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Selecting the parameters of the lens-array photographing system in integral photography

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The characteristics of the basic schemes for taking and reconstructing fragmented three-dimensional images are discussed. The conditions necessary for forming an integral image of an object are determined.

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The generally acknowledged trend in the evolution of still and motion-picture photography is that of printing a volume onto a photograph or screen. Lenslet array photographic systems have come into ever wider use in recent years.

The obtaining of fragmented three-dimensional images presumes the use of lenslet-array photographic systems under various picture-taking and reconstruction conditions. Parallax-panoramogram methods, when the picture is taken with a special lenslet-array camera containing an objective lens and a lenslet photographic system consisting of an array with cylindrical (less frequently spherical) lens elements and a film,[1] are the best known. In this case the exit pupil of the objective lens is projected onto the plane of the film, while the image itself is projected onto the plane of the lenslet array. As a result, the pattern on the film is a series of quite uniformly illuminated bands (for a cylindrical lens array) or circles (for a spherical lens array).

The Lippmann method of integral photography and its modifications[2,3] are less well-known but more promising methods. In these methods the lens elements of the array play the role of micro-objectives, imaging the object itself or its "aerial" image, formed by the picture-taking objective, in the film plane. As a result, the pattern on the film is a series of microimages of the object or its parts, with the quality of the reproduction of the details of the object being determined by the imaging properties of the system comprising the array elements and the film.[4] The diaphragm of the objective lends, as a rule, plays the role of a field diaphragm for the entire system.[3] During reconstruction the lenslet-array photographic system forms a three-dimensional image similar to the object being photographed. This is called an integral image since it is composed of the elementary images formed by each array element during the reconstruction. The integral image is an "optical model" of the object[5] and is easily detected in well-known physical experiments (for example, in a smoke-filled space).

Because of the many obvious advantages, frequently discussed in the literature, modifications of the integral photography method are finding wide application in new three-dimensional motion-picture and television systems, for producing "composite" holograms, in the making of three-dimensional copies of rare museum objects, etc.[6-9]

Despite, however, the widespread use of the integral photography method, thus far some of the questions relating to the evaluation of the quality of the integral image and to a determination of the associated parameters of the lenslet-array photographic system have not been completely answered.

Various authors, replacing the array with a system of stenopic cameras and applying the tools of projective geometry[10] or the theory of the spatial moire,[11] have easily explained the fact that the location of the integral image is preserved during reconstruction. But such a simplified approach did not permit evaluating the image quality nor finding the optimum array spacing (or the associated diameter of the lens element).

Many investigators[5,12,13] have departed from Lipp-

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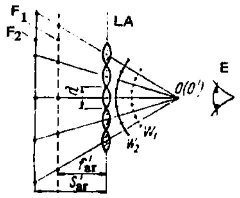

FIG. 1. Scheme for forming elementary waves in the reconstruction of the integral image of a point: O—point object; O'—point image; LA—spherical lens array; f'_{ar} —focal length of array element; S'_{ar} —rear focusing distance of array when it is focused on the point object O; W_1—front composed of series of elementary plane waves; F_1—location of film at which wavefront W_1 is formed; W_2—front composed of series of elementary spherical waves with the same radius of curvature; F_2—location of film at which front W_2 is formed; E—observer's eye.

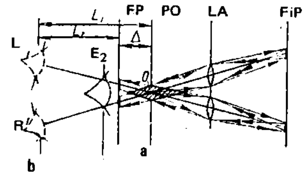

FIG. 2. Scheme for forming and examining integral image of point O: LA—spherical lens array; FP—focus plane of array; FiP—film plane; a—location of observer's eye at which several elementary waves enter its pupil; b—location of observer's eyes at which one elementary wave enters each pupil L_1 and R_1; L_1—convergence distance; L_2—accommodation distance; Δ—the gap between accomodation and convergence. Shaded region is perceived by observer as the integral image of point.

mann's[2] original viewpoint concerning the necessity of restricting the array spacing to the diameter of the pupil of the observer's eye, although in later papers[14,15] he showed experimentally the lack of any relationship between the spacing and the eye pupil diameter when the integral image was formed by an array composed of lens squares with a side dimension of 4 cm. The notion that there is no relationship between the array spacing and the eye pupil diameter was also confirmed by Van Albada.[16] Denisyuk[17] performed a qualitative evaluation of the capabilities of integral photography. After assuming that the film is located in the focal plane of the elements (Fig. 1), he arrived at the conclusion that each lens element will reconstruct a portion of the plane wave whose ray vector coincides with the ray vector of the spherical wave of the object, i.e., during the reconstruction a sum of plane waves replaces the spherical wave. Then the size of the array element must be reduced for an exact reproduction of the spherical wavefront. But this decrease leads to a lowering of the resolution of each lens element and of the image as a whole. This conclusion was cited as a basic contradiction of the integral photography method.

Thus, despite the large number of published papers, there is no clearcut opinion about many of the problems associated with the study of the lenslet-array photographic systems used in integral photography. The purpose of this paper is to explain the physical essence of the differences between the integral photography method and other methods of lens-array photography. This will make it possible to proceed, with justification, toward selecting sensible parameters for a lenslet-array photographic system for forming a three-dimensional image of an object during reconstruction.

RECONSTRUCTION OF INTEGRAL IMAGE

The integral image is a summation of the elemental images which are reconstructed by the corresponding array lens elements.

1. Since the film is optically conjugate to the focusing plane FP of the array, images of points of the object, lying in the arbitrary plane PO, will be constructed in the focus plane FP upon projection through one lens element (Fig. 2). However, since the integral image is reconstructed simultaneously by the group of lens elements, the rays, coming from its microimages on the film, will intersect at the original location of the point. The eye perceives this intersection of beams as the image of the point. This image is also called integral.[18] Thus, to form the integral image it is necessary that each of its points be formed by the rays originated from at least two lens elements.

2. The integral image is reconstructed regardless of what plane the array-film system is focused at. In the general case when the focus plane lies at a finite distance from the array and coincides with the point object O, the series of plane waves (Fig. 1), propagating from the array during the reconstruction of the image of the point lying in the focus plane, must be replaced by a series of spherical waves comprising, in the aggregate, the spherical wave with center at O' lying in the focus plane. Then the accuracy of the reconstruction of the spherical wavefront of a point of the object will depend primarily on the quality of the image formed by each of the lens elements, i.e., there is no need, as indicated in Ref. 17, to reduce the size of the lens element *ad infinitum* since it is possible in principle to achieve wave sphericity even when it has a finite size.

Thus, since usually an extended three-dimensional object is photographed, it is natural to place the focus plane inside the object (or at its surface). Then the effect of defocusing of the lens elements on the sphericity of the reconstructed waves will be a minimum. It should be noted that this quite obvious conclusion is ignored by most investigators, who generally place the film in the focal plane of the lens elements even if the object is located extremely close to the array.

EXAMINATION OF THE INTEGRAL IMAGE

The integral image can be examined by an observer or holographed, as in the formation of "composite" holograms.[6,8] In any case the final image will be examined by eyes; this imposes restrictions on the schematic implementations of the method.

1. An integral photography scheme can be constructed in such a manner that one elementary wave (from one lens element) enters the observer's eye from a point of the integral image. Then the eye, because of accommodation, will see the given point not in its original location, but in the focus plane. If the point will be ex-

amined by two eyes, then it will be perceived in its original location because of convergence. Consequently, there will be a disturbance of the factors of binocular vision, which is a serious and well-known drawback of the stereoscopic representation.[19] It has been established that such a construction scheme is acceptable if this disturbance of the accommodation and convergence occurs within the "comfort" zone (±1 diopter).[20] Let us note that the location of the focus plane in the three-dimensional object (or at its surface) makes it possible to reduce considerably the disturbance of the accommodation and convergence during reconstruction.

2. An integral photography scheme can be constructed in such a manner that a point of the integral image sends to the eye at least two elementary waves. Then the eye will accommodate to the location of the intersection of these waves, i.e., to the true location of the point. Thus, the contradiction, inherent to the case described above, is eliminated. It is natural that if the eye is to examine a series of points at different depths, then it will accommodate to each of them successively. When the second eye is brought into operation, the factors of binocular vision are totally fused, i.e., the eye will see the image of the points in their true location both because of accommodation and because of convergence. In this case, surveying the image results in seeing it from other aspects.

3. The integral photography system is most often constructed in such a manner that both of the construction methods listed are combined in it, i.e., one elementary wave arrives at the eye from some of the points of the integral image, while at least two elementary waves reach the eye from other points. In this situation if the points from which one elementary wave arrives at the eye are located at a distance from the focus plane that does not exceed the "comfort" zone, then the eye of the observer will examine the entire integral image with no strain.

CONCLUSIONS

1. In order to form an integral image of an object it is necessary that each of its points be formed by at least two bundles of rays originating from different elements of the array.

2. In order to increase the accuracy of the reconstruction of the image of an object in integral photography there is no need to reduce the size of the lens element ad infinitum. This accuracy depends on the location of the focus plane of the array and is a maximum if the latter is conjugate to the plane located within the object.

3. In order to fuse the factors of binocular vision it is necessary that at least two elementary waves reach the observer's eye from each point of the integral image; otherwise a breakdown between these factors is inevitable.

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