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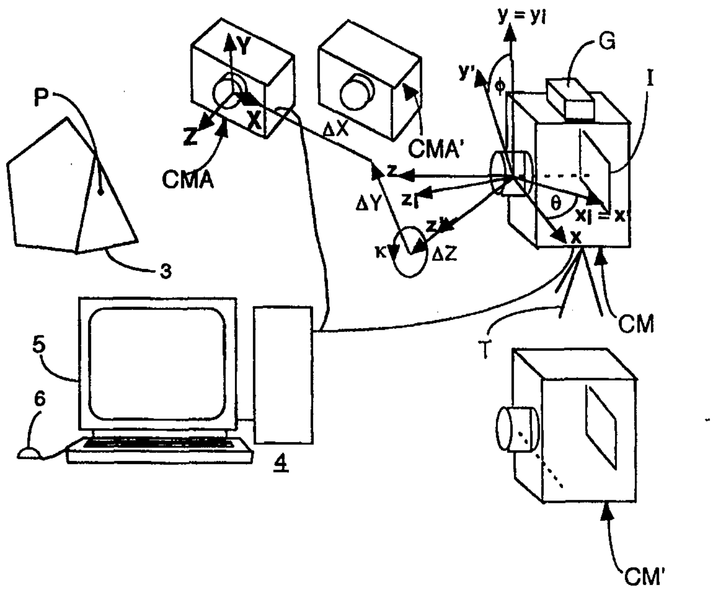

(57) Abstract

An arrangement (Figure 1) for generating a 3D representation of an object (3) comprises a camera (CM) freely movable to a further viewpoint (CM') and arranged to acquire respective overlapping images at each viewpoint. The orientation of the camera is maintained roughly constant at the two viewpoints and after correlating the images e.g. by Gruen's algorithm an approximate 3D representation is generated in a computer (4) by deriving the vector (V, Figure 3) between the viewpoints. In other embodiments (Figures 13 and 15) the object is illuminated with structured optical radiation and a 3D representation is derived from the correlation of images of the object and a target acquired at a common viewpoint. Methods of tracking the camera (Figures 4 to 6) are also disclosed.

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Method and Apparatus for 3D Representation

The present invention relates to a method and apparatus for deriving a three-dimensional representation from two or more two-dimensional images.

As is well known, in general such a 3D representation can only be generated if the features (eg points) of the images are correlated. Respective features of two overlapping images are correlated if they are derived from (ie conjugate with) the same feature (eg a point) of the object. If the positions and orientations of the camera at which the overlapping images are acquired are known, then the 3D coordinates of the object in the region of overlap can be determined, assuming that the camera geometry (in particular its focal length) is known.

Hu *et al* "Matching Point Features with ordered Geometric, Rigidity and Disparity Constraints" IEEE Transactions on Pattern Analysis and Machine Intelligence Vol 16 No 10, 1994 pp1041-1049 (and references cited therein) discloses suitable algorithms for correlating features of overlapping images. Such algorithms can be used in the present invention and will not be discussed further. However it should be noted that in some circumstances (eg when the object is relatively simple or one of the known algorithms has failed to correlate sufficient features to enable an accurate reconstruction of part of an object to be derived) the features of the overlapping images can be correlated by eye and the correlation recorded on screen when using an embodiment of the method and apparatus of the present invention.

Assuming that the correlated points of the images have been derived, in principle the information about the position and orientation of the camera required to reconstruct the object in 3D can be obtained either by direct measurement or by various sophisticated mathematical techniques involving processing all the correlated pairs of features. (Stereoscopic camera arrangements in which the cameras are fixed are ignored for the purposes of the present discussion).

EP-A-782,100 discloses a method and apparatus in the first category, namely a photographic 3D acquisition arrangement in which a camera displacement signal and a lens position signal are used to enable a 3D representation of an object to be built up from 2D images acquired by a digital camera. Both the position and the orientation of the camera are monitored. The hardware required to achieve this is expected to be expensive.

A number of research papers have addressed the more difficult question of deriving the correct orientation from the correlated features of the images, as follows:

i) E H Thompson "A rational Algebraic Formulation of the problem of Relative Orientation" Photogrammetric Record Vol 3 No 14 (1959) pp 152-159 sets out a mathematical procedure for aligning two images of the same scene to the correct orientation for reconstructing the scene in 3D, involving an iterative solution of five simultaneous equations derived from five pairs of correlated points.

ii) Richard Hartley *et al* "Stereo from uncalibrated cameras" Proc. IEEE Conf Computer Vision and Pattern Recognition (1992) pp 761-763 teaches that two 3x4 camera matrices define the camera orientations and locations as well as the internal camera parameters such as focal length. If the cameras are calibrated (ie the internal parameters are known) then the camera matrices can be found from the matched points and hence the true 3D locations of all the points can be found. If the cameras are not calibrated then known "ground control" points must be used to derive the camera matrices and hence the 3D locations of the matched points.

iii) Richard Hartley "Estimation of Relative Camera Positions for Uncalibrated Cameras" Computer Vision-ECCV'92, LNCS-Series, Vol 588, 1992 pp 579-587 is a development of the above Hartley paper and shows that the focal lengths as well as the positions and orientations of the cameras can be found from the matched points if all the other internal camera parameters are known.

iv) Hartley *et al* "Computing Matched-epipolar projections" Computer Vision and Pattern Recognition 1993, pp 549-555 is a development of the above which introduces the epipolar transformation matrix to transform the images to images that would be acquired by cameras placed side-by-side with their optical axes parallel. The remaining points can then be correlated more easily. Also the cameras do not need to be calibrated.

A disadvantage of the above mathematical methods is the intensive computation required to process all the correlated points. Much of this computation involves the determination of the camera positions and orientations from multiple points and is effectively wasted because the positions and orientations are grossly over-determined by the large number of processed points.

It has been shown that in general all the information on the viewpoints (ie position and orientation) of the camera(s) can be found from eight pairs of correlated points. However there are special cases in which this is not possible. One extreme example is a situation in which all eight points on the object corresponding to the pairs of corelated points in the images are colinear.

Importantly, another situation in which the camera positions cannot be determined is when the camera orientations (in the reference frame of the object) are identical. As will be apparent from Figure 3 (discusssed below) the camera separation in such a situation is quite indeterminate, no matter how many pairs of points are correlated. In such a situation the size of the object cannot be determined from the two images, even if the focal length and other camera parameters are known, and the 3D reconstruction will need to be multiplied by a scaling factor.

Bearing in mind that the resolution of many digital cameras is severely limited (eg to 640 x 480 pixels) it will be apparent that if the camera orientations are only slightly different then there will be considerable uncertainty in the camera positions and hence in the 3D reconstruction of the object. On the other hand if the camera orientations are deliberately chosen to be very different (ie converging sharply on the object) then points on the object in overhanging regions which are in the field of view when one image is acquired will not be in the field of view when the other image is acquired, preventing 3D reconstruction of regions of overhang.

An object of the present invention is to overcome or alleviate at least some disadvantages of the known methods and apparatus, particularly when the resolution of the images from which the 3D reconstruction is generated is limited

Accordingly, in one aspect the invention provides a method of deriving a 3D representation of at least part of an object from correlated overlapping 2D images of the object acquired from different spaced apart viewpoints relative to the object, the separation between the viewpoints not being precisely known, the method comprising the step of digitally processing the 2D images to form a 3D representation which extends in a simulated 3D space in dependence upon both the mutual offset between correspondences of the respective 2D images and a scaling variable, the scaling variable being representative of the separation between the viewpoints at which the 2D images were acquired.

The invention also provides image processing apparatus for deriving a 3D representation of at least part of an object from correlated overlapping 2D images of the object acquired from different spaced apart viewpoints relative to the object, the apparatus comprising image processing means which is arranged to digitally process the 2D images to form a 3D representation which extends in a simulated 3D space in dependence upon both the mutual offset between correspondences of the respective 2D images and a scaling variable, the scaling variable being representative of the separation between the viewpoints at which the 2D images were acquired.

In use the scaling variable is preferably entered by a user.

For example if the actual camera separation is a and the partial 3D reconstruction is generated by virtual projectors with the same optical parameters as the camera(s) and having a separation of a' in simulated 3D space then the scaling factor could be a/a' to magnify the partial 3D reconstruction by a factor of a/a' and thereby generate a partial 3D reconstruction having the same size as the object. Such a partial 3D reconstruction will be able to be fitted to other life-size partial 3D reconstructions generated similarly from other pairs of images. In these embodiments, any value of scaling factor which will enable the partial 3D reconstructions to be fitted together will be satisfactory, and can for example be applied by the user during a process of fitting together the partial 3D reconstructions on-screen.

In these embodiments the camera orientation (in the reference frame of the object) at each of the two viewpoints is preferably the same or nearly the same (eg ± 10 degrees) and the or each partial 3D reconstruction is preferably generated by virtual projectors having the same orientation as the camera(s) and having optical centres on the line joining the optical centres of the camera(s).

Preferably the method further comprises the step of acquiring the overlapping 2D images from a camera which is moved relative to the object between the different viewpoints, the net movement of the camera between the viewpoints not being fully constrained.

For example the camera could be mounted on a fixed slide so as to move transversely to its optical axis (so that its orientation and movement along two axes is constrained but its movement along the third axis is not) or it could be mounted on a tripod (so that its movement in the vertical direction and rotation about a horizontal axis are constrained).

However in a preferred embodiment the camera is hand-held.

Optionally, the camera orientation can be measured with an inertial sensor eg a vibratory gyroscope and appropriate filtering and integrating circuitry as disclosed in our UK patent GB 2,292,605B which is hereby incorporated by reference. A Kalman filter is presently preferred for filtering the inertial sensor output signals.

Preferably the orientation of the camera is varied after acquiring a first image from one viewpoint and before acquiring a second image from the other viewpoint so as to maintain its orientation relative to the reference frame of the object when acquiring the second image.

One purely optical way of ensuring that the orientation of the camera is unchanged relative to the orientation at the first viewpoint is to vary the orientation until the projections in the image plane of the camera of the correlated points of the first image and the corresponding points of the second image (which is preferably instantaneously displayed on screen) converge at a common point. In the special case in which the distance to the object from the image plane along the camera's optical axis is unchanged between the two viewpoints (in which case the above common point would be at infinity) then the orientation at the second viewpoint can be adjusted until the above projections are parallel.

The present invention also relates to a method and apparatus for deriving a representation of the three-dimensional (3D) shape of an object from an image (referred to herein as an object image) of the projection of structured optical radiation onto the object surface. The term "structured optical radiation" is a generalisation of the term "structured light" and is intended to cover not only structured light but also structured electromagnetic radiation of other wavelengths which obeys the laws of optics.

In principle the 3D shape of part of an object surface can be obtained by projecting structured light, eg a grid pattern onto a surface of the object, acquiring an image of the illuminated region of the object surface and identifying the elements of the structured light (eg the crossed lines of the grid pattern) which correspond to the respective features (eg crossed lines) of the image, assuming that the spatial distribution of the structured light is known.

One such arrangement is shown by Hu & Stockman in "3-D Surface Solution Using Structured Light and Constraint Propagation" in *IEEE Trans PAMI* Vol 2 No 4 pp 390 - 402, 1989, who discuss the advantages of the technique over stereoscopic imaging techniques.

In a second aspect the invention provides a method of deriving a 3D representation of at least part of an object from a 2D image thereof, comprising the steps of illuminating the object with structured projected optical radiation, acquiring a 2D image of the illuminated object, correlating the 2D image with rays of the structured optical radiation, and digitally processing the 2D image to form a 3D representation which extends in a simulated 3D space in dependence upon both the correlation and a scaling variable, the scaling variable being representative of the separation between a location from which the structured optical radiation is projected and the viewpoint at which the 2D image is acquired.

In this aspect the invention also provides image processing apparatus for deriving a 3D representation of at least part of an object from a 2D image of the illuminated object, the object being illuminated with structured optical radiation projected from a location spaced apart from the viewpoint at which the 2D image is acquired, the 2D image being correlated with the structured radiation, the apparatus comprising digital processing means arranged to form a 3D representation which extends in a simulated 3D space in dependence upon both the correlation and a scaling variable, the scaling variable being representative of the separation between the location from which the structured optical radiation is projected and the viewpoint at which the 2D image is acquired.

This aspect is related to the first aspect in that the separation of perspective centres of the cameras does not need to be known in the apparatus and method of the first aspect and the separation of theperspective centres of the projector and camera does not need to be known in the apparatus and method of the second aspect. There is a clear analogy between the camera-camera arrangement employed in the first aspect and the camera-projector arrangement employed in the second aspect. In each case, a 3D representation can be derived from the intersection of two projections, in the one case representing the respective pencils of camera rays and in the other case representing the respective pencils of projector rays and camera rays.

The calibration image can for example be of the projection of the structured optical radiation onto a calibration surface or can for example be a further object image obtained after moving the object relative to the camera used to acquire the initial object image and the projector means used to project the structured optical radiation.

Preferably the first and second projections are from a baseline linking an origin of the structured optical radiation and a perspective centre associated with the image (eg the optical centre of the camera lens used to acquire the image), the reconstruction processing means being arranged to derive said baseline from two or more pairs of correlated features. This feature is illustrated in Figures 3 and 13 discussed in detail below.

In one embodiment the image processing means is arranged to generate correspondences between two or more calibration images and to determine the spacing between origins of the first and second projections in dependence upon both the correspondences of the two or more calibration images and input or stored metric information associated with the calibration images. This feature is illustrated in

Figure 15, discussed in detail below.

In another embodiment the reconstruction processing means is arranged to vary the spacing between the origins of the first and second projections in dependence upon a scaling variable enterable by a user. In this embodiment a further calibration image is not required. Preferably the apparatus includes means for displaying the 3D representation with a relative scaling dependent upon the value of the scaling variable.

In a further aspect the invention provides a method of generating a 3D representation of an object from an object image of the projection of structured optical radiation onto the object surface and from at least one calibration image of the projection of the structured optical radiation onto a surface displaced from the object surface, the method comprising the steps of:

i) correlating at least one calibration image with the object image and optionally with a further calibration image;

ii) simulating a first projection of the object image and a second projection of the structured optical radiation, and

iii) deriving said 3D representation from the mutual intersections of the first and second projections.

In a related aspect the invention provides image processing apparatus for generating a 3D representation of at least part of an object from an object image of the projection of structured optical radiation onto the object surface and from at least one calibration image of the projection of the structured optical radiation onto a surface displaced from the object surface, the apparatus comprising image processing means arranged to generate correspondences between at least one calibration image and the object image and optionally a further calibration image, and reconstruction processing means arranged to simulate a first projection of the object image and a second projection linking respective correspondences of at least two of the correlated images and to derive said 3D representation from the mutual intersections of the first and second projections.

Preferred features of the invention are defined in the dependent claims.

In another aspect the invention provides image processing apparatus for deriving a 3D representation of at least part of an object from a 2D image thereof, the object being illuminated with structured optical radiation projected from a location spaced apart from the viewpoint at which the 2D image is acquired, the 2D image being correlated with rays of the structured radiation, the apparatus comprising digital processing means arranged to form a 3D reconstruction which extends in a simulated 3D space in dependence upon both the correlation and a scaling variable, the scaling variable being representative of the separation between the location from which the structured optical radiation is projected and the viewpoint at which the 2D image is acquired.

This aspect of the invention is illustrated in Figure 13. Following a simple calibration procedure requiring no knowledge of the position of the camera or the projector relative to the object it enables a 3D representation to be generated. This can optionally be displayed and scaled or it can be distorted eg for special effects in graphics and animation.

Preferably the apparatus is arranged to derive a further 3D representation from a further 2D image acquired from a different viewpoint relative to the object, the combining means being arranged to combine the first-mentioned 3D representation and the further 3D representation by manipulations in a simulated 3D space involving one or more of rotation and translation, the apparatus further comprising scaling means arranged to reduce or eliminate any remaining discrepancies between the 3D reconstructions by scaling one 3D reconstruction relative to the other along at least one axis.

Preferably the apparatus is arranged to display both 3D representations simultaneously and to manipulate them in simulated 3D space in response to commands entered by a user.

In one embodiment the apparatus is arranged to perform the manipulations of the 3D reconstructions under the control of a computer pointing device.

Preferably the apparatus includes means for combining two or more 3D representations and means for adjusting the relative scaling of the representations to enable them to fit each other.

In other embodiments the variable will correct for one or more distortions of the partial 3D reconstruction either laterally or in the depth direction (curvature of field) which, as shown below in connection with Figures 8 to 11 can arise from incorrect positioning of the virtual projectors eg a misalignment relative to the camera viewpoints.

In certain embodiments the partial 3D reconstruction will be distorted by delibarately misaligning one or both the virtual projectors relative to the camera viewpoints or camera and projector viewpoints.

Such a feature is useful in the fields of design, graphics and animation.

Some difference in orientation can be tolerated and the resulting distortion in the 3D reconstruction subsequently corrected, as will be shown below.

The smaller the difference in orientation, the smaller the distortion in the 3D reconstruction. Ideally the orientation of the camera is maintained unchanged between the two viewpoints.

Preferably the angle subtended by a pair of correlated features at the corresponding feature of the object is 90 degrees ± 30 degrees (more preferably ± 10 degrees). Ideally the subtended angle is exactly 90 degrees. This feature enables any distortion resulting from a slight change in orientation to be corrected more accurately.

Following the partial reconstruction by the above method, complementary 3D reconstructions of different parts of the object obtained similarly from further sets of overlapping images can be fitted together.

To the extent that the reconstruction is distorted then simple compensations for distortion parallel to the image plane and for curvature of field can be applied in order to enable the 3D reconstruction to be fitted.

Preferably a view of the reconstruction in the simulated 3D space is displayed eg on a screen and the variable is varied by the user in response to the view displayed on screen.

Preferably the image processing means is arranged to generate said correspondences of said images by comparing local radiometric distributions of said images.

In a related aspect the invention provides a method of deriving a 3D representation of at least part of an object from a 2D image thereof, comprising the steps of illuminating the object with structured projected optical radiation, acquiring a 2D image of the illuminated object, correlating the 2D image with rays of the structured optical radiation, and digitally processing the 2D image to form a 3D reconstruction which extends in a simulated 3D space in dependence upon both the correlation and a scaling variable, the scaling variable being representative of the separation between a location from which the structured optical radiation is projected and the viewpoint at which the 2D image is acquired.

Suitable algorithms for correlating (generating correspondences between) overlapping images are already known - eg Gruen's algorithm (see Gruen, A W "Adaptive least squares correlation: a powerful image matching technique" *S Afr J of Photogrammetry, remote sensing and Cartography* Vol 14 No 3 (1985) and Gruen, A W and Baltsavias, E P "High precision image matching for digital terrain model generation" *Int Arch photogrammetry* Vol 25 No 3 (1986) p254) and particularly the "region-growing" modification thereto which is described in Otto and Chau "Region-growing algorithm for matching terrain images" *Image and Vision Computing Vol* 7 No 2 May 1989 p83, all of which are incorporated herein by reference.

Essentially, Gruen's algorithm is an adaptive least squares correlation algorithm in which two image patches of typically 15 x 15 to 30 x 30 pixels are correlated (ie selected from larger left and right images in such a manner as to give the most consistent match between patches) by allowing an affine geometric distortion between coordinates in the images (ie stretching or compression in which originally parallel lines remain parallel in the transformation) and allowing an additive radiometric distortion between the grey levels of the pixels in the image patches, generating an over-constrained set of linear equations representing the discrepancies between the correlated pixels and finding a least squares solution which minimises the discrepancies.

The Gruen algorithm is essentially an iterative algorithm and requires a reasonable approximation for the correlation to be fed in before it will converge to the correct solution. The Otto and Chau region-growing algorithm begins with an approximate match between a point in one image and a point in the other, utilises Gruen's algorithm to produce a more accurate match and to generate the geometric and radiometric distortion parameters, and uses the distortion parameters to predict approximate matches for points in the region of the neighbourhood of the initial matching point. The neighbouring points are selected by choosing the adjacent points on a grid having a grid spacing of eg 5 or 10 pixels in order to avoid running Gruen's algorithm for every pixel.

Hu *et al* "Matching Point Features with ordered Geometric, Rigidity and Disparity Constraints" IEEE Transactions on Pattern Analysis and Machine Intelligence Vol 16 No 10, 1994 pp1041-1049 (and references cited therein) discloses further methods for correlating features of overlapping images.

Since the above algorithms were developed for generating correspondences between images having poorly defined features (eg aerial photographs) whereas the projection of structured light onto an object surface will generate distinct local radiometric distributions, the problem of correlation is less critical in the context of the present invention. Accordingly the precise correlation algorithm is not critical. However we have found a number of improvements to the Gruen algorithm, as follows:

i) the additive radiometric shift employed in the algorithm can be dispensed with;

ii) if during successive iterations, a candidate matched point moves by more than a certain amount (eg 3 pixels) per iteration then it is not a valid matched point and should be rejected;

iii) during the growing of a matched region it is useful to check for sufficient contrast at at least three of the four sides of the region in order to ensure that there is sufficient data for a stable convergence - in order to facilitate this it is desirable to make the algorithm configurable to enable the parameters (eg required contrast) to be optimised for different environments, and

iv) in order to quantify the validity of the correspondences between images it has been found useful to re-derive the original grid point in the starting image by applying the algorithm to the matched point in the other image (ie reversing the stereo matching process) and measuring the distance between the original grid point and the new grid point found in the starting image from the reverse stereo matching. The smaller the distance the better the correspondence.

It is not necessary (and indeed in many cases it will be computationally inefficient) to correlate all possible features prior to determining the viewpoints of the camera(s) relative to the object. It will usually be simpler to derive the remaining correlations between features of the respective images once the viewpoints have been determined from a small number eg eight pairs of correlated features, by searching for further correlated features along epipolar lines determined from the viewpoint determination .

Once the correlations and positions and orientations of the cameras are known, the 3D configuration of the object is obtainable by projecting each image from (eg a virtual) projector having the same focal length and viewpoint (position and orientation) as the camera which acquired that image. The principal rays from corresponding features of the respective images will intersect in (virtual) 3D space at the location of the object feature.

Accordingly, in another aspect the invention provides a method of generating a 3D reconstruction of an object comprising the steps of projecting images of the object acquired by mutually aligned cameras into simulated 3D space from aligned virtual projectors, the separation of the virtual projectors being variable by the user.

In this aspect the invention also provides apparatus for generating a 3D reconstruction of an object comprising two aligned virtual projector means arranged to project images of the object acquired by mutually aligned cameras into simulated 3D space, the separation of the virtual projectors being variable by the user.

Preferably the difference in alignment of the virtual projectors (ie the angle between them) is less than 45 degrees, more preferably less 30 degrees, and is most preferably less than 20 degrees, eg less than 10 degrees. Desirably this angle is less than 5 degrees, eg less than one degree. This feature enables overhanging features of the object to be captured from both camera viewpoints and also facilitates the determination of the line connecting the optical centres of the camera(s) at the different viewpoints as well as the correlation of features between the images.

Preferably the origin of each projection is located on a line in simulated 3D space connecting the corresponding optical centres of the camera at the two viewpoints. As explained below with reference to Figure 3, this will result in a scaled partial 3D reconstruction of the object.

In one embodiment a distortion parameter is entered by the user and applied to the 3D reconstruction. For example, after projecting the overlapping 2D images from their nominal viewpoints such that the projections intersect to form an initial 3D reconstruction in simulated 3D space, the initial 3D reconstruction can be rotated whilst constraining the features of the initial 3D reconstruction which are generated from the intersecting projections of correlated features of the projected images to lie on the projections of those features from one of the 2D images, thereby forming a further 3D reconstruction. As is illustrated in Figure 9 (discussed below) this can be used to generate a reconstruction which is parallel to, and therefore a scaled replica of, the actual object surface. The above-mentioned rotation and constraint correct for the lateral distortion caused by the lack of parallelism of the initial 3D reconstruction and the 3D reconstruction generated from correctly aligned virtual projectors.

However as noted above, in many applications it will be desirable to distort the 3D reconstruction relative to the original object in order to achieve a desired artistic effect.

It should be noted that the aspect of the invention concerning the derivation of a 3D reconstruction is applicable to previously acquired images in conjunction with their associated pairs of correlated points, however acquired.

Preferably the viewpoints are calculated from at least two (desirably at least three) pairs of correlated features and the 3D reconstruction of the object is generated in dependence upon said calculation of the viewpoints, the calculation of the viewpoints being performed on fewer than all derivable pairs of correlated features.

This preferred feature of the invention is illustrated in Figure 3 (discussed below) which shows the derivation of the line connecting the viewpoints from the pencil of projections from three pairs of correlated features. Since the third projection from the third pair of correlated features P3 and P3' intersects the point VP already defined by the other two projections' intersection (and thus merely onfirms the unchanged orientation between the viewpoints) it is not strictly necessary to find the straight line joining the viewpoints. Hence this line can be found from just two pairs of correlated features if there is no change in camera orientation. However greater accuracy will be obtained if more than two pairs of correlated features are processed.

Preferably said calculation is performed on fewer than one thousand pairs of correlated features, more preferably fewer than one hundred pairs of correlated features, desirably fewer than fifty pairs of correlated features eg eight or fewer pairs.. For example the calculation can be performed on four, three or two pairs of correlated points.

Particularly when the viewpoints are parallel or nearly parallel (eg within 10 degrees of each other) the above preferred features result in a greater or lesser degree of economy of processing.

Further preferred features of the invention are defined in the dependent claims.

Preferred embodiments of the invention are described below by way of example only with reference to Figures 1 to 20 of the accompanying drawings, wherein:

Figure 1 is a diagrammatic view of one apparatus in accordance with the two-camera aspects of the invention;

Figure 2 is a flow diagram of one method in accordance with the two-camera aspects of the invention;

Figure 3 is a ray diagram showing the relationship between the object, camera and projector viewpoints, virtual projector viewpoints and partial 3D reconstruction in one embodiment of the invention;

Figure 4 is a ray diagram in 3D showing a derivation in accordance with one aspect of the invention of the direction of movement of the camera from the acquired images in the method of Figure 2 and apparatus of Figure 1;

Figure 5 is a ray diagram in 3D showing a derivation of the direction of movement of the camera from the acquired images in the method of Figure 2 and apparatus of Figure 1 in the special case in which the camera does not move relative to the object in the Z direction;

Figure 6 is a diagram showing the movement of the image of the object in the image plane I of Figure 5;

Figure 7 is a flow diagram summarising the image processing steps utilised in the method of Figure 2 and the apparatus of Figure 1;

Figure 8 is a 2D ray diagram illustrating the curvature of field resulting from misalignment of one virtual projector relative to the other in the apparatus of Figure 1 and method of Figure 2;

Figure 9 is a 2D ray diagram illustrating correction of distortion of the partial 3D reconstruction in an embodiment of the invention;

Figure 10A is a 2D ray diagram illustrating the curvature of field resulting from a misalignment of a virtual projector by 5 degrees;

Figure 10B is a ray diagram illustrating the curvature of field resulting from a misalignment of a virtual projector by 10 degrees;

Figure 10C is a ray diagram illustrating the curvature of field resulting from a misalignment of a virtual projector by 15 degrees;

Figure 11 is a plot of curvature of field:misalignment in the arrangements of Figures 10A to 10C;

Figure 12 is a schematic representation of one apparatus in accordance with projector-camera aspects of the invention;

Figure 13 is a sketch perspective ray diagram showing one optical arrangement of the apparatus of Figure 12;

Figure 14 shows an object image and a calibration image acquired by the apparatus of Figures 12 and 13 and the correlation of their features;

Figure 15 is a sketch perspective ray diagram showing a variant of Figure 13 in which two reference surfaces are used to locate the camera and projector of the apparatus of Figures 12 on the baseline connecting their respective perspective centres;

Figure 16 is a flow diagram illustrating a method of operation of the apparatus of Figures 12 and 13 in accordance with a projector-camera aspect of the invention;

Figure 17 is a screenshot illustrating the fitting together of two 3D surface portions of the object using the apparatus of Figures 1 and 2 or the apparatus of Figure 12;

Figure 18 is further screenshot showing the scaling of the resulting composite 3D surface portion along vertical and horizontal axes;

Figure 19 is a further screenshot showing the scaling of intersecting 3D surface portions to fit each other, and

Figure 20 is a screenshot showing a user interface provided by the apparatus of Figures 1 and 2 or the apparatus of Figure 12 for manipulating the images and 3D surface portions.

Referring to Figure 1, the apparatus comprises a personal computer 4 (eg a Pentium® PC) having conventional CPU, ROM, RAM and a hard drive and a connection at an input port to a digital camera 1 as well as a video output port connected to a screen 5 and conventional input ports connected to a keyboard and a mouse 6 or other pointing device. The hard drive is loaded with conventional operating system such as Windows®95 and software:

a) to display images acquired by the camera 1;

b) to correlate points in overlapping regions of images input from the camera 1;

c) to derive the line of movement of the camera from the acquired images;

d) to project images acquired by the camera into a simulated 3D space from virtual projectors located on the line of movement at a separation selected (with the keyboard or pointing device) by the user (thereby creating a partial 3D reconstruction);

e) to scale the partial 3D reconstruction along one or more axes and combine such partial 3D reconstructions as illustrated in Figures 12 and 13, and

f) to apply or compensate for lateral distortion and curvature of field as illustrated in Figure 9 and Figures 10A to 10C.

The software to carry out function a) can be any suitable graphics program and the software to carry out function b) can be based on the algorithms disclosed in Hu *et al* "Matching Point Features with ordered Geometric, Rigidity and Disparity Constraints" IEEE Transactions on Pattern Analysis and Machine Intelligence Vol 16 No 10, 1994 pp1041-1049 (and references cited therein). One suitable algorithm is the Gruens algorithm.

Referring to Figure 1, the camera CM, a Pulnix M-9701 progressive scan digital camera, which may be hand-held and carrying a 3-axis vibratory gyroscope G with associated filtering circuitry (a Kalman filter is presently preferred) and integrating circuitry to generate and display on screen 3-axis orientation signals or (as shown at 1') may be mounted on a tripod T or other support, for example, defines a first set of axes **x, y, z** in its initial viewpoint (ie position and orientation) and is used to acquire an image of the object 3 and to display the image on screen 5. The origin of the **x y z** coordinate system is taken to be the optical centre of the camera lens. The camera is then moved an arbitrary distance to a new position CM' and a second image of object 3 is acquired with the orientation of the camera (relative to the **x y z** coordinate system) maintained unchanged. This unchanged orientation can be achieved with the aid of a suitable support if necessary. A method of checking for changes in orientation, based on the convergence of the projections from corresponding points of the two images in the image plane I of the camera, will subsequently be described with reference to Figure 4. Only a few (eg 3, 4, 5 or up to eg 10) pairs of correlated points need to be found for this purpose and can be derived visually by the user from the images displayed on screen or by the software in computer 4. As will become apparent from Figure 4, the camera movement (ie the line in the **x y z** coordinate system joining the optical centre of the camera lens in its two positions) can also be found at his stage. In some cases however in which a highly accurate reconstruction is not required, the direction of camera movement can be estimated by the user.

The remaining corresponding points in the two images are then correlated by the computer 4 (preferably taking advantage of the information on camera movement obtained in the previous step, eg by searching along the epipolar line in one image corresponding to a point of interest in the other image) and a partial 3D reconstruction of the object 3 in simulated 3D space is generated from the correlated points as will be described below with reference to Figure 3. Since the distance between the positions 1 and 1' is not known, a parameter representing this distance is entered by the user, either form the keyboard or from the pointing device 6 for example. The computer 4 is programmed to display the resulting 3D reconstruction on screen and the user can vary the parameter interactively in order to arrive at a partial 3D reconstruction in the **x y z** coordinate system which bears a desired relationship to the actual object 3. Typically this will be stretched or compressed in the direction of movement between positions CM and CM', relative to the actual object.

Depending on the accuracy with which the camera orientation is maintained in the two positions (eg with the aid of orientation signals from gyroscope G) and the accuracy of the estimated or optically derived camera movement there may be distortions in the partial 3D reconstruction which can be corrected at this stage. The correction of such distortion (and indeed the deliberate addition of such distortion when this is desired) will be described subsequently with reference to Figures 9 and 10A to 10C.

A further partial 3D reconstruction is then generated by moving the camera CM to a new viewpoint CMA such that the object lies in a region of overlap ie such that at least one point P in the camera's field of view at viewpoints CM and CM' remains in the camera's field of view at viewpoint CMA. This movement can be represented by a rotation θ about the **y** axis (resulting in new axes $\mathbf{x_i}$, $\mathbf{y_i}$ and $\mathbf{z_i}$) followed by a rotation ϕ about the $\mathbf{x_i}$ axis (resulting in new axes **x'**, **y'** and **z'**) followed by a rotation κ about the **z'** axis, followed by translations ΔX, ΔY and ΔZ along the resulting axes. Therotation κ about the **z'** axis will in many cases be zero, as shown in Figure 1.

After acquiring an image at the viewpoint CMA the camera is moved to a new position 1A' and a further image is acquired and displayed (the orientation of the camera being adjusted to remain the same as at viewpoint CMA). A further partial 3D reconstruction of object 3 is then performed by the computer 4 in a manner analogous to that described above in connection with viewpoints CM and CM'.

If it is assumed that the origin of the **x'**, **y'**, **z'** coordinate system is shifted to the optical centre of the camera at viewpoint CMA to give a new coordinate system **X**, **Y**, **Z** then the relationship between any point XYZ in the new **XYZ** coordinate system and the same point xyz in the **xyz** coordinate system is given by:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\kappa\cos\theta & \sin\kappa\cos\phi - \cos\kappa\sin\theta\sin\phi & \sin\kappa\sin\phi + \cos\kappa\sin\theta\cos\phi \\ -\sin\kappa\cos\theta & \cos\kappa\cos\phi + \sin\kappa\sin\theta\sin\phi & \cos\kappa\sin\phi - \sin\kappa\sin\theta\cos\phi \\ -\sin\theta & -\cos\theta\sin\phi & \cos\theta\cos\phi \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \begin{matrix} + \\ + \\ + \end{matrix} \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix}$$

The terms in the 3x3 matrix can be shown to be the cosines of the angles between the axes of the **XYZ** and **xyz** coordinate systems (see eg Boas*Mathematical Methods in the Physical Sciences* Pub John Wiley & Sons, 2nd Edn pp437 and 438).

Accordingly the partial 3D reconstructions can be transformed to a common coordinate system and elongated/compressed along all three axes to minimise discrepancies between them in their region of overlap and to build up a more complete reconstruction of the object 3.

In the present embodiment this process is carried out under the control of a user by displaying the partial 3D reconstructions on screen and varying their relative elongation/compression along three axes, as will be described in ore detail with reference to Figure 19.

In another embodiment the partial 3D reconstructions are combined without user intervention using the Iterative Closest Point algorithm. This algorithm is publicly available and therefore it is not necessary to describe it in detail. Briefly however, it registers two surface edges by searching for a group of (say) the ten closest pairs of points on the respective edges. The surfaces are then repositioned to minimise the aggregate distance between these pairs of points and then a new group of closest pairs of points is found. The repositioning step is then repeated. Other methods of correlating 3D surface regions are disclosed in our GB 2,292,605B. In accordance with one aspect of the present invention, a scaling factor or other variable is generated either by the user or iteratively under software control in order to adjust the relative sizes of the partial 3D reconstructions to ensure they can be fitted together into a self-consistent overall surface description of the object.

Returning to the description of the embodiment of Figures 1 and 2, further partial 3D reconstructions can be derived similarly from the other sides of the object 3 and combined with each other and/or with the existing combination of partial 3D reconstructions until a complete 3D representation of the object is achieved.

The method is summarised in Figure 2.

Overlapping images are captured (step S10), pairs of points (or larger features eg lines or areas) are correlated (step S20) and at least the approximate camera movement between the viewpoints is determined (step S30). In the preferred embodiment this is determined with a high degree of accuracy by processing the two images. Partial 3D reconstructions of the object surface are then generated in a simulated 3D space using the computer 4 to process the correlated pairs of points and camera movement (step S40) and these are combined, preferably interactively on screen by the user to give a consistent but possibly distorted (eg compressed or elongated) 3D representation (step S50). Optionally, this is distorted or undistorted by applying appropriate compression or elongation (step S60).

In an alternative embodiment, steps S30 and S40 can be combined in a matrix processing method, eg using the commercially available INTERSECT program produced by 3D Construction Inc.

Step S40 will now be described in more detail with reference to Figure 3.

Figure 3 shows the object 3 in the field of view of the camera CM at positions CM and CM'. Principal ray lines from points Qa, Qb and Qc on the surface of the object pass through optical centres O_C and O_C' of the camera in the respective positions CM and CM' and are each imaged on the image plane. The pair of points thus formed on the image plane from each of points Qa, Qb and Qc (and many other points, not shown) are corresponding points and can be correlated by known algorithms.

Accordingly it will be appreciated that if virtual projectors pr1 and pr2 with the same orientation, focal length and other optical characteristics as the camera at its respective viewpoints were placed at positions CM and CM' then they would project ray lines into virtual 3D space from the correlated pairs of points which would intersect at the true locations of the corresponding points Qa, Qb, Qc... and all other points on the object surface corresponding to a correlated pair of image points. By a virtual projector is meant any operator on the image which behaves as an optical projector of the image. A suitable software routine for processing the image in the required manner could be written without difficulty be persons skilled in the art.

Although the projectors are shown in Figure 3 with the same orientation in the reference frame of the object (corresponding to the common camera orientation) this is merely a preferred feature which enables the vector V to be determined more easily by the image processing method disclosed in Figure 4. In principle the above analysis is also applicable to virtual projectors of different orientations, corresponding to respective, different camera orientations. As noted above, the camera orientations can be determined by an inertial sensor and integrating circuitry similar to that disclosed in our above-mentioned UK patent GB 2,292,605B.

If the vector V joining the optical centres of the camera/projector lenses in positions CM and CM' is extended and projector pr2 is moved along this vector with its orientation unchanged (eg to position pr2' as shown) and the same ray lines are projected from it then these will still intersect the ray lines from projector pr1 but at different positions in simulated 3D space. For example the intersections at Qa, Qb and Qc will be replaced by intersections at Qa', Qb' and Qc' respectively. This is because any ray line from Op' parallel to a ray line from Op will lie in the same plane as a ray line from O_C intersecting the ray line from Op and therefore intersect that ray line from O_C. For example line Op'Qa' lies in the same plane as triangle $O_C O_C$'Qa and will therefore intersect line O_CQa, in this case at Qa'.

Hence a scaled representation 3/3' can be generated by any pair of virtual projectors on vector V, if V is parallel to the line joining the optical centres of the camera lens at the two positions at which the projected images are acquired and the projectors have the same orientation(s) as the camera. This last condition can be satisfied even if the correct orientation is initially unknown, namely by adjusting the orientation about any axis perpendicular to vector V until the respective ray lines from any pair of correlated points intersect. This procedure can be carried out either manually be the user with the aid of a suitable display of the images and ray lines on screen or automatically in software.

Accordingly a 3D representation of the object can be generated once the direction of vector V is known. Figure 3 will be referred to again in connection with a very similar method applicable to the virtual projectors associated with the projector-camera aspects of the invention.

Figure 4 illustrates one derivation of vector V (step S40 in Figure 2). For ease of understanding, the camera (having a lens with optical centre O) is considered to be stationary and the object 3 is considered to move to position 3' along line M. Points P1, P2 and P3 are imaged as points p1, p2 and p3 when the object is in position 3 and as points p1', p2' and p3' when the object is in position 3'. If and only if the orientation of the camera relative to the object frame is unchanged between the two positions, then the projections of the lines L1, L2 and L3 joining Pn and pn' (n = 1 to 3 in this illustration but in general will be much larger) will meet at a common point VP, which is somewhat akin to the vanishing point in perspective drawing.

It will be seen that the line joining VP to the optical centre O is the vector V which is the locus of the optical centre of the camera (or desired locus of the virtual projector) relative to the object.

In general, if the camera is hand-held, the lines L1, L2, L3....Ln connecting the correlated points will not meet at a common point, owing to a change in orientation of the camera between the two positions. However the orientation of the camera can be varied about the X, Y and Z axes by the user at the second position whilst displaying the lines L1, L2, L3...Ln on screen and the second image captured only when these lines converge on or near a common point, as determined either visually or by a software routine. Indeed the image can be captured, under control of the software routine, only when the necessary convergence is achieved.

If gyroscope G is used then its 3-axis orientation signals can be used to maintain the orientation of the camera between the two viewpoints.

It should be noted that if the camera is considered to be moving and the object to be fixed, then the movement of the camera from its original position is derived by superimposing the image plane and associated image of the camera in its new position on the image plane (and image) of the camera in its first position, projecting the lines L1, L2, L3....Ln in the image plane of the camera in its first position and connecting the resulting point of intersection VP to the optical centre of the camera in its first position. The resulting vector V is the movement of the object in the coordinate frame of the camera at its first position.

In a variant of the above method, a moving image or a rapid succession of still images are acquired by the camera as it moves and the (assumed) rectilinear movement of the camera between each still image or between sequential frames of the moving image is derived by projecting the lines L1, L2, L3....Ln in the image plane of the camera to derive the point VP for each incremental movement of the camera. The resulting vector V for each incremental movement of the camera will change direction as the direction of movement of the camera moves and the segments can be integrated to determine the overall movement (including any change in orientation) of the camera.

It should be noted that when there is little or no movement of the camera relative to the object in the depth (Z) direction then lines L1, L2, L3...Ln will be parallel or nearly so and VP will be at infinity or too far away to be determined with accuracy.

This special case is illustrated in Figures 5 and 6. Points A, B and C at corners of object 3 in its initial position are imaged by lens L as triangle abc in the image plane I of the camera. When the object moves to a new position 3' these corners A', B' and C' are imaged as triangle a'b'c' which will be similar (in the narrow geometrical sense) to triangle abc but may for example be rotated. For reasons whch are explained below, it will be assumed initiallly that points A, B and C lie in a plane which is substantially parallel to the image plane I.

It should be noted that the images abc and a'b'c' would also be obtained from a smaller object of the same shape correspondingly nearer the camera, as illustrated by face A1B1C1.

Referring now to Figure 6 which shows the object 3/3' (not its image) as seen by the camera, various possible faces ABC, A1B1C1 and A2B2C2 are shown. There will be a continuous range of possible sizes for face ABC; for the sake of clarity only the above three are shown. However the possible faces all have a common centroid P.

When the object moves to a new position 3' illustrated by face A'B'C' the centroid will move to a new position Q and the line PQ, which will be parallel to the image plane I (Figure 5) will represent the direction of movement irrespective of the true size and distance of the object. In fact this will remain true even if there is some rotation about the Z axis (such that the lines AA', BB' and CC' are not parallel).

However if the camera is rotated at the second position about the Z axis to ensure that the above lines AA', BB' and CC' are in fact parallel, then the above analysis holds true even if the points A, B and C do not lie in a plane parallel to the image plane I; for example if the image abc is derived from points A1BC in Figure 5. The corresponding centroid (not shown) of A1BC in Figure 6 is displaced from centroid P and the corresponding centroid of A1'B'C' after movement of the object to position 3' is similarly displaced from centroid Q. However the line joining these new centroids will be parallel to line PQ and will therefore correctly indicate the direction of movement of the object relative to the camera.

Even if there is some movement of the camera in the Z direction such that lines AA', BB' and CC' are not parallel but converge to a distant point, line PQ will still correctly represent the direction of movement of the object 3.

Thus the above method overlaps to some extent with the method of Figure 4.

The overall method of determining the direction of movement of the camera is illustrated in Figure 7. A first image is captured (step S11) and the camera is moved to a new position with the object still in its field of view and the first image is displayed on screen 5 (Figure 1), superimposed on the instantaneous image seen by the camera at the new position (step S12). Corresponding points are correlated, either by eye (ie by the user) or by a suitable software routine (step S13). Only a small number of points need to be correlated at this stage, eg 100 or fewer, eg 10, depending on the processing speed and the accuracy required.

If it appears to the user that there has been movement in the Z direction the method branches to step S14 at which the orientation of the camera is adjusted about the X, Y and Z axes until the correlated points converge to a common "vanishing point" VP (Figure 4). At this stage the second image is captured and stored in memory.

In step S15 a line is projected from the point VP through the optical centre of the camera lens to find the locus V (Figure 4) and with the aid of this information, further correlation of the images is performed and a partial 3D reconstruction is generated by the moethod illustrated in Figure 3 (step S17).

Preferably, step S15 also involves or is preceded by the selection of a camera model (eg from a list displayed on screen) by the user. The computer 4 is programmed to store a list of camera models M1, M2....Mn in association with the parameters of each model needed for the calculation of the required projection and other processing.The following parameters may be stored:

Camera model Mn:

pixel size in x direction
pixel size in y direction
focal length
x dimension of film plane (in pixels)
y dimesnion of film plane (in pixels).

If it appears to the user (eg as a result of a failure to find a reasonably close "vanishing point" VP) that there has not been significant movement in the Z direction then the movement of the object is assumed to be parallel to the image plane and the line PQ is found from the images of a group of eg three or more points (not necessarily corners) preferably lying in or close to a plane parallel to the image plane (step S16) before proceeding to step S17.

If only because most digital cameras currently on the market have a limited resolution (eg 1024 x 768 pixels, 640 x 480 pixels or even less) there will almost inevitably be some error in the determination of the camera movement and hence in the relative placement and orientation of the virtual projectors PR1 and PR2 in Figure 3. The effect of this error is illustrated in Figure 8.

Figure 8 is a ray diagram orthogonal to the image plane showing the imaging of a line of points P1, P2 and P3 on the surface of the object 3 by a camera at positions CM and CM'. For the sake of clarity the lens L is shown only at the first position CM. It will be noted that the orientation of the camera is the same at the two positions.

Virtual projectors pr1 and pr2 would correctly reconstruct the object as reconstruction 30 if located at the above positions with the above orientation. If projector pr2 were moved to position pr2' along the direction of movement V (Figure 4) of the cameras then the resulting reconstruction 30' would still show the points (P1', P2' and P3') on a straight line with no curvature of field,with correct scaling in the lateral direction (ie the length ratio P1P2/P2P3 = P1'P2'/P2'P3').

If the projector is successively rotated to a new positions pr2'' and pr2''' then successively greater curvature is introduced into the reconstruction 30'' or 30''', as shown. The relationship between the above curvature of field of the reconstruction 30 and the angular error in the orientation of the second virtual projector relative to the first is considered below in relation to Figures 10A to 10C.

However, referring to Figure 9, in which the respective ray lines from the correlated points of the images projected by projectors pr1 amd pr2 are substantially orthogonal, it can be seen that an error in the relative orientation of the projectors, resulting in the projection of the second image from projector pr2', results in a negligible curvature of field: line 30' defined by the intersection of the ray lines from pr2' with the corresponding ray lines from projector pr1 is substantially straight, like line 30 which is defined by the corresponding intersections of the ray lines from correctly co-oriented projectors pr1 and pr2. Accordingly it is a preferred feature of the invention that the camera positions are so chosen that the angle subtended by the ray lines from a pair of correlated points at their intersection at their corresponding point at the object surface is substantially 90 degrees, eg 90 degrees ± 30 degrees, preferably 90 degrees ± 20 degrees, most preferably 90 degrees ± 10 degrees. This minimises the correction required due to curvature of field.

There remains the lateral distortion of the reconstruction, ie the discrepancy between the ratios P1P2/P2P3 and P1'P2'/P2'P3' (Figure 8). If however the partial 3D reconstruction 30' is rotated to position 30C so as to lie parallel to the image plane of projector PR1, as shown in Figure 9, and all its points are shifted so as to to be intercepted by the ray lines from projector pr1, then the triangles defined by these shifted points and the ray lines from pr1 will be geometrically similar to the triangles defined by the corresponding points on line 30 and these ray lines, and hence the distribution of points along line 30C will be a scaled replica of the corresponding distribution along line 30. It will be understood that this is so irrespective of the angle subtended by the ray lines at their intersection at their corresponding point at the object surface.

Accordingly, distortion parallel to the image plane can be corrected for (or deliberately applied) by rotating the partial 3D reconstruction about an axis perpendicular to the image plane of a projector used to generate that partial reconstruction whilst constraining the points in the partial 3D reconstruction to lie on their ray lines from that projector.

Figures 10A to 10C illustrate the curvature of field resulting from angular misalignment of one projector pr2' from its correct orientation pr2. In each case the correct reconstruction 30 defined by pr1 and pr2 is planar and the centre of curvature CN of the actual reconstruction 30' is shown (and was derived geometrically). In Figures 10A to 10C, the misalignment is generated by rotation of the projector pr2 about its perspective centre by 5 degrees, 10 degrees and 15 degrees respectively.

The radius of curvature R of reconstruction 30' is inversely proportional to the misalignment as shown in Figure 11. It should be noted that in Figures 10A to 10C, the angle subtended by the ray lines at their intersection at their corresponding point at (the reconstruction 30 of) the object surface is very much less than the optimum angle of 90 degrees and hence the degree of curvature is very much greater than would normally be obtained in practice.

Hence the above method of the invention allows a considerable latitude in the orientation of the projectors which implies that a considerable uncertainty in the relative orientation of the camera at the two viewpoints is permissible.

The corrections noted above can be applied at any stage during the generation or fitting together of the partial 3D reconstructions.

It should be noted however that only a limited misalignment of the virtual projectors pr1 and pr2 (Figure 3) is permissible. Referring to Figure 3, all the principal ray lines projected from the correlated points will intersect only if the projectors have the correct orientation. The latitude in orientation arises only from the finite resolution of the camera(s) which implies that the ray lines from the projectors have a finite thickness or do not intersect exactly. Thus a point on the reconstruction 30 can be found by determining the midpoint of the shortest line joining the ray lines from the respective projectors, provided that the length of this shortest line does not exceed a predetrmined limit corresponding to the resolution of the camera(s).

A projector-camera embodiment closely analagous to the camera-camera embodiment of Figure 1 will now be described with reference to Figure 12.

Referring to Figure 12, the apparatus comprises a personal computer 4 (eg a Pentium® PC) having conventional CPU, ROM, RAM and a hard drive and a frame grabber connection at an input port to a digital camera CM as well as a video output port connected to a screen 5 and conventional input ports connected to a keyboard and a mouse 6 or other pointing device. The hard drive is loaded with conventional operating system such as Windows®95 and software:

a) to display images acquired by the camera CM;

b) to generate correspondences between overlapping regions of images input from the camera CM;

c) to derive from the acquired images the baseline joining the perspective centres of the camera and projector;

d) to project images acquired by the camera into a simulated 3D space from virtual projectors located on the baseline at a separation selected (with the keyboard or pointing device) by the user or determined (thereby creating a partial 3D reconstruction);

e) to scale the partial 3D reconstruction along one or more axes and combine such partial 3D reconstructions as illustrated in Figures 17, 18 and 19, and

f) to determine the separation of the perspective centres of the camera and projector along the baseline from further correlations of object images and calibration images, and thence derive an accurate partial 3D reconstruction of the object surface.

Additionally the software is preferably arranged to correct the images for distortion due eg to curvature of field of the camera and projector optics before they are processed as described above, either during an initial calibration procedure or as part of a ray bundle adjustment process during the processing of the object and calibration image(s). Suitable correction and calibration procedures are described by Tsai in "An Efficient and Accurate Camera Calibration Technique for 3D Machine Vision" *Proc IEEE CVPR* (1986) pp 364-374 (*supra*) and will not be described further.

The camera, a Pulnix M-9701 progressive scan digital camera, is shown mounted at one end of a support frame F on eg a ball and socket mounting and a slide projector PR is shown securely mounted on the other end of the frame. Slide projector PR is provided with a speckle pattern slide S and is arranged to project the resulting speckle pattern onto the surface of region R of an object 3 which is in the field of view of camera CM.

The intrinsic camera parameters are initially determined by acquiring images of a reference plate (not shown) in known positions. The reference plate is planar and has an array of printed blobs of uniform and known spacing. The following parameters are determined and are therefore assumed to be known in the subsequent description:

i) focal length of the camera
ii) distortion parameters of the lenses of the camera and projector
iii) scale factor
iv) image coordinates of principal point.

Additionally the pixel size (determined by the camera manucturer) is assumed to be known.

Optionally, the following extrinsic camera parameters are determined:

a) camera location
b) camera orientation.

Alternatively the camera location and orientation can be taken to define the coordinate system relative to which the object surface coordinates are determined.

Referring now to Figure 2, the camera CM is shown with its perspective centre O_C located on a baseline vector V and viewing (initially) a target surface T and (subsequently) object 3. The (virtual) origin or perspective centre Op of projector PR also lies on baseline vector V and is defined by the optical system of the projector comprising field lenses OL and condenser lenses CL. A point light source LS such as a filament bulb illuminates slide S and directs a speckle pattern onto (initially) target surface T and (subsequently) the surface of object 3.

The baseline vector V is found by the following procedure:

Firstly an image I1 (Figure 14) of the region of the surface of object 3 illuminated by the projected speckle pattern is acquired and stored in the memory of computer 4 and an arbitrary group of at least two spaced apart points Q1 and Q2 of this region are selected as points q1 and q2 in the image formed on the photodetector plane PD of the camera. The group of points q1 and q2 is stored.

Secondly the object 3 is substituted by target surface T and an image I2 (Figure 3) of the illuminated region of the target surface is acquired by camera CM. The position and orientation of the target T relative to the camera are found by acquiring an image of the target in the absence of any illumination from the projector, utilising a known pattern of blobs BL formed on the periphery of the target. The image I2 is stored and and a patch defined by its central point (eg Q_n, Figure 3) of the first image I1 is correlated with the corresponding point P_n of the second image I2 by selecting a surrounding region R of initially 3 x 3 pixels and, by comparing local radiometric intensity distributions by means of the above-described modified Gruens algorithm, searching for the corresponding region R' in image I2 which is allowed to be distorted with an affine geometric distortion (eg in the simple case illustrated in

Figure 14, horizontally elongated). The correlated patch is expanded (up to a maximum of 19 x 19 pixels) and the process is repeated. In this manner the corresponding point P_n is found.

This process is repeated to find a large number of pairs of correspondences PQ (Figure 14) and in particular to correlate the patches centered on P1, P2 (Figure 13) with the points in the group Q1, Q2 (Figure 13). Since the algorithm has a sub-pixel resolution, the latter are not necessarily centred on particular pixels.

In the following geometric discussion the correspondences are treated for the sake of simplicity as correlated pairs of points but it should be noted that this does not imply anything about their topography - in particular it does not imply that they lie at corners or edges of the object, for example.

Referring to Figure 13, the origin O_P (perspective centre) of the projector PR will lie at the intersection of P1Q1 and P2Q2. However the 3D locations of these four points are not known, only the ray lines from the camera on which they lie, namely p1P1, q1Q1, p2P2 and q2Q2. But the line P1Q1 will lie in the plane O_CP1Q1 ie plane O_Cp1q1 which is available form the calibration process and the two images I1 and I2 and the line P2Q2 will lie in the plane O_CP2Q2 ie plane O_Cp2q2 which is similarly available from the calibration process and the two images I1 and I2. These planes define a baseline vector V by their intersection, which passes through OC and the perspective centre O_P of the projector.

A particularly simple way of finding the baseline vector V is to project p1q1 and p2q2 which will meet at a point X in the plane of photodetector PD. The projection from point X through the perspective centre O_C is the baseline vector V as shown.

In this manner the baseline vector V can be determined, though not the position of the projector origin O_P along this baseline. In practice the groups of points P and Q will each comprise more than two pairs and hence overdetermine the baseline vector V. Accordingly the computer 4 is preferably arranged to derive a bundle of such vectors as determined by the sets of points PQ, to eliminate "outliers" ie those vectors which deviate by more than a given threshold from the mean and to perform a least squares estimate of vector V on the remainder of the vectors, in accordance with known statistical methods.

The derivation of a three-dimensional representation of the object 3 is shown in the ray diagram of Figure 3.

The camera CM and projector PR are shown located on baseline vector V. A first virtual projector pr1 is implemented by the image processing software in computer 4 and has the same optical characteristics as the camera (as determined in the initial calibration procedure). Image I1 (Figure 14) is projected from this virtual projector in a 3D space simulated by the image processing software.

A second virtual projector pr2 is similarly implemented by the image processing software and preferably has the same optical characteristics as the projector PR (which is also represented in Figure 3). This virtual projector projects a set of ray lines in the simulated 3D space corresponding to the respective physical projector rays PQ and the ray lines are each labelled with the respective correlated pixels of the image I1 as found in the image correlation process described with reference to Figure 14. It will be appreciated that the image I2 and target T define, and can be equated with, a set of rays originating from the perspective centre Op of the projector. Since it is known which ray line from the projector PR/pr1 intersects each ray line from its corresponding pixel in image I1, the point in 3D space corresponding to each intersection can be found, and hence the set of points Qa, Qb, Qc... defining the surface.

In practice many ray lines will not intersect and the best estimate of the corresponding 3D surface point will be the mid-point of the perpendicular line joining them at their closest approach. Algorithms for this purpose are known *per se*.

In the above discussion of Figure 3 it has been assumed that the relative positions of the camera CM and and projector PR on baseline vector V (and hence the positions of the virtual projectors pr1 and pr2) are known. In fact these are assumed or entered as a scaling variable by the user of the computer 4.

That the ray lines from the respective virtual projectors will intersect irrespective of the spacing between the virtual projectors, assuming that their orientations are unchanged, is illustrated in Figure 3 by the alternative virtual projector position pr2' corresponding to an assumed real projector position PR'. The resulting 3D reconstruction of the object 3' will be different in size but of the same shape: a single scaling factor will be required to interconvert objects 3 and 3'. However it may be convenient in practice to provide for different horizontal and vertical scaling factors (eg because of different horizontal and vertical magnifications of the camera) and in general only one set of scaling factors will be consistent with fitting together a set of partial 3D surfaces of the same object acquired from different directions.

Accordingly the software in computer 4 is arranged to scale such acquired 3D representations to enable them to be fitted together to form a self-consistent overall 3D representation of the object. This aspect is described below with reference to Figures 17 to 20.

Before doing so however, an alternative calibration procedure will be described with reference to Figure 15, which shows two planar calibration targets T1 and T2 (having peripheral blobs or discs BL similar to target T of Figure 13) whose orientations (and preferably positions) relative to the camera axis system are known, eg as a result of a photogrammetric determination involving separately acquiring images of them in the absence of any illumination from the projector, and processing the images in a procedure similar to that described above in connection with Figure 2. The perspective centres O_C and O_P of the camera and projector are also shown.

In a first stage of the calibration procedure, target T1 is illuminated by the structured light from the projector and an image is acquired by the camera CM. Figure 15 illustrates three points p1, p2 and p3 at which the structured light impinges on target T1. These (and many other points, not shown) will be imaged by the camera CM.

In a second stage of the calibration procedure, target T1 is removed and target T2 is illuminated by the structured light from the projector. An image is acquired by the camera CM. The three points P1, P2 and P3 corresponding to points p1, p2 and p3 are found by correlating the newly acquired image of the projection of the structured radiation on target T2 with the previously acquired image of the corresponding projection on T1 by the procedure described above with reference to Figure 13.

Figure 15 illustrates further the relationship between the positions of two calibration targets T1 and T2 and the perspective centre O_P of the projector PR (the camera CM being assumed fixed on the baseline vector V). A pair of points P1 and P2 on target

T1 form image points p1 and p2 respectively on the photodetector array PD of camera CM and (in a subsequent step following the removal of target T1) a pair of points P3 and P4 on target T2 which are correlated with P1 and P2 respectively form image points p3 and p4 respectively on photo detector array PD.

Accordingly in a third stage the pencil of rays formed by corresponding points on targets T1 and T2 (eg P1 and P3; P2 and P4) is constructed to find the position of the perspective centre Op of the projector. In practice the rays will not intersect at a point but a best estimate can be found from a least squares algorithm.

It will be appreciated that other calibration procedures are possible. For example the camera could be calibrated by the Tsai method (Roger Y Tsai, *IEEE Journal of Robotics and Automation* RA-3, No 4, August 1987 p 323 - see also references cited therein).

Claims

1. A method of deriving a 3D representation (30) of at least part of an object (3) from correlated overlapping 2D images of the object acquired from different spaced apart viewpoints (CM, CM') relative to the object, the separation between the viewpoints not being precisely known, the method comprising the step of digitally processing the 2D images to form a 3D representation which extends in a simulated 3D space in dependence upon both the mutual offset between correspondences of the respective 2D images and a scaling variable, the scaling variable being representative of the separation between the viewpoints at which the 2D images were acquired.

2. A method of deriving a 3D representation (30) of at least part of an object (3) from a 2D image thereof, comprising the steps of illuminating the object with structured projected optical radiation, acquiring a 2D image (I1) of the illuminated object, correlating the 2D image with rays of the structured optical radiation, and digitally processing the 2D image to form a 3D representation which extends in a simulated 3D space in dependence upon both the correlation and a scaling variable, the scaling variable being representative of the separation between a location from which the structured optical radiation is projected and the viewpoint at which the 2D image is acquired.

3. A method as claimed in claim 1 or claim 2 wherein a view of the representation (30) in the simulated 3D space is displayed and the scaling variable is entered by a user.

4. A method as claimed in any preceding claim, comprising the step of acquiring overlapping 2D images from a camera (CM) which is moved relative to the object, the net movement of the camera not being fully constrained.

5. A method as claimed in claim 4 wherein the respective orientations of the camera (CM) at the different viewpoints relative to a reference frame which is fixed with respect to the object (3) differ by less than 45 degrees.

6. A method as claimed in claim 5 wherein the difference between said respective orientations of the camera (CM) is less than 30 degrees.

7. A method as claimed in claim 6 wherein the difference between said respective orientations of the camera (CM) is less than 10 degrees.

8. A method as claimed in any of claims 4 to 7 wherein the 2D images are acquired by a hand-held camera (CM).

9. A method as claimed in any preceding claim wherein at least one 2D image is acquired by a camera (CM) whose orientation is determined from an output signal of an inertial sensor (G).

10. A method as claimed in any preceding claim wherein the 3D representation (30) is generated by projections from positions on a straight line (V) in simulated 3D space which corresponds to the straight line joining respective perspective centres of said 2D images or joining respective perspective centres of said structured optical radiation and 2D image of the illuminated object (3).

11. A method as claimed in claim 10 wherein said straight line (V) in simulated 3D space is determined from a pencil of projections from correspondences of aligned 2D images (I1, I2).

12. A method as claimed in claim 10 wherein said straight line in simulated 3D space (V) is determined from the intersection of planes (O_CP1O_P, O_CP2O_P) defined by at least one perspective centre (O_C, O_P) and at least two pairs of correspondences (PQ) between acquired 2D images (I1, I2).

13. A method as claimed in any preceding claim wherein said scaling variable is varied by the user to enable the 3D representation (R1) to be fitted to another, similarly derived 3D representation (R2).

14. A method as claimed in any preceding claim wherein the 3D representation (30) is generated from the intersection of respective projections from spaced apart perspective centres (O_C, O_P), the perspective centres being derived from the mutual offset between a first pair of correspondences (PQ) between respective 2D images (I1, I2) and from a further mutual offset between a second pair of correspondences between respective 2D images, further pairs of correspondences are derived from a search constrained by the above perspective centre determination and the 3D

representation of the object is derived from the further pairs of correspondences and the projections.

15. A method as claimed in claim 14 wherein said calculation is performed on fewer than one thousand pairs of image correspondences (PQ).

16. A method as claimed in claim 15 wherein said calculation is performed on fewer than one hundred pairs of image correspondences (PQ).

17. A method as claimed in claim 16 wherein said calculation is performed on fewer than fifty pairs of image correspondences (PQ).

18. A method as claimed in claim 17 wherein said calculation is performed on eight or fewer pairs of image correspondences (PQ).

19. A method as claimed in claim 18 wherein said calculation is performed on two or three or four pairs of image correspondences (PQ).

20. A method as claimed in any preceding claim comprising the step of repeating the method of claim 1 or claim 2 by digitally processing further 2D images of the object acquired from different further viewpoints (CMA, CMA') to form a further 3D representation, the first-mentioned 3D representation and the further 3D representation being combined by manipulations in a simulated 3D space involving one or more of rotation and translation, any remaining discrepancies between the 3D recpresentations optionally being reduced or eliminated by scaling one 3D representation relative to the other along at least one axis.

21. A method as claimed in claim 20 wherein at least two of the 3D representations (R1, R2) are simultaneously displayed on screen (5) and their manipulations are performed in response to commands entered by a user.

22. A method as claimed in claim 21 wherein the manipulations of the 3D representations (R1, R2) are performed under the control of a computer pointing device (6) operated by the user.

23. A method as claimed in any of claims 20 to 22 wherein a distortion parameter is

entered by the user and applied to said first-mentioned and/or said further 3D representation.

24. A method as claimed in claim 23 wherein an initial 3D representation (30', Figure 9) in simulated 3D space is generated by intersecting projections from spaced apart perspective centres, and the initial 3D representation is rotated whilst constraining the points of the initial 3D representation which are generated from the intersecting projections to lie on the projections of those features from their respective perspective centres, thereby forming a further 3D representation (30C, Figure 9).

25. A method as claimed in any of claims 20 to 24 wherein a further parameter indicative of curvature of field is entered by the user and used to adjust the curvature of field of said first-mentioned and/or said further 3D representation.

26. Image processing apparatus for deriving a 3D representation of at least part of an object from correlated overlapping 2D images of the object acquired from different spaced apart viewpoints relative to the object, the apparatus comprising image processing means (4) which is arranged to digitally process the 2D images to form a 3D representation (30) which extends in a simulated 3D space in dependence upon both the mutual offset between correspondences of the respective 2D images and a scaling variable, the scaling variable being representative of the separation between the viewpoints (CM, CM') at which the 2D images were acquired.

27. Image processing apparatus for deriving a 3D representation of at least part of an object from a 2D image of the illuminated object, the object being illuminated with structured optical radiation projected from a location (O_P) spaced apart from the viewpoint (O_C) at which the 2D image is acquired, the 2D image being correlated with the structured radiation, the apparatus comprising digital processing means (4) arranged to form a 3D representation which extends in a simulated 3D space in dependence upon both the correlation and a scaling variable, the scaling variable being representative of the separation between the location from which the structured optical radiation is projected and the viewpoint at which the 2D image is acquired.

28. Apparatus as claimed in claim 26 or claim 27 comprising display means (5)

arranged to display a view of the representation in simulated 3D space, the size of the displayed representation being dependent upon the value of the scaling variable .

29. Image processing apparatus as claimed in claim 28, further comprising a camera (CM) whose position and/or orientation are not fully constrained with respect to the frame of the object, the camera being arranged to acquire said 2D images.

30. Apparatus according to claim 29 comprising inertial sensor means (G) arranged to determine the orientation of the camera relative to the object at the time of acquisition of said 2D images.

31. Apparatus as claimed in any of claims 26 to 30 which is arranged to generate the 3D representation from the intersection of respective projections from spaced apart perspective centres (pr1, Pr2/pr2'), the perspective centres being derived from the mutual offset between a first pair of correspondences between respective 2D images and from a further mutual offset between a second pair of correspondences between respective 2D images, to derive further pairs of correspondences from a search constrained by the above perspective centre determination and to derive the 3D representation of the object from the further pairs of correspondences and the projections.

32. Apparatus as claimed in any of claims 26 to 31 which is arranged to derive a further 3D representation from further intersections of further projections from further perspective centres (CMA.m CMA'), the apparatus including combining means (4) arranged to combine the first-mentioned 3D representation and the further 3D representation by manipulations in a simulated 3D space involving one or more of rotation and translation, the apparatus further comprising scaling means (BN, W1, W2) arranged to reduce or eliminate any remaining discrepancies between the 3D representations by scaling one 3D representation relative to the other along at least one axis.

33. Apparatus as claimed in claim 32 which is arranged to display both 3D representations (R1, R2) simultaneously and to manipulate them in simulated 3D space in response to commands entered by a user.

34. Apparatus as claimed in claim 32 or claim 33 which is arranged to correct

distortion of said first-mentioned and/or said further 3D representation resulting from an incorrect or incomplete calculation of a said perspective centre.

35. Apparatus as claimed in any of claims 32 to 34 which is arranged to correct the curvature of field of said first-mentioned and/or said further 3D representation (30' Figure 9) resulting from an incorrect or incomplete calculation of a said perspective centre (pr2' - Figure 9).

36. A method of determining the motion of a camera (CM) relative to an object (3) in the field of view of the camera comprising the steps of projecting the paths (L1, L2, L3 - Figure 4) of features of the image of the object to a common vanishing point (VP) and determining the vector (V) between the perspective centre of the camera (O) and this vanishing point.

37. Apparatus for determining the motion of a camera relative to an object in the field of view of the camera comprising means (4) for projecting the paths (L1, L2, L3 - Figure 4) of features of the image of the object to a common vanishing point and means for determining the vector (V) between the perspective centre (O) of the camera and this vanishing point.

38. A method of generating a 3D reconstruction of an object (3) comprising the steps of projecting images of the object acquired by mutually aligned cameras (CM, CM') into simulated 3D space from aligned virtual projectors (pr1, pr2), the separation of the virtual projectors being variable by the user.

39. Apparatus for generating a 3D reconstruction of an object (3) comprising two aligned virtual projector means (pr1, pr2) arranged to project images of the object acquired by mutually aligned cameras into simulated 3D space, the separation of the virtual projectors being variable by the user.

40. Apparatus for generating a 3D representation of at least part of an object (3) from an object image (I1) of the projection of structured optical radiation onto the object surface and from at least one calibration image (I2) of the projection of the structured optical radiation onto a surface displaced from the object surface, the apparatus comprising image processing means (4) arranged to generate correspondences (PQ) between at least one calibration image and the object image

and optionally a further calibration image, and reconstruction processing means arranged to simulate a first projection of the object image and a second projection linking respective correspondences of at least two of the correlated images and to derive said 3D representation from the mutual intersections of the first and second projections.

41. Apparatus as claimed in claim 40 wherein the first and second projections are from a baseline (V) linking an origin of the structured optical radiation (O_P) and a perspective centre (O_C) associated with the images (I1, I2), the reconstruction processing means (4) being arranged to derive said baseline from the correlation (PQ).

42. Apparatus as claimed in claim 40 or claim 41 wherein the image processing means (4) is arranged to correlate two or more calibration images and to determine the spacing between origins of the first and second projections (O_C, O_P) in dependence upon both the correlation of the two or more calibration images and input or stored metric information associated with the calibration .

43. Apparatus as claimed in any of claims 40 to 42 further comprising projector means (PR) arranged to project the structured optical radiation onto the object surface and at least one calibration surface (T1, T2).

44. Apparatus as claimed in any of claims 40 to 42 further comprising a camera (CM) arranged to acquire the object image (I1) and at least one calibration image (I2).

45. Apparatus as claimed in any of claims 40 to 42 further comprising at least one calibration target (T1, T2) which in use is illuminated by the structured radiation.

46. Apparatus as claimed in any of claims 40 to 42 wherein the image processing means (4) is arranged to correlate pixels in one of said images (I1) with corresponding locations in the other of said images (I2) by comparing the local radiometric distributions associated with said pixels and locations respectively.

47. Apparatus as claimed in claim 46 wherein the image processing means (4) is arranged to allow a radiometric and/or geometric distortion during the correlation

process.

48. A method of generating a 3D representation of an object (3) from an object image (I1) of the projection of structured optical radiation onto the object surface and from at least one calibration image (I2) of the projection of the structured optical radiation onto a surface displaced from the object surface, the method comprising the steps of:

i) correlating at least one calibration image with the object image and optionally with a further calibration image;

ii) simulating a first projection of the object image and a second projection of the structured optical radiation, and

iii) deriving said 3D representation from the mutual intersections of the first and second projections.

49. A method as claimed in claim 48 wherein the first and second projections are from a baseline (V) linking an origin of the structured optical radiation (Op) and a perspective centre (O_C) associated with the image respectively, said baseline being derived from two or more pairs of image correspondences (PQ).

50. A method as claimed in claim 48 or claim 49 wherein two or more calibration images are correlated and the spacing between origins of the first and second projections (O_C, Op) is determined in dependence upon both the correlation of the two or more calibration images and input or stored metric information associated with the calibration images.

51. A method as claimed in any of claims 48 to 50 wherein regions (R) of said images (I1, I2) are correlated by comparing the local radiometric and/or colorimetric distributions associated with said regions.

52. A method as claimed in claim 51 wherein a radiometric and/or geometric distortion is allowed between potentially corresponding regions (R).

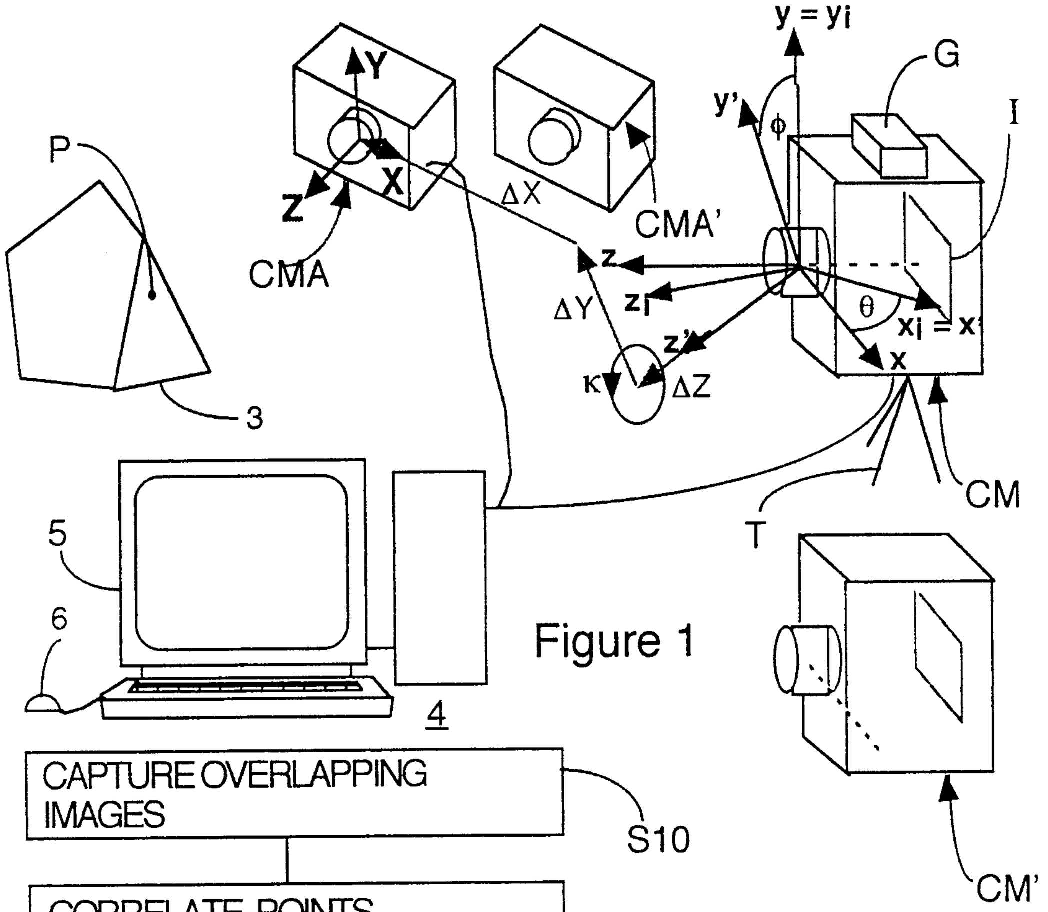

Figure 1

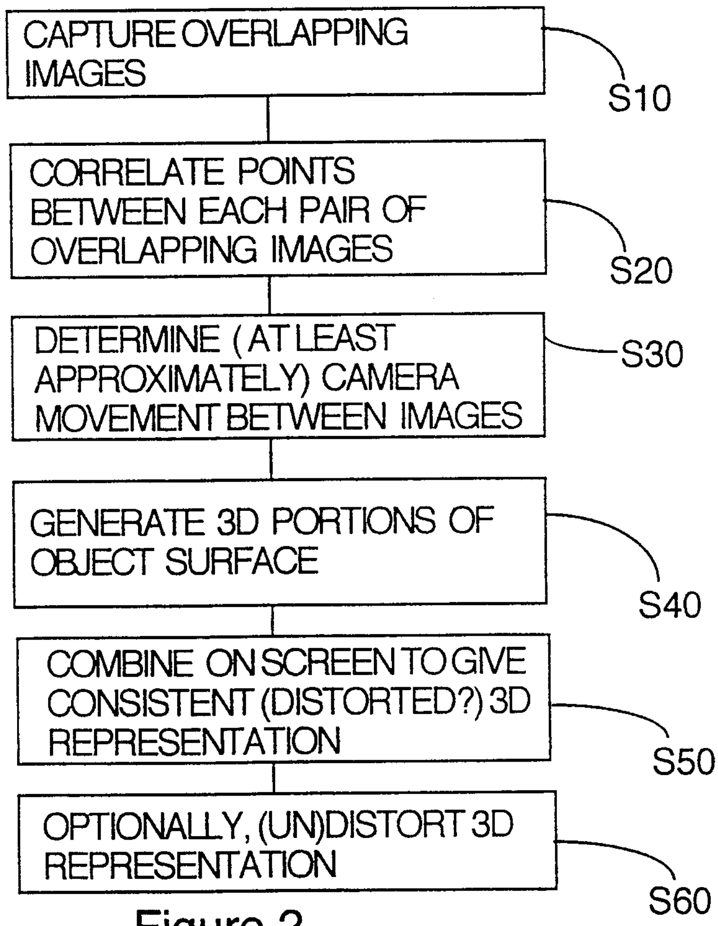

Figure 2

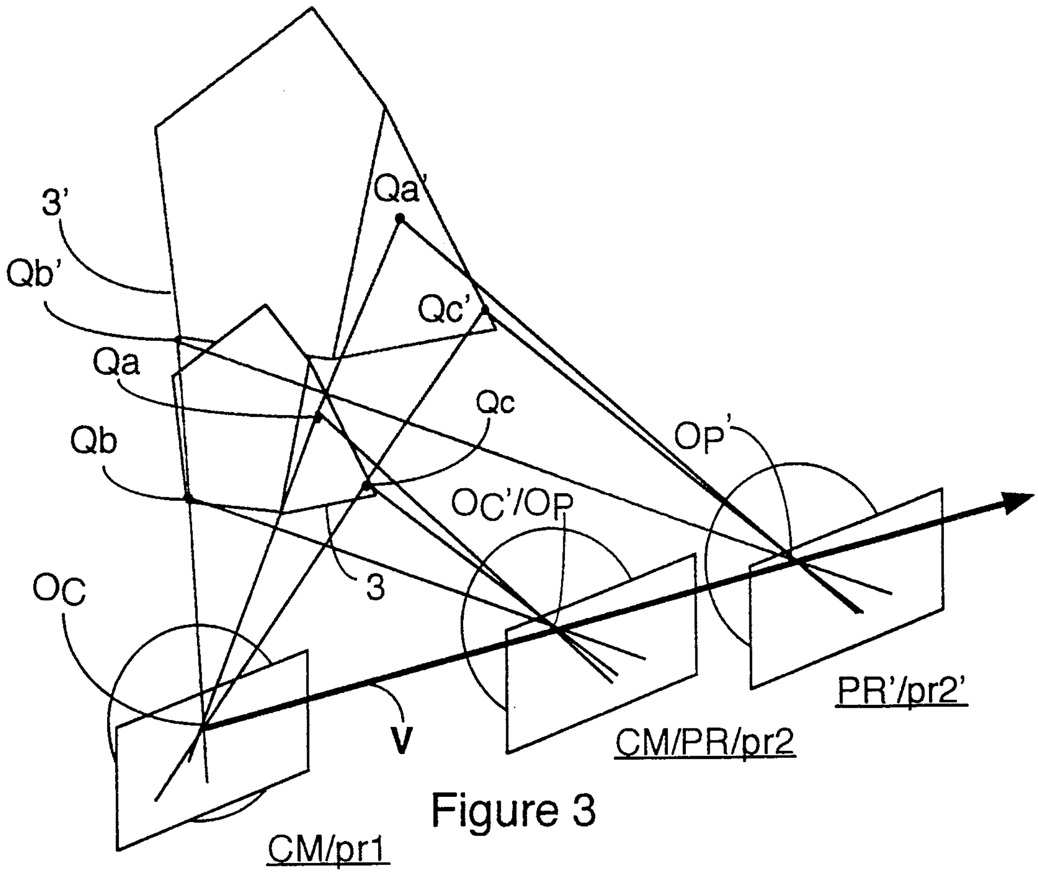

Figure 3

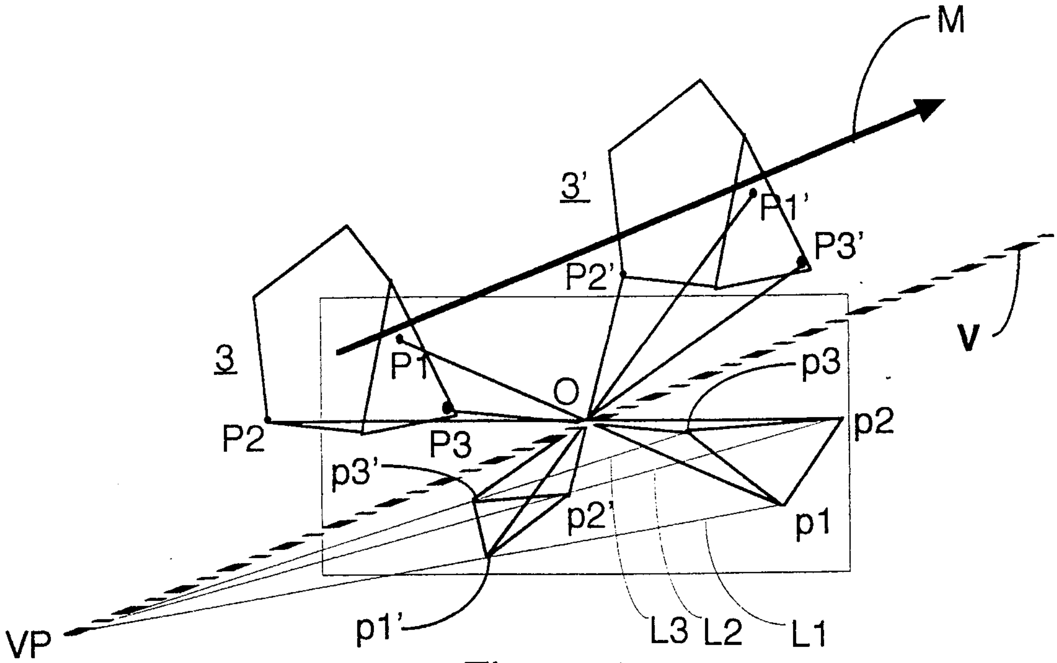

Figure 4

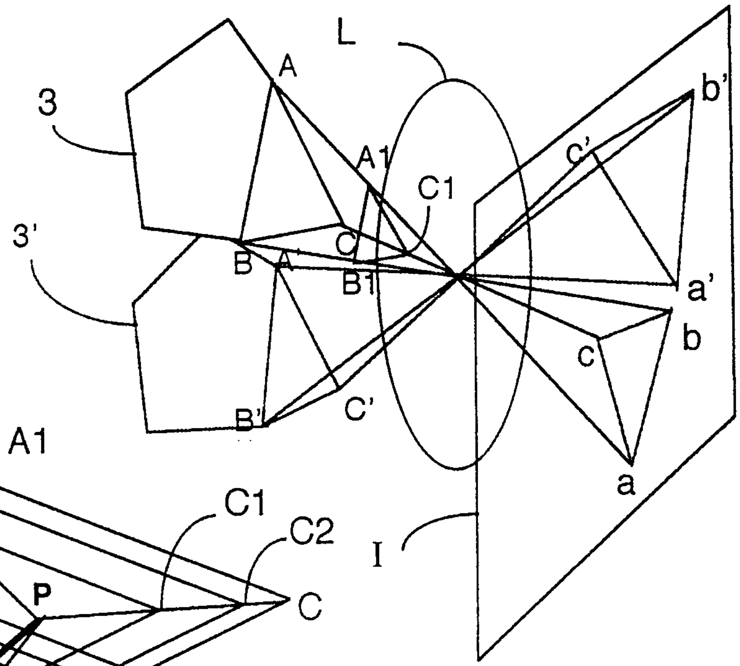

Figure 5

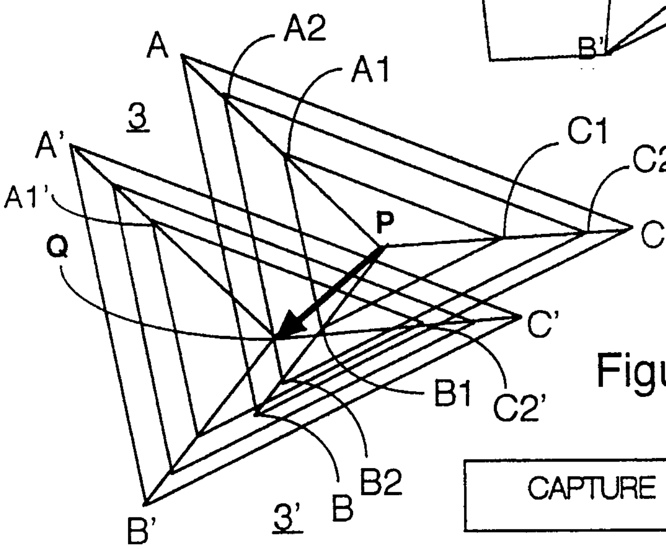

Figure 6

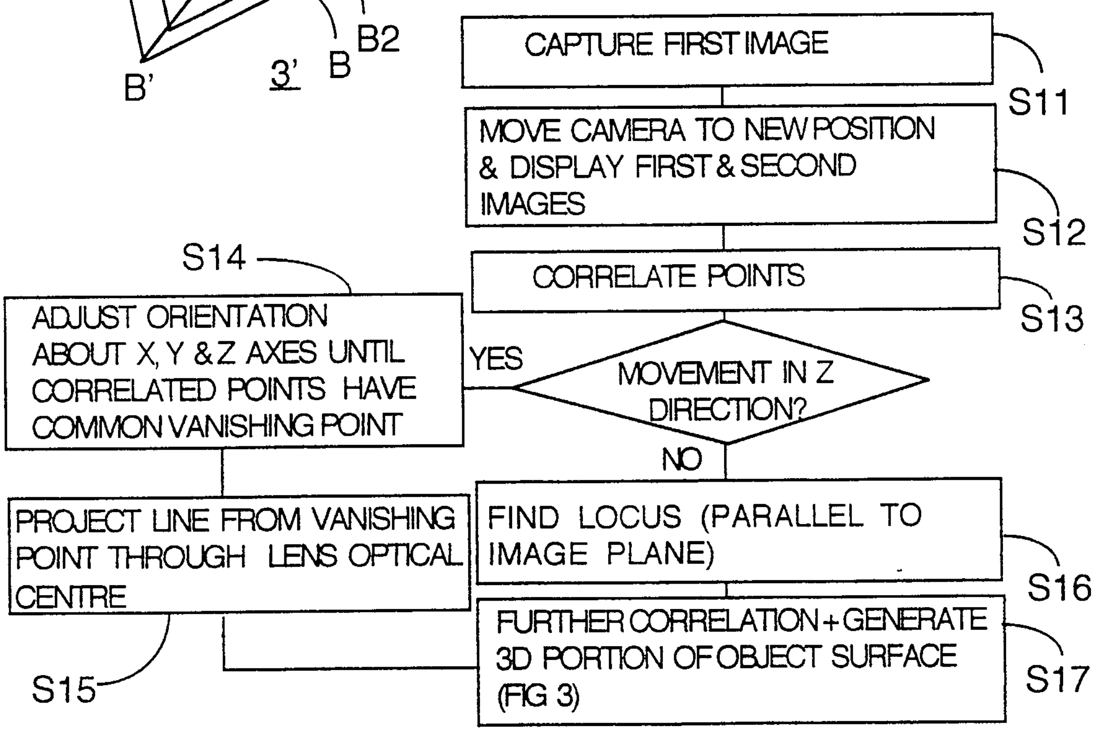

Figure 7

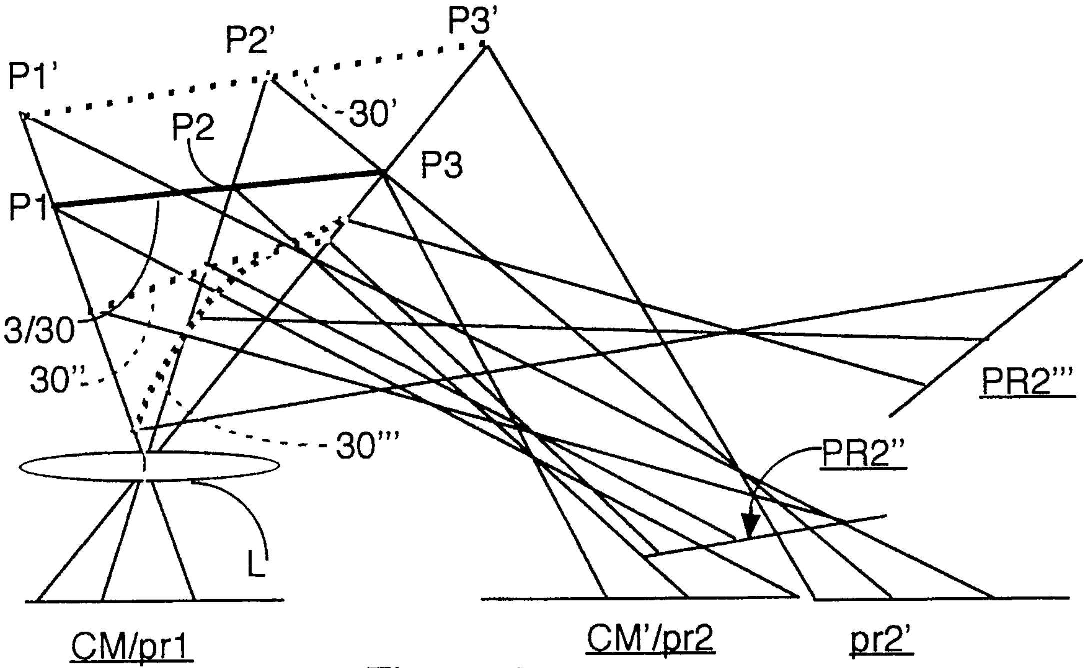

Figure 8

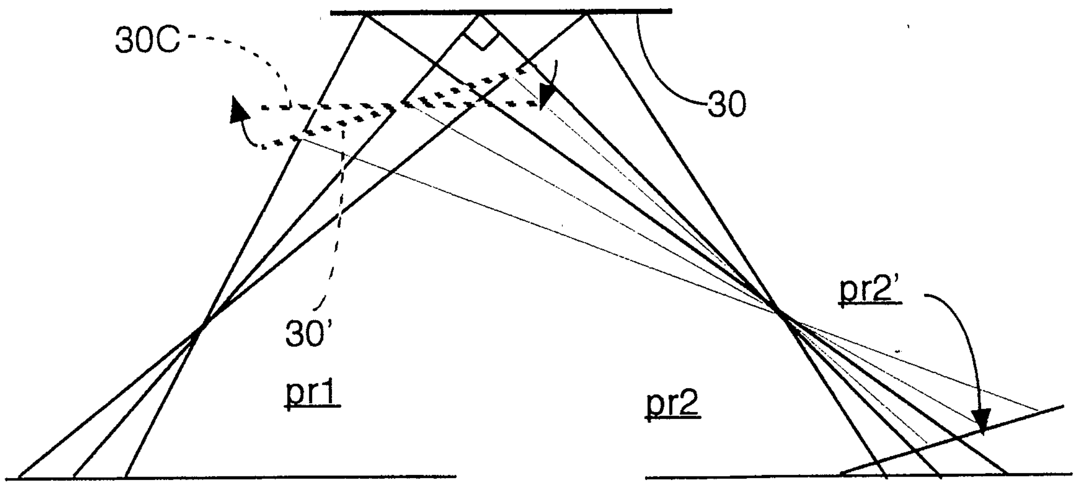

Figure 9

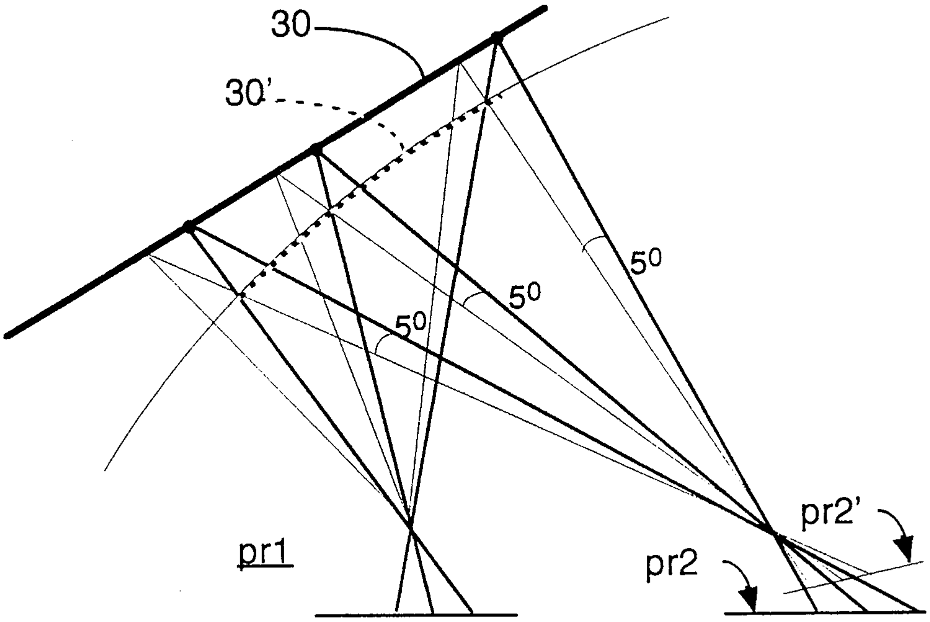

Figure 10A

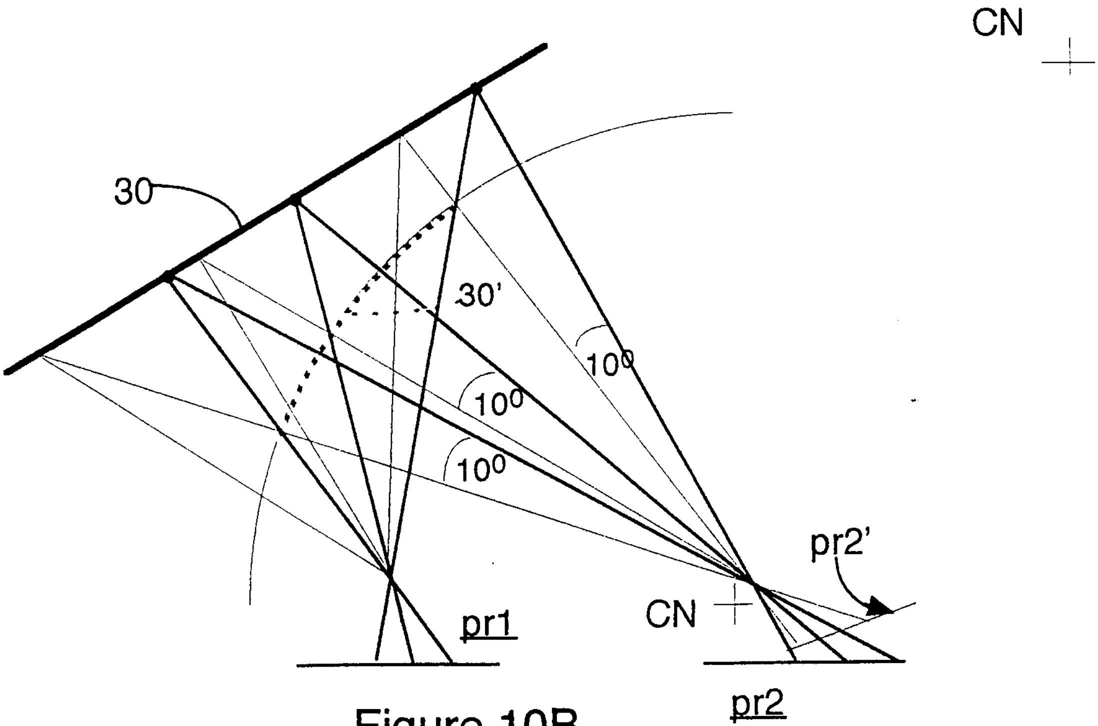

Figure 10B

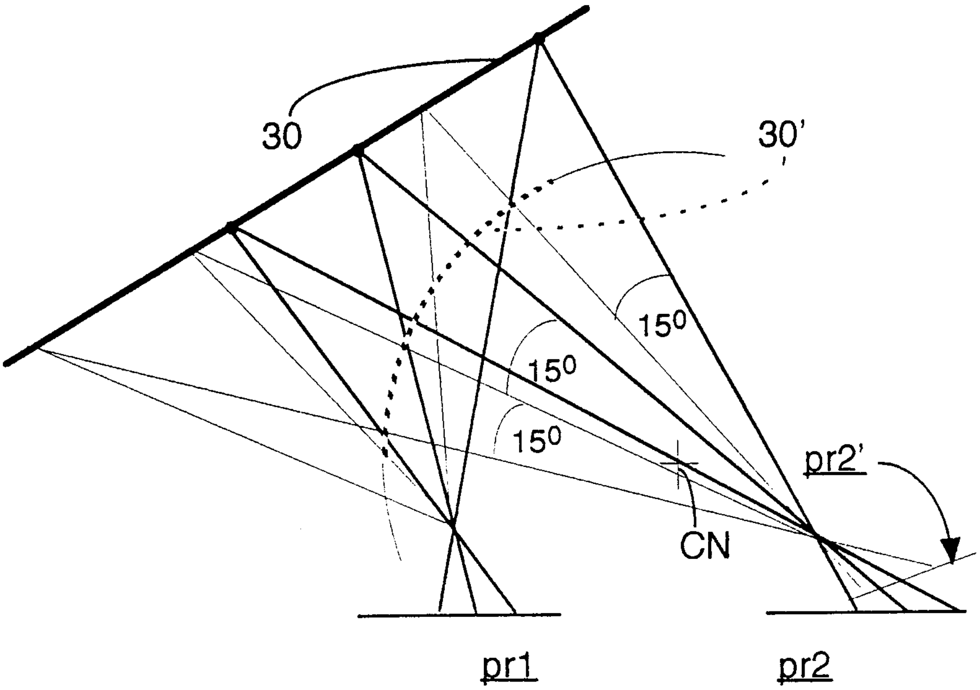

Figure 10C

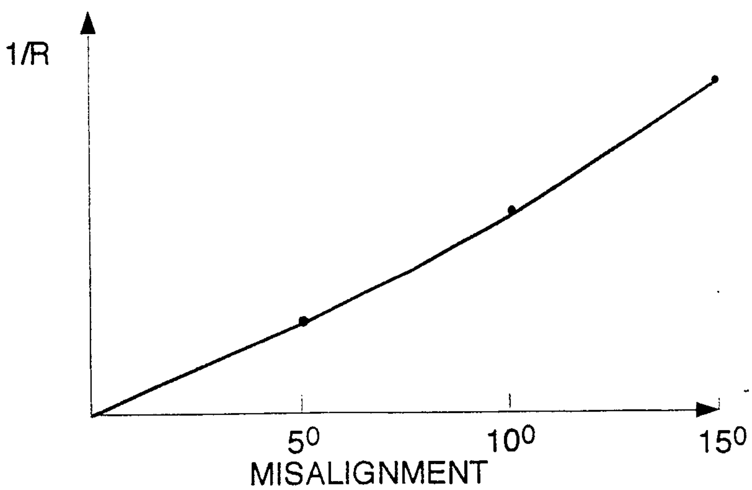

Figure 11

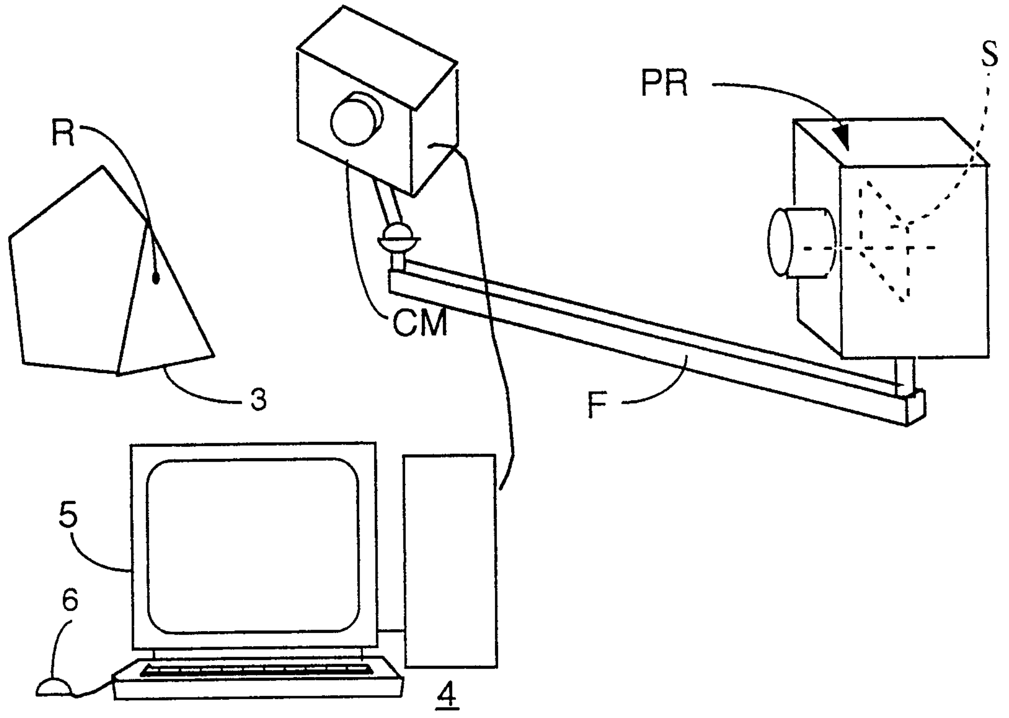

Figure 12

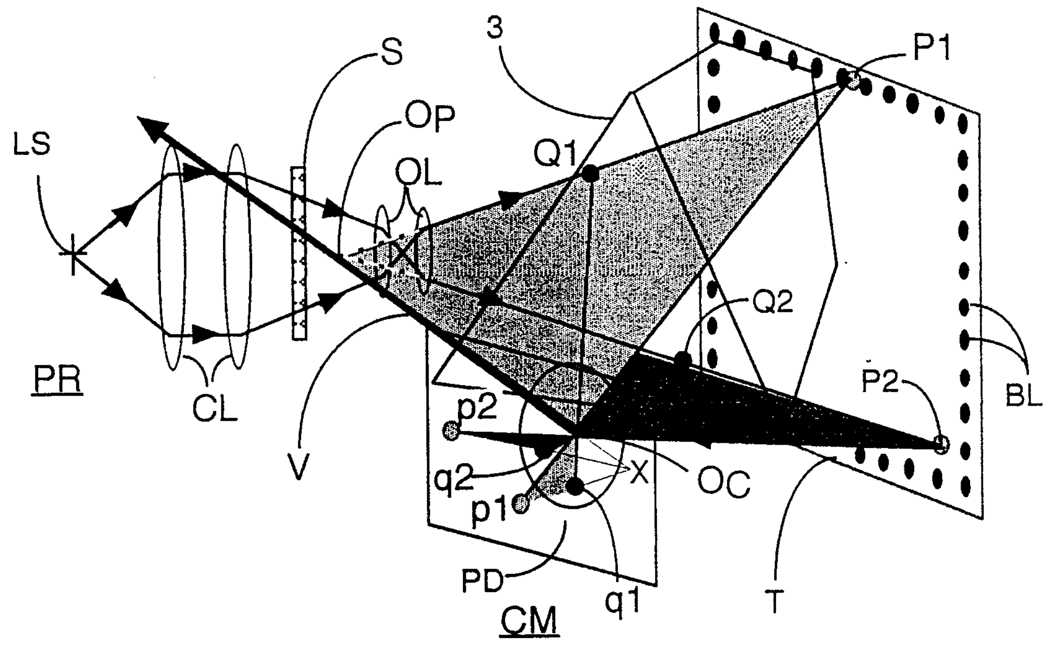

Figure 13

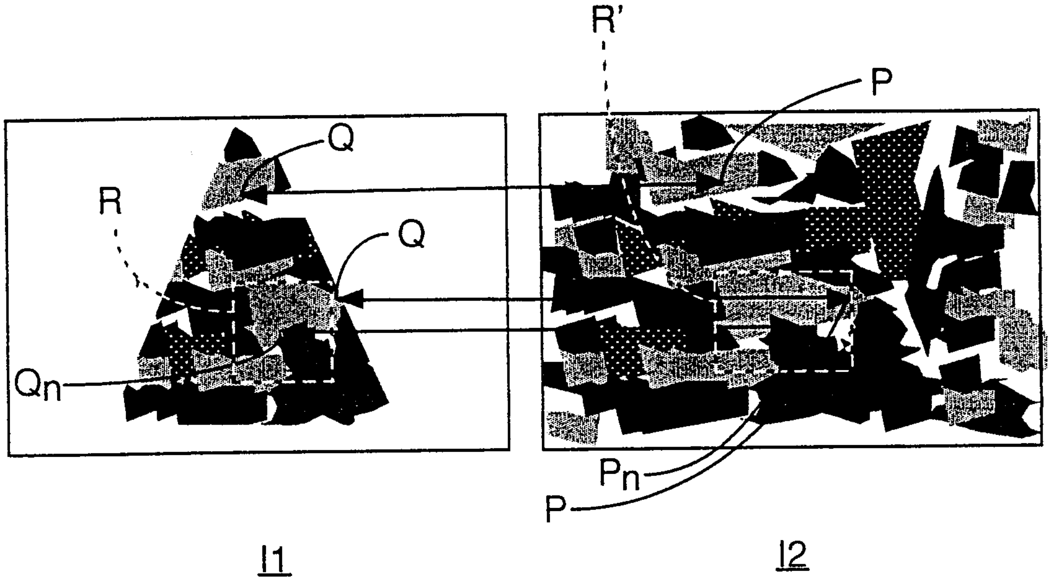

Figure 14

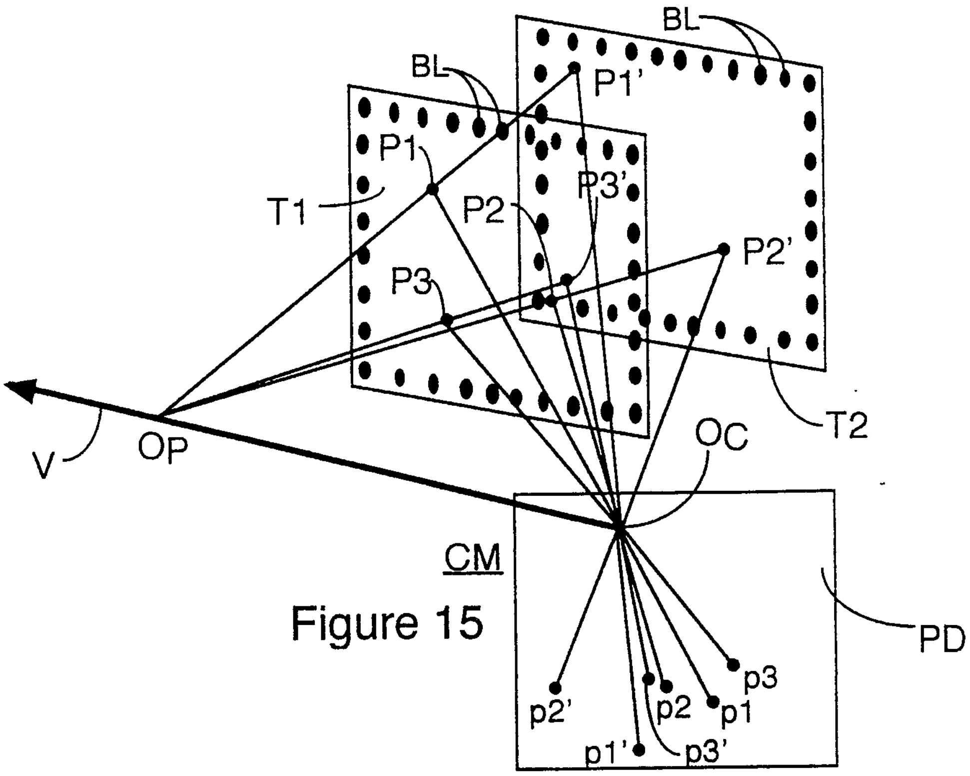

Figure 15

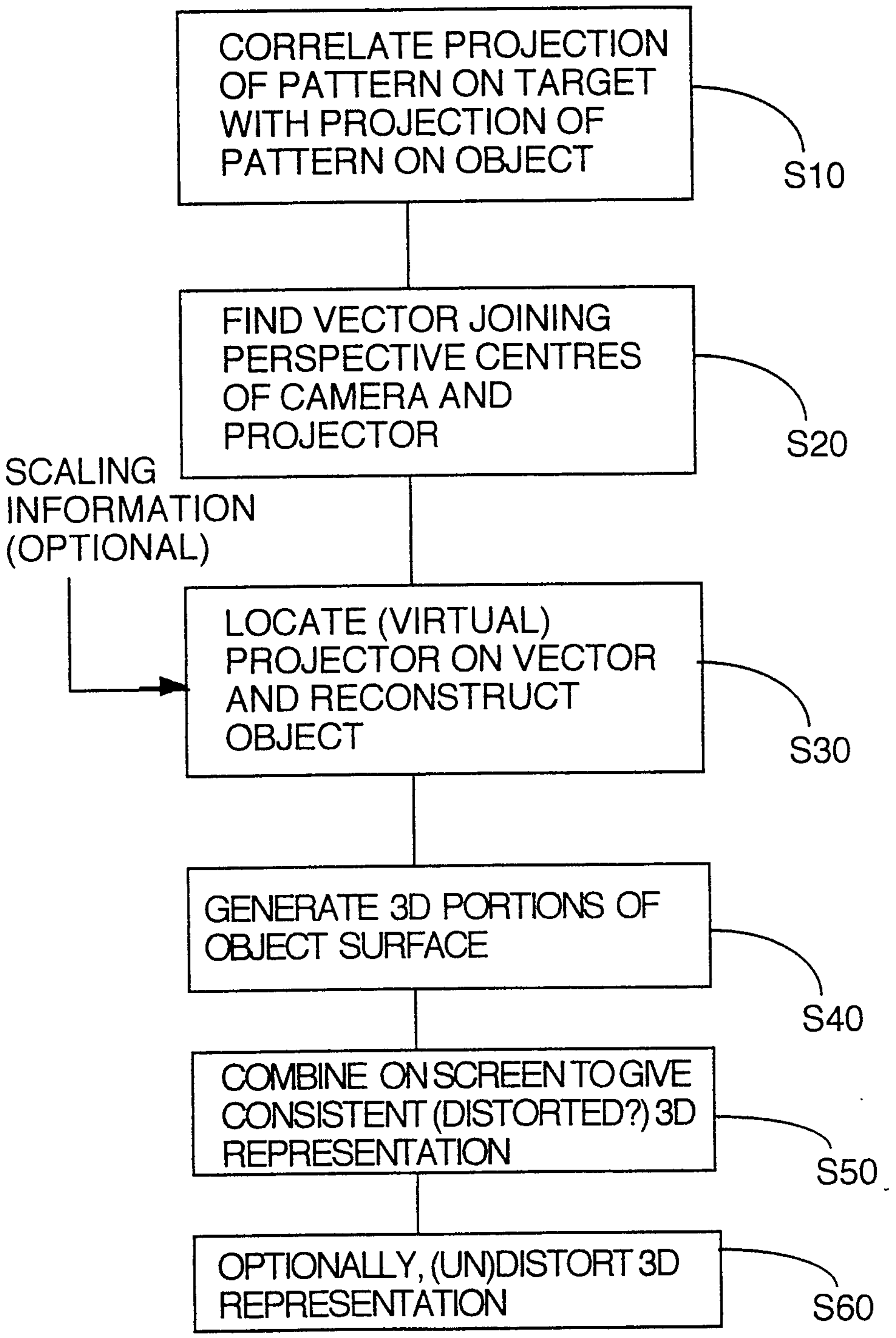
CORRELATE PROJECTION OF PATTERN ON TARGET WITH PROJECTION OF PATTERN ON OBJECT
S10
FIND VECTOR JOINING PERSPECTIVE CENTRES OF CAMERA AND PROJECTOR
S20
SCALING INFORMATION (OPTIONAL)
LOCATE (VIRTUAL) PROJECTOR ON VECTOR AND RECONSTRUCT OBJECT
S30
GENERATE 3D PORTIONS OF OBJECT SURFACE
S40
COMBINE ON SCREEN TO GIVE CONSISTENT (DISTORTED?) 3D REPRESENTATION
S50
OPTIONALLY, (UN)DISTORT 3D REPRESENTATION
S60

Figure 16

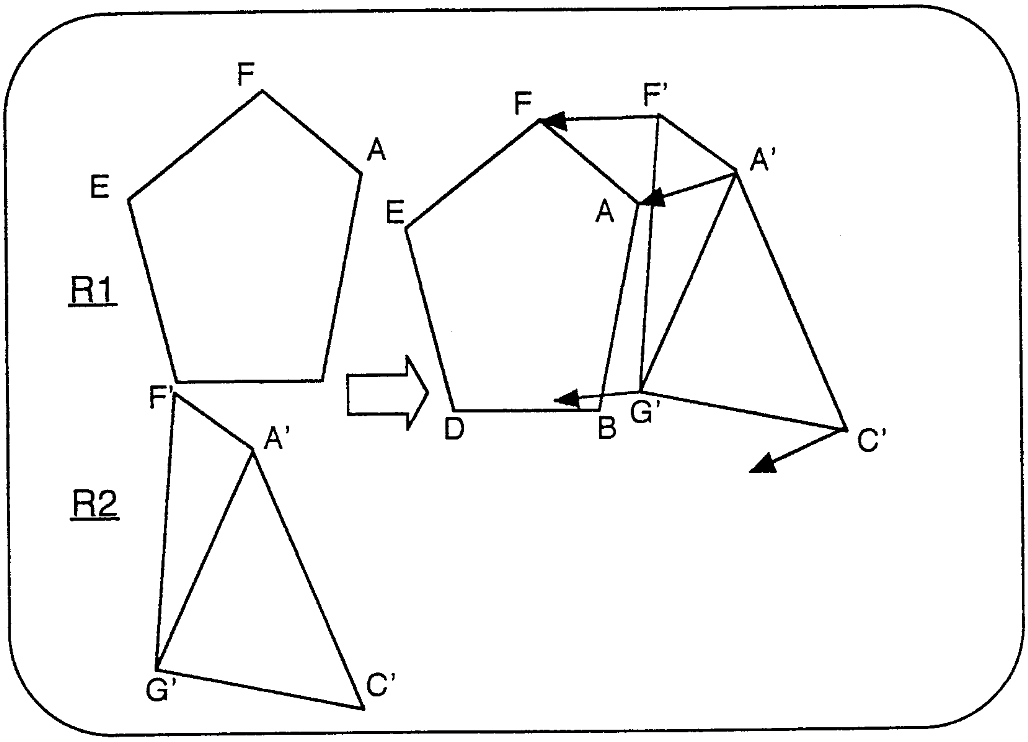

Figure 17

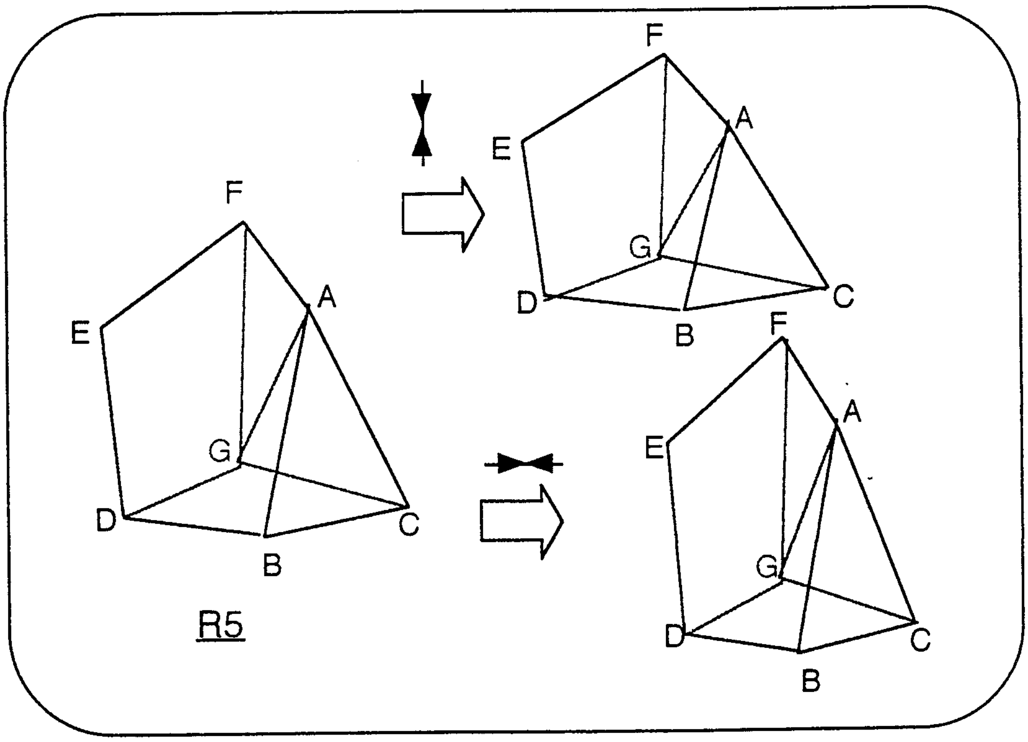

Figure 18

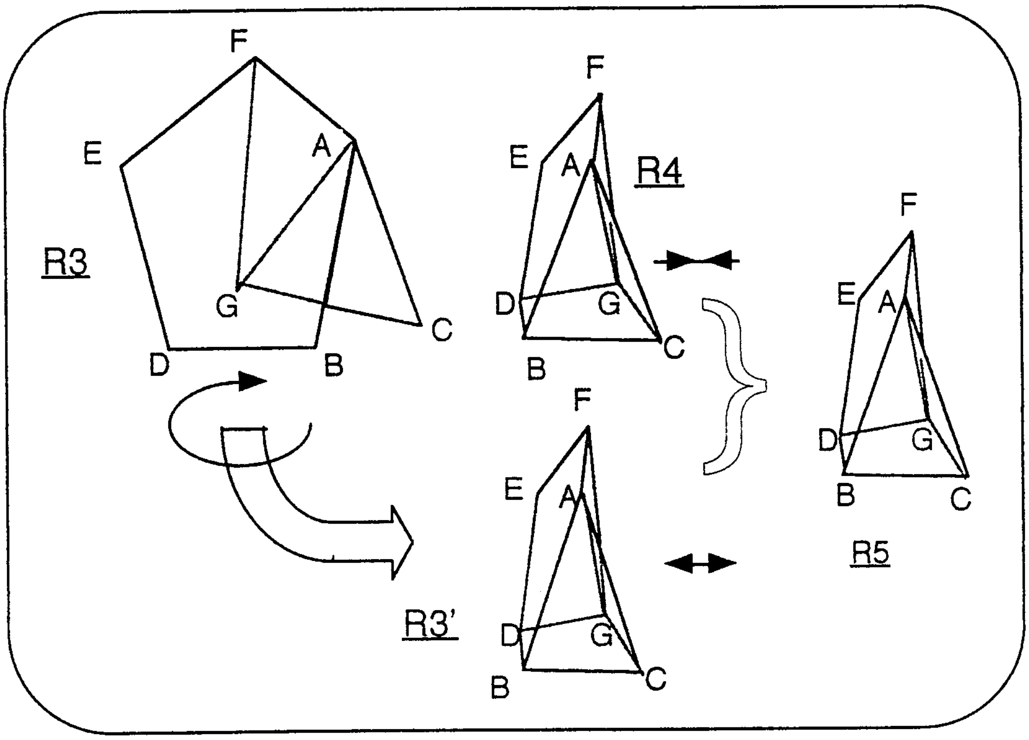

Figure 19

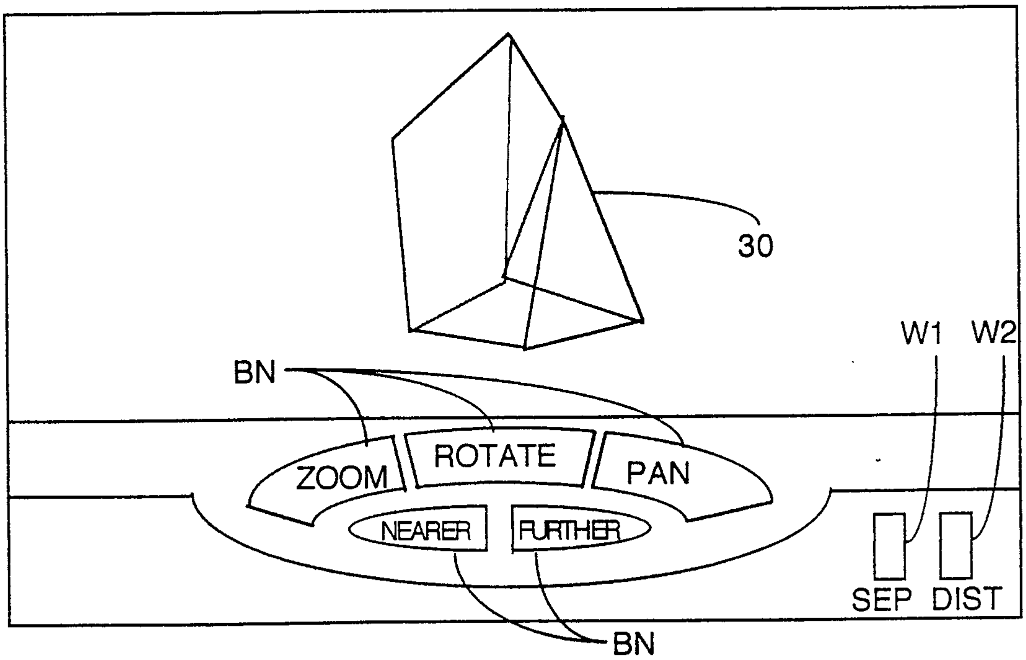

Figure 20

INTERNATIONAL SEARCH REPORT

Inte 'onal Application No
PCT/GB 99/01556

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G06T7/00 G06T15/20

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G06T

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	HARTLEY R I: "IN DEFENCE OF THE 8-POINT ALGORTHM" PROC. FIFTH INTERNAT. CONF. ON COMPUTER VISION, CAMBRIDGE, MA., JUNE 20 - 23, 1995, no. 5, pages 1064-1070, XP000557481 IEEE, ISBN: 0-7803-2925-2 abstract paragraphs '0001!,'0006!,'0007! --- -/--	1,26,38, 39

[X] Further documents are listed in the continuation of box C.

[ ] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

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Date of the actual completion of the international search	Date of mailing of the international search report
13 September 1999	28/09/1999

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 99/01556

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	HARTLEY R ET AL: "STEREO FROM UNCALIBRATED CAMERAS" PROC. COMP. SOC. CONF. ON COMPUTER VISION AND PATTERN RECOGNITION, CHAMPAIGN, IL, JUNE 15 - 18, 1992, 15 June 1992 (1992-06-15), pages 761-764, XP000357427 IEEE, ISBN: 0-8186-2855-3 cited in the application abstract paragraph '0001! ---	1,26,38, 39
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