the hologram in each portion of the spectrum. Since these images are spatially separated, a blurred image of the object appears on the screen. To eliminate blurring it is necessary to have an optical image of the object on the hologram. In this case the images reconstructed in the different portions of the spectrum coincide with the plane of the hologram. This makes it possible to obtain sharp contours of the object in the shadow pattern.

Shadowgrams of the air flow around a cylinder with a hemispherical tip in a supersonic wind tunnel (the Mach number of the unperturbed flow is 2.9) are shown in Figs. 2 and 3. The two photographs were obtained upon the reconstruction of the same hologram and examination by the methods considered above. The pattern in Fig. 2 is obtained by the slit and knife-edge method. The direction of the fringes in the holographic grating is parallel to the axis of the cylinder, and the knife-edge and slit were perpendicular to it during the reconstruction. The shadowgram in Fig. 3 is obtained by the slit and wire method [1].

The hologram-recording unit was built around the collimators from the IAB-451 shadowgram instrument. An "Arzin-207" ruby laser served as the light source for hologram construction, and a DRSh-250 mercury lamp was the light source for wavefront reconstruction.

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Elimination of Image Pseudoscopy in Integral Photography

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A theoretical analysis of known methods of eliminating integral image pseudoscopy showed that only two methods are capable of giving an orthoscopic image. Two additional methods of generating such images are proposed. An experimental test confirms the conclusions of the theoretical analysis.

The ability of integral photography to create the complete illusion of a real object in an image, including its stereoscopic properties, the illusion of looking "around" an object, and the play of highlights, has recently attracted the interest of many investigators.

The division of the integral photography process into two steps—the creation of a photographic image and the reconstruction of the integral image by reverse illumination of the same integral plate—inevitably leads to pseudoscopy, i.e., the relief of the integral image is opposite to the relief of the object seen by the observer (convexities appear concave, and vice versa) [1].

In Tudorovskiy's classification [2], all optical systems fall into two classes, differing in the sign of the longitudinal magnification. In integral photography, the image is reconstructed by the same optical system as that used to make the photograph. Regardless of the sign of the longitudinal magnification, i.e., regardless of the class of system, this leads to image pseudoscopy. The need to eliminate this has forced investigators to look for methods and devices able to impart orthoscopicity to the image.

A method of producing orthoscopic integral photographs, involving copying the integral photograph onto a second, identical emulsion-carrying plate, was suggested by Lippman [3]. Let us call it Lippman's second method. Chutjan and Collier [4] described a technique involving photographing a pseudo-object, i.e., an object with an inverted relief. Burkhardt et al. [5] have used a special device, which they called an autocollimating screen, to produce an orthoscopic integral image.

We were interested in examining the theory and experimentally testing the above-listed methods, as well as techniques borrowed from classical and scanning stereoscopy, for producing orthoscopic integral photographs and attempting to find new ways of solving this problem.

In the simplest case the problem is to find a system which would produce normal relief of the partial three-dimensional image in an integral photograph formed by only two lenslets.

In classical stereoscopy the problem is solved by splitting the negative and shifting its parts. In integral photography this technique is not applicable. The inversion of the relief of a stereoimage in stereocameras is accomplished simultaneously and independently by two identical optical systems, located in front of the stereocamera lenses. One cannot employ a single optical system in front of the two stereocamera lenses because such a system would have to rotate the two images of the object in two opposite directions simultaneously. It follows that one cannot hope to invert the relief of an integral image with a single optical system. There remains one possibility, namely, the use of a composite optical system that would individually invert each microimage in the integral photograph under each lenslet.

We are proposing two variants of a system capable of individually inverting the microimages, either at the time the photograph is made (Fig. 1, a, b) or when the photographic print is produced (Fig. 1, c). The system that inverts the image when the photograph is being made (Fig. 1, a) consists of two identical or similar fly's-eye lenses with spherical lenslets. Fly's-eye lens I produces a series of intermediate optical microimages of the object, which are then independently transmitted by the lenslets of fly's-eye lens III to the emulsion plane IV. Reconstruction of the integral image is done by transilluminating the fly's-eye lens III and emulsion IV combination separated by a distance which produces a reconstruction of the integral image at the same distance from the combination as the object is from fly's-eye lens I. To improve the optical characteristics of the system, a fly's-eye lens, composed of long-focus collecting lenslets, can be placed in plane II. The configuration of this fly's-eye lens must be exactly the same as that of fly's-eye lenses I and III.

In using the composite optical system for inverting the image in the print-making stage, the first-generation print, produced by the usual integral photography process, is reprinted via a fly's-eye lens identical to the one used to make the photograph, so that each lenslet of the fly's-eye lens generates an individual reprint of the particular microimage which was produced by its twin lenslet on the original emulsion. Reconstruction of the integral image is done by transilluminating the system consisting of the photograph-making fly's-eye lens and the second-generation print, separated by a certain prescribed distance. With composite optical systems, there is no need to reconstruct the first-generation pseudoscopic integral image. The erecting lens systems used in telescopes can be construed as the analog of the elements of the combined systems. Employing

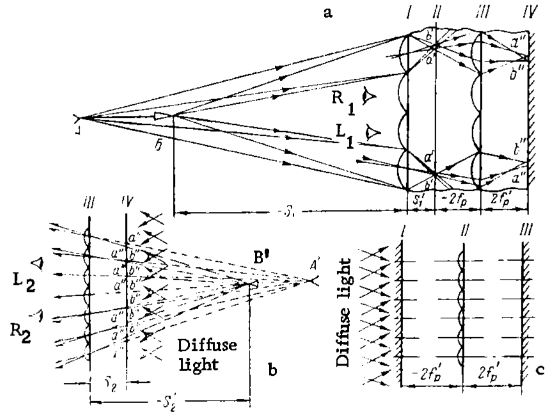

Fig. 1. a) Photographing an object with the composite optical system, comprising the integral plate, b) reconstruction through this plate, c) use of the composite optical system during the photographic printing operation.

projective geometry methods, we were able to demonstrate that after all of the above transformations, the individual microimages will be synthesized in viewing into a single integral image.

We also analyzed several methods borrowed from classical and scanning stereoscopy, in particular, the method proposed by Sokolov and Ives of viewing the integral image through an emulsion layer with the camera obscuras replaced by lenticular elements [6], Estanave's method [7], printing through a large-diameter lens, and contact printing. Our analysis involved tracing the change in the direction of the axes of the Cartesian coordinate system, associated with the object, through the processes involved in the above-named methods. We found that an orthoscopic integral image can be produced only by Lippman's second method, the "autocollimating screen", and the composite optical systems. All the other methods yield a pseudoscopic integral image.

The next step consisted of experimental verification of our conclusion and a comparison of the methods for producing an orthoscopic relief from the viewpoint of the quality of the final integral image. Side effects that occur in practice were also analyzed.

A one-piece assembly, composed of a fly's-eye lens and "Mikrat VR" or "Mikrat Fine-Grain Agfa" photographic plates, clamped in a metal bracket and potted in "Protakril" self-hardening plastic, was used as the integral photographic plate. Two types of fly's-eye lenses were used: a) glass * with a honeycomb array of lenslets having the following characteristics: spacing -3.7 mm, relative aperture - 1:3.5, focal length - 4.8 mm; and b) plastic**

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*Made by D. D. Zhdanov.

**Developed by the Bureau of Semiconductor Machine Building.

with a glass substrate and a linear arrangement of lenslets and the following characteristics: spacing - 0.4 mm, relative aperture - 1:6, focal length - 1.48 mm. Focusing of the integral plate on the object was done by means of a 100x microscope, with a halftone test target replacing the photographic plate. To obtain a positive image, the integral plate was developed in reversal. The development process was that recommended by Kodak for "Mikrat" type plates.

To obtain an integral image of a flat object by Lippman's second method, we used a wide-angle collimator with 36- and 6-element pie chart-type targets, incorporating a "Record-4" lens (52 mm focal length and 1:0.9 relative aperture).

The composite optical system that inverts the image during the photographing stage consisted of two pairs of identical fly's-eye lenses of the types described above; the same fly's lenses, but singly, were also used at the printing stage.

The relief in the image was checked by sectioning the integral image with planes and recording these sections on photographic plates. We also magnified adjacent microimages to normal frame dimensions, made stereopairs from the resulting positives, viewed them in a stereoscope and determined the relief of the stereoscopic image.

During tests we observed ghost integral images, similar to the principal image and due to the multiplying properties of the fly's-eye lenses. The reason for these images can be explained by projective geometry [8], as well as by the theory of the three-dimensional moiré effect. To eliminate these ghost images, we must turn to Lippman's idea of barriers between the lenslets of the fly's-eye lens. The use of real fly's-eye lenses requires careful control of the relative position of the elements of the optical system used. Thus, for example, Lippman's second method works only if the spacing between the plates is such that only rays forming the principal integral image are incident on the unexposed plate. A less then optimal spacing between the plates (less than 30 mm), produces a moire effect, that is, ghost of microimages (Fig. 2, b) which, in turn, generate ghosts in the reconstructed image.

Measurements of more than 120 microimages, made in four independent tests with the above two types of photographic plates, showed that the loss of resolution in the second-generation microimages produced by Lippman's second method (see table) involves a factor of about 1.6; this agrees with the theoretical loss in resolution by a factor of $\sqrt{2}$ [9] (Fig. 2, c).

The principal drawback of the "autocollimating screen" scheme is its extremely poor illumination characteristics and the presence of spurious highlights superimposed on the principal image and brighter than it. The use of a nonplanar front surface on the "autocollimating screen", suggested by Doherty [10], does not eliminate these highlights, but only reduces their brightness. These faults have forced Burkhardt et al. [5] to eliminate the "autocollimating screen" during photography and to substitute pseudoscopic holographic image as the object. The "autocollimating screen" method has been used successfully only as a substitute for a microscope in visual focusing of the fly's-eye lens onto the object [10].

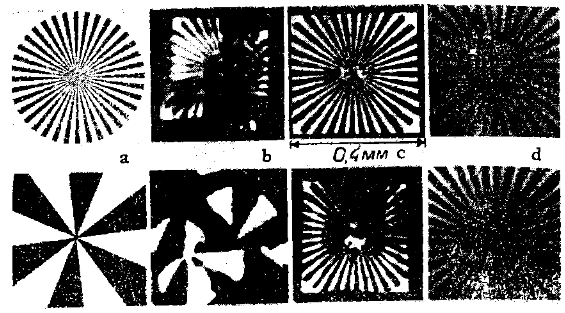

Fig. 2. a) 6- and 36-element pie chart-type absolute-contrast targets used as test objects; b) Lippman's second method. Appearance of developed emulsion in the presence of noise-type microimages, resulting from the moiré effect. c) Lippman's second method. Appearance of microimage in the first-generation (top) and second-generation (bottom) integral plate; d) appearance of microimage after one fly's-eye lens (top) and after the composite optical system (bottom).

Lippman's second method

Photographic plate	Resolution in image, mm^{-1}				Theoretical resolution in second-generation image
	first generation		second generation		
	average	± Δ	average	± Δ	
"Mikrat Fine-Grain Agfa"	219	±20	141	±22	155
"Mikrat VR"	140	±12	80	±14	99

Composite optical system during photography

Photographic plate	Resolution in image, mm^{-1}				Theoretical resolution in composite optical system
	first-generation		In comp. opt. syst.		
	Average	± Δ	Average	± Δ	
"Mikrat Fine-Grain Agfa"	219	±20	198	±20	219
"Mikrat VR"	140	±12	122	±10	140

Normal-relief integral images can be obtained by using a composite optical system for photography (Fig. 2, d). This yields an important advantage over the methods described above in that a normal-relief integral image is produced immediately in the first-generation reconstruction. This gives the maximum resolution possible in the integral photography, which is at least a factor of $\sqrt{2}$ better than in Lippman's second method (see table). Measurements were made on 80 microimages, produced in two independent tests.

We also discovered the principal drawback of Lippman's method—the necessity of developing the photographic plate separately from the fly's-eye lens with respect to the print when combining them into a single assembly. This alignment can be accomplished by means of micrometer screws and a microscope, and also visually, from the nature of the moiré pattern on the surface of the fly's-eye lens.

A moiré pattern was also found when the composite optical system was used at the printing stage. This effect, just as in the foregoing case, can be used to adjust the position of the fly's-eye lens through which the printing is done, with respect to the developed photographic plate.

Conclusions

1. We suggest two arrangements for producing an orthoscopic integral image with a composite optical system.

2. We have shown theoretically and checked experimentally that Lippman's second method, the "autocollimating screen" method and the composite optical system method are all capable of producing orthoscopic integral images.

3. Orthoscopic integral images have been produced by a purely photographic method, apparently for the first time.

4. It has been experimentally demonstrated that integral photographs, produced with composite optical systems, have the maximum possible resolution. The integral image made by Lippman's second method shows lower resolution of the second-generation microimages. This resolution agrees with the theoretical prediction ($\sqrt{2}$ times less than in the first recording).

5. It is impossible, practically speaking, to produce an orthoscopic integral image with the "autocollimating screen" method. It can only be used for focusing the integral plate.

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