WIDE-ANGLE INTEGRAL PHOTOGRAPHY – THE INTEGRAM* SYSTEM

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Abstract

A technique has been designed, developed, and implemented on a semi-routine basis, whereby the major hindrance of Lippmann's elegant concept of integral photography is circumvented without trade-offs, owing chiefly to a novel method of conversion from pseudoscopic negative to orthoscopic positive, involving a single integral network, without recourse to additional conventional or holographic optics. The Integram* system retains the originally intended full parallax, with very wide acceptance and viewing solid angles; only ordinary incoherent natural or artificial light is used at all stages. The three-dimensional, autostereoscopic, orthoscopic and orthostereoscopic summation image is generated at a 1/1 scale, in full natural colors, and is viewed by transmitted or ambient illumination; it may also be enlarged or reduced without distortions. Angles of over 80° have been achieved in the current 11 x 14 inch samples, where the refractive index of the polyester resin spherilenticulated viewing screens is 1.56. The background, the optics, the technology, proposed refinements, variations and applications of the Integram* system are discussed.

Background

Gabriel Lippmann

On March 3, 1908, the Nobel Prize winner Gabriel Lippmann announced that he had invented integral photography. This major contribution was the subject of his communication to the French Académie des Sciences under the title "La Photographie Intégrale".(1)

The objective of Lippmann's system was the creation of a directly viewable (we say today autostereoscopic) three-dimensional image without using a camera -- in the conventional sense. According to Herbert E. Ives(2) it:

"...consisted of a sheet of transparent material embossed with a multitude of small convex lenses, each of which formed a minute picture upon the photographic emulsion on the rear surface. When such a sheet is held before the eye a composite or 'integral' image (appears), a single tiny element of each minute picture being seen from any given position, and since the elements seen change with the position of the eye, the character of the integral picture changes as the observer moves." (Figure 1, a, b.)

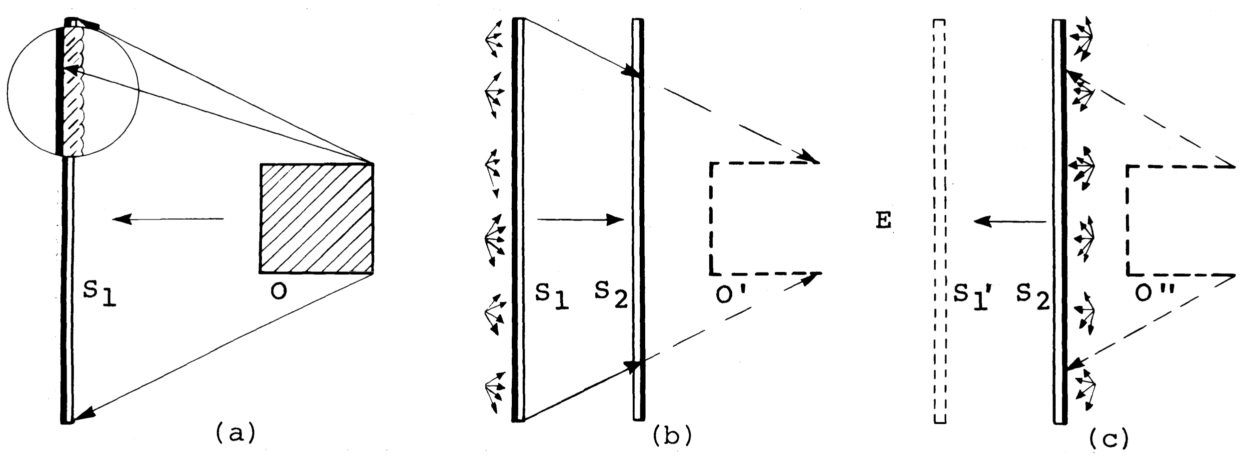


Fig. 1. Schematic diagram of the Lippmann proposition. At (a), an object O is imaged by each one of the lenslets of sheet S_1 (detailed in the "balloon") onto the photographic emulsion coated on the back. At (b), the sheet S_1 with its developed elemental images is diffusely illuminated, and an eye at E sees the summation image O' as real but pseudoscopic. A sheet S_2 identical to S_1 intercepts and records the pseudoscopic image O'. At (c) sheet S_2 is illuminated and an eye at E sees the summation image O" as virtual and orthoscopic, but its quality leaves much to be desired, and the image S_1' of S_1 is conspicuous.

*Trademark

It seems fit to mention here that Lippmann's momentous proposition was born in the climate of Ives' father's Parallax Stereograms[3] in which the two component pictures of a stereo pair were presented as alternating fine strips, each series of strips being separately visible through a grating made of clear and opaque lines. This was a way of avoiding, under controlled conditions, the hand-held parlor stereoscope very "en vogue" in those days but which allowed only one person at a time to enjoy its magic. Whether Professor Lippmann was aware or not of Frederic E. Ives' invention is uncertain but does in no way affect the value of his own, completely original and supremely elegant concept.

However, it is surprising, even baffling, that such a brilliant mind could have been so totally unaware of a formidable limitation of his proposition: the pseudoscopic character of the summation image (similar to the first order real image in holography).

Ives went on:

"Lippmann proposed two methods of making photographic positive pictures, using the lenticulated sheet. The first method consisted in carrying through a purely photographic reversal, that is, the original negative was reversed by dissolving out the developed image and re-exposing, simply to light, and was thus ready for observing from the side which faced the object. The second method consisted in setting up another, unexposed, lenticular sheet at some convenient distance from the original negative, and exposing it to the light transmitted through the latter. This second method (Figure 1. b and c) produced a geometrical as well as photographic reversal..." because the pseudoscopic copy of a pseudoscopic image is orthoscopic (as theorized by Ives, and copiously demonstrated in holography as well as, by this author, in integraphy).

"Now", Ives continued, "it is abundantly clear, from Lippmann's descriptions of his idea, and from his accounts of attempts to demonstrate the principle,[4, 5] that he believed these two methods to be equivalent, that is that a true relief picture would be obtained by either procedure... The originally exposed lenticulated sheet exhibits reversed or pseudoscopic relief; the procedure involving rephotography is not merely an alternative method, it is imperative, if a true relief picture is to be obtained."

Shortcomings of the Original Concept

As pointed out by Ives, Lippmann's second copying method is indeed imperative. That is, some method for converting the pseudoscopic image to an orthoscopic one is imperative. But it does not have to be necessarily Lippmann's, which presents its own severe limitations: for all but extremely small lenslets, too small to be practicable, as discussed further on in this paper, his method requires that the two sheets be placed at such a distance from each other that the second sheet may not resolve and record the pattern of lenslets of the first sheet, which would result in a "moiré" effect and would degrade seriously the orthoscopic image thus obtained. To overcome this hurdle, the distance between the sheets has to be relatively great. This, per se, is not necessarily objectionable, but the presence of a real image of the first sheet, in the orthoscopic image of the second, constitutes a field aperture which restricts substantially the acceptance angle (Figure 1.c).

Another and major shortcoming of the original concept is the very large aperture of the lenslets, hence their small f/number, imposed by the need for very wide acceptance and viewing angles (essential to the initial goal of the system) as well as for the preclusion of image repetition, characteristic of parallax panoramagrams. With such apertures, spherical and other optical aberrations would have intolerably limited the definition of the elemental images, recorded with the same, large aperture sheets, at both the Taking and Printing stages.

Previous Solutions and "Trade-Offs"

Many contributions have been made to this fascinating field. Variously ingenious devices were evolved, in efforts to overcome or circumvent the obstacles of the original process of integral photography. It is regretted that a comprehensive review of all of these propositions would exceed the scope of this paper.

Countless are those who have drifted away from integral photography to embrace more accessible related fields such as that of parallax panoramagrams -- originally introduced (again!) by Herbert E. Ives.[6] A substantial few[7-11] have persisted and (mostly in order to achieve acceptable definition of the recorded elemental images) have resorted to using large central lenses, fiber optics, mirrors, autocollimating gratings, and the like, both to more adequately focus the mini-images and/or to effect the indispensable conversion from pseudo to orthoscopic. (The word "indispensable" used here must be qualified: there are special instances in which a pseudoscopic image is or may become desirable; some elaboration of this statement is destined for another paper.)

All these focusing or converting elements, unfortunately, effective as some of them may be, share one distinguishing trait: they restrict the acceptance and viewing angles of the summation image. This may be acceptable for specific applications; but it is no longer true integral photography, in the absolute intended meaning of the word (see Introduction -- Philosophy of the Integral Concept). H. E. Ives proposed a new, most elegant device for direct orthoscopy at the taking stage, using an array of negative lenslets.[12] But there again, no wide angle unfortunately, due to the very nature of these lenslets.

Introduction

N.A. Valyus, in his book on stereoscopy,(13) notes:

"Until now it has not been possible to produce a complete integral image. Modern resources are not adequate for a complete solution of this practical problem. Many difficulties of a very high order are encountered in preparing the photographic plates made up of a collection of microscopically small lens elements."

Although nothing indicates whether Valyus was aware or not of the need for diaphragm and field apertures, (unlikely indeed to have been considered, in microscopically small elements) this statement overlooks the practical acceptability of non-microscopic lens elements, a realization which has led this author to evolve the sophisticated technique presented here, which is believed to have carried the original concept beyond the stage of a laboratory curiosity to that of a marketable product.

(a) (b) (c)

Fig. 2. One single Integram, seen from three different vantage points: (a) from upper left, 35° off axis; (b) on center, from below, 30° off axis; (c) from upper right, 42° off axis. Note the "stopped" smoke of the pipe, due to flash exposure. Full color, on pre-embossed Ektacolor Print Film.

Philosophy of the Integral Concept

Once the attractions and the practical potential of integral photography were established and identified, two major considerations were to be observed and to guide this undertaking, resulting in the Integram system, whose development was started in 1950.

The first consideration was rather of a pragmatic nature; it concerned the predictably high precision requirements of the developmental phases and of some marginal aspects of the production, which to be practicable had to afford some flexibility.

The other consideration was of a more theoretical nature: It postulated that the goal of integral photography would not be fully realized unless both meanings of the expression "integral" were satisfied, i.e.:

a. The integral image of course must be an integration (a summation) of sub-elements; to quote Malpighi, as Lippmann did: "Tota in minimis existit natura...".

b. It should also represent the object with a maximum of integrity, that is it should be a true and complete visual replica, as described for example below, under the heading: The Integram System.

The first meaning (a.) is satisfied by definition as long as no additional, non-integral, optics are used to record or transpose the image.

The second meaning (b.) is probably the chief guideline of this undertaking and it must be thoroughly understood and accepted before the system's merits can be clearly assessed.

What this second postulate implies in effect is that, within certain limits which vary with the observer's perceptual threshold, the object recorded and reconstructed using this system must appear to be there, not as a mere, more or less faithful representation, but as itself. This illusion should be so complete as not to be revealed by visual clues alone; in other words an integral photograph encased in a wall should be readily mistaken for a "window". If the "windowpane" appears more as a slightly coarse screen than as a smooth glassplate (see Figure 2), it does not seriously affect the illusion, because it is not a part of the reconstructed scene. Furthermore, it has now been shown that even summation images which are not needle-sharp can be mistaken for the object because their appearance is subconsciously attributed to the "window pane" alone.

This purpose is usually achieved (for an observer moving towards, away from, laterally, or up and down) when the assumed object: 1/ is and remains free of distortions, 2/ does not "migrate", or seem to follow the observer's motion, 3/ does not "jump" back to an initial aspect (as in parallax-panoramagrams) and 4/ beyond the useful viewing angle simply ceases to be visible either because it is cut off by another virtual object or by an edge of the "window" or because the screen becomes darker or lighter, cloudy or specular, etc. whereby it obscures the virtual object, as it might have obscured a real object.

To achieve these requirements the acceptance angle must be solid (full parallax), and at least wide enough in all directions to preclude any image repetition. The wider the angle, the more believable the illusion, since the virtual object remains visible for a greater number of vantage points, without losing any of its orthoscopic and orthostereoscopic character. This has been dramatically demonstrated in total darkness as early as 1952 by the author, in black and white, with an 11 x 14 inch integral pinhole screen having an acceptance angle of 180°. While, with lenslets instead of pinholes, the extreme, ideal angle of 180° seems, at this time, limited to a special class of Integram viewing screens having a relatively low transmittance, a more realistic maximum (about 120°) with high transmittance, is probably within reach, since it is a function of predictable increases in the clarity of existing refringent materials having high refractive indices, to be used for the viewing screens. Naturally however, for each degree gained some resolving power is lost.

Pinhole Screen Analogy

For those not intimately familiar with the optical principles of integral photography, it may be useful to establish an analogy between the lenticulated screens and earlier forms which employed pinhole screens, before attempting a detailed analysis of the system as implemented.(14)

In Figure 3, which is a cross-sectional schematic diagram of the complete system, P_1, P_2 etc. represent the pinholes. F_1 is a photographic emulsion placed at a distance T_1 from the pinhole sheet S. On this emulsion are recorded elemental images such as A'B'C' of the object ABC, formed by pinholes such as P_1. It is understood that actually there are provided numerous pinholes only a few of which are shown, and corresponding elemental images, only one of which is shown for all three points A, B, and C, together.

If a panel of diffused light is placed at L_R, an eye located at E_R will perceive the brightness of pinholes P_1, P_4, and P_5 as modified by points A', B'_4, and C'_5 of the emulsion F_1, corresponding respectively to points A, B, and C, of the object, and a summation image A'''B'''C''' of this object will therefore be seen from the rear so to speak, i.e. through its back ADC, shown in dashed line, and which of course is not even recorded. Both eyes of an observer would interpret correctly the summation image of the object as being located at ABC, but the real image so produced would be pseudoscopic since the curvature A'''B'''C''' as seen from E_R is negative, (the opposite of the object curvature). But since so far we are dealing with pinholes, i.e. non-refracting, non-focusing light-passageways, the panel of light can just as well be placed at L_V instead of L_R; in this case an eye located at E_V sees the pinholes, e.g. P_1, P_2, and P_3 <u>through the image points</u> A', B'_2, and C'_3 on the emulsion F_1, corresponding respectively to object points A, B, and C, whereby the brightness of each pinhole is modified in the same manner as when the image was <u>behind</u> the pinholes. Two eyes situated in the same general location would correctly see the summation image as occupying the place of the object ABC, and this image would be virtual, (it would be perceived in effect behind the screen S and even behind the panel L_V, as formed by virtual rays); it would be orthoscopic since the face A'''B'''C''' would now be seen in the positive (convex) mode as that of the object.

Thus, in the case of a <u>pinhole screen</u> the summation can be viewed from either side of the screen and, because it remains so to speak geometrically "attached" to the same side of the screen, regardless of the orientation of the observer, it is either real-and-pseudoscopic (when the eyes are located on the object side E_R) or virtual-and-orthoscopic (when the eyes are located on the opposite or image side E_V).

Nothing would be changed in this geometry if a new emulsion were placed say at F_2, at a distance $T_2 \approx T_1$ from the pinhole, and the light panel at L_R would cause elemental images such as A'B'C' to be re-imaged, inverted, by the pinholes, on emulsion F_2 at A''B''C'' and therein recorded and subsequently processed. In this schematic drawing, the spaces T_1 and T_2 are assumed to be air, to simplify ray tracing. In practice, they would be glass or plastic, serving as supports or bases for the emulsions, and the rays in that medium would of course be deviated by refraction; but to repeat, nothing would be changed in the geometry as long as both supports had approximately equal refractive indices.

If then the first emulsion F_1 were removed with its support T_1, the eyes at E_R or E_V would still perceive a summation image corresponding to the object, in the same manner as before, at the proper angle since the eye located at E_R or E_V sees, e.g. point A at A''' in line with pinhole P_1, whether by means of image point A' or image point A'', indifferently.

The situation just analyzed occurs of course for any point, hence for all points. Furthermore, the viewing angle may be as wide as 180°, the thickness of the supports T_1 and T_2 being easily selected (as a function of the refractive index) such that, at the critical angle, the elemental images are adjacent but not overlapping.

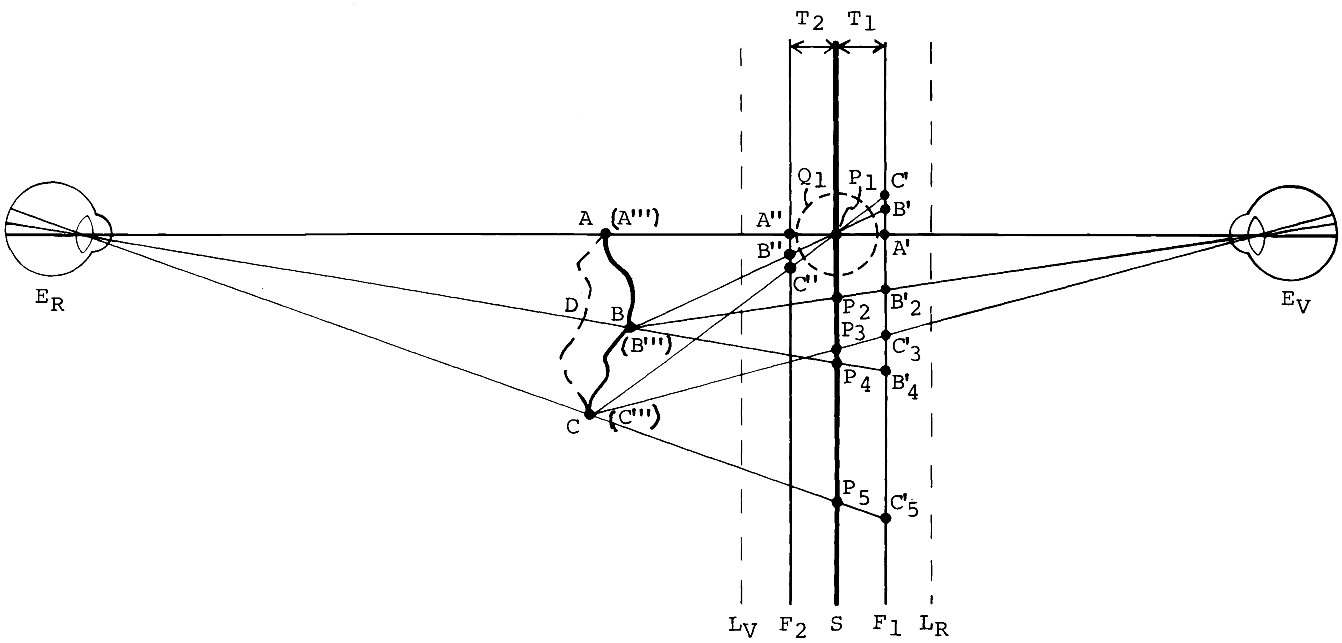


Fig. 3. Pinhole screen analogy. A spherical lenslet is symbolically shown in dotted line. It is used to indiscriminately represent the lenslets of all three stages.

Conversion from Pinhole to Lenticulated Screen. Unfortunately the images provided by pinholes have poor definition, especially at the second generation; furthermore, the small size of the pinholes reduces drastically the transmittance of the integral screen at the Viewing stage, (to as little as 1/15,000 of the available luminous flux; e.g. if we take the luminance of the diffusing sheets L_1, L_2 as 200 fL, the pinhole diameter as 0.001 in. and the space between them as 0.125 in., the luminance of the pinhole plate will be $200/125^2 = .0128$ fL). Hence, instead of pinholes, lenslets must be provided. Their function, in terms of the overall geometry of the integral optics, is so similar to that of pinholes that it can be described using the same schematic diagram of Figure 3.

In this diagram, at the recording (or Taking) stage, a lenslet is schematically shown as a sphere in dotted line Q_1. Provided that the image layer F_1 is substantially in the back focal surface of the lenslet Q_1, it is evident that from position E_R the eye would see, refracted and magnified by that lenslet, the point A'; this is true for all other lenslets and image points on layer F_1, as it was in the case of pinholes, whereby a summation image, real-and-pseudoscopic, as discussed above, would be formed and perceived. On the other hand, from position E_V the eye would see the emulsion F_1 directly rather than through the lenslet and therefore optical projection would not take place, and no 3-D summation image could be perceived from that side. Consequently, when lenslets are used rather than pinholes, a conversion step is indispensable as mentioned before, in order that an orthoscopic image be obtained.

Referring to the dotted circle Q_1 and assuming that it denotes now one of a new array of lenslets constituting the conversion screen and having a shorter focal length such that F_1 and F_2 are respectively in two conjugate surfaces of the lenslet, image A'B'C' of layer F_1 can be projected and focused on layer F_2, thereby producing an inverted image A''B''C'' as was the case with the pinhole P_1. Now if, later, the dotted circle Q_1 is assumed to denote one lenslet of a third, different array intended for the Viewing stage and such that the image layer F_2 is substantially in the back focal surface of the new array of lenslets or preferably somewhat closer, an eye at E_V can see, as required, the new image points A'', B'', and C'', magnified by the lenslet. The conditions are thus satisfied where as intended the eyes located in the image space E_V will perceive the summation image A'''B'''C''' as virtual and orthoscopic, and located in the object space, this with maximum light transmittance.

To sum up this discussion: It has been demonstrated that to convert the summation image from pseudoscopic to orthoscopic it is necessary and sufficient to invert individually, by 180°, each one of the elemental images without, however, changing their position with relation to the other elemental images. The system is not centered on the summation image. It is, and must be, centered on each one of its thousands of component elements (inverting the ensemble of the array -- as with a central lens -- would only invert the general orientation of the summation image; it would not alter its pseudoscopic character).

The Integram System

While it does not seem to have ever been fully achieved, before the development of the Integram technique reported here, the main, and extremely ambitious objective of integral photography was, and remains, to record a volume of space on a relatively thin sheet or plate so as to subsequently reconstruct an optical duplicate of the recorded volume of space, with all of its three-dimensional characteristics. The ideal integral image is akin, in some ways, to a full hologram, in that it reproduces the three coordinates of the original space, or object, in their natural relationship and with full parallax, as observed within a very wide solid angle.

In spite of the rather striking geometrical similarities between integraphic and holographic images, Integrams , unlike holograms, need only common natural or artificial light at all stages, and no special equipment, to be displayed either as transparencies (the more effective) or as reflection prints under ambient lighting. The exposure may be instantaneous, as by high-speed flash, and can take place indifferently indoor or outdoor. Full natural color does not present any special problem.

Distinguishing Characteristics

Before describing the Integram System in more detail, a comparative review of its dominant characteristics will assist, hopefully, in an evaluation of the process, and of its differences with the original and subsequent propositions:

An overriding characteristic of this technique (to repeat) is the provision of full parallax within very wide field and viewing angles.

Another chief characteristic of the process, resides in its being carried through with integral optics exclusively.

A third, essential, characteristic consists in its use of arrays of diaphragm and field apertures, some embedded, at certain stages.

A vital aspect of this system is the particular method employed for the indispensable conversion of the integral image from pseudoscopic to orthoscopic.

A curious and very significant difference between this and Lippmann's proposition is that, at the Viewing stage, the array of positive elemental images is not placed so as to coincide with the back focal surface of the lenslets, but closer to their principal point, in some cases substantially so.

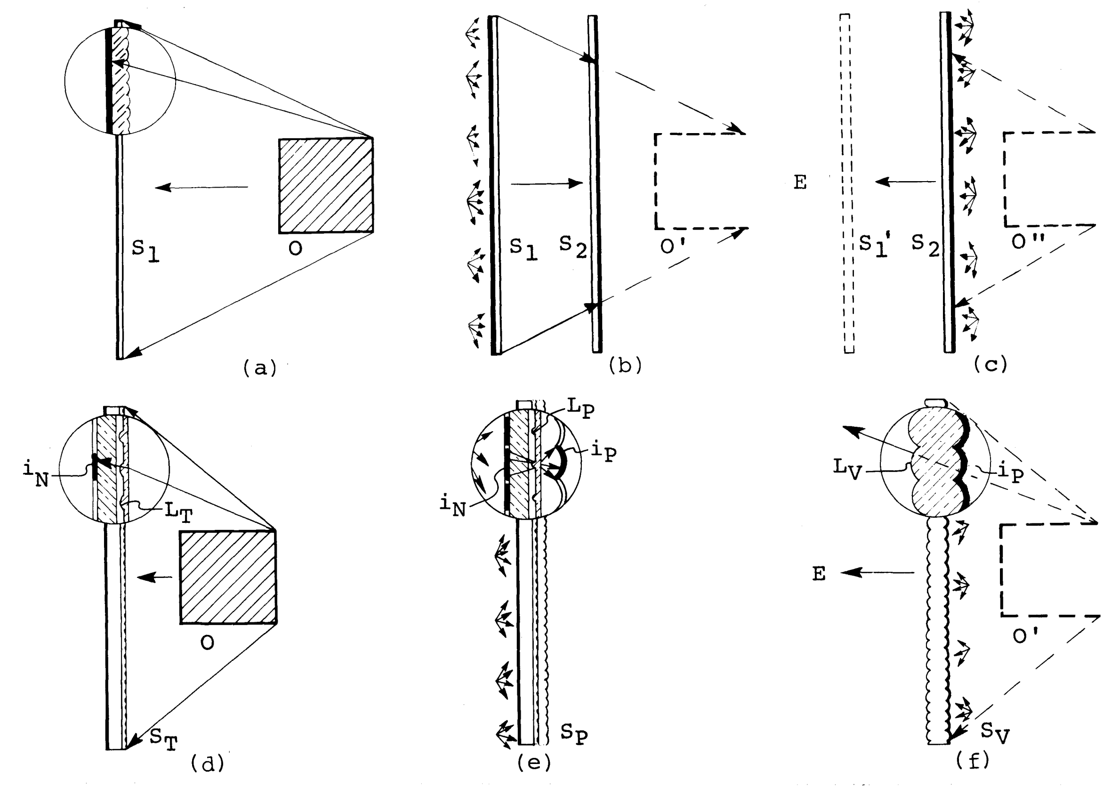


Fig. 4. Parallel between Lippmann's second method and the Integram system. At (a), (b), and (c), are shown Lippmann's three steps: recording, re-recording, and viewing, using two similar integral sheets. At (d), (e), and (f), are shown the three steps of the Integram system: recording, transposing, and viewing, using three dissimilar integral screens and two separate films.

Direct Parallel with the Lippmann Method. Of the two methods proposed by Lippmann for the sole purpose of obtaining positives, the second method happened also, by accident, to convert the pseudoscopic negative into the desired orthoscopic positive. It has been shown however that, elegant and simple as it would be, it turns out to be unusable in practice.

Lippmann's two sheet procedure (Figure 4, a, b, and c) consists in:
1) Recording a scene with the lenslets of the first integral sheet onto a photographic emulsion coated on the back of the sheet.
2) Using a second, similar sheet to record the resulting negative-and-pseudoscopic summation image.
3) Viewing with the same second sheet the resulting positive-and-orthoscopic summation image, albeit with some serious drawbacks.

The present technique (Figure 4, d, e, and f) uses, not one, not two, but three integral sheets -- or more precisely screens since the emulsion is not coated thereon.

The Integram procedure consists in:
1) Recording a scene with the lenslets of the first integral screen onto the emulsion of a separate film.
2) Using a second, different screen to record each one of the elemental images of the first film, individually inverted, onto the emulsion of a second, separate film, the films being placed at two conjugate surfaces of the screen's lenslets.
3) Attaching the second film to the back of a third, still different screen to view the resulting positive-and-orthoscopic summation image.

Outline of the Three Stages

At the Taking stage [Fig. 4,(d)] there is produced and recorded on a single sheet of photographic film, color or black and white, through the lenslets L_T of a first integral lenticular network S_T, an array of negative minute elemental images i_N, each one representing the whole field visible from the vantage point of the lenslet through which was produced that particular elemental image.

At the Printing stage (e) which is truly the core of the Integram system, a new image array is produced, where the geometric orientation of each of the original elemental images is individually inverted. To achieve this inversion the developed film, bearing the original image array i_N is placed at one of the conjugate surfaces of a new, different network S_P, in axial register with the lenslets L_P of this network, and diffusely illuminated; a specially embossed photographic material is positioned at the other conjugate surface of this network, and records, in the array of spherical concavities which bear the emulsion, a new array of elemental images i_P which are the positive counterparts of the original images i_N, focused and inverted by each one of the lenslets of the network. In this way the new images, although inverted 180°, are nevertheless in the same location with respect to each other as were the corresponding images in the original array, a necessary condition for the desired orthoscopic result, as has been demonstrated above with a pinhole screen analogy.

At both the Taking and Printing stages, each lenslet of the networks includes a diaphragm and field aperture; it is to be clearly understood that no additional central optical element is used at any stage since its very presence would necessarily restrict the acceptance angle of the system.

At the Viewing stage, the embossed photographic material bearing the developed array of inverted images i_P is optically cemented to the back surface of a third integral network S_V having (generally) no diaphragms or field apertures (see also Figures 6 and 7). This material falls automatically in axial register with the lenslets L_V, owing to the fact that it conforms with the spherically curved rear surfaces of these lenslets.

* * *

An interesting aspect of the process lies in the previously mentioned fact that the lenticular structures used at all three stages of the system can be substantially coarser than generally recognized by Lippmann and other authors, hence greatly minimizing problems of registration, and many other technological hurdles.[15]

In determining a suitable lenslet diameter and pitch, one can and should take into account an important factor, which helps select a pitch greater than conventional two-dimensional computing would impose. In two-dimensional computation one assumes monocular viewing from a fixed station of an image situated in the plane of the network: since the viewing is usually binocular, the points of information are seen from a different angle by each eye through corresponding lenslets, and the actual number of points in the cyclopean image is about twice that received by either eye. Furthermore, the observer rarely remains completely still in the presence of a three-dimensional image; he wants to see more, and his motion unveils more points of information. Last but not least, the eyes do not focus on the network but rather beyond, in the virtual image space; this tends to blur the pattern of the lenslets. All this contributes to substantially increase the perception of the information actually available in the summation image for any one station of the observer.

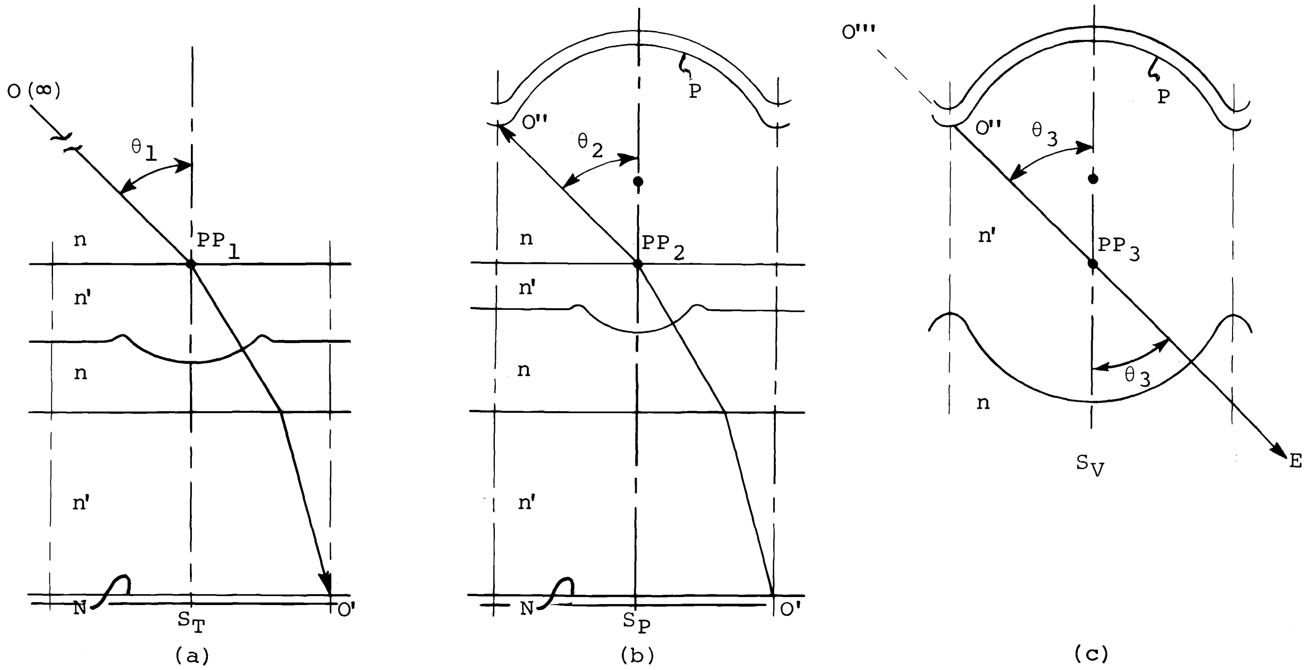


Fig. 5. Ray diagrams of the three stages, Taking, Printing, and Viewing, of the Integram system. All optical paths are centered on the respectively corresponding principal points PP_1, PP_2, and PP_3 of each one of the thousands of lenslets of each one of the three stages, one of each being shown here, greatly magnified.

The Optical Paths

In Figure 5, to simplify the diagrams, no apertures or other structural details are shown; the complete structure appears in Figure 10. At (a), Figure 5, is shown in cross-section one of the plano-convex lenslets of the current Integram recording (Taking) network. A chief ray from an object point O at infinity (most of the field is at infinity for all practical purposes in view of the relatively small proportions of the optical elements) enters the system at the principal point (and optical center) PP_1 on the planar surface of the plano-convex lenslet and at the limit of its maximum half-angle of acceptance $\theta_1=45°$; it is refracted, and is refracted again at the entrance surface of a plano-parallel sheet of clear plastic having, as the lenslet, a refractive index of $n'=1.56$ and whose presence helps flatten somewhat the spherical back focal surface of the lenslet, to approximately coincide with the negative emulsion N placed against the back of the plano parallel sheet, and on which is formed an image O' of the object point O and similarly of all object points within the acceptance angle of the lenslet. In view of the changes of direction of the rays at the planar surfaces respectively of the lenslet and of the plano-parallel sheet, the negative elemental image is radially and inwardly compressed; this results in a pronounced barrel distortion, a small price to pay (since it is later rectified) for the relative ease of manufacturing and appreciable correction of spherical aberration it offers; even though it results in a very slight loss of sharpness at the marginal viewing angles of the summation image.

At (b) Figure 5, is shown one of the plano-convex lenslets of the transposing (Printing) network, which is identical in all respects, relative to its pitch, to the recording network, except that the radius of curvature of its lenslets is shorter, in order that the processed negative N may lie close to one of its conjugate surfaces while the unexposed, embossed positive film P lies close to the other conjugate surface. A chief ray from image point O' is shown following, in reverse, exactly the same path as the corresponding ray from the object point at the recording stage, to form a positive image point O'', whereby the original angle of incidence of the chief ray from point O is restored, with the maximum half-angle $\theta_2=\theta_1=45°$; and the barrel distortion is corrected in the positive elemental image on the concave, spherically curved emulsion P.

At (c) Figure 5, the Viewing network, or screen, is composed of lenslets of substantially greater radius of curvature than the lenslets of either of the two other stages; so that, for an equivalent pitch, they can be close-packed in a hexagonal (triangular) array, (Figure 7, a) with similar lenslets formed in coaxial register on the back side (Figure 6). The total thickness of the screen is such that the distance between the lenslets and their back counterparts be less than their paraxial focal length in view of their wide aperture and therefore of the predominance of non-paraxial rays.

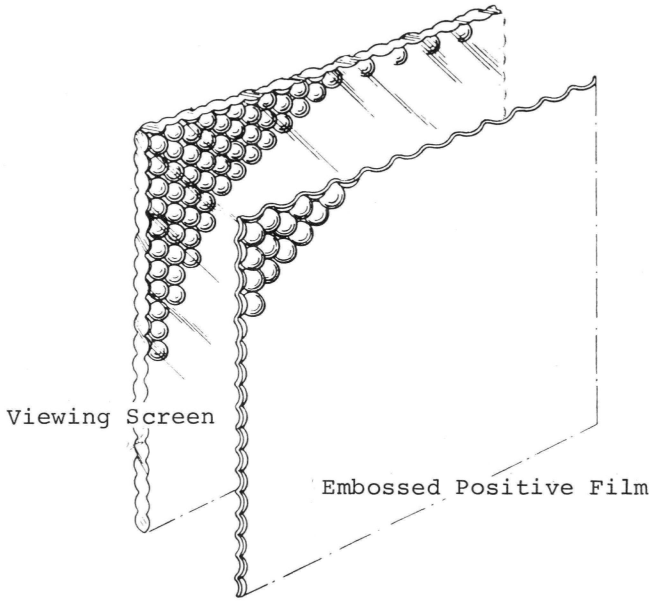
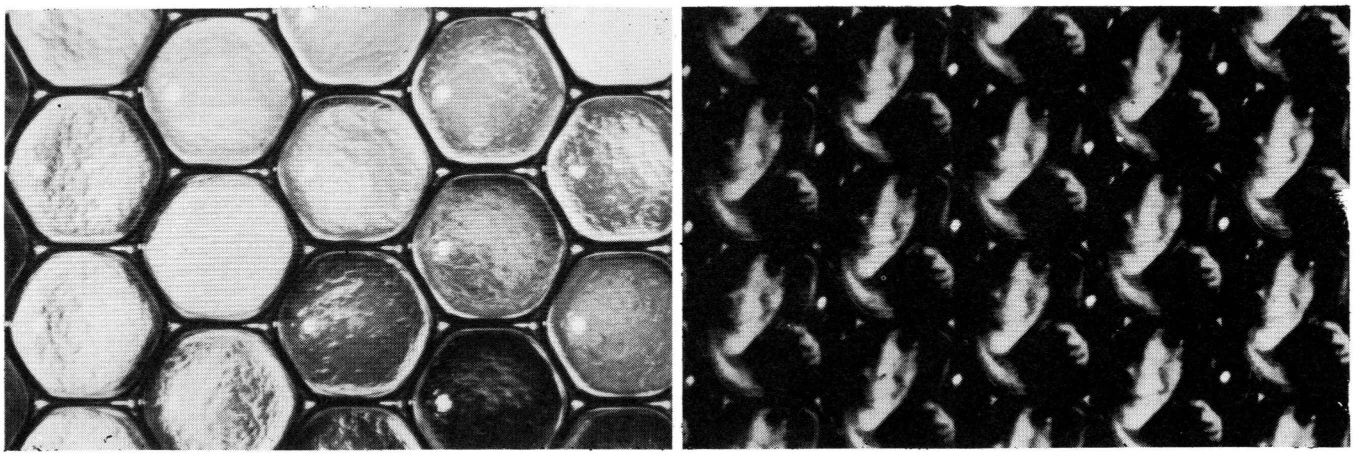


Fig. 6. Exploded perspective rear view of corresponding corners of an Integram Viewing screen and of the embossed positive film to be cemented thereon.

The processed, embossed positive film is transferred to the back of the Viewing screen where its elemental images (Figure 7, b) fall automatically in register with the lenslets (Figures 6, and 7, a) due to their coaxiality with the back curvature of the lenslets, which match precisely the concavities of the film.

Returning to Figure 5,(c): The chief ray originating at elemental image point O'' emerges from the Viewing screen after passing through the principal point PP_3 at an angle θ_3 equal to the angle of incidence θ_1 from object point O and therefore apparently from virtual image point O''', from which all homologous rays projected by other lenslets appear to emanate, thus forming at O''' a virtual reconstruction of the object point. Since this is true for any object point, the whole scene is thus reconstructed in space, in the virtual summation image, as desired.

Although it is easy to extrapolate from chief rays to paraxial bundles (which is the case at the Taking and Printing stages, where the stop is about f/7), it is not quite so obvious at the Viewing stage, where there is no stop other than provided by the edges of the lenslets, for a speed, in the present form, of about f/1.3, and where each lenslet behaves for the observer as a Stanhope loupe, magnifying the point in the line of sight, such as O'', to fill almost entirely the area of the lenslet; the emerging parallel bundle is not shown in the figure, for simplicity.



(a) (b)

Fig. 7. At (a) and (b) are shown 8X magnifications of, respectively, the current Viewing screen and the positive embossed film with its elemental images where parallactic differences are very slight, for the actual width of this portion of film is less than one half inch. Crossed or parallel natural fusion, however, does reveal some of the parallax.

Fig. 8. This and Figure 9 are two different views of a single Integram of a live model, full size. The camera was deliberately thrown out of focus to reduce the screen pattern; it is in fact invisible but the summation image, in this reproduction, is also "softer" than in the original, although this Integram 3-D picture, and the one in Figure 2 above, do not incorporate any of the scheduled improvements. Both, however, are in full color.

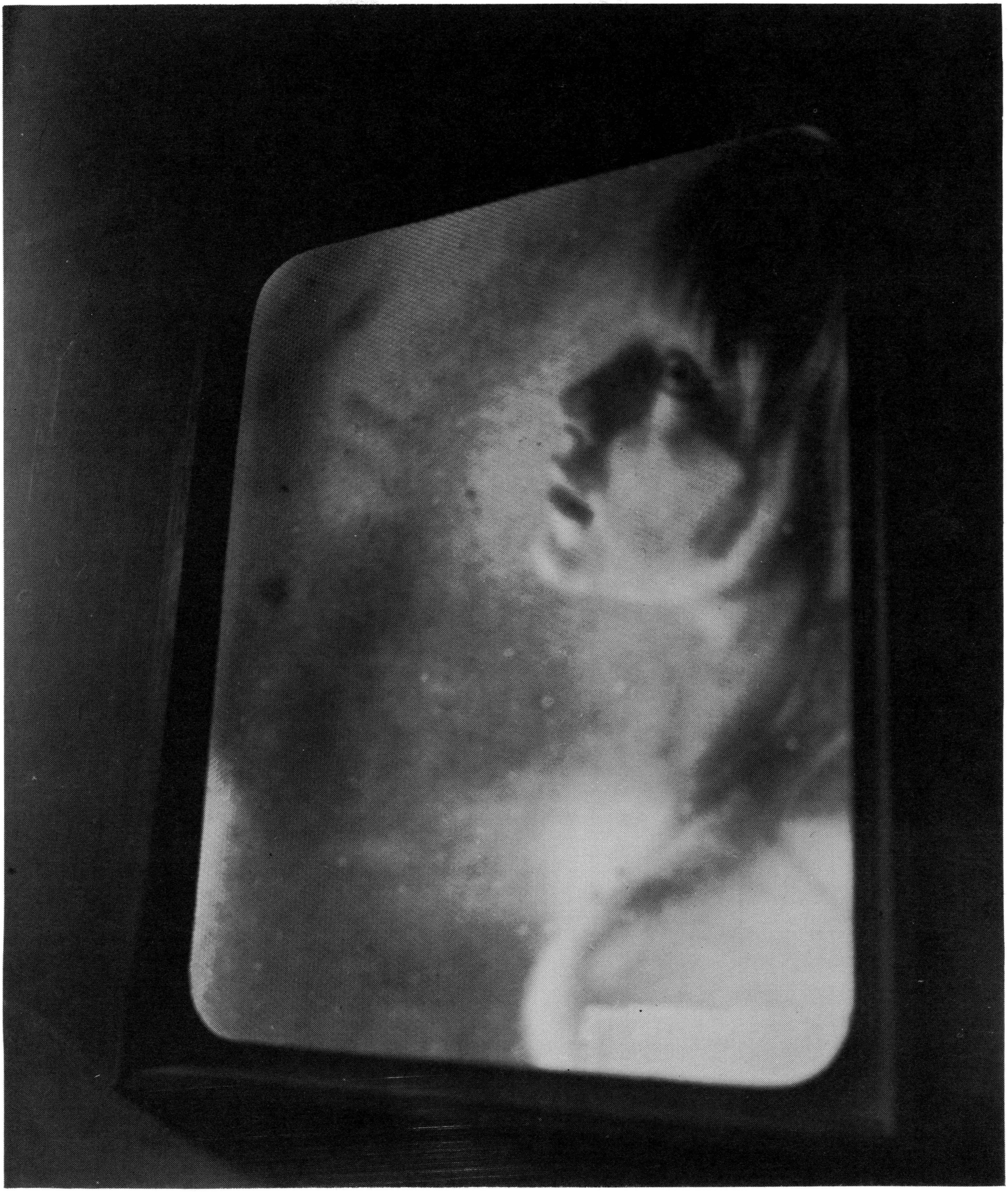


Fig. 9. Same Integram as in Figure 8, photographed from a different angle.. Part of the screen here has remained somewhat visible, towards the left side and upper left corner. While the original, viewed directly, is substantially sharper than the reproduction, so is the viewing screen pattern, at close range, on account of the unnecessarily wide interstices between lenslets (cf. Figures 7 and 11).

Physical Structure

In all of the lenticular screens the radii of curvature of the lenslets are adjusted to the index of refraction by using simple manipulations and adaptations of Snell's law ($n \sin \phi = n' \sin \phi'$). At the Viewing stage, the higher the refractive index the wider the potential field and viewing angles, since for a given radius of curvature the focal length decreases as the index increases. Although the viewing screen's thickness, generally, must be less than its focal length, further adjustments can be made to favor a particular scene depth in the summation image (an interesting phenomenon whose cause is not yet very clear since, whether far or close-up, the objects are all imaged on the same surface...).

Figure 10 is a cross-sectional representation of a structure conform to the system's current form;[16] again, one element of the network is shown for each stage: Taking (a), Printing [transposition] (b) and Viewing (c). As shown in Figure 10(a) the screen assembly S_T is essentially composed of the following layers: a lenticulated sheet A_T of polyester resin formed with a large number of regularly spaced identical plano-convex lenslets L_T arranged in a hexagonal pattern and separated by substantially flat areas B_T. In the sheet A_T is embedded a thin reinforcing perforated metallic sheet H_T. The apertures in this sheet are relatively large and substantially in register with the axes of the lenslets. On the flat external face of sheet A_T, which is to be facing the scene, is a diaphragm aperture sheet D_T having minute apertures d_T in register with the optical axes of the lenslets and lying in their principal plane, i.e. concentric with said lenslets.

On the side of the lenticulated sheet away from the scene, there is another metallic apertured sheet F_T of appropriate thickness, with relatively large field apertures f_T centered on the optical axes of the lenslets; the size of the apertures is such that the images formed by the lenslets do not overlap each other.

In contact with the field sheet F_T is a somewhat thicker plano parallel layer of clear resin C_T at the rear face of which is pressed a flat sheet of photographic film, with its emulsion E_T against the rear face of the transparent layer. The thickness of this layer is such that the curved focal surface of the lenslets L_T, displaced further away by the presence of this refringent layer, may coincide approximately with its rear face and therefore with the emulsion. The assembly of elements constituting the Taking screen S_T is supported in a "camera", not shown.

After exposure, the film is processed and dried and transferred in register to the Printing screen assembly S_P shown at (b), which is essentially similar to the assembly S_T shown at (a) and is of equal total thickness, but in which the lenslets L_P are of smaller radius so that the exposed film may lie approximately at one of two relatively close conjugate surfaces of these lenslets.

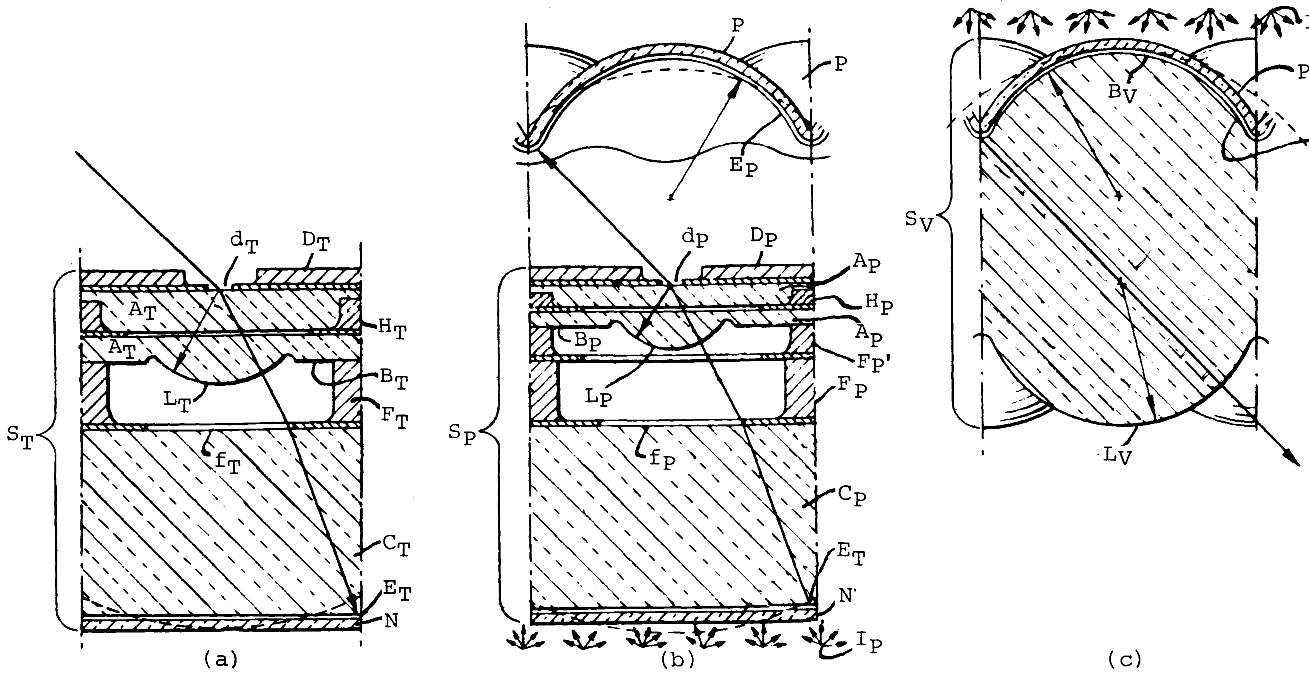


Fig. 10. Physical structure of one element each of the three stages, shown in cross-section and greatly magnified. In the bi-metal sheets, the thin portions are Ni and the thicker portions, cross-hatched in a leftward direction, are Cu. The diameters of the diaphragm apertures d_T and d_P are respectively 0.20 and 0.15 mm; the corresponding curvature radii are 0.79 and 0.50 mm; the Viewing screen front and back radii are both 1.19 mm; the pitch is at all stages 2.37 mm (0.09375 in.).

Outside the diaphragm sheet D_P, is mounted in register an unexposed embossed film P having its concave emulsion side E_P facing the diaphragm sheet. The film concavities are formed with a radius of curvature corresponding to that of the back lenslet elements B_V of the Viewing screen S_V shown at (c). These concavities and their position in the screen assembly Sp serve to compute the radius of curvature of the lenslets L_P so that their conjugate surfaces lie close, the first to the processed emulsion of the negative film N, at E_T, and the second to the yet unexposed emulsion of the embossed film P at E_P. The film is held in place by vacuum applied to its rear surface. To repeat: the structure of the Printing screen S_P is such that the film is, in both the Taking and the Printing screens, at the same distance (relative to the screen's pitch) from the principal planes of the corresponding lenslets. The lenticular sheet A_P of the Printing screen assembly being thinner than that of the Taking screen assembly, an additional spacer metal sheet F_P' is provided between the lenticular sheet A_P and the metal field sheet F_P, so as to maintain equal the total thickness of both screens, not counting the air space and embossed film P.

For viewing, the embossed film P with its inverted positive images E_P is positioned in register with the rear lenslets of the Viewing lenticulated screen S_V and cemented in optical contact therewith, and the film is illuminated by diffused light as indicated at I_V, and is viewed binocularly with the observer looking through the lenslets toward the light. For reflection Integrams, the film base is preferably white, and the lighting is provided by ambient illumination.

At all three stages the nominal distance between lenslets centers, or pitch, was 2.37 mm (0.09375 in.). The three radii of curvature of the lenslets were, respectively, 0.79 mm 0.50 mm, and 1.19 mm.

Technology

In the course of this discussion, some of the problems encountered in developing the Integram technology may have become apparent. To name a few: Fabricating the necessary sets of thin, accurately and uniformly apertured bi-metal sheets, with the size of the apertures varying from sheet to sheet without change in the pitch; and, in some cases,* with deliberate change in the pitch; all of this with immovable fiducial marks for semi-automatic register; fabricating the molds for the recording (Taking) and converting or reorienting (Printing) screens, with high polish and accurate sphericity (of the order of 0.000005 in.); fabricating the corresponding screens, by casting, avoiding any shrink marks and maintaining such tolerances as to allow for the negative and positive films to be aligned coaxially, image for lenslet, for image, relying upon semi-automatic register; embedding the 11x14 in. apertured bi-metal sheets in their respective lenticulated screens, in precisely spaced discrete planes and, again, in exact register with each other and with the corresponding lenslets without creating further shrink marks on the flat surfaces or, even more difficult to detect, on the curved surfaces of the lenslets; casting truly plano-parallel sheets of polyester resin in thicknesses varying from 0.002 to 0.070 in. in increments of 0.002 in.; fabricating the molds for the Viewing screens, and developing a relatively fast method of casting and releasing said screens; embossing integral tripack color film <u>before</u> exposure and processing (this step alone has required holding one's breath... for months, before the procedure was mastered); matching the latter (which does not necessarily, even for "stable" base type materials, vary isotropically, albeit so little) with the Printing <u>and</u> Viewing screens, which also vary from batch to batch unless extraordinary precautions are taken; cementing adequately the embossed film to the Viewing screen, i.e. optically and permanently.

After numerous, more conventional approaches had failed, the solution to the ensemble of problems was found. It consisted in relying upon the already existing very high degree of accuracy presented by miniature bearing balls made of stainless steel 440-C.

Once again it was Lippmann's Malpighi quote: "Tota in minimis existit Natura...". In an array of high precision balls there is no appreciable cumulative increment to be feared. The Integram principle of elemental centering was respected. As good as the elements, was their plurality. The best steel balls at the time of this development had diameter tolerances of 5 micro-inches (today they are down to 3) and maximum roughness of 0.7 micro-inch, and 150 of these balls, aligned over the 14 in. dimension of an 11x14 in. array could not accumulate even as much as 0.00075 in. (based on the current lenslet size and pitch in the Viewing screen, of 0.09375 in.). In effect, the expected maximum accumulation would be one half of that figure: 0.000375 in. but such maximum variations are highly improbable and did not occur.

These exceedingly reliable balls, obtained from New England Miniature Ball Company, were arranged in a triangular pattern on a flat ground and precision lapped surface where "true" orthogonally arranged walls maintained them in close contact. Thermoplastic sheets forming a bag containing thermosetting resin were pressed on the array. The resulting impression could be used to cast directly, or male then female electroformed replications constituted a mold cavity, the other cavity being a 12x15 in. optically flat glass slab. Polyester resin was cast with special care, and the resulting plano-convex lenticulated

* To compensate for increments of expansion or contraction of films or screens.

sheet was used in a specially designed "copy" camera to obtain several 11x14 in. dot arrays, from exposure of Kodalith plates to central circles of appropriate diameters.

The dot arrays were then used to expose, nickel electroplate, and etch, in that order, copper sheets, resulting in aperture arrays where the apertures were smaller in the thin (0.001 in.) Ni layer, and larger in the Cu sheet which served as a support, as shown in Figure 10 in cross-section.

Some of these bi-metal sheets served as diaphragm or field apertures, or as spacers or reinforcers. Others were laminated to thick flat ground and lapped aluminum slabs to hold at the appropriate pitch, respectively, steel balls of the sizes corresponding to those of the desired Taking and Printing lenslets. Plastic masters were pressed against the spaced tiny balls, and from there, directly or via electroforming again, were derived mold cavities for said lenslet screens. A special multi-step casting technique was devised to form the thin lenticulated sheets with embedded and otherwise attached aperture sheets in register with the respective lenslets within the required tolerance.

The same method was used to produce dies for embossing the positive films. This latter operation took one or two seconds. The Viewing screens mold cavities were obtained in the same manner and, after computing the final dimensions of the embossed and processed film, the Viewing screens were cast between two mirror-image cavities maintained in close register. The casting time, temp-humidity, and pressure, were calculated to assure minimal and fairly constant out-of-mold shrinkage. Thereafter, the screens were sprayed on the back with a thin layer of thermosetting cement, and stored to dry until used.

The final step was to apply to the dry sprayed back of the Viewing screens the exposed and processed embossed film, after semi-automatic dimension matching, and without need for any special registering care since the concavities of the film are made to conform exactly with the convexities of the screen's back. Heat and pressure were applied for about 10 or 15 seconds.

Details of the Copy Camera, Camera, Printer, Dies, and Molds would exceed the scope of this paper, as would the hundreds of lesser steps involved throughout the procedure.

Strong emphasis had to be placed on the computation of all coefficients of expansion to dimension the various components and maintain correct relationship over relatively very large areas at all steps and integrating unavoidable variations. It goes without saying that most of the known steps of quality control associated with sophisticated high precision technology had to be implemented: environmental, optical, electro-optical, mechanical, chemical. Even vibrations (to a lesser extent than in holography, and not at the photography or printing stages) nevertheless had to be kept to a minimum at certain fabrication stages. Naturally hundreds of other, related or subservient problems were encountered and had to be solved.

Remarks

As may be evident already, Lippmann's idea was infinitely simpler, more elegant, and easier to implement. There were no problems of register; the second sheet did not even have to match in any way the first; provided that the sheets could have been made rigid enough to substantially maintain their original shape - planar or curved - no distortions were to be feared since the emulsion was (literally) an integral part of the sheets. And the cost would have been almost insignificant. A dream.

Unfortunately, this is just what it was. And to realize this beautiful dream an enormously more elaborate and exacting technology had to be woven around the pure concept.

Once this technology was reduced to practice, however, there were no serious problems in its application, and more than a hundred samples were produced quite routinely, some in black-and-white but most in full color, in as little time as 2-D photography.

And everything in the laboratory was geared and ready to cope with the next, advanced stages of development and pilot production.

Chronology

This all happened eleven years ago, in 1966. Strange occurrences, including two years of deliberate shelving by an option holding organization; then erratic or just inadequate funding, helped by stock market fantasies, have delayed the realization of the full potential of this rich and barely scratched, non-holographic technique of three-dimensional photography. Some of the intervening time was used by this author to contribute additional advances, believed to be significant. Most were fully tested; others were at least simulated; they are now incorporated in the evolving process. The few early samples that have escaped filching are supporting evidence of the portion of the work reported here.* They were presented at the SPIE 21st International Technical Symposium where their reception was gratifying.

* * *

*Integrams can be seen in New York, by contacting the author (212) 737-2346.

Analysis of Current Results and Projected Refinements

Current Results

The existing 11 x 14 in. color and black-&-white Integram photographs have such pictorial and three-dimensional attributes that, at first sight, one tends to overlook or accept residual imperfections such as insufficient resolution. And, while in many areas they can be considerably improved, even as they are now they do produce on the beholder a profound impression. After all they are, next to holograms, with which they share many geometric characteristics, plus full color and minus laser, the only other "lensless" 3-D system.

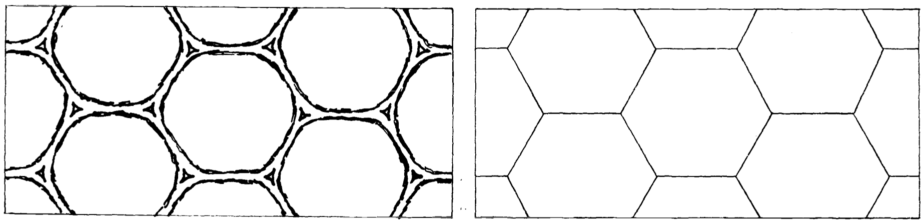


Fig. 11. Left: Schematic diagram of the viewing screen, showing (enlarged 7x) the current pattern of interstices, which occupy about 20% of the total area (cf. Figure 7, a). Their effect upon the summation image, aside from obvious obtrusiveness, is analyzed in the text. At right is shown the correct configuration, with close-packed intersecting lenslets, as planned for the next generation, and which is almost invisible when compared to the present configuration at left.

1. Image Depth and Sharpness. The useful depth of scene of the color summation image is in the vicinity of 8 in. -- in black-and-white it exceeds 20 in.* on account of the resolution gain afforded by the black-and-white emulsions , compared to integral tripack color emulsions, as measured in the elemental images.

Scenes with depths of six to ten feet have been recorded also, and reconstructed, but in the present state of the art, (and in the current 11 x 14 in. size, with a pitch and lenslet diameter of 0.09375 in.) such very deep scenes are still much too defocused to be practical, as can be seen in Table 1. Using a different, exploratory approach, this author has obtained scenes with exceedingly greater depths, some reaching to the horizon. Unfortunately, to this end, one of the "commandments" of the Integram concept had to be ignored: the Z, or depth axis was substantially compressed, with regard to the other two axes, in order to bring the horizon "within reach". In view of its departure from the true nature of an Integram, that approach falls outside the scope of the present paper and will have to be treated separately, together with other special forms of the process.

The sharpness and acutance of the summation image could unquestionably stand some improvement, within the limits imposed by the necessarily finite size of the lenslets, which precludes achieving anywhere near the extraordinary resolution of holograms (the true, all coherent-light type), where tiny particles can be inspected with a microscope.

The purpose of the Integram technique does not lie in feats of this nature. It suffices that the three-dimensional image be reasonably defined and esthetically pleasing on a human level, without attempting to "split hairs". Nevertheless, speaking of hairs, even in the present relatively rough stage of the development, some of the black-and-white summation images are sharp enough that single hairs can be identified (of course a single line may be resolved where a pair of lines of the same width may not be).

Although the sharpness of the summation image is essentially a subjective notion, an approximation of objective analysis can be achieved and a criterion defined, in terms of the angular subtense of summation image components. (MTF was not analyzed at the time.)

2. Screen Pattern Visibility -- Effect on Contrast and Color. Figure 7 (a) is a photograph, and Figure 11 (left) a schematic drawing, both greatly magnified, of the face of the current Viewing screens. The separations between the lenslets are quite wide, not by design but for practical reasons: As a consequence of the method employed to make the mold (pressing a plastic "bag" over an array of close-packed balls) relatively deep valleys limit the depth of the interstices between lenslets (whose surfaces, if extended, would be mutually tangent) and thereby cause wide dead spaces. These form a prominent tulle-like pattern standing between the observer and the virtual 3-D summation image, which it degrades for the following reasons:

* The similarity of these numbers in inches to those in L/mm in Table 1 is coincidental.

a. "because it is there"... and visible.
b. because its mere presence does interfere with a portion of the actually available image resolution, and
c. because it substantially reduces the image contrast, since the "tulle" pattern tends to be dark in the light areas of the image and, worse, light in the dark areas. This flattening of the image gamma also predictably reduces the color saturation. Even at a viewing distance where the eye can no longer resolve the pattern, its effect persists, in the form of an apparent veil over the entire summation image. (This effect is not necessarily obvious and is not generally recognized as such by the observer, who takes for granted that what he sees is simply typical of the Integram image inherent characteristics.)

3. Clarity and Uniformity of the "Window". A few dark or light spots and some apparent variations in the transmittance of more extended zones of the "window" are, understandably, blamed on the Viewing screen itself; actually they are not at all a part of it but coincide, on the screen, with over- or underexposures of certain elemental images, resulting from variations in the dimensions of the corresponding diaphragm apertures in the Taking and/or the Printing screens.

4. Acceptance and Viewing Angles. The acceptance angle of each of the current minute elemental images is in general as designed, between 80 and 90°, depending largely upon the extent to which the film has been successfully embossed. This solid angle has its apex at the principal point of each of the viewing lenslets. In the summation image, because it is not observed from infinity but generally from a few feet, one of the edges starts disappearing while the balance of the image is still visible; as a result, the effective useful viewing angle is reduced to between 70 and 80°.

It is interesting to note that the difference between the available elemental angles and the summation viewing angle is inversely proportional to the magnitude of the elemental angles. E.g., for an 11 x 14 in. Integram, and for an observer at a distance of about six screen widths (the average observing distance) we find:

W_e=45°:	W_s=28°.	Loss: 17°, or 37.7%
W_e=90°:	W_s=80°.	" : 10°, or 11.1%
W_e=120°:	W_s=116°.	" 4°, or 2.6%

(where (W) denotes a whole solid angle while (e) and (s), respectively, denote elemental, and summation images). Note that, for a hypothetical 120° elemental angle, the loss in the summation image has become insignificant, thereby appreciably compounding the advantages of the broader angle.

Projected Refinements

As the above analysis of current results has demonstrated, there are four major areas of this technology where refinements, or in some instances corrections, are desirable. A certain number of related and less evident needs for refinements will have to be attacked in parallel but their analysis would overburden this discussion, which therefore will be limited to those areas already analyzed.

1. Resolution tests conducted with Kodak SO 343 high resolution material have indicated that the system, as designed today, is capable of at least the following performances:

Negative made with extant Camera: 250 L/mm (Under controlled
Positive " " " Printer: 125 L/mm conditions)

Concurrently, the average resolution of the semi-routinely produced black-and-white negative elemental images is 180 L/mm, but the resolution of the positive drops to 20 L/mm (in black-and-white) and to 8 L/mm in color (Ektacolor Print Film). The cause for this loss is known; it resides in the fact that the Printer as used did not correspond to the design, for trivial reasons, but was not corrected because the available budget called for immediate proof of feasibility.

Using Kingslake's (17) relation:

$$1/R_L + 1/R_O = 1/R_P \tag{1}$$

where R_L is the resolution of the lens, R_O the resolution of the original, and R_P the resolution of the print, and solving for black-and-white, we find that the resolution of the printing lens used semi-routinely was (the original being the negative):

$$R_L = \frac{1}{1/R_P - 1/R_O} = \frac{1}{1/20 - 1/180} = 22.5 \text{ L/mm} \tag{2}$$

But we know, from the tests reported above, that the printing lens, when used adequately, can perform much better; indeed, according to the tests, we have, for the Printing lenslets:

$$R_L = \frac{1}{1/125 - 1/250} = 250 \text{ L/mm} \tag{3}$$

and consequently:

$$R_P = \frac{1}{1/R_L + 1/R_O} = \frac{1}{1/250 + 1/180} = 105 \text{ L/mm} \tag{4}$$

(using the low figure of semi-routinely produced black and white negatives). The theoretical resolution obtainable, therefore, in black and white, is five times better than that of the current samples. In color, using Agfa Gevaert Scientiacolor material (which has a published resolving power of 200 L/mm but has resolved as many as 400 L/mm under laboratory conditions) an equivalent level of resolution should be attained, say 100 L/mm. This resolution in the elemental images would result in a summation image angular resolution of 0°13'30", one order away from that of the human eye, therefore quite satisfying. According to Table 1 this would permit to distinguish, in the summation image, single lines or object points, e.g. 0.023 in. wide (0.56 mm) at 6 in. beyond the screen, from observer's stations up to where the eye resolution becomes the limiting factor. This performance, for color Integrams, represents a leap forward of an order of magnitude. It only concerns however one particular set of structural parameters, based on the 0.09375 in. pitch. Much larger Integrams with increased pitch and lenslet sizes shall afford many more "pixels" per elemental image and, consequently, sharper and much deeper scenes.

Table 1. Comparative Resolution Analysis: L/mm in Elemental Images vs. Angular Subtense and Width of Corresponding Lines in the Summation Image, for Various Object Distances.

L/mm Resolved in Elemental Images	Width of Individual Lines in the Summation Image at [Distance from Screen]				Angular Subtense of Lines, in °
	[8 ft.]	[2 ft.]	[6 in.]	[1 in.]	
8 *	4.00 in.	1.00 in.	0.250 in.	0.042 in.	2°30'00"
20 **	1.90	0.480	0.120	0.020	1°08'00"
31	1.20	0.300	0.075	0.013 ††	0°40'33"
50	0.760	0.190	0.048	0.008 ††	0°27'00"
62	0.600	0.150	0.038	0.006 ††	0°20'16"
100 †	0.380	0.090	0.023 ††	0.004 ††	0°13'30"
Isolated Single Lines †	0.190	0.050	0.012 ††	0.002 ††	0°06'45"

* The current color Integram early samples.
** The current B & W Integram early samples.
† Projected refined Integram samples, color and B & W.
†† These fine details may not be perceived, or be perceived only subjectively, due to the finite size of the Viewing lenslets.

The above data are the results of partial tests and computations. It must be emphasized that actual reduction to practice of the projected refinements leading to those findings may disprove their optimism. Nevertheless, even if the best resolution obtainable under the described conditions were to be reduced by 50% (and this minimum has been fully demonstrated experimentally)* the improvement would still be dramatic, as a glance at the table will show.

2. The reason for the current configuration of the Viewing screens is that, when the mold was made, the major preoccupation was (again, as in the case of the Printer) to demonstrate feasibility, not to achieve as yet the best performance. Thus, the easiest and fastest method (all being relative) of mold making was selected in spite of its known limitations.

Referring to Figure 11 (right), it can be seen that with a Viewing screen configuration where the lenslets' parti-spherical surfaces intersect instead of being tangent, the tulle-like, 20% dead space (left) almost entirely disappears.

A tested modification of the mold making technique has been shown to afford this almost invisible structure, thereby retaining in the summation image the contrast and color saturation of the improved elemental images as well as their resolution, thus further increasing (at least subjectively) the resolution gains discussed above.

* These experiments were conducted in July 1962. Though not exhaustive they were conclusive.

3. A careful review, and exercise of appropriate constraints in the procedure leading to and including the bimetal sheet micromilling operations, will afford a more uniform distribution of diaphragm aperture size at Taking and Printing stages. The randomly scattered spots detected at the Viewing stage are thus expected to be suppressed. Any residual departures could be neutralized by photographic selective neutral density masking at the Printing stage.

4. The acceptance and viewing angles can be increased to presumably as much as 120°. This is quite conceivable since it depends in part on announced improvements of the whiteness and clarity of certain industrial plastics having very high and adjustable refractive indices (as high as 1.6 to 1.8, for instance in polysulfones, for injection molding of the Viewing screens) and/or in part on tested fractional modifications of the present design of one or more of the Integram screens. (Two other forms of the Integram methodology, designed for special purposes, are indeed capable, even in the present state of the art, of affording solid angles approaching 180°.)

Further refinements and simplifications are in sight, stemming out of advances accomplished independently during the past eleven years in various related industries, some of which may well render obsolete certain technological steps reported here with regard to the existing early Integram samples. It is also expected that some of the already existing independent advances will facilitate maintaining the cost of this full parallax, full color and even "lensless", yet non-holographic, system of autostereoscopic photography at a relatively low level, compatible with conventional two-dimensional photography. Even when casting the screens (a method considered rather expensive) the increment over the cost of conventional transparencies or quality prints did not seem excessive, in the 11 x 14 in. size, and would have placed production Integrams in a favorable position. The anticipated switch from casting to injection molding, for the Viewing screens at least, could result in an even more competitive position in view of the gain in manufacturing speed.

Applications

Once the corrections and refinements discussed above have been incorporated, the improved quality of future Integrams is bound to greatly expand the potential fields of application of this rich and apparently multifarious methodology.

The system should prove exceptionnally well suited in its present and other forms to the reproduction of three-dimensional works of art, especially polychrome sculptures and artifacts, jewelry, porcelain and ceramics, objets d'art, furniture, costumes, etc., for inter- and intramuseum uses (comparative studies, accession visual aides, and of course sales of the reproductions in museum shops, a profitable and rapidly growing field); other types of museums such as Natural History, Science, and planetaria should also offer choice outlets, as probably would commercial galleries, and stores. Naturally, in many fields of education, several forms of the process would appear to be tailor-made.

A perhaps relatively limited but captivating new field could be opened: that of providing live, yet still models to the art student or accomplished painter or sculptor, since a single Integram does supply to the artist a great number of viewpoints, not to "copy" photographs but literally to draw, paint, or sculpt "from life", most obedient, patient, and very, very still models, stock or custom posed.

This, quite naturally, leads us to the huge field of portrait photography. Several early Integram portraits have been made. In the case of portraits, the present lack of sharpness is rather a plus, for evident reasons. An understandable appeal for these fully three-dimensional portraits resides, as time has already shown, in that one does not tire of looking, for there always seems to be something new to discover, and the subtle, illusory changes of expression occurring with changes of perspective or viewpoint impart a very attaching quality to the Integram portrait.

There is also evidence of a challenging interest in medical and probably other scientific disciplines calling for three-dimensional presentation or reconstruction,* as well as in industry, as long as the application does not require definition of a micrographic order (which, if color is not necessary, holography provides admirably).

Because the system lends itself to mass production, the fields most immediately and frequently suggested are those of advertising and promotion: point-of-sale, airport and railroad or bus terminal displays, sales aides, corporate gifts, and the like.

A very provoking, possibly major application must be mentioned before closing this tentative list. It has not been tested to scale yet but there is some indication of feasibility. It would consist of very large size screens having correspondingly larger than current size lenslets and pitch, which would afford proportionately more information per elemental image, thus greater depth and relative sharpness. These wall-size volumes of space would, hopefully, provide not only presentations of large merchandise such as the inside or outside of automobiles or boats "in situ", but also, for decoration of homes or public places, "windows" overlooking gardens or many scenes which would enrich and expand the actual surroundings.

Let us remember, to conclude, that other, different forms of Integrams have been successfully tested in the laboratory and might open new and intriguing avenues of exploitation.

* Isodose curves in irradiated lungs were reconstructed for the Sloan-Kettering Institute.[18]

Summary

The Integram* system of wide angle integral photography has been presented. Current results are conclusive evidence of the successful solution of most of the many problems posed by Lippmann's elegant but incomplete concept, initially difficult to implement.

The only optics utilized in carrying out the process consist of three different integral screens of novel design, two of which have integrated apertures and one of which serves to reorient each elemental image onto an embossed positive film.

While this system is also "lensless" in the broader sense, it is entirely non-holographic, i.e. it does not have recourse to coherent illumination, at any stage. Interestingly, though, its imagery presents striking geometric similarities with holograms, in both its pseudoscopic real, and orthoscopic virtual, summation images.

The current samples exhibit full parallax within 80° to 90° acceptance, and 70° to 80° viewing solid angles, permitting to uncover, on the far side of the viewing screen, scenes substantially ampler than the screen window, with a real depth of as much as 20 inches, and a pleasant, if somewhat "soft" angular resolution at the screen of 2° to 1°, respectively for color and black-&-white.

Tested and scheduled advances are expected to increase the resolution and scene depth by one order of magnitude, and to reduce the viewing screens dead space pattern visibility from its present 20% to near zero.

Without attaining the micrographic definition of holograms, which it cannot seek, the increased sharpness, scene depth and esthetic qualities of the Integram system, coupled with its handling ease and display simplicity, are expected to open considerable markets to this rich and promising technique which, even in its early form, draws repeated and sustained attention.

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