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(54) CAMERA FOR STEREOPHOTOGRAPHY

(71) We, DIMENSIONAL DEVELOPMENT CORPORATION, a corporation organised under the laws of the State of Georgia, United States of America, of 2403 Johnson Ferry Road NE, Atlanta, Georgia 30341, United States of America, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to the production of stereoscopic pictures of the type employing a lenticular screen.

A well-known technique for producing a stereoscopic picture of a given scene is to photograph the scene a number of times from different vantage points or angles with respect to the elements or objects in the scene. Normally, the successive picture-taking vantage points all have the same vertical elevation and are spaced apart horizontally at equal intervals either along a straight line or the arc of a circle.

It is also known to photograph the scene a number of times from a single vantage point and to translate or rotate the scene relative to the photographic position for each successive picture. The latter technique is entirely analogous to the former one since the relative positions of camera and scene are varied in the identical manner.

There are essentially two methods whereby the photographic images for a stereoscopic picture are caused to be registered on a film or plate behind a lenticular screen: these are the so-called "direct" and the "indirect" methods. In the direct method a lenticular screen is arranged in the camera immediately in front of the photographic negative. After each exposure of the negative (if separate pictures are taken at different relative positions of the camera and scene) or during exposure of the negative (if the relative positions of camera and scene are continuously changed while a single time-exposure is taken), the lenticular screen is moved laterally with respect to the

negative or the negative and screen are moved together in the same direction as the camera (if lenticular film is used), so as to maintain successive images of the so-called "key subject matter" of the scene in registry with a selected point on the lenticular screen. After the negative has been fully exposed, it is removed from the camera and developed in the normal way to produce a print or transparency. Finally, another lenticular screen (assuming lenticular film is not employed) is superimposed in proper registry on the print or transparency to complete the stereoscopic picture.

One technique for producing pictures according to the "direct" or in-camera method is fully described, for example, in the United States Patent No. 3,380,360 to Stockbridge, et al.

With the "indirect" method of taking pictures a lenticular screen is not used in the camera and a separate negative is exposed at each different relative position of the camera and scene.

After exposure, the negatives are developed and successively projected and imaged by an enlarger upon photosensitive film which is overlaid with a lenticular screen.

The negatives are so projected that the successive narrowed image bands, which are focused on the film by the lenticular screen, lie adjacent to one another on the film. This technique of successive imaging is known in the art as "composing" the stereoscopic picture.

Thereafter the photosensitive film is developed and the same or an identical lenticular screen to that used for composing is properly registered with the composite image to present a stereoscopic picture to the viewer.

Important and useful improvements in the foregoing composing technique, as applied to the indirect photographic method, are described in U.S. Patent No. 3,895,867.

In order to obtain photographic negatives, whether by the direct or indirect photographic method, the photographer may adjust one or

more of a large number of variables within his immediate control. These variables include such knowns and unknowns as the desired size of the stereoscopic picture to be produced, the resolving power and lenticule width of the lenticular screen, the number and size of two-dimensional picture negatives which are to be taken and included in the stereoscopic picture, the distance between adjacent camera vantage points from which the negatives are taken, the camera focal length, the distance from the camera to the nearest element or object of the scene to be photographed, the distance from the camera to the farthest element or object of the scene to be photographed, and the distance from the camera to an element or object — the "key subject matter" — in the scene which is to lie in the plane of the picture. Not only is the coordination of these numerous variables an extremely difficult task for a photographer in the field, but it has not previously been known how these variables may be adjusted so that the resulting stereoscopic pictures will be of consistently high quality.

It is therefore an object of the present invention to provide apparatus, for aiding the photographer in determining, coordinating and adjusting the numerous variables which bear on the quality of a stereoscopic picture in a manner permitting the consistent production of high quality stereoscopic pictures under substantially all photographic conditions.

This object is achieved, according to the present invention, by maintaining the parallax imparted to the final stereoscopic pictures within certain minimum and maximum values, and preferably at an optimum value. This procedure, as will be explained in detail hereinafter, involves a function of the lenticule width of the lenticular screen of the stereoscopic picture, the enlargement ratio between the size of the two-dimensional negative or negatives taken by the camera to the size of the final stereoscopic picture, the composition and contrast of the photographed scene, and the number (or the effective number) of exposures made of the scene and to be included in the picture.

Given the appropriate parallax, the remaining relevant variables which must be determined in taking and composing a stereoscopic picture may be coordinated in a manner which will be derived and set forth hereinafter. Conversely, it is possible to start with the photographic variables and determine whether the parallax associated with those variables falls within the permissible range for proper picture quality. This latter aspect also allows control of the parallax of the stereoscopic picture during the composing process when the indirect method is used.

Before the present invention is more particularly described, it is necessary to define a

number of terms which will be used throughout this specification in connection with the inventive process of taking an appropriate negative or negatives for use in a stereoscopic picture. In the typical photographic arrangement, whether the photographic conditions be characterizable as close-up or telescopic photography, macro-photography, micro-photography, radiography, etc., a photographic camera must make an "image record" of an "object field" at a plurality of "vantage points". The image record, as the term is used hereinafter, is intended to include either a single three-dimensional (lineform) negative if the direct method of stereoscopic photography is employed, or a plurality of two-dimensional negatives if the indirect method is employed. The object field, as used hereinafter, is intended to define the scene to be photographed. The term "object field" is used rather than "scene" since, for example, in X-ray photography and micro-photography, the object field may constitute subject matter such as a single object alone. Also, it is desirable in certain photographic conditions, such as electron micro-photography and X-ray photography, to make the image record of the object field from an image intensifier screen or the like. The "object field", in such conditions, is the object undergoing examination, not the intensifier screen, which merely presents a projected image of the object field.

When taking an image record of the object field, the camera is situated at a plurality of "vantage points", or positions relative to the object field. The term vantage points, as used hereinafter, is intended to include the case where the object field is moved relative to the camera as well as the converse situation. Successive vantage points define a line or "path" which may be either a straight line or the arc of a circle. For example, if the camera is provided with a plurality of lenses and is operable to take a plurality of two-dimensional negatives *simultaneously*, the path of the vantage points is defined by the camera itself. However, where a single lens camera is used (either with the direct or indirect method) to take *successive* pictures at a plurality of vantage points, the movement of the camera normally follows the path of the vantage points.

The path of the vantage points in the photographic arrangement is spaced from a point or plane in the object field which is to lie in the plane of the stereoscopic picture. This plane, which contains the "key subject matter" of the object field, will be hereinafter denoted as the "object field plane".

For the purposes of the present invention, it is necessary to define three points or "elements" in the object field; namely, a "nearest foreground element", which is that foreground element closest to the path of the

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vantage points that is to appear in focus and sharp in the final stereoscopic picture; a "farthest background element", which is the background element farthest from the path of the vantage points that is to appear in focus and sharp in the final stereoscopic picture; and an element of the key subject matter which is located at an intermediate position in the object field. If the stereoscopic picture is to have both foreground and background it will include a foreground plane that is parallel to the object field plane and passes through the foreground element and a background plane that is parallel to the object field plane and passes through the background element. If the stereoscopic picture is to have only a foreground (without a background) or a background (without a foreground) the background element and plane or the foreground element and plane, respectively, are eliminated.

Foreground elements and background elements other than the "nearest foreground element" and the "farthest background element", respectively, may of course be included in a picture. In accordance with the invention, those foreground and background elements lying closer to the key subject matter than the corresponding "nearest" and "farthest" elements will appear focused and sharp in the final picture, while those spaced beyond the "nearest" or "farthest" elements will be blurred. For artistic or other reasons, however, it may be desirable in some circumstances to include such blurred images. One example of such a situation would be where a comparatively small or unimportant object is located in front of the foreground elements of principal interest, or behind the background elements of principal interest. In this case, the quality (sharpness and focus) of the images of the principal foreground elements or of the principal background elements is of primary importance, and not that of the unimportant foreground element or background element even though that element is more distantly spaced from the key subject matter element. For purposes of the invention, therefore, the "nearest foreground element" in this example would be the principal foreground element spaced closest to the path of the vantage points, and the "farthest background element" would be the principal background element spaced farthest from the path of the vantage points.

Finally, it is necessary to define the term "principal axis" of the object field. Generally, this axis is a line drawn through the centre of the object field perpendicular to the object field plane. In the usual case, it will also pass through the central vantage point. Since the object field plane is parallel to both the foreground and background plane, the principal axis will also be perpendicular to these two planes. In some cases, though not necessarily, the principal axis will pass through

one or more of the nearest foreground element, the key subject matter element and the farthest background element.

As was mentioned above, the image record for a stereoscopic picture must be taken at a plurality of vantage points. In a stereoscopic picture utilizing a lenticular screen, each separate view from each separate vantage point produces a separate lineiform image beneath each lenticule of the final picture. Hence, within the resolution limit of the lenticular screen, the greater the number of pictures taken at different vantage points, the higher will be the quality of the stereoscopic picture.

It will be understood, however, that when the indirect method is used, all of the two-dimensional negatives that are taken may not be used in composing the final picture. In fact, it is a feature of the present invention to provide a method whereby the parallax in the final stereoscopic picture may be controlled by limiting the number of negatives used in the composing process.

Thus, with the indirect method the number of vantage points at which two-dimensional negatives are taken may not be equal to the number of negatives used to compose the stereoscopic picture. However, for consistency between the direct and indirect methods, those vantage points at which are taken negatives not used in the final stereoscopic picture will be ignored. Consequently, the number (N) of vantage points is hereby defined to be the number of those vantage points at which an image record is made that is utilized in the stereoscopic picture.

According to the present invention, there is provided a camera for taking a plurality N of two-dimensional views of an object field for use in composing a stereoscopic picture of the type incorporating a viewing lenticular screen of lenticule width W, the camera including corresponding pluralities N of lenses and associated film frames, the lenses being aligned in a row with their optical axes substantially equidistantly spaced apart and substantially in parallel; the distance T between the optical axes of the endmost lenses being related to predetermined values of X_T , R, f, a, and b generally in accordance with:

$$T = \frac{X_T \cdot ab}{Rf(b-a)}$$

wherein X_T , R, f, a, and b, have meanings as hereinafter given.

This application is divided from our co-pending Application No. 45325/73 (Serial No. 1445583), which claims a method of obtaining an image record for use in producing a stereoscopic picture, and a method of producing a stereoscopic picture, employing techniques hereinafter described.

Preferred features of the invention will now be described, with reference to the accompanying drawings, in which:—

Figure 1A is a diagrammatic view showing three object field element positions and three different photographic vantage points for making photographic exposures of an object field in accordance with the principles of the invention.

Figure 1B is a diagrammatic view similar to Figure 1A, showing three object field element positions and five different photographic vantage points for making photographic exposures of an object field in accordance with the principles of the invention.

Figure 2 is a diagrammatic view showing three object field element positions, one photographic vantage point and an enlarged stereoscopic picture.

Figure 3 is a diagrammatic view illustrating the effect of three values of parallax in a five-frame stereoscopic picture.

Figure 4 is a diagrammatic view illustrating the effect of optimum parallax in a stereoscopic picture.

Figure 5 is a diagrammatic view illustrating the effect of a greater than optimum parallax in a stereoscopic picture.

Figure 6 is a somewhat diagrammatic view illustrating one photographic arrangement when taking a stereoscopic picture.

Figure 7 is a diagrammatic view of an optical system employed in taking a stereoscopic picture.

Figure 8 is a representational view illustrating a finished stereoscopic picture.

Figure 9 is a representational view, related to Figure 8, illustrating a technique for locating the object images within the picture area of the final stereoscopic picture.

Figure 10 is a diagrammatic plan view of a scene to be photographed.

Figure 11 is a diagrammatic plan view which, taken in conjunction with Figure 10, illustrates a particular photographic technique.

Figure 12 is an elevational view of a camera according to a preferred embodiment of the present invention.

Figure 13 is a top view of the camera illustrated in Figure 12.

Theoretical Explanation: The quality of a stereoscopic picture is directly related to the amount of parallax, which, as will be explained in detail below, is the apparent shift in position of an element of an object field due to the relative change in position of the element and/or the place from where the element is viewed. Thus, when the parallax value in a finished stereoscopic picture is small, the image of the photographed object or objects in the picture look flat and lack depth. In contrast, when the parallax value is large, the image of the photographed object or objects appear blurred and out of focus

since different portions of the image interfere with each other.

Although for somewhat different reasons, variations in parallax have essentially the same effect on human vision. When a remote object is viewed and the parallax is small, depth and separation — the so-called "three-dimensional effect" — is lacking. When the object viewed is very close to the eyes, however, and the parallax value is large, it is difficult to see a solid image of that object.

In an ideal stereoscopic picture with perfect three-dimensional effect, all elements of the photographed object field should be totally in focus and sharp. In order to approach such an ideal, it is necessary to establish a range of permissible parallax values. In addition, it is necessary to control the photographic variables so that the proper parallax value will be obtained under each photographic condition, be such condition characterizable as close-up or telescopic photography, macro-photography, micro-photography or X-ray photography.

The phenomenon of parallax may be observed either when viewing a single element of an object field from two or more vantage points or when viewing two or more elements from a single vantage point. In the former case, parallax may be defined as the apparent displacement or the difference in apparent direction of one element as seen from different vantage points not on a straight line with the element. In the latter case, the parallax is the apparent displacement or difference in apparent direction of the several elements as seen from a single vantage point not on a straight line with the elements. These two types of parallax are illustrated in Figure 1A.

Figure 1A is a plan view showing three element positions A, K and B, a camera objective plane 20 and a focal plane 22. An element of the object field at position A is intended to be the "nearest foreground element" to be photographed. This element, when its image is viewed in the stereoscopic picture, would appear to be closer to the viewer than the plane of the picture. An element at position B is intended to be the "farthest background element" to be photographed. The image of this element in the stereoscopic picture would appear to the viewer to lie in back of the plane of the picture. An element at position K is intended to be the so-called "key subject matter" in the object field. The image of this element in the stereoscopic picture would appear to lie in the plane of the picture.

Three photographic camera lenses 24, 26 and 28 are shown in Figure 1A oriented along the camera objective plane 20 with their respective axes perpendicular to this plane. These lenses respectively focus images of the object field to be photographed on suitable

photographic negative field 30, 32 and 34 oriented in the focal plane 22.

5 As will be understood from the laws of optics, the object field elements at positions A, K and B will all be imaged at a common point 36 by the lens 24. This point will lie on a common axis with the element positions A, K and B which is the axis 35 of the lens 24. This axis, which has been defined above as the "principal axis" of the object field, has been illustrated as intersecting the element positions A, B and K for simplicity and clarity in describing the invention. It will be understood that the points A, K and B need not lie in a straight line and that, generally, the principal axis of the object field may be taken as the line which passes through the centre of the field.

10 Object field elements at positions A, K and B are focused by the lens 26 at the positions 38, 40 and 42, respectively, on the photographic negative 32. Because the optical axis 44 of the lens 26 is displaced by an amount "T₁", from the principal axis of the object field, the respective positions of points 38, 40 and 42 will be displaced from each other and from the optical axis 44. The amount of this displacement is the value of parallax which will hereinafter be designated by symbol "X".

15 As indicated in Figure 1A, there is parallax X_A, X_K, and X_B between the optical axis 44 and the points of image 38, 40 and 42 of the element positions A, K and B respectively. This parallax is of the type first defined above; i.e., the displacement of object field images resulting from a change in the viewing axis from the principal axis 35 to the optical axis 44.

20 As also shown in Figure 1A, there is parallax between the points 38, 40 and 42 with respect to the points themselves. The parallax between the points 38 and 40 is designated in the figures as X_{KA}, whereas the parallax between the points 40 and 42 is designated X_{BK}. The parallax between the points 38 and 42 (the total of the parallax X_{KA} and X_{BK}) on the right-hand side of the principal axis is designated X_R.

25 This second type of parallax, which occurs when a single object field element successively is moved to the positions A, K and B or when a plurality of elements at these positions are simultaneously viewed, is the parallax which affects the quality of a stereoscopic picture. In particular, as will be explained in detail hereinafter, the clarity of image in a stereoscopic picture is dependent upon these parallax values X_{KA}, X_{BK} and X_R.

30 It is apparent from Figure 1A that the parallax values X_{KA}, X_{BK} and X_R may be controlled by changing one or more of the following variables: (1) the distances from the respective element positions A, K and B

to the camera objective plane 20 (this includes the relative spacing of these positions with respect to each other); (2) the distances from the respective optical axes of view to the principal axis 35; and (3) the distance between the objective plane 20 and the focal plane 22 upon which the images are focused. This last variable is a function of the focal length of the lenses 24, 26 and 28.

35 Clearly, the respective distances of the nearest foreground element at position A, key subject matter element at position K and farthest background element at position B from the plane 20 at which the objective plane of the camera is positioned are, to some extent, a matter of choice with the photographer. Normally, the photographer is interested in obtaining a picture of certain key subject matter, or perhaps key subject matter and either a particular background or foreground, and needs to know the distances at which the remaining background and foreground objects should be placed from the camera.

40 The distances between the optical axes of view and the principal axis of the object field may also be varied by the photographer. As illustrated in Figure 1A by the respective distances T₁ and T₂, the greater these the distances are, the larger will be the parallax values X_{KA}, X_{BK} and X_R.

45 As may be seen, the relative spacing of the points 38, 40 and 42 (optical axis 44 to principal axis 35 equals T₁) is considerably less than the spacing between points 48, 50 and 52 (optical axis 46 to the principal axis 35 equals T₂). In Figure 1A T₁ is one-half the value of T₂ since, in three-dimensional photography, the optical axes of successive lenses are equally spaced.

50 Finally, the photographer may in some cases also control the distance between the objective plane 20 and the focal plane 22 of the photographic camera. As shown at the right-hand side of Figure 1A, the parallax values X_{KA}, X_{BK} and X_R may be reduced if the focal plane 22 is moved closer to the objective plane, as indicated by the plane 22'.

55 As may be seen, the relative spacing of the points 54, 56 and 58 (where the objective to focal plane distance equals e₂), is less than that of the points 48, 50 and 52 (where the objective to focal plane distance equals e₁).

60 The precise, quantitative dependency of the parallax values upon the variables identified above will be calculated and set forth hereafter; however, before this is done, it is necessary to determine the range of values, as well as the optimum value for the parallax on the final stereoscopic picture.

65 Figure 1B illustrates the conventional situation in three-dimensional photography wherein a plurality of negatives are exposed from vantage points on both sides of the prin-

5 cipal axis of the object field. It will be understood, however, that the present invention is in no way limited to this particular configuration and that the principles derived and discussed hereinafter are applicable no matter what the orientation of the vantage points may be with respect to the principal axis of the object field.

10 In the arrangement shown in Figure 1B the object field containing element positions A, K and B is viewed from five vantage points, indicated by the five lenses 59, equidistantly spaced along a "path" 61 (a straight line in this case) that is oriented perpendicular to the principal axis 63. Images of the object field elements at points A, K and B are focused on respective negatives 65 beneath each lens. Because the left-most and right-most lenses are symmetrically spaced about the principal axis, the parallax X_L between the images formed by the left-most lens will equal the parallax X_R between the images formed by the right-most lens.

If we define total parallax as:

$$25 \quad X_T = X_L + X_R, \quad (1)$$

then

$$X_L = X_R = X_T/2$$

30 It may readily be seen from the geometry of the diagram of Figure 1B that the maximum parallax values will occur at the left-most and right-most vantage points. It is also apparent that, for a given focal length (f) for the lenses 59 and, in turn, given distance (e) to the plane of the negatives 65, and for a given object field, the total parallax value X_T will depend entirely upon the distance T between the left-most and right-most vantage points. It may be shown, in fact, that this total parallax value is invariant to the position of the vantage points with respect to the principal axis. Thus, for example, if the vantage points in Figure 1B were moved to the right so that the left-most vantage point were aligned with the principal axis as shown in Figure 1A (and $X_L = 0$), X_R would double its value so that X_T would remain unchanged.

50 Figure 2 illustrates the manner in which a photographed object field is imaged on photosensitive film 60 adjacent a lenticular screen 62 by means of a technique known in the art as "composing". As explained above in the introduction to this specification, the technique of composing is used in the "indirect" method of producing stereoscopic pictures. After a plurality of two-dimensional negatives 64 have been exposed by a camera at different vantage points with respect to the object field, the negatives are developed and the images thereon projected by means of an enlarger onto a lenticular screen 62 and photosensitive film 60.

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In order to achieve the stereoscopic effect, the negative images are successively projected onto the lenticular screen 62 and film 60 in such a manner that the key subject matter element in every image will be in registry. Suitable techniques of composing in this manner are described, for example, in the aforementioned U.S. Patent No. 3,895,867.

During the composing process the actual size of the stereoscopic picture can be controlled; i.e. by the degree of enlargement permitted. In Figure 2 an enlargement ratio of approximately 3:1 is illustrated so that the parallax values $X_{KA'}$, $X_{BK'}$ and $X_{R'}$ in the final picture are actually three times as large as the corresponding values of X_{KA} , X_{BK} , and X_R in the photographic negative 64.

In an ideal three-dimensional picture, the shifting distance or displacement of the nearest foreground element image (the image of an element at position A) and the farthest background element (the image of an element at position B) between each successive two-dimensional negative image should equal the width of one lenticule of the lenticular screen. As will be pointed out hereinafter in connection with Figures 4 and 5, this relationship allows the observer to see a solid, sharply focused image of the foreground object and the background object, although these objects are photographed from different viewpoints. If the shifting distance of either of the nearest foreground or the farthest background element images between successive two-dimensional negative images exceeds the width of one lenticule of the lenticular screen, then the foreground element image will interfere with the key subject matter and the background element image, and *vice versa*. A clear picture will therefore not be presented to the observer so that all the photographed images will look blurred and out of focus.

Figure 3 illustrates the positions of the nearest foreground element images A'', the key subject matter element images K'' and the farthest background element images B'' from five different two-dimensional negatives (1-5) as these images would be aligned in the composing process. In the particular example chosen, the five negatives were exposed from vantage points starting at the principal axis of the object field and extending, at equally spaced intervals, toward the right. Thus, the negative taken at the left-most vantage point ("frame 1") results in no parallax at all, while the negative taken at the right-most vantage point ("frame 5") produces the maximum parallax on the lenticular screen. Since in this case $X_L = 0$, $X_T = X_R$, pursuant to equation (1), above.

Notwithstanding the special case illustrated in Figure 3 which was chosen for the purpose of clarity in describing the invention, it should be understood that the values of X_T and

X_T , which will be derived below are applicable to other vantage point-to-principal axis configurations and, in particular, to the symmetrical configuration shown in Figure 1B.

The upper lenticular screen 66 in Figure 3 illustrates the ideal three-dimensional picture in which the nearest foreground element images and the farthest background element images from successive negatives are spaced exactly one lenticule width apart. If the width of each lenticule of the lenticular screen be designated as W , the optimum parallax between the key subject matter images K''_{1-s} and the nearest foreground element image A''_s , (or the key subject matter images K''_{1-s} and the farthest background element image B''_s) on the first and last frames in the final picture will equal $(N-1)W$, where N is the total number of frames or negatives.

Hence, the optimum parallax values for the final picture are:

$$X_{BK}'' = (N-1)W$$

$$X_{KA}'' = (N-1)W;$$

and

$$X_T'' = 2(N-1)W$$

If the final picture is an enlargement of the negatives taken by the camera as illustrated in Figure 2, the parallax on the camera negatives must be reduced from this value in the final picture by the enlargement ratio. If this ratio of final picture size to the negative size be designated as R , the optimum parallax values for the camera negatives will be given by:

$$X_{BK}' = \frac{1}{R}(N-1)W;$$

$$X_{KA}' = \frac{1}{R}(N-1)W;$$

and

$$X_T' = \frac{2}{R}(N-1)W.$$

From a practical and economic point of view, it may be desirable to increase the parallax somewhat so that the shift between successive frames on the final picture is greater than the width of one lenticule. Depending upon the size and colour of the objects to be photographed as well as the desired lightness and contrast of the final picture, it is possible to increase the parallax without substantial degradation in the quality of the picture. Such an increased parallax is illustrated in Figure 3 with the lenticular screen 68. In this particular case the shift between successive frames is exactly three times the lenticule width W of the lenticular screen 68.

The actual shift between successive frames may be either greater or less than $3W$ depending upon the nature of the scene to be photographed. This shift may, in fact, vary anywhere from

$$\frac{1}{(N-1)}$$

times the lenticule width W up to five times W . This factor, which equals the number of lenticules, or fraction thereof, shifted between frames, will hereinafter be designated by the letter c . As an example, if the images of the object photographed are small in comparison to the lenticule width W of the lenticular screen (e.g. $10W$ or less) and/or a high contrast picture (e.g., between the key subject matter and background) is desired, c may lie between 1 and 3. However, when the images of the objects photographed are large in comparison to the lenticule width W and/or the resulting picture is to be of low contrast, c may range from 3 to 5. In some cases an even larger value of c may be acceptable. The maximum parallax values for the final picture may therefore be expressed as:

$$X_{BK}'' = c(N-1)W;$$

$$X_{KA}'' = c(N-1)W;$$

and

$$X_T'' = 2c(N-1)W;$$

where c is the number of lenticules shifted between frames (normally between 1 and 5), N is the number of photographic frames, and W the lenticule width of the lenticular screen.

The corresponding maximum values for the photographic negatives are equal to the above maximum values divided by the enlargement ratio R . Thus;

$$\left. \begin{aligned} X_{BK}' &= \frac{c}{R}(N-1)W; \\ X_{KA}' &= \frac{c}{R}(N-1)W; \text{ and} \\ X_T' &= \frac{2c}{R}(N-1)W \end{aligned} \right\} \quad (2)$$

As a specific example of the acceptable range of values for X_T'' , for a stereoscopic picture, it has been found, in practice, that for a lenticular screen having a thickness of 2 millimeters and a lenticule width of 0.48 millimeters, high quality pictures are obtained under general photographic conditions if the total parallax value (X_T'') on the stereoscopic picture is within the range of from 16 to 48 times the lenticule width when 9 frames are taken and used to com-

pose the picture. In this case c varies from 1.0 to 3.0.

The minimum desirable parallax condition is illustrated at the bottom of Figure 3 with the viewing lenticular screen 70. As may be seen, the image B''_s (or A''_s) from the final frame in the succession of frames should be spaced from the B''_1 (or A''_1) image from the initial frame by at least the width W of one lenticule. If the distance between the images B''_1 and B''_s (or A''_1 and A''_s) be less than the width of one lenticule, all of the images will fall within a single lenticule with the result that, while the separate images may still be seen, the angle of convergence between the separate images will be too small for significant stereoscopic relief.

The minimum parallax value permissible for a lenticular screen type stereoscopic picture is therefore:

$$X_{BK} = W;$$

$$X_{KA} = W;$$

and

$$X_T = 2W.$$

Consequently, the minimum permissible parallax value for the images on the negatives is:

$$X_{BK} = \frac{W}{R}$$

$$X_{KA} = \frac{W}{R};$$

and

$$X_T = \frac{2W}{R}.$$

Upon comparing these equations with the equations (2) above, it may be seen that the lower limit of parallax in the equations (2) would be reached if c were made equal to

$$\frac{1}{(N-1)}.$$

Accordingly, the equations (2) may be made generally applicable if the range of c is chosen between the limits

$$\frac{1}{(N-1)}$$

to 5.0, inclusive. As explained above, c is a function of the photographic conditions such as the size of the object or objects to be photographed, the amount of light, degree of contrast, and the like, and has an optimum value of 1.

Finally, it should be noted that the total number of photographic frames N of a stereoscopic picture also has an upper and a lower limit. Since the width of the condensed image from each frame beneath each lenticule on the photosensitive film must be at least within the resolving power of the lenticular screen, the number of condensed images per lenticule cannot exceed L , where L is the resolving power of the lenticular screen in lines per lenticule. Since, where the parallax is at a minimum, the number of condensed images per lenticule equals the number of frames N , the number of frames should not exceed L .

For better image and colour reproduction in a stereoscopic picture the condensed two-dimensional images should be at least two times the width of the resolution line of the viewing lenticular screen of the final picture. Therefore, the number of negative frames N which are exposed preferably is less than $L/2$. Since the minimum number of two-dimensional picture frames required to produce a three-dimensional picture is 2, N preferably falls in the following range:

$$2 \leq N \leq L/2.$$

In the above consideration of the parallax involved in a stereoscopic picture, the example of the indirect method of producing pictures was used. Since the principles of parallax remain the same for a stereoscopic picture no matter how the picture is produced, the equations (2) are applicable to the direct method as well. Although a single three-dimensional negative with lineiform images is produced with the direct method (instead of a plurality of two-dimensional negatives), the single three-dimensional negative is nevertheless exposed at a plurality of vantage points. The number of different vantage points may therefore be used for the quantity N in equations (2).

In some instances with the direct method, the single three-dimensional negative is exposed while the camera is caused to scan the object field in a continuous manner along a vantage "path". Since there are an infinite number of vantage points along this path, obviously this number (infinity) cannot be used as a value of N . In this case, the resolving power of the lenticular screen divides the continuously moving image of the object field during exposure into a finite number of resolution lines on the camera negative. This resolving power of lines per lenticule can therefore be used as the number N . For example, if the resolving power of the viewing (in camera) lenticular screen is 60 lines per lenticule element, then N should not exceed 60, and preferably is less than 30 ($L/2$) where the continuous scanning technique is employed.

Figures 4 and 5 illustrate the advantage of maintaining the parallax in a stereoscopic picture at its optimum value; in particular, at a value such that corresponding nearest foreground and farthest background element images from each successive photographic frame will be composed in the final picture beneath a successive lenticule of the lenticular screen. In Figures 4 and 5, the views of the object field, including elements at positions A, K and B, as seen from five vantage points, and as photographically recorded from each vantage point, are superimposed with the images of the element at position K in alignment. The effect on the final stereoscopic picture, as viewed (also illustrated), resulting from shifting of foreground and background element images (e.g., A'', A'', A'', etc) between frames may therefore be readily appreciated. As may be seen in Figure 4, when the shifting distance between adjacent frames of the image of the foreground element at position A is equal to the width W of one lenticule, an observer can see that image from all angles and positions of view of the final stereoscopic picture. However, as in Figure 5, when the shifting distance of the image of the foreground element is greater than the lenticule width, the nearby images 72 of the key subject matter and/or background elements will interfere with the foreground element image. This will obstruct the observer's vision and create an out-of-focus effect.

In a low contrast picture the interfering rays extending from the nearby images of the key subject matter and/or background elements are relatively weak. In this case, the parallax can be increased to enhance the three-dimensional effect in the picture (e.g. $c=3$ or 4). In a high contrast picture where the interfering rays are strong, the parallax value should be kept near the optimum ($c=1$) so that these rays will not interfere with the observer's vision and the three-dimensional picture will appear sharply focused.

The optimum as well as the permissible range of parallax values for a stereoscopic picture have now been derived. It remains to be determined how a photographer should select those variables within his immediate and direct control so as to achieve the proper parallax and, in turn, the desired picture quality.

At the outset, it will be noted that for each of the maximum, optimum and minimum parallax values, the value between element images at positions B and K (X_{BK}) and the value between element images at positions K and A (X_{KA}) are preferably equal. Thus, in order to obtain a high quality stereoscopic picture in which both background and foreground are present:

$$X_{BK} = X_{KA}$$

It should be emphasized, however, that not all stereoscopic pictures include both a background and foreground. In some cases, it is desirable to photograph key subject matter which is to lie in the plane of the picture together with only background elements or objects which are to lie behind the plane of the picture. In this case, only the parallax value X_{BK} need be considered so that for the images obtained from the right-most and left-most vantage points, respectively:

$$X_{BK} = X_R;$$

$$X_{BK} = X_L.$$

Similarly, it may be desirable to photograph a scene having only key subject matter which is to lie in the plane of the picture and foreground elements or objects which are to lie in front of the plane of the picture. In this case, only the parallax X_{KA} need be considered so that for the right-most and left-most vantage points, respectively:

$$X_{KA} = X_R;$$

$$X_{KA} = X_L.$$

Figure 6 illustrates a typical snapshot-type photographic situation in which a camera 74, capable of taking a plurality of horizontally spaced photographs, is arranged facing to the left and in position to photograph the scene depicted. In this scene, there is a nearest object (a bush) indicated generally by the reference character 76 and a farthest object (a tree) indicated generally by the reference character 78. The key subject matter of the scene, the two persons indicated generally by the reference character 80, are located between the nearest and farthest objects 76 and 78, respectively.

As explained above, in order to obtain a high quality stereoscopic picture it is necessary for the photographer to control the parallax between the images appearing on the negatives of the camera 74. In particular, he should maintain the parallax between the images of objects 76 and 80 approximately equal to the parallax between the images of objects 78 and 80, and he should maintain the total parallax X_T close to, or slightly greater than, the optimum value

$$\frac{2}{R}(N-1)W.$$

This is accomplished, as will be explained in detail hereinafter, by relating the following variables (see also Figure 7):

(1) a —the distance from the camera objective plane to the nearest foreground element to be photographed.

(2) k —the distance from the camera objective plane to the key subject matter element.

(3) b —the distance from the camera objective plane to the farthest background element to be photographed.

(4) f —the focal length of the camera lens (or lenses).

(5) e —the distance from the objective plane to the film plane of the camera.

(6) N —the number of vantage points from which pictures are taken (or, in the case of the continuous scanning direct method, the number of resolution lines per lenticule).

(7) R —the enlargement ratio of the size of the final stereoscopic picture to the size of the camera negative or negatives.

(8) T —the maximum horizontal distance between the left-most vantage point and the right-most vantage point; i.e., from one extreme photographic vantage point to the other.

(9) W —the lenticule width of the lenticular screen of the final stereoscopic picture.

The value of c , which will hereinafter be called the parallax factor, may also be considered a "variable" under control of the photographer.

The relationship of the above variables to each other and to the values of parallax X_{BK} , X_{KA} , and X_T will now be derived with reference to Figure 7. Figure 7 is a schematic illustration similar to Figure 1 showing three object field element positions A, K and B arranged on a line or principal axis 82, a lens 84 arranged with its optical axis 86 parallel to the principal axis 82, and a film plane 88.

It will be assumed in this case that the lens 84 is situated at the right-most vantage point of a plurality of vantage points and that the left-most vantage point is arranged symmetrically with respect to the principal axis 82, so that:

$$X_R = X_L;$$

and

$$X_T = 2X_R.$$

The basic optical equation for the configuration shown in Figure 7, where the lens is focused on an element at position K at a distance k from the lens plane is:

$$1/e + 1/k = 1/f$$

or

$$e = \frac{kf}{k-f}$$

By simple trigonometric relations, it may be seen that:

$$k' = \frac{Te}{2K} = \frac{T}{2k} \frac{(kf)}{(k-f)} = \frac{Tf}{2(k-f)} \quad 60$$

$$a' = \frac{Te}{2a} = \frac{kTf}{2a(k-f)} = \frac{k}{a} k'$$

$$b' = \frac{Te}{2b} = \frac{kTf}{2b(k-f)} = \frac{k}{b} k'$$

As explained above, the parallax values X_{BK} and X_{KA} should be made equal for a high quality three-plane stereoscopic picture. Thus:

$$a' - k' = k' - b'.$$

Substituting the values derived above for a' and b' , it can be shown that:

$$k/a + k/b = 2 \quad (3) \quad 70$$

Now the total parallax value at the film negative is given by

$$X_R = a' - b'$$

or

$$X_R = \frac{k}{a} k' - \frac{k}{b} k' \quad 75$$

Substituting the value for k' derived above and transposing the preceding equation:

$$\frac{kTf}{a2(k-f)} - \frac{kTf}{b2(k-f)} = X_R = \frac{X_T}{2}$$

Assuming

$$\frac{k}{k-f} \quad 80$$

is approximately unity, as will be the case in most photographic conditions, then:

$$T = \frac{X_T}{f} \frac{(ab)}{(b-a)} \quad (4)$$

Thus, substituting the value of parallax given in equations (2) above, the result is:

$$T = \frac{2abc(N-1)W}{f(b-a)R} \quad (5)$$

Using the equations (1), (2), (3), and (4)

or equations (3) and (5), a photographer can choose and control the parallax in a stereoscopic picture. He will therefore be assured that all the stereoscopic pictures taken will be of consistently high quality.

To illustrate the photographic technique which may be employed by a photographer according to the present invention, let us assume that the photographer desires to photograph an object field having a particular key subject matter and particular background and that, in addition to the key subject matter and background, the photographer would like to include a suitable foreground object. First, the photographer chooses a suitable distance k between his camera and an element of the key subject matter which he would like to fall in the plane of the picture; next he notes the distance b from his camera to the farthest element or point of the background. Using equation (3) the photographer then solves for the distance a to the nearest foreground point includable in the picture, consistent with good picture quality.

Similarly, if the distances k and a or even a and b are initially known, the photographer may solve for the unknown distance b or k , respectively, using equation (3).

Thereafter, knowing a and b as well as all the variables R , c , N , f and W (any or all of which are subject to choice) the photographer determines the distance T using equation (5). The value of c is selected from

$$\frac{1}{(N-1)}$$

to 5.0, as described above, depending upon photographic conditions such as the nature, lighting and contrast of the object field. The photographer then proceeds to take N equally spaced photographs of the object field with the distance between the optical axes of the camera objective in taking the left-most photograph and the right-most photograph equal to T . The central photographic vantage point should be, in this case, on the principal axis of the object field.

Conversely, assuming that the photographer has a fixed distance T between the optical axes of the left-most objective and the right-most objective on a plural-lens camera, the photographer may use equation (5) to determine one of the distances a or b given the other and use equation (3) to determine the distance k .

If the photographer wishes to position the left-most (or right-most) vantage point on the principal axis of the object field, X_L (or X_R) will equal zero, so that:

$$X_R = X_T = \frac{2c}{R}(N-1)W;$$

or

$$X_L = X_T = \frac{2c}{R}(N-1)W, \quad 60$$

using equations (1) and (2). Similarly, if the left-most and right-most vantage points are to be positioned arbitrarily with respect to the principal axis:

$$X_T = X_R + X_L = \frac{2c}{R}(N-1)W \quad 65$$

from equations (1) and (2). Given the value of X_T , the distances a , b , k and T may be determined in accordance with equations (3) and (4).

If the photographer desires to take a three-dimensional picture of a scene having only key subject matter and background, or key subject matter and foreground, the total parallax (X_T) must appropriately be reduced by a factor of two. In particular, one of the parallax values X_{BK} and X_{KA} , respectively, must be substituted for the value X_T in the equation (4). In addition, since the key subject matter element will be the nearest foreground element in the case of an object field having only key subject matter and background, or will be the farthest background element in an object field having only key subject matter and foreground, the distance k should be substituted for a or b , respectively, in equation (4). That is, for a picture having only key subject matter and background:

$$T = \frac{X_{BK}}{f} \left(\frac{kb}{b-k} \right);$$

and for a picture having only key subject matter and foreground:

$$T = \frac{X_{KA}}{f} \left(\frac{ak}{k-a} \right).$$

When photographing the scene, the photographer must consider the effect of parallax on the picture composition. Figure 8 shows the desired appearance of a composed stereoscopic picture wherein the small and large objects 90a and 90b diagrammatically depicted are just within the picture area. The images of the large and small objects indicated by solid lines represent those recorded at the right-most vantage point, while the dashed lines indicate the images of the objects recorded at the left-most vantage point. To assure that all images of the objects will be within the picture area, the photographer should make certain that ample margins (M) are included at the left and right-hand sides of the photographic negatives, relative to the positions (indicated by solid lines in Figure

9) of the images of 90a and 90b at the central vantage point, so that, because of parallax, the object images in the stereoscopic picture, as shown in Figure 8, will not extend beyond the opposite sides of the picture area.

One special technique available to a photographer when taking stereoscopic pictures permits selected objects in the picture to either change position or disappear, depending upon the angle with which the stereoscopic picture is viewed. For example, the effect of disappearing objects can be achieved as shown in Figures 10 and 11 by shooting the left-most half of the N frames with the selected object 92 in position, and then shooting the right-most half of the N frames with the object 92 removed. The disappearing object 92 must be maintained within the general plane of the key subject matter 94. The effect of moving objects can be achieved in a similar manner by changing the position of the selected object when shooting the left half and right half of the N frames.

A representative embodiment of the present invention, by which the foregoing inventive concepts may be practiced, will now be described with reference to Figures 12 and 13 of the drawings.

Figures 12 and 13 show a plural lens camera capable of simultaneously taking, for example, from two to five pictures (N is in the range: 2—5). This camera includes a housing or body 96; a shutter button 98; five lenses 100, 102, 104, 106 and 108 and a viewing or sighting device 110. In accordance with the present invention, the photographer can control the distance T between the optical axes of the left-most and the right-most picture-taking lenses in any suitable way; for instance:

(1) The camera may be constructed to permit selection of those lenses 100—108 through which pictures will be taken. Thus, for example, the photographer may select lenses 100, 102 and 104 to give $T=T_2$; or he may select all lenses so that $T=T_4$. A camera and shutter mechanism appropriate for this purpose are described in U.S. Patent No. 3,852,787.

(2) The camera may be constructed to permit expansion or contraction of the body 96 in a direction transverse to the lens axes, thus permitting adjustment of the lateral spacing between the optical axes of the lenses 100—108. Although this expandable construction is not illustrated in Figures 12 and

13, it will be understood that any suitable arrangement permitting an adjustable separation of the respective lenses may be provided. For example, five separate camera lenses, with corresponding camera bodies may be slidably arranged on a common base.

In addition to or in lieu of means for adjustment of the parameter T, the camera shown in Figures 12 and 13 may also be constructed to permit variation of the focal length f. This adjustment would give the photographer added flexibility to control the parallax pursuant to the equations (4) and (5) above. As an example, each of the lenses 100—108 may be made interchangeable with other lenses of different focal length. All of the lenses used in taking a picture, however, preferably will have the same focal length.

WHAT WE CLAIM IS:—

1. A camera for taking a plurality N of two-dimensional views of an object field for use in composing a stereoscopic picture of the type incorporating a viewing lenticular screen of lenticule width W, the camera including corresponding pluralities of N of lenses and associated film frames, the lenses being aligned in a row with their optical axes substantially equidistantly spaced apart and substantially in parallel; the distance T between the optical axes of the endmost lenses being related to predetermined values of $X_{T..}$, R, f, a and b generally in accordance with:

$$T = \frac{X_{T..}ab}{Rf(b-a)}$$

wherein $X_{T..}$, R, f, a, and b, have meanings as hereinbefore given.

2. A camera according to claim 1 wherein the predetermined value of $X_{T..}$ is within the range of from substantially $2W(N-1)$ to substantially $2cW(N-1)$, wherein c is selected within the range of from 1.0 to 5.0, inclusive, as a function of photographic conditions.

3. A camera according to claim 1 and substantially as herein described with reference to Figures 12 and 13 of the accompanying drawings.

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