13 displays the dilation of the detected edges, then overlays them onto the original image.

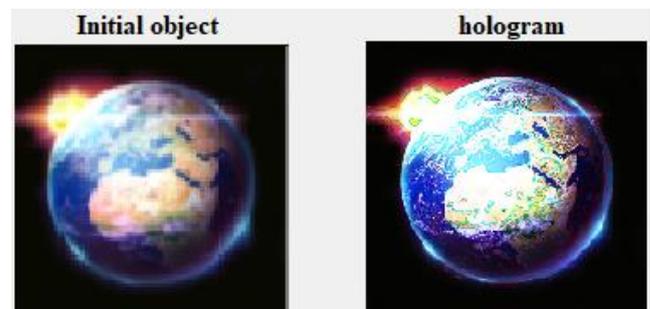


Figure 13. Result obtained from MATLAB after image preprocessing process.

Generally, the objective of edge dilation in image processing is to thicken the detected edges, making them more visible and prominent. Dilation is a morphological operation that expands the edges by adding neighboring pixels to the original edge. Overlaying the edges onto the original image allows visualizing the detected edges by visually combining them with the original image. This allows for a better visualization of the edges in the image.

3.3. Result to Obtain an Image Corresponding to the Pyramidal Display

Following the image reduction outlined in Section 2.3.1 for display in the holographic pyramid, it is necessary to divide the image into four sections along the pyramid plane, as detailed in Section 2.3.2. Figure 14 illustrates this result.

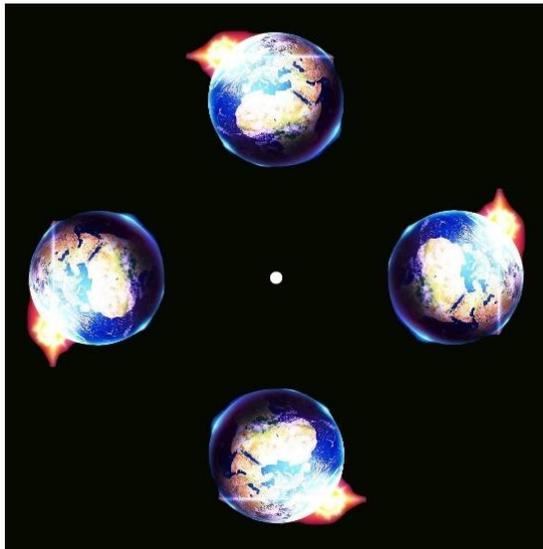


Figure 14. Final result in the holographic plane.

4. Discussion

The aim was to create a clear hologram viewable from

multiple angles. However, limitations on viewing angles were noted during the projection of computer-generated holograms, as indicated to [6]: “the range where the observer can see the three-dimensional image is narrow”. To tackle this, it was integrated with pyramid display technology, enabling multi-angle viewing, albeit with reduced clarity in brighter daylight conditions. Analysis indicated that optimizing the object's resolution was crucial to overcome this challenge.

On one hand, during its evaluation using MATLAB, the modified system showed improvements, although the desired outcome was not fully achieved. On the other hand, the resolution efficiency proved satisfactory. Indeed, without image preprocessing [11], the result is obtained using several techniques, including kinoform, Gerchberg–Saxton algorithm (GS algorithm), Iterative Fourier Transform (IFT), ... are found in [17] by W. Lohmann, [18] by P. Hariharan, [19] by N. C. G. B. Liu, [20] by N. C. Gallagher, and B. Liu, [21] by W. O. S. R. W. Gerchberg, whereas with optimization preprocessing, the obtained result was enhanced. This highlights the positive impact of implementing the image processing algorithm. The following Table 1 presents the comparison of the system's results before and after modification.

Table 1. Comparison Table before and after treatment.

	CGH	Pyramidal	CGH Pyramidal
Advantages	Digital Holography	Viewing angle	Both
Disadvantages	Weak diffraction Viewing angle Computation time Hardware configuration	Holography process	Computation time Hardware configuration

5. Conclusions

In conclusion, while various projection methods present their own advantages and limitations rooted in the principle of diffraction, MATLAB simulations indicate that a combined approach integrating computer-generated holography with pyramid display, utilizing techniques on preprocessing techniques, image processing, demonstrates enhanced efficiency. This fusion not only holds potential for stimulating creativity and innovation in visual expression but also addresses the necessity of projecting holograms from diverse viewing angles. Nevertheless, challenges persist, particularly concerning constraints related to image size and hardware configuration necessary for real-time display, underscoring the imperative for continuous improvement and refinement. Future research endeavors should focus on optimizing computational processes and hardware setups to overcome these limitations and

further advance holographic display technology. Such enhancements are essential for unlocking the full potential of holography and expanding its applicability across various domains, ranging from entertainment and education to medical imaging and beyond.

Abbreviations

CGH: Computer Generated Holography
SLM: Spatial Light Modulation
RMSE: Root Mean Square Error
GS: Gerchberg–Saxton
IFT: Iterative Fourier Transform

Acknowledgments

I would like to express my sincere gratitude to:
Mr. Andrianarison Ravalison Edouard, Professor, Director

of the Doctoral School of Engineering Sciences and Innovation Techniques,

Mr. Randriamaroson Rivo Mahandrisoa, Professor, Head of the Doctoral Hosting Team in Embedded Systems, Instrumentation, Modeling of Systems and Electronic Devices, my co-supervisor, for their invaluable assistance.

Mr. Rakotomiraho Soloniaina, Professor at the Ecole Supérieure Polytechnique d'Antananarivo, my thesis supervisor, for agreeing to supervise this thesis.

Author Contributions

Randrianasoa Lalaridimby Iano: Conceptualization; Resources; Data curation; Software; Formal Analysis; Investigation; Methodology; Writing – original draft; Writing – review & editing

Randriamaroson Rivo Mahandrisoa: Supervision; Validation; Visualization; Project administration

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography



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Research Field

Iano Lalaridimby Randrianasoa: Electronics, Numerical, Photonics, Automatism

Rivo Mahandrisoa Randriamaroson: Electronics, Photonics, Electromagnetics, Thermodynamics, Robotics, Numerical Modeling.