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Carpentier et al.

[11] **3,884,577**

[45] **May 20, 1975**

[54] **METHODS AND APPARATUS FOR OBJECT REPRODUCTION**

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[52] **U.S. Cl.** **355/77;** 353/65; 156/58; 356/163

[51] **Int. Cl.** **G03b 21/06**

[58] **Field of Search** 353/65; 156/58; 356/163; 355/77

[56] **References Cited**

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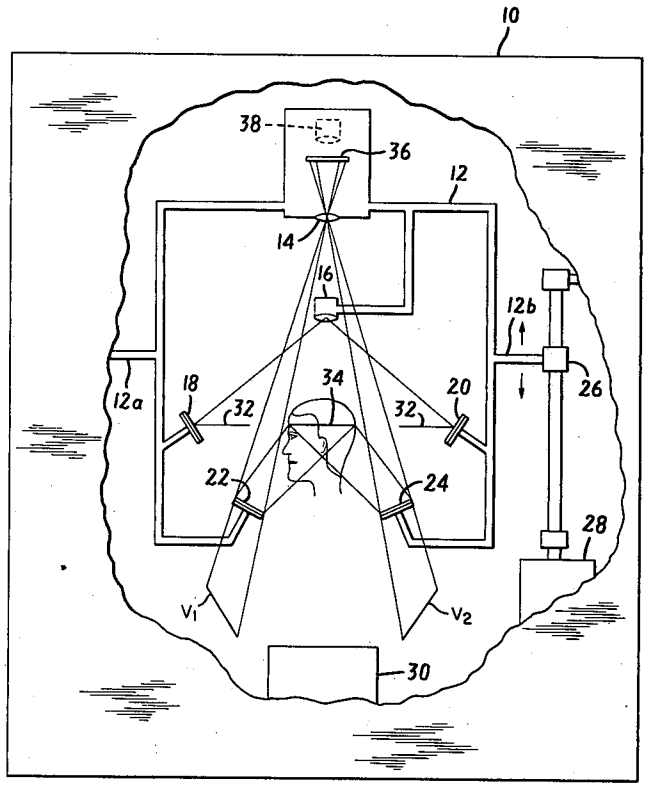
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[57] **ABSTRACT**

Methods and apparatus for photographically-assisted reproduction of continuous line boundaries of three-dimensional objects are disclosed wherein cooperative parts of continuous line boundaries are compositely recreated by use of a mirror plurality disposed in selectively overlapping viewing relation to the boundaries and lens means in viewing relation to the mirror plurality.

12 Claims, 7 Drawing Figures



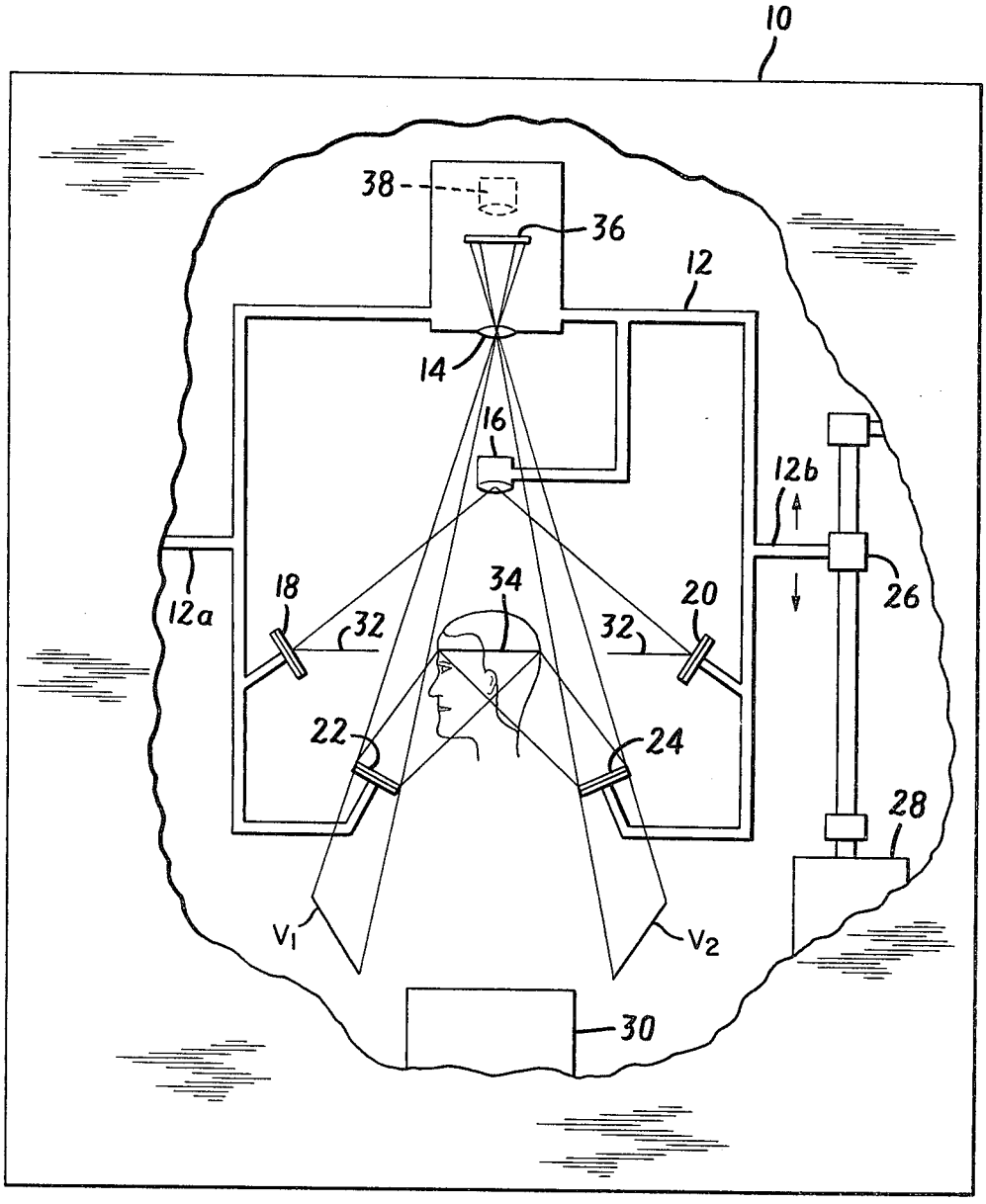


FIG. 1

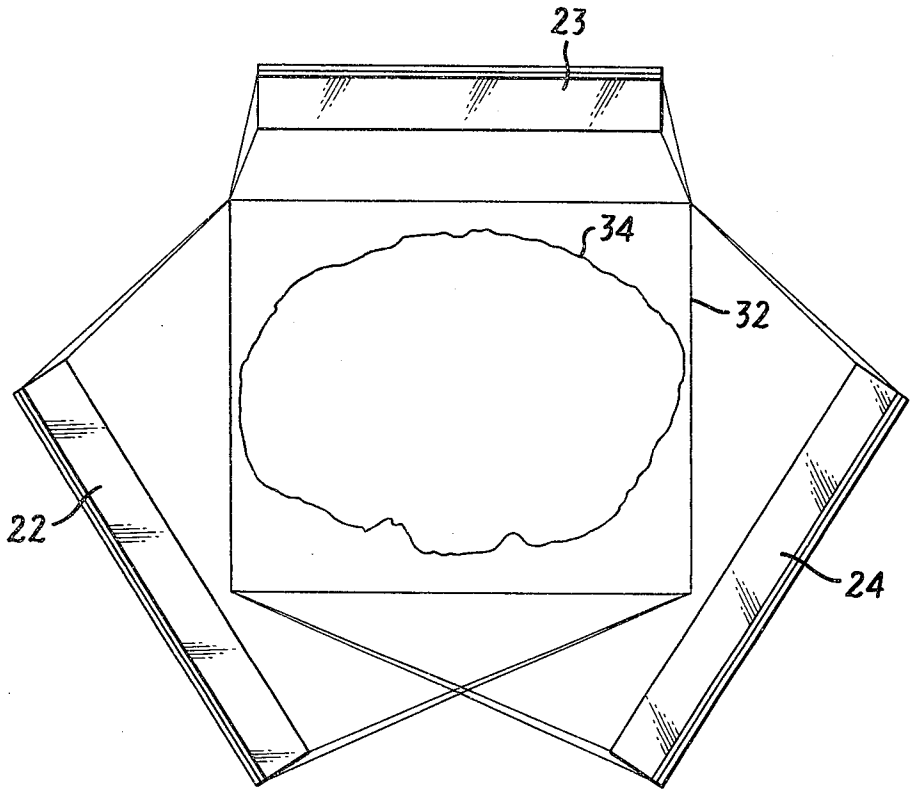


FIG. 2

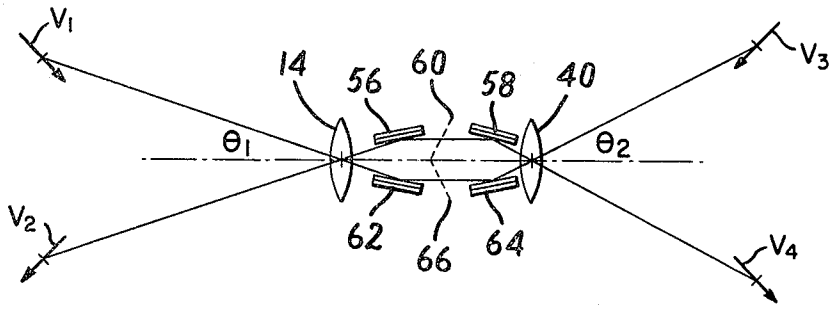


FIG. 6

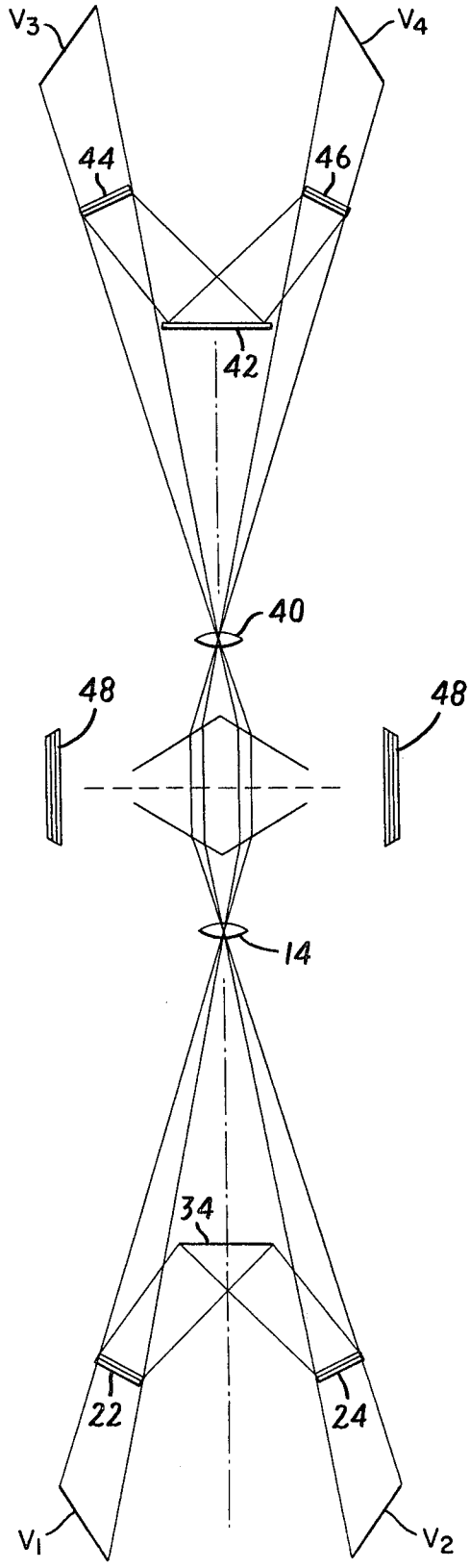

V3
V4
44
46
42
40
48
48
14
34
22
24
V1
V2

FIG. 3

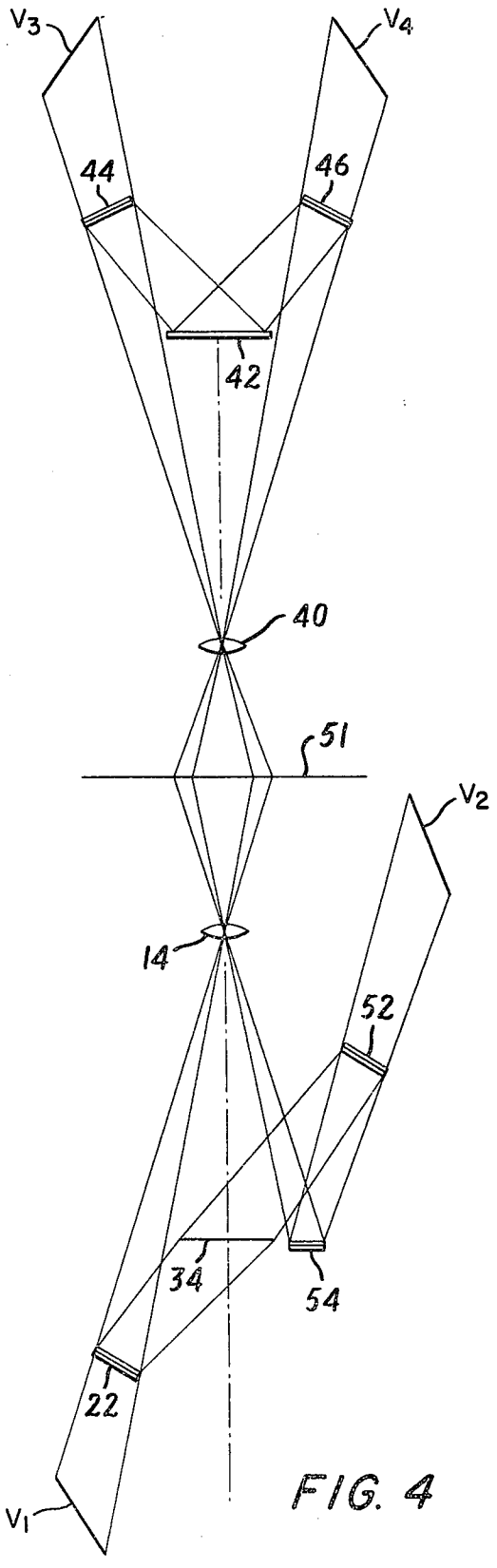

V3
V4
44
46
42
40
51
V2
14
52
34
54
22
V1

FIG. 4

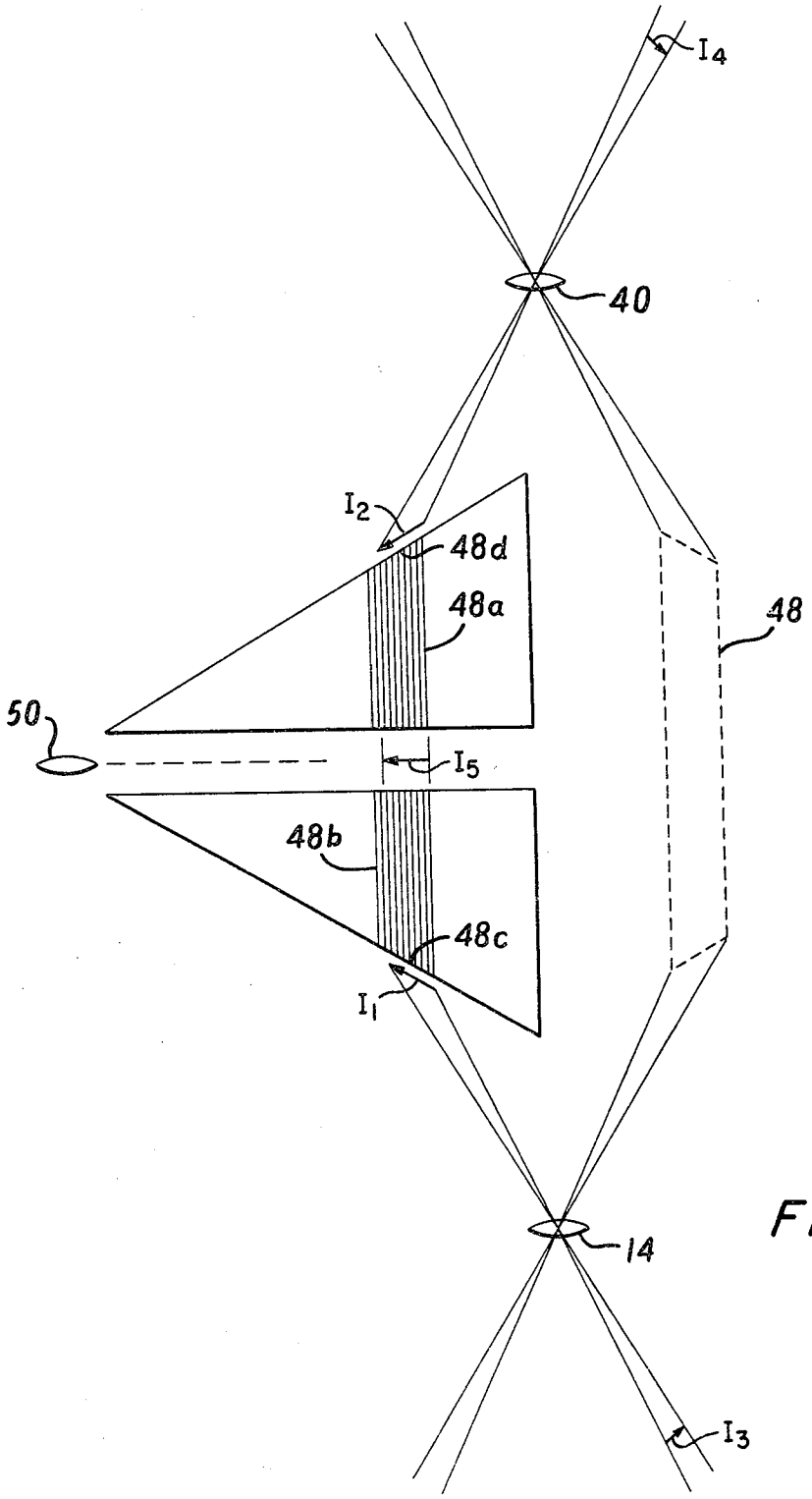


FIG. 5

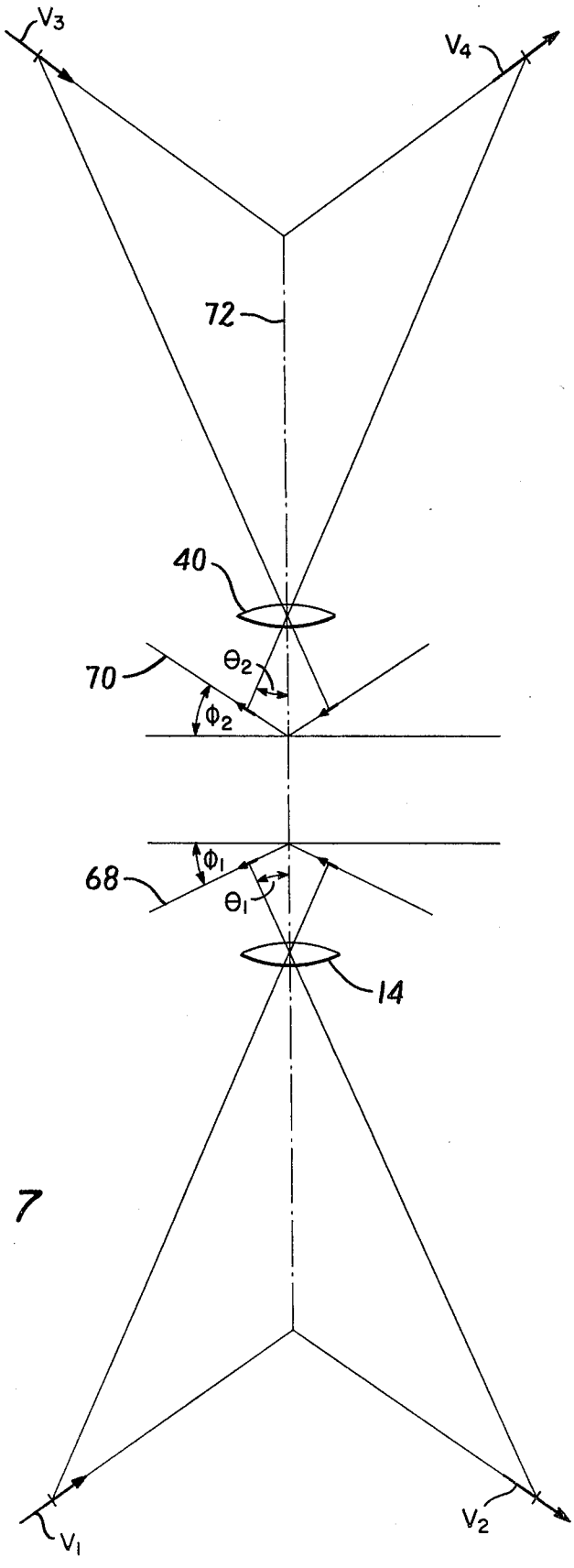


FIG. 7

METHODS AND APPARATUS FOR OBJECT REPRODUCTION

FIELD OF THE INVENTION

This invention relates to methods and apparatus for use in the reproduction of three-dimensional objects and more particularly for use in photographically-assisted reproduction thereof.

BACKGROUND OF THE INVENTION

In one presently known method for making reliefs of three-dimensional objects, slices of readily workable material are provided in volume exceeding that of the object and each material slice is worked until its surface boundary accords with the surface boundary of a corresponding like-thickness slice of the object. Materials such as wood, metal and the like are employable with various working techniques, e.g., carving, chemical etching, etc., as discussed in U.S. Pats. No. 2,189,592 and 3,539,410, particularly in connection with the making of topographical reliefs.

Realization of the referenced method in making topographical reliefs may be conveniently accomplished since requisite positional information defining object surface boundaries is directly available from a contour map, which provides visualization of all object surface boundaries. On the other hand, when the method is applied to irregularly-shaped objects whose surface boundaries are not charted and which include surface boundary portions recessed relative to one another and hence not directly viewable from a single viewing location, practice of the method is impeded at the outset by the need for deriving exacting positional information defining object surface boundaries.

Presently known efforts for deriving such positional information defining the surface boundaries of irregularly-shaped objects, e.g., as discussed in U.S. Pats. Nos. 3,338,766, Reissue 25,930, 2,891,339, 2,350,796, 1,719,483, 2,335,127, 2,066,996 and 2,015,457, have in common the piecemeal derivation of positional information respecting the surface boundaries of selective object slices by composite techniques, machine-performable in initial part but subsequently manipulative. Typically, such efforts involve the use of a single camera movable relative to the object slice, or fixed multiple cameras, for the taking of plural angularly-displaced photographs of an illuminated object slice surface boundary. As discussed in the above-referenced patents, and particularly in U.S. Pat. No. 2,891,339, such machine-performable photographic step must be supplemented by the complex and tedious further manipulative step of interfitting and size-adjusting the separately derived photographs of different segments of the slice surface boundary in order to provide positional information respecting the continuous encircling boundary surface of the object slice necessary for visualization thereof.

Such known efforts to reproduce irregularly-surfaced objects are evidently less efficient than is desired, based on their apparatus requirements, i.e., either multiple cameras or a single camera together with means for angularly displacing the same, and by their method limitations, i.e., the need for separately deriving multiple photographs of each slice surface boundary and for manipulative steps of processing the photographs. Accordingly, need clearly exists for improved apparatus and method for use in this field.

SUMMARY OF THE INVENTION

The present invention has as its object the provision of methods and apparatus enabling more efficient derivation of positional information and visualization of surface boundaries for use in irregularly-shaped object reproduction.

A more particular object of the invention is the provision of methods and apparatus for deriving such positional information and effecting such visualization in machineperformable manner throughout.

In attaining these and other objects, the invention provides for the positioning of a plurality of reflective means in viewing relation both to a preselected line boundary of an object and to a lens, the further positioning of adjacent ones of the reflective means in viewing relation to a common extent of the line boundary, and irradiation of the line boundary. The radiant energy image thereupon generated by the lens contains the desired positional information and may be recorded on a single film frame for use, after development, in providing visualization of the continuous line boundary. Alternatively, the radiant energy image may be used directly in providing such visualization by further method and apparatus.

The foregoing and other objects and features of the invention will be evident from the following detailed description of preferred embodiments thereof and from the drawings wherein like reference numerals identify like parts throughout.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates method and apparatus in accordance with the invention and optical relationships among elements used therein.

FIG. 2 illustrates further optical relationships among elements of the apparatus of FIG. 1.

FIGS. 3 and 4 illustrate further embodiments of method and apparatus in accordance with the invention.

FIGS. 5, 6 and 7 illustrate techniques and elements for image rotation in accordance with the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Referring to FIG. 1, a housing **10** supports therewithin a frame **12** in turn supporting, in mutually fixed relation, a lens **14**, a radiant energy projector **16** and mirrors **18, 20, 22** and **24.** Mirrors **18** and **20** are two mirrors in a plurality of projection mirrors disposed peripherally of the interior of frame **12.** The same applies in the case of mirrors **22** and **24,** whose lens plurality may comprise three mirrors and thus include one further mirror **23** (FIG. 2). Disposed laterally of frame **12** and connected thereto by arms **12***a* and **12***b* are a pair of lead screw mechanisms, one of which **26** is shown in FIG. 1 fixed in housing **10** and in driven engagement with the output shaft of reversible motor **28.** Pedestal **30** is secured to the floor of housing **10** in position supporting an object to be reproduced interiorly of frame **12.**

Projector **16** incorporates a slit mask providing for application of pencil-line light beams to mirrors **18** and **20** which are reflected therefrom into a preselected plane **32** extending between the mirrors. Motor **28** is

energized to provide for selective movement of frame **12** relative to the object, such that plane **32** may be caused to intersect the object in preselected manner to define distinct line boundaries in the object boundary surface, e.g., illustrated at **34** in FIGS. **1** and **2.**

Frame **12** supports mirrors **22–24** in viewing relation to both lens **14** and, wherein an object is disposed in housing **10,** in viewing relation to the object line boundary surface defined by projector **16** and mirrors **18–20.** Further, mirrors **22–24** are supported by the frame such that adjacent ones thereof are in viewing relation to a common segment of such object line boundary, i.e., have overlapping fields of view (FIG. **2**). By this arrangement, mirrors **22–24** convey to lens **14** images which embody positional information respecting the entire line boundary **34.** Suitable masking may be employed to eliminate direct viewing of the object by lens **14** since direct views of the object are surplusage to the instant methods. Where masking is not employed, any directly viewed representation of the object generated by lens **14** is ignored. While projector **16** preferably incorporated a visible energy source, and such images are light images, the invention of course contemplates the use in projector **16** of any suitable radiant energy source.

A further preferred optical relationship among elements of the apparatus of FIG. **1,** and a preferred practice of the invention, resides in the angular relationship among the virtual images produced by mirrors **22–24.** By appropriate positioning of mirrors **22–24,** their virtual images, V_1 and V_2 of which are illustrated, are equidistant at their midpoints from lens **14** and form the same angle with a common axis, preferably the optical axis of lens **14.** As will be evident, this practice facilitates focusing of the multiple views of the line boundary.

The images provided by the foregoing fundamental apparatus and basic method of the invention may be recorded on a single frame of a recording medium **36,** preferably comprising photographic film. Video tape or the like may be used in which cases, the energy source of projector **16** is selected accordingly. Upon development of the recording medium, the same provides a composite image which, while not itself defining a reproduction of line boundary **34,** may be employed as now discussed in accordance with further method and apparatus of the invention to provide such reproduction as follows.

The developed frame of the recording medium is returned to its original position relative to lens **14,** i.e., in the focal plane defined by the lens for mirrors **22–24,** and projector **16** is deenergized. The object is removed from the interior of frame **12** and visualizing means, i.e., a viewing screen, such as ground glass in the case of light energy, is positioned coincidently with plane **32.** A further projector **38,** shown in broken lines in FIG. **1,** is now energized and projects radiant energy successively through recording medium **36,** lens **14** and mirrors **22–24** onto the surface of the viewing screen. There results on the screen surface a reproduction of object line boundary **34** which may be recorded, as by photographing the same, and subsequently used in accordance with the techniques discussed in the above-referenced patents to reproduce a three-dimensional slice of the object.

The procedure discussed to this point may be repeated for other preselected planes of the object by controllably displacing frame **12** through selective energization of motor **28.** The plurality of object slices thus produced are unitarily assembled to provide a reproduction of the entire object. To facilitate the assembly of such slices, an elongate element defining an assembly registration axis may be disposed adjacent the object during practice of the method and will appear in cross-section in all frames of developed recording medium.

The methods discussed to this point require that visualizing means be substituted for the object in the visualization of each line boundary. Such requirement may be eliminated by the practice of further methods now discussed.

The apparatus in the lower half of FIG. **3** comprises a portion of that of FIG. **1,** namely, lens **14** and mirrors **22–24.** For simplification, frame **12** and the object are omitted, as are projector **16** and mirrors **18–20.** Recording medium **36** and projector **38** are not employed. A second lens **40** is disposed with the optical axis thereof coincident with that of lens **14.** A viewing screen, which may comprise ground glass plate **42,** is disposed in a field of view of lens **40** extending oppositely from the field of view thereof extending to lens **14.** A further plurality of mirrors **44–46,** in number corresponding with mirrors **22–24,** is positioned in viewing relation to both lens **40** and plate **42.** Further, mirror **44** is positioned such that it is in viewing relation with a selective one of mirrors **22–24,** namely, mirror **22.** Likewise, mirror **46** is positioned so as to be in selective viewing relation with mirror **24.** The above-discussed optical arrangement among mirrors **22–24** respecting the orientation of virtual images and distance between the same and lens **14** is also preferably practiced for mirrors **44–46,** virtual images V_3 and V_4 of which are illustrated in FIG. **3.**

In operation of the FIG. **3** apparatus, each image generated by mirror **22** and conveyed to lens **14,** as heretofore discussed, is projected by lens **40** onto mirror **44** and thence onto plate **42.** Likewise, each image generated by mirror **24** and conveyed to lens **14** is projected by lens **40** onto mirror **46** and thence onto plate **42.** In the example illustrated in FIG. **3,** line boundary **34** is reproduced in its entirety on plate **42** and may be recorded for further use in object slice construction.

All optical elements of FIG. **3** are supported in mutually fixed relation in a frame similar to frame **12** of FIG. **1.** Such frame is supported for selective movement relative to an object disposed interiorly of the apparatus of the lower half of the figure. By this arrangement, records of the continuous line boundaries of incrementally spaced portions of an object may be produced successively without the need for removing the object from the apparatus at any time during record production.

Where focus relations in the two-lens system of FIG. **3** are unduly conflicting or where it is desired to employ relatively large lenses in the apparatus of the invention for improving the amount of image energy transmitted through the apparatus and hence image contrast, it is convenient to introduce in the apparatus elements effecting the particular image exchange between lens **14** and lens **40** shown in FIG. **3,** i.e., corrective of lens depth of focus limitations. One form of element **48** suitable for such use is laterally displaced from operative position in FIG. **3** for clarity, and is shown in operative position in FIG. **5.**

Image I_1 of FIG. 5 generated by lens **14** and disposed in its illustrated orientation should be in the substantially different orientation, i.e., that of image I_2, in order that images I_3 and I_4 may be in their illustrated orientations. To this end, element **48**, shown in FIG. **5** for purposes of explanation as comprising sections **48***a* and **48***b* , is comprised of fiber optic members formed into a wedge defining input plane **48***c*, having the orientation of image I_1, and output plane **48***d*, having the orientation of image I_2. By way of explanation of the function of the wedge, its individual members conduct image I_1 to the horizontal plane as shown by image I_5 and thence to plane **48***d*, in effect providing a rotation of the image in desired manner.

In the wedge arrangement of FIGS. **3** and **5**, images are rotated without scale change. Where desired, scale change, either of magnification or demagnification, may be introduced by forming element **48** in separate sections and inserting a lens **50** (FIG. **5**) therebetween. The spatial relationships between mirrors **44–46**, lens **40** and viewing screen **42** are scaled from their relationship absent scale change in accordance with the scale change adopted. Such relationship absent scale change requires that the apparatus supporting lens **40** and mirrors **44–46** be of the same size as the apparatus supporting lens **14** and mirrors **22–24**. Evidently, demagnifying scale change will permit extensive size reduction for the composite apparatus.

Scale change may be introduced alternatively by changing the orientation of wedge output plane **48**d and the projection throw distance of the final image. In this connection, lens **40** is repositioned relative to wedge output plane **48***d* and the distance between lens **40** and mirrors **44** and **46** is adjusted such that images V_3 and V_4 have the same orientation as in the absence of scale change.

The apparatus of FIG. **3** is duplicated in large part in the modified embodiment thereof shown in FIG. **4**. The variation introduced in the FIG. **4** apparatus, which may be introduced in all discussed practices of the invention, involves the substitution of intermediate viewing screen **51**, e.g., ground glass, for members **48**, and the substitution of mirror **24** by a pair of mirrors **52** and **54**.

Viewing screen **51** provides a common plane for all images as contrasted with the four image planes defined by members **48** of FIG. **3**. As will be appreciated, the use of viewing screen **51**, or its equivalent in function, i.e., a field lens (not shown) intervening lenses **14** and **40**, is satisfactory in instances not involving exacting correction of lens depth of focus limitations.

Mirror **52** of FIG. **4** is positioned to view line boundary **34** from the side thereof opposite to that viewed by mirror **22**. Mirror **52**, while not itself positioned in the direct field of view of lens **14**, is in the field of view of mirror **54**, and mirror **54** is in the direct field of view of lens **14**. Mirror **52** is further in viewing relation to one side of a segment of line boundary **34**, the other side or the same side of which is in the field of view of a mirror adjacent to mirror **52**. As illustrated, mirror **54** is preferably further positioned such that its virtual image forms the same angle of intersection with a common axis as do the virtual images formed by counterpart mirrors in the apparatus.

A further arrangement employable where image rotation is desired in practicing the invention is shown in FIG. **6**. In this arrangement, a mirror system is disposed between lenses **14** and **40**. Mirrors **56** and **58** are so positioned as to define a common focal plane **60** thereby providing line of sight relations for images V_2 and V_4, produced by counterpart mirrors (not shown) on opposite sides of and in selective viewing relation through the lenses. Mirrors **62** and **64** are likewise positioned to define a common focal plane **66** thereby providing line of sight relations for virtual images V_1 and V_3. This arrangement is suited for use where the optical conditions illustrated in FIG. **7** exist.

Referring to FIG. **7**, virtual image V_2 is focused by lens **14** in plane **68**. Focal plane **70** is the plane in which lens **40** requires this image in order to project a virtual image thereof in the orientation shown for V_4. The optical axes of lenses **14** and **40** are coincident with axis **72**. Where the sum of the focal plane skew angles, ϕ_1 and ϕ_2, is equal to the sum of lens angles, θ_1 and θ_2, a plurality of mirrors may be positioned between lenses **14** and **40** to provide the requisite image rotation.

Various changes now made evident to those skilled in the art may be effected in the foregoing methods and apparatus without departing from the present invention. For example, while disclosure has been made of the use of the invention in the reproduction of continuous encircling line boundaries, reproduction may be had merely of a continuous line boundary of an object. Where images are recorded in practicing the invention, it will be appreciated that the term development, as applied to records of images, is intended to connote processing the record such that its information content may be visualized. Thus, the particularly disclosed embodiments above are intended in a descriptive and not a limiting sense. The true spirit and scope of the invention is set forth in the following claims.

What is claimed is:

1. Apparatus for use in the reproduction of a three-dimensional object, comprising:

a. first means for supporting said object;

b. second means for generating a plurality of separate overlapping radiant energy images of said object, said second means defining an interior in which said object is positionable and supporting at said interior in mutually fixed relation:

1. lens means providing said separate overlapping images and being inclusive of at least one lens;

2. means for projecting radiant energy in a predetermined planar portion of said interior;

3. a plurality of radiant energy reflective means, each disposed in distinct viewing relation to said predetermined interior portion, each pair of said reflective means being further disposed in the field of view of at least one lens in said lens means; and

4. image rotating means for separately turning the plane of each of said images provided by said lens means to effect joint focusing and positioning thereof in a common plane; and

c. third means for providing relative movement between said first and second means to selectively position said object within said second means.

2. The apparatus claimed in claim **1** further including means for recording radiant energy images generated by said second means.

3. Apparatus for use in the reproduction of a three-dimensional object, comprising:

a. first means for supporting said object;

b. second means for generating radiant energy images of said object, said second means defining an interior in which said object is positionable and supporting at said interior in mutually fixed relation:
1. a first lens;
2. means for projecting radiant energy in a predetermined planar portion of said interior;
3. a plurality of first radiant energy reflective means, each disposed in a first field of view of said first lens and in viewing relation to said predetermined interior portion;
4. a second lens disposed in a second field of view of said first lens;
5. means for visualizing radiant energy images incident thereon; and
6. a plurality of second radiant energy reflective means, each disposed in viewing relation to said visualizing means and in viewing relation through said first lens and said second lens to a selective one of said first reflective means; and
c. third means for providing relative movement between said first and second means to selectively position said object within said second means.

4. The apparatus claimed in claim **3** further including means for recording radiant energy images generated by said second means.

5. The apparatus claimed in claim **3** wherein said second means further includes means disposed between said first lens and said second lens for rotating radiant energy images applied thereto by said first lens.

6. The apparatus claimed in claim **5** wherein said image rotating means is comprised of first and second image rotating members, said second means further including a third lens disposed between said members.

7. The method for generating a radiant energy pattern for use in reproducing the surface boundary of a threedimensional object, comprising the steps of:
a. defining a lens field of view extending from an origin to said object;
b. preselecting a plane intersecting said object and defining a continuous encircling line boundary in said object surface;
c. applying radiant energy to said object line boundary;
d. reflecting into said lens field of view and through said origin thereof a plurality of separate radiant energy images of overlapping portions of said object line boundary;
e. separately turning the plane of each of said radiant energy images upon reflection thereof through said origin of said lens field of view to effect joint focusing and positioning thereof in a common plane exteriorly of said lens field of view; and
f. recording such turned radiant energy images at said common plane.

8. The method claimed in claim **7** wherein all virtual images of said object line boundary generated in said step (d) form the same angle of intersection with a common axis.

9. The method claimed in claim **7** wherein the optical axis of said lens field of view intersects said object.

10. The method claimed in claim **9** wherein all virtual images of said object line boundary generated in said step (d) form the same angle of intersection with said optical axis.

11. The method claimed in claim **7,** wherein said radiant energy is light energy and wherein said step (f) is practiced by recording said images on photographic film.

12. A method for visibly reproducing a continuous part of the surface boundary of a three-dimensional object, comprising the steps of:
a. defining a lens field of view extending from an origin to said object;
b. preselecting a plane intersecting said object and defining a continuous encircling line boundary in said object surface;
c. applying radiant energy to said object line boundary;
d. reflecting into said lens field of view and through said origin thereof a plurality of separate radiant energy images of overlapping portions of said object line boundary.
e. separately turning the plane of each of such reflected radiant energy images upon reflection thereof through said origin of said lens field of view to effect joint focusing and positioning thereof in a common plane exteriorly of said lens field of view;
f. recording such turned radiant energy images at said common plane to provide a record thereof defining a composite image comprised of separated partial images of said object line. boundary;
g. developing said record and then repositioning the same in said focal plane; and
h. applying radiant energy to said record, thereby generating a reproduction of said object line boundary from such recorded composite image.

* * * * *