

# Computer holography: 3D digital art based on high-definition CGH

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**Abstract.** Our recent works of high-definition computer-generated holograms (CGH) and the techniques used for the creation, such as the polygon-based method, silhouette method and digitized holography, are summarized and reviewed in this paper. The concept of computer holography is proposed in terms of integrating and crystalizing the techniques into novel digital art.

## 1. Introduction

In the past few years, we presented some high-definition full-parallax CGHs calculated by the polygon-based [1] and silhouette method [2, 3] and fabricated by laser lithography system [4, 5]. These holograms, composed of more than billions pixels, produce very fine spatial 3D images of occluded virtual scenes and objects. The optical reconstruction is comparable to that in classical holography. Strong sensation of depth caused by these high-definition CGHs has never been achieved by any conventional 3D systems and pictures other than holograms.

In addition, we have also presented a new technique called *digitized holography* [6]. In this technique, the fringe generated by optical interference between the object wave of a real existing object and a reference wave is digitally recorded by image sensors with a wide area and at a high sampling density. The recorded object wave is numerically incorporated in a virtual 3D scene constructed of CG-like 2D and 3D objects. The total field of the virtual scene, which keeps the proper occluded relation, is calculated and optically reconstructed by the technique of high-definition CGHs. This means that the whole process of classical holography, i.e. recording and reconstructing the object wave, is replaced and extended by digital counterparts. Digitized holography makes it possible to edit the 3D scene of holograms after recording object waves.

These techniques are opening the world of novel digital art, referred to as *computer holography* in this report. Various source materials can be input data in computer holography, for example, digital photos, illustrations, polygon-mesh 3D objects, multi-viewpoints images and captured fields of real existing objects. The 3D scene including these materials is designed with the technique of field-based digital-editing and optically reconstructed by a CGH as designers intended.

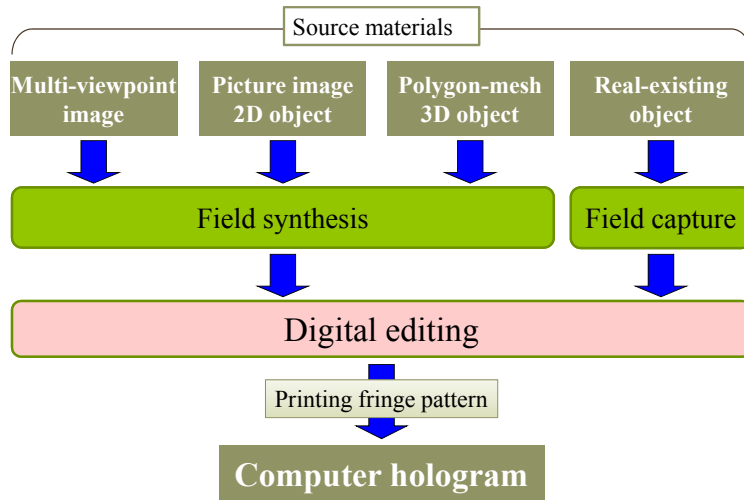
This paper is intended to present summary report of the concept of computer holography, technique used for creation, and some of our recent works.

**Table 1.** A summary of major works in computer holography.

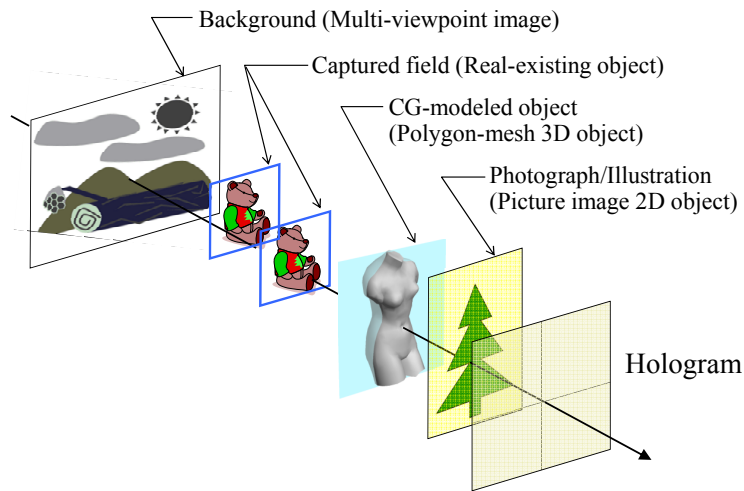
Title	Dimensions $W \times H$ [cm <sup>2</sup> ]	No. of pixels $W \times H$	Pixel pitches [ $\mu\text{m}$ ] $\times$ [ $\mu\text{m}$ ]	Creator(s) <sup>1</sup>	Date <sup>2</sup>	Ref.	Notes
The Venus	6.5 $\times$ 6.5	65, 536 $\times$ 65, 536	1.0 $\times$ 1.0	KM	Jan. 2009	[4, 7, 8]	The first computer hologram created by our method
Moai I	6.5 $\times$ 6.5	65, 536 $\times$ 65, 536	1.0 $\times$ 1.0	KM	Jun. 2009	[9]	Shifted Fresnel method [10] for numerical propagation
Moai II	6.5 $\times$ 6.5	65, 536 $\times$ 65, 536	1.0 $\times$ 1.0	KM	Oct. 2009	[9, 11, 12]	Shifted angular spectrum method [13] for numerical propagation
Aqua 2	10.5 $\times$ 6.5	131, 072 $\times$ 65, 536	0.8 $\times$ 1.0	MN	Dec. 2009	[14]	Acceleration algorithm for the silhouette method in sparse 3D scenes
The Moon	10.5 $\times$ 6.5	131, 072 $\times$ 65, 536	0.8 $\times$ 1.0	KM	Mar. 2010	[11, 12]	Texture-mapping
Shion	10.5 $\times$ 5.2	131, 072 $\times$ 65, 536	0.8 $\times$ 0.8	KM, HN	Dec. 2010	[12, 15]	Texture-mapping, Gouraud shading, Shape measuring by 3D laser scanner
Bear II	6.5 $\times$ 6.5	65, 536 $\times$ 65, 536	1.0 $\times$ 1.0	YA, HN	Oct. 2010	[6, 15, 16]	The first major work in digitized holography
Mountain	3.3 $\times$ 3.3	32, 768 $\times$ 32, 768	1.0 $\times$ 1.0	KH	Nov. 2010	[15]	Big object for mountain scenery
The Metal Venus I	6.5 $\times$ 6.5	65, 536 $\times$ 65, 536	1.0 $\times$ 1.0	HN	Nov. 2010	[15, 17]	Specular flat shading
The Metal Venus II	6.5 $\times$ 6.5	65, 536 $\times$ 65, 536	1.0 $\times$ 1.0	HN	Jan. 2011	[18, 19]	Specular smooth shading
The Hands	3.3 $\times$ 3.3	32, 768 $\times$ 32, 768	1.0 $\times$ 1.0	MN	Jan. 2011	[20]	Prototype using “Switch-back method”; new algorithm for accelerating silhouette method
iShion V2	5.2 $\times$ 5.2	65, 536 $\times$ 65, 536	0.8 $\times$ 0.8	HY	Dec. 2011	[21]	Image hologram, Reconstruction by white light
iShion V3	10.5 $\times$ 10.5	131, 072 $\times$ 131, 072	0.8 $\times$ 0.8	HY	May 2012		Prototype of floating hologram
Hamsters	6.5 $\times$ 6.5	65, 536 $\times$ 65, 536	1.0 $\times$ 1.0	DF	Apr. 2012		Resizing object in digitized holography
Parked car 1	6.5 $\times$ 6.5	65, 536 $\times$ 65, 536	1.0 $\times$ 1.0	YY	Jun. 2012		Prototype using multi-viewpoint images for background
Penguin	13.1 $\times$ 6.5	131, 072 $\times$ 65, 536	1.0 $\times$ 1.0	YA	Nov. 2011		Large hologram in digitized holography
Rose in Ring	10.5 $\times$ 10.5	131, 072 $\times$ 131, 072	0.8 $\times$ 0.8	KM, HN, KO	Nov. 2011		“Switch-back method”, Specular smooth shading
Brothers	12.6 $\times$ 10.5	196, 608 $\times$ 131, 072	0.64 $\times$ 0.8	KM	Apr. 2012		Texture-mapping, Gouraud shading, Two live faces measured by 3D laser scanner

<sup>1</sup> Here, creator means programmer and/or designer. The abbreviations of creators are as follows, KM: Kyoji MATSUSHIMA, MN: Masaki NAKAMURA, HN: Hirohito NISHI, YA: Yasuaki ARIMA, KH: Kentaro HIGASHI, HY: Hiroshi YAMASHITA, YY: Yutaka YOSHIZAKI, DF: Daichi FUJITA, KO: Kohei OGAWA. All holograms are fabricated by Sumio NAKAHARA.

<sup>2</sup> The indication is usually the printed date of the work. There is ambiguity, because several versions are sometimes reprinted for improvement.



**Figure 1.** Conceptual illustration of the process of computer holography.



**Figure 2.** A typical configuration of the 3D scene in computer holography.

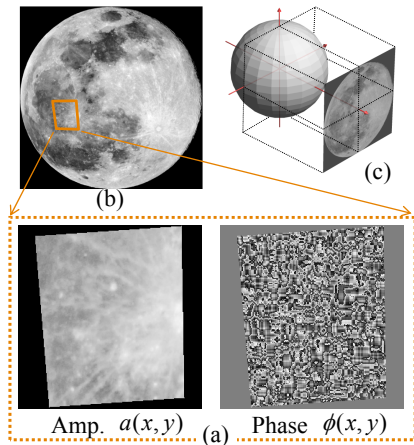
## 2. Computer holography and the materials for 3D scenes

Some major computer holograms we presented so far are summarized in Table 1. The process and typical 3D scene of computer holography are illustrated in Fig. 1 and Fig. 2, respectively. As shown in these figures, various materials can be source input in computer holography.

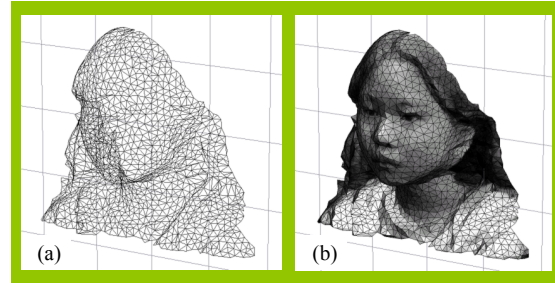
CG-modeled 3D objects are the most important materials for computer holography. The shapes of 3D objects are usually given by polygon-meshes. Instead of conventional point-based methods, we mainly use the polygon-based method [1, 4] for numerical synthesis, because the polygon-based method considerably reduces the computation time of full-parallax CGHs for surface-modeled objects. The point-based methods are also used complementarily in some works such as “The Moon”.

Two dimensional (2D) objects such as digital illustrations or photographs are also included in the 3D scene. These digital 2D images are easily converted to distribution of complex amplitudes by oversampling and adding random or quasi-random phase patterns that give diffusiveness to the objects [4].

Although the 2D objects were used for the background of the 3D scene so far, multi-viewpoint images are more desirable for the background, because the simple 2D pictures do not produce any binocular disparity. Many special techniques have been proposed to create holograms from



**Figure 3.** An example of the surface function (a) for texture-mapping of an astrophotograph (b) onto a polygon-mesh sphere (c) [12].



**Figure 4.** The polygon-mesh of “Shion” before and after texture-mapping [12].

multi-viewpoint images [22]. It is also possible to emulate conventional holographic stereograms by using technique of field propagation.

These input data of computer holography mentioned so far is not the data of the light itself. The polygon-mesh is a just shape data of 3D objects. Picture and multi-viewpoint images are also not object light but only intensity distribution of the light, even though these are of the real-existing objects. However, the object wave, i.e. the field of the real-existing objects, can be digitally captured by using image sensors. This technique is called *digital holography* in contemporary optics [23, 24] and has many applications in industry. In general, 2D images is numerically reconstructed by computers in the digital holography. In *digitized holography*, however, the captured field is incorporated in a virtual 3D scene and optically reconstructed through computer holography. The technique of digitized holography is briefly summarized in section 3.2.

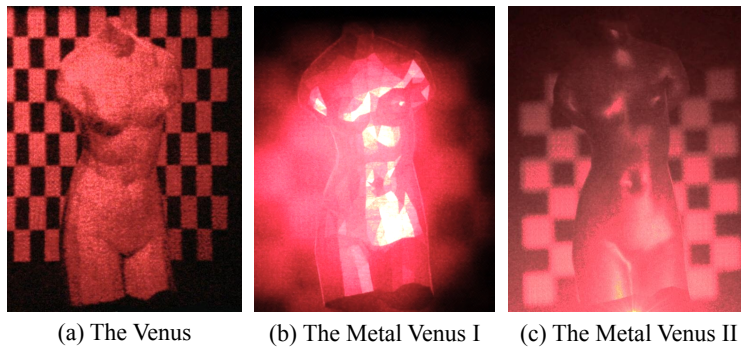
All materials; 2D/3D objects, multi-viewpoint images and captured fields are arranged in a 3D scene in computer holography. The 3D scene is digitally edited in the form of wave fields. Since the occluded relations among the multiple objects should be reproduced in the optical reconstruction, we use the silhouette method and related techniques, as briefly summarized in section 3.3.

### 3. Basic techniques

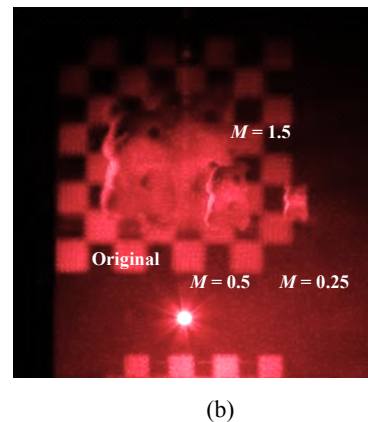
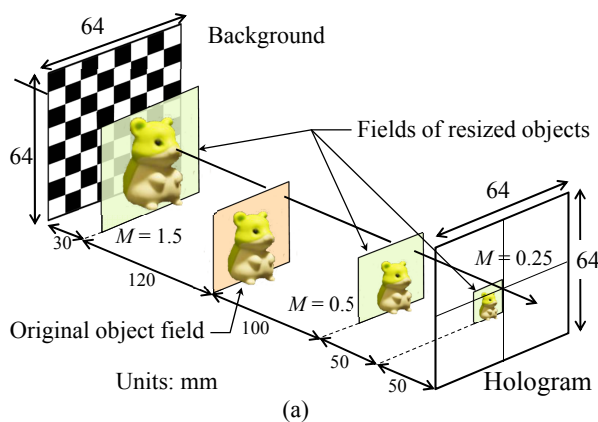
#### 3.1. Polygon-based method

The polygon-based method treats the object surfaces as polygonal (usually triangular or rectangular) surface sources of light [1]. A facet of the object is numerically expressed by 2D distribution of complex amplitudes referred to as the surface function. The first high-definition computer hologram “The Venus” was created in 2009 by using this technique. The parameters are shown in the top of Table 1. The 3D scene of the Venus, named after the famous statue of the Venus de Milo, included a 3D object composed of 718 polygons and a 2D background image. The computation time was approximately 45 h at that time [4]. However, the Venus is currently computed less than 3 h [17].

Another feature of the polygon-based method is similarity to conventional computer graphics (CG). This similarity makes it possible to apply CG technique to holography. Therefore,



**Figure 5.** A comparison of three different techniques of wave-field rendering in the polygon-based method; (a) diffused flat, (b) specular flat and (c) specular smooth shading.

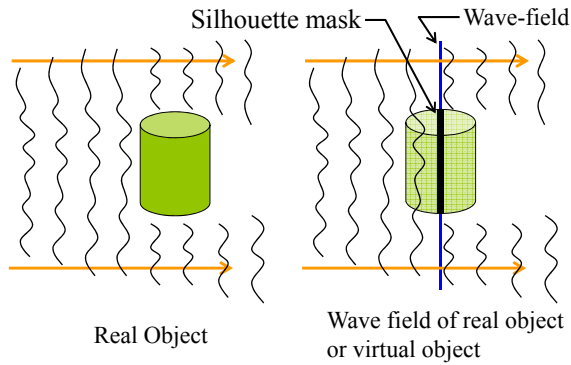


**Figure 6.** The 3D scene (a) and optical reconstruction (b) of “Hamsters” that include multiple fields of the resized objects.

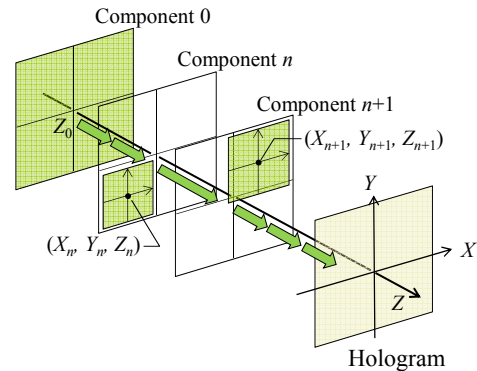
the rendering techniques in the polygon-based method are sometimes referred to as *wave-field rendering* [12]. A disadvantage of early wave-field rendering was that the reconstructed surface is not a smooth curved surface but an angular faceted surface. This issue is avoided by modulating the amplitude distribution of the surface function using techniques in CG, such as Gouraud and Phong shading. Texture-mapping in CG can also be introduced into wave-field rendering by modulating the amplitude of the surface function [12]. As shown in Fig. 3, computer holograms “The Moon” and “Shion” are created by using these shading and texture-mapping techniques.

Since all objects do not have diffused surfaces, the rendering technique of specular metallic surfaces is necessary for increasing the power of expression in computer holography. To create specular surfaces, the direction of reflection light must be limited to a narrow range. This is achieved by limiting the spatial bandwidth of the surface function. A technique based on the Phong reflection model has been proposed [17] and “The Metal Venus I”, i.e. a metallic version of “The Venus”, is successfully created as shown in Fig. 5 (b).

The Metal Venus I, however, reconstructs angular faceted surfaces. Tessellation of polygons is necessary to create specular smooth surface, but the tessellation most likely leads to increasing the computation time. Thus, a technique of subdividing the surface function has been proposed instead of tessellating polygons [19]. “The Metal Venus II” created by using this new technique reconstructs metal-like curved surfaces without any seams between polygons, as shown in Fig. 5 (c).



**Figure 7.** The principle of the silhouette method for shielding light behind objects.



**Figure 8.** Field-based digital editing of 3D scenes in computer holography [6].

### 3.2. Digitized holography [6]

Real object fields are recorded by an image sensor using lensless-Fourier setup that uses a spherical reference field instead of a collimated field. In this technique, the object fields is given by Fourier transform of the captured wave-field. Here, phase shifting technique is used for removing the non-diffractive light and conjugate image [25]. The sampling intervals of the Fourier-transformed field is determined by the number of samplings and distance between the center of the spherical reference field and the image sensor [26]. We can adjust the sampling intervals by changing these parameters. In addition, the synthetic aperture technique [26, 27] is used for capturing large-scale fields and increasing the number of samplings.

An advantage of digitized holography is that the 3D scene can be digitally edited after recording. This is almost impossible in classical holography. In the digital editing, the captured objects are: (i) freely arranged and (ii) mixed with virtual objects in the 3D scene. In addition, (iii) a single object captured once can be duplicated in the 3D scene.

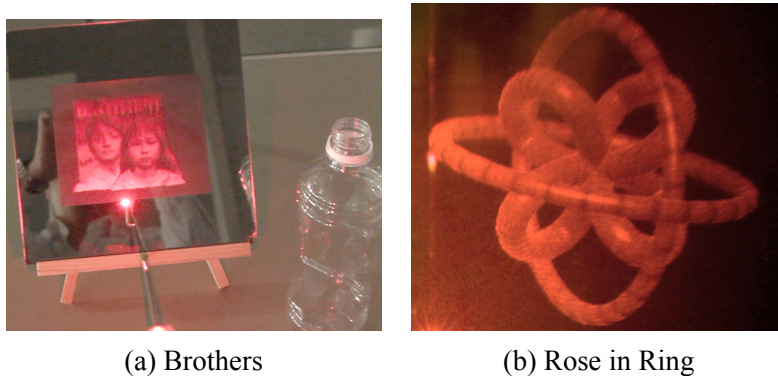
However, the captured objects cannot be simply resized unlike conventional digital images, because the recorded object field contains the phase information of the object light. Virtual optics is required to resize the objects in the 3D scene. Figure 6 shows optical reconstruction of “Hamsters” whose 3D scene includes multiple objects resized by virtual image formation using a numerical lens.

### 3.3. The silhouette method for light shielding in 3D scenes

In the field-based digital editing of 3D scenes, as in Fig. 2, the silhouette method plays an important roll to prevent objects from being see-through [2, 3] and awoke a strong depth perception in viewers. The principle of the silhouette method is shown in Fig. 7. Real objects shield the light behind the object. The silhouette method emulates this phenomenon by blocking the wave-field using a binary mask whose shape agrees with the silhouette of the object. This silhouette-masking is made sequentially from the deepest object to the hologram plane, as shown in Fig. 8. Note that a numerical operation for propagation is necessary for each masking.

As for CG-modeled virtual 3D objects and 2D objects, the silhouette mask is easily generated by projecting the 3D/2D shape onto the field plane. In digitized holography, the silhouette mask is produced from the numerically reconstructed 2D image of the captured object [6].

However, for both virtual and real objects, the silhouette method does not work well in some cases where the object has severe self-occlusion or the silhouette shape of the object does not fit with the cross section. In the cases, the silhouette masking must be applied polygon by polygon, i.e. the silhouette masking must be made by individual polygons. Since this is



**Figure 9.** Optical reconstruction of “Brothers” (a) and “Rose in Ring” (b). The parameters are summarized in Table 1

commonly very time-consuming, a technique using Babinet’s law has been proposed for speeding up the computation [14].

#### 4. Some of recent works

The fringe patterns of the holograms were printed on photoresist coated on ordinary photomask blanks by employing DWL-66 laser lithography system made by Heidelberg Instruments GmbH, which is the equipment constructed for fabricating photomasks [5]. Since the chromium thin film coated on glass substrate forms binary amplitude fringe, the fabricated holograms are chemically very stable without suffering aging-degradation.

##### 4.1. Brothers

This is the biggest computer hologram created with wave-field rendering up to now. The total number of pixels reaches to 25 billion pixels. The optical reconstruction is shown in Fig. 9 (a). The shapes of two live faces of a boy and girl are measured by using a 3D laser scanner. The photographs taken from the same view-point as the measurement are texture-mapped onto the polygon-meshes that are shaded with Gouraud shading.

##### 4.2. Rose in Ring

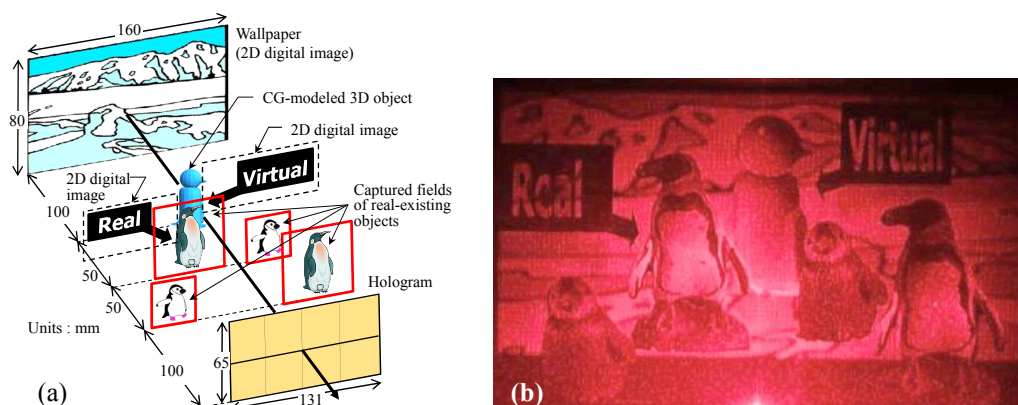
This computer hologram is named “Rose in Ring”, because the main object is generated by a mathematical 3D curve based on well-known 2D parametric curves called Rose curve. The optical reconstruction is shown in Fig. 9 (b). This model has severe self-occlusion, thus a new algorithm for accelerating the silhouette masking, named “switch-back method” is used for calculation.

##### 4.3. Penguin

This is currently the biggest hologram created in digitized holography. The optical reconstruction is shown in Fig 10 (b). Two objects recorded using digital holography is arranged two times for each in the 3D scene, as shown in (a).

#### 5. Conclusion

Techniques for creating high-definition CGHs and some works created so far are reviewed and summarized. The created CGHs usually make a great impact on viewers, because these synthetic holograms reconstruct continuous motion parallax in both vertical and horizontal directions and convey a strong sensation of depth like that in conventional holography. Therefore, the term “computer holography” is suitable for the techniques for creating works by high-definition CGHs. Computer holography is new digital art in 3D imaging like computer graphics in 2D imaging.



**Figure 10.** The 3D scene (a) and optical reconstruction (b) of “Penguin”.

### Acknowledgment

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