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## VERIFICATION AND CERTIFICATION OF TRANSLATION

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Martin Cross  
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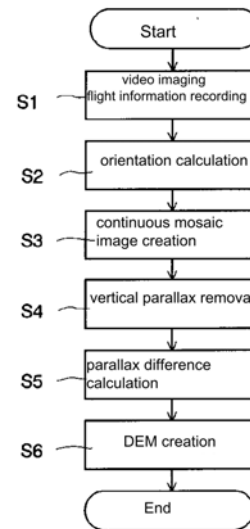
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(54) **[Title of invention]** Three-Dimensional Data Extraction Method and Device, and Stereo Image Forming Device(57) **[Abstract]****[Object]** To create DEM data from video images.

**[Constitution]** Video images are taken of a target region from the air (S1). At this time, the camera position is measured by way of differential GPS. The camera is mounted on an anti-vibration device, and the orientation of the camera is measured precisely by way of gyroscope output and magnetic bearing sensor output thereof. Exterior orientation elements are determined accurately by matching fields in video images that overlap 60% (S2). The leading line, middle line, and final line of each field are extracted, and are separately combined to create continuous mosaic images consisting of a forward view image, a nadir view image and a rearward view image (S3). The vertical parallax is removed from the continuous mosaic images (S4). The parallax difference is calculated from the forward view image and the rearward view image (or the nadir view image) (S5), and the height is calculated from the parallax difference (S6).



**[Claims]**

**[Claim 1]** A three-dimensional data extraction method comprising: a basic information collection step of imaging a three-dimensional data extraction target while moving, recording that image signal, and recording imaging information including the position and orientation of the imaging camera; and a three-dimensional data generation step of generating three-dimensional data for said extracted object from the images and imaging information collected in said basic information collection step, the three-dimensional data extraction method being characterized in that said three-dimensional data generation step comprises:

a continuous mosaic image generation step of extracting image data of prescribed lines in prescribed screens in consecutive screens of captured images, and generating at least two continuous mosaic images from among a forward view image, a nadir view image, and a rearward view image;

a vertical parallax removal step of removing vertical parallax from the continuous mosaic images generated in said continuous mosaic image generation step,

a parallax difference calculation step of calculating the parallax difference for a prescribed position in the continuous mosaic images from which vertical parallax was removed in said vertical parallax removal step; and

a height calculation step of calculating the height of said prescribed position from the parallax difference calculated in said parallax difference calculation step.

**[Claim 2]** The three-dimensional data extraction method recited in claim 1, further comprising an orientation calculation step of establishing, by way of relative orientation and successive orientation, exterior orientation elements from consecutive screens of captured images.

**[Claim 3]** The three-dimensional data extraction method recited in claim 2, wherein said orientation calculation step comprises: a relative orientation step of extracting, from consecutive screens of captured images, two screens that overlap in a prescribed proportion and performing relative orientation; and a successive orientation step of associating models that have been relatively oriented by said relative orientation step.

**[Claim 4]** The three-dimensional data extraction method recited in claim 3, wherein said prescribed proportion is 60%.

**[Claim 5]** The three-dimensional data extraction method recited in any one of claims 2 to 4, wherein said vertical parallax removal step comprises: an exterior orientation element interpolation step of interpolating exterior orientation elements for each line of the continuous mosaic images generated in said continuous mosaic image generation step, in accordance with the exterior orientation elements determined in said orientation calculation step; and a projection step of transforming the lines of the continuous mosaic images generated in said continuous mosaic image generation step into images projected to a prescribed altitude in accordance with the exterior orientation elements of said lines.

**[Claim 6]** The three-dimensional data extraction method recited in any one of claims 1 to 5, wherein said parallax difference calculation step comprises: an intermediate image formation step of forming one or more intermediate images between said continuous mosaic images; a corresponding point detection step of going through said one or more intermediate images and detecting corresponding points in said continuous mosaic images; and a computation step of calculating the parallax difference of said corresponding points in accordance with the detection results of said corresponding point detection step.

**[Claim 7]** The three-dimensional data extraction method recited in claim 6, wherein said intermediate image formation step

extracts image data of intermediate lines in prescribed screens in consecutive screens of captured images, and forms said intermediate image.

**[Claim 8]** The three-dimensional data extraction method recited in any one of claims 1 to 7, wherein a GPS reception means is provided as a means for detecting the position of said camera.

**[Claim 9]** The three-dimensional data extraction method recited claim 8, wherein a correction means that differentially corrects the output of the GPS reception means is further provided.

**[Claim 10]** The three-dimensional data extraction method recited in any one of claims 1 to 9, wherein said camera is prevented from vibrating by an anti-vibration means.

**[Claim 11]** A three-dimensional data extraction device characterized by comprising: a video camera that images a three-dimensional data extraction target; a position measurement means that measures the position of said video camera; a recording means that records images captured by said video camera and measurement values of said position measurement means; a conveyance means that conveys said video camera and said position measurement system [sic]; a reproduction means that reproduces the image information and position information recorded by said recording means; a continuous mosaic image generation means that extracts image data of prescribed lines in prescribed screens in consecutive screens of captured images, and generates at least two continuous mosaic images from among a forward view image, a nadir view image, and a rearward view image; a vertical parallax removal means that removes vertical parallax from the continuous mosaic images generated by said continuous mosaic image generation means; a parallax difference calculation means that calculates parallax difference in continuous mosaic images from which vertical parallax has been removed by said vertical parallax removal means; and a height calculation means that calculates the height of said [sic] prescribed position from the parallax difference calculated by said parallax difference calculation means.

**[Claim 12]** The three-dimensional data extraction device recited in claim 11, further comprising an orientation calculation means that establishes, by way of relative orientation and successive orientation, exterior orientation elements from consecutive screens of captured images.

**[Claim 13]** The three-dimensional data extraction device recited in claim 12, wherein said orientation calculation means provides: a relative orientation step of extracting, from consecutive screens of captured images, two screens that overlap in a prescribed proportion and performing relative orientation; and a successive orientation step of associating models that have been relatively oriented by said relative orientation step.

**[Claim 14]** The three-dimensional data extraction device recited in claim 13, wherein said prescribed proportion is 60%.

**[Claim 15]** The three-dimensional data extraction device recited in any one of claims 12 to 14, wherein said vertical parallax removal means comprises an exterior orientation element interpolation means that interpolates exterior orientation elements in each line of the continuous mosaic images generated by said continuous mosaic image generation means, in accordance with the exterior orientation elements determined by said orientation calculation means; and a projection means that transforms the lines of the continuous mosaic images generated by said continuous mosaic image generation means into images projected to a prescribed altitude in accordance with the exterior

orientation elements of said lines.

**[Claim 16]** The three-dimensional data extraction device recited in any one of claims 11 to 15, wherein said parallax difference calculation means comprises: an intermediate image formation means that forms one or more intermediate images between said continuous mosaic images; a corresponding point detection means that goes through said one or more intermediate images and detects corresponding points in said continuous mosaic images; and a computation means that calculates the parallax difference of said corresponding points in accordance with the detection results of said corresponding point detection means.

**[Claim 17]** The three-dimensional data extraction device recited in claim 16, wherein said intermediate image formation means extracts image data of intermediate lines in prescribed screens in consecutive screens of captured images, and forms said intermediate image.

**[Claim 18]** The three-dimensional data extraction device recited in any one of claims 11 to 17, wherein said position measurement means is a GPS reception means.

**[Claim 19]** The three-dimensional data extraction device recited in claim 18, further comprising a correction means that differentially corrects the output of the GPS reception means.

**[Claim 20]** The three-dimensional data extraction device recited in any one of claims 11 to 19, wherein said camera is mounted on said conveyance means via an anti-vibration means.

**[Claim 21]** The three-dimensional data extraction device recited in any one of claims 11 to 20, wherein said conveyance means is an aircraft.

**[Claim 22]** The three-dimensional data extraction device recited in any one of claims 11 to 21, further comprising a bearing detection means that detects the bearing of said camera, wherein the output of said bearing detection means is also recorded in said recording means.

**[Claim 23]** The three-dimensional data extraction device recited in any one of claims 11 to 22, wherein said camera is disposed so that the direction of travel of said conveyance means is a direction that is perpendicular to the direction of the scan lines of the camera.

**[Claim 24]** A stereo image formation device characterized by comprising: an extraction means that extracts line image data, at two or more different prescribed line positions in screens, in a video captured image; and a combining means that combines line image data from the same line positions.

**[Claim 25]** The stereo image formation device recited in claim 24, further comprising a vertical parallax removal means that removes vertical parallax from the images combined by said combining means, based on exterior orientation elements of each of the line image data on which [the images] are based.

#### **[Detailed Description of the Invention]**

##### **[0001]**

**[Field of Industrial Application]** The present invention relates to a method and a device for three-dimensional data extraction, and to a stereo image formation device; more specifically, it relates to a method and device for extracting three-dimensional data from video images, and to a stereo image formation device that forms stereo images from video images.

##### **[0002]**

**[Prior Art]** Conventionally, aerial survey technology based on aerial photographs has been used in creating three-dimensional topographical maps. But aerial survey technology involves having a helicopter or light airplane fly above a locality while taking stereoscopic photographs of the ground, and analyzing the resulting stereo photographs; obtaining stereographic photographs alone requires a great deal of time and expense, and analysis of the same likewise entails enormous effort and

expense. If three-dimensional measurement is done by stereo matching using aerial photographs taken from a low altitude, matching errors will occur due to the influence of occlusion. This is because the two images that form a stereo image are seen from different viewing directions, and differences in the image due to differences in the observation direction make perfect matching impossible. In conventional cases, attempts have been made to eliminate such influence by using multiple orientation points on the ground, but with this, automation is impossible.

##### **[0003]**

**[Problems to Be Solved by the Invention]** In contrast, it is easy to automate the technology using video images to create topographical maps. But in the prior art, in extracting photographic three-dimensional data, in the same way as in an aerial survey, it is considered necessary to have several air-photo signal points in the image (signals for which clear three-dimensional coordinates are known), and even if the necessary number of air-photo signals are assured, the errors will be of poor precision, which is in meter units, making this impractical.

**[0004]** Three-dimensional topographical maps are useful for the management of roads, rivers, railroads, and the like, and for planning new routes for the same and surveying the state of development of cities and the like; there is a demand for a system that makes it possible to acquire three-dimensional topographical data quickly, cheaply, and simply. If three-dimensional topographical data is available, bird's-eye views can also be created easily (shown on a display or output on a printer), and various simulations can be run. And if three-dimensional data can be obtained by processing video images, it will also be easy to extract just the parts that have changed, thus also making it easy to survey the state of development of cities and the like.

**[0005]** An object of the present invention is to propose a three-dimensional data extraction method and device, which extract three-dimensional data automatically.

**[0006]** Another object of the present invention is to propose a three-dimensional data extraction method and device, which extract three-dimensional data from video images.

**[0007]** Another object of the present invention is to propose a stereo image formation device that forms stereo images (two images suitable for stereo matching) from video images.

##### **[0008]**

**[Means for Solving the Problems]** In the present invention, image data of prescribed lines of video images are extracted, and continuous mosaic images having different parallax are formed. After vertical parallax is removed from these continuous mosaic images, the parallax difference is calculated by stereo matching. Heights are calculated from the resulting parallax differences.

**[0009]** Preferably, at least three images that overlap in a

prescribed proportion are extracted from consecutive screens of captured images, the screens are matched by way of the overlapping parts thereof, and exterior orientation elements are established. Then, in accordance with the exterior orientation elements determined by this orientation calculation, the exterior orientation elements are interpolated for each line of the continuous mosaic images, and the lines of the continuous mosaic images are transformed into images projected to a prescribed altitude, in accordance with the exterior orientation elements of said lines.

**[0010]**

**[Operation]** The above processing can be automated on a computer, thus making it possible to automatically execute on a computer all the processes by which the stereo images needed for stereo matching are obtained from images resulting from video imaging, and by which heights are calculated, making it possible to quickly obtain three-dimensional data for a desired region or the like.

**[0011]** Being video images, a great deal of information is available that is needed for establishing exterior orientation elements, and the precision of the exterior orientation elements is increased. Consequently, the height data that is ultimately obtained is also of good precision. Furthermore, in the stereo image matching computation as well, by temporarily creating intermediate images for said stereo images, and searching for corresponding points chainwise, the corresponding points between stereo images can be established with greater precision than in the case of stereo photographs, and the occlusion problem can be completely solved.

**[0012]**

**[Working Example]** Hereafter, referring to the drawings, a working example of the present invention is described in detail.

**[0013]** FIG. 1 shows a schematic block diagram of an airborne measurement system in a working example of the present invention; FIG. 2 shows a schematic block diagram of an on-the-ground measurement system; and FIG. 3 shows schematic block diagram of an on-the-ground analysis system.

**[0014]** The airborne measurement system shown in FIG. 1 will be described. In this working example, the airborne measurement system shown in FIG. 1 is aboard a helicopter. In this working example, a high-quality camera 10 is mounted on a high-precision anti-vibration stabilizing device (anti-vibration device) 12, and the high-quality image signal output thereof is recorded on videotape by a high-quality video tape recorder 14. Note that, the camera 10 is generally facing downward, and is set so that the image directly below moves in a direction that is perpendicular to the scan lines. The output image signal of the camera 10 is also applied to a high-quality monitor 16. This allows visual confirmation of what the camera 10 is capturing and the state of imaging.

**[0015]** The high-precision anti-vibration stabilizing device 12 is made so that vibration from the aircraft does not affect the camera 10. This makes it possible to record images without blurring. That is to say, by combining a gyroscope and gimbal servo, the high-precision anti-vibration stabilizing device 12 has a spatial stabilization function that keeps the optical axis of the camera 10 pointed in a fixed direction in inertial space against any fluctuations in the angles about the roll, pitch, and yaw axes that arise in the airframe.

**[0016]** [Reference numeral] 18 is a personal computer that, along with collecting and recording measurement data, controls the high-precision anti-vibration stabilizing device 12 via a three-axis control device 20, controls the camera 10 via a camera control device 22, and controls the VTR 14 via a VTR control device 24. With the three-axis control device 20, the target bearing of the

anti-vibration stabilizing device 12 can be set arbitrarily; the camera control device 22 controls the focus, zoom, diaphragm value, color balance and the like of the camera 10, and the VTR control device 24 controls the recording start, stop, and pause on the VTR 14, and also acquires and transfers to the computer 18 a time code that is recorded together with the output image signal of the camera 10. This time code is used for synchronization when analyzing the image information and other measurement data that is recorded on the VTR 14, in the on-the-ground analysis system.

**[0017]** A height above ground sensor 26 detects the height above ground, and the magnetic bearing sensor 28 detects the magnetic bearing. Because, even with the high-precision anti-vibration stabilizing device 12, there is slow directional movement caused by gyroscopic drift, it is necessary to correct the orientation of the camera by way of the magnetic bearing sensor 28. The outputs of the sensors 26 and 28 are applied to the computer 18 as digital data. Also input to the computer 18 is tri-axial gyroscopic data from the anti-vibration stabilizing device 12 indicating the tri-axial orientation of the camera 10 (roll angle, pitch angle, and yaw angle), and zoom data indicating the zoom value from the camera 10.

**[0018]** [Reference numeral] 30 is a GPS (global positioning system) receiving antenna, and 32 is a GPS reception device that collects the current ground coordinates (longitude, latitude, and altitude) from the GPS antenna 30. The GPS position measurement data output from the GPS reception device 32 is applied to the computer 18 for recording, and is also applied to a navigation system 34 for navigation. The navigation system 34 performs three-dimensional graphic display of the current position on a screen of a monitor 38, with respect to set survey lines in accordance with navigational (survey line data) that has been previously recorded on a floppy disk 36. This makes it possible to capture images following along desired survey lines in regions where there are no target objects on the ground, or in regions where they cannot be ascertained (for example, mountainous regions or sea regions or the like).

**[0019]** Note that, the differential GPS (D-GPS) method in which, even at reference points where the coordinates are known, measurements are taken by GPS, and the GPS position measurement data is corrected by the measurement error, is known as a way to improve GPS measurement precision. In this working example, this differential GPS method is adopted; the coordinates of a reference station of known coordinates are measured at the same time by GPS, and the measurement error data is radioed to the helicopter as GPS correction data. The communication device 40 receives the GPS correction data from the reference station and transfers it to the computer 18.

**[0020]** The computer 18 records the flight data that is input (height above ground data, magnetic bearing data, zoom data, tri-axial gyroscopic data), together with GPS correction data and

timer codes from the VTR control device 24, to the floppy disk 42. The computer 18 can also display various input data on the monitor 44 as necessary, and an operator can input various instructions to the computer 18 from a keyboard 46.

**[0021]** In readiness for cases in which the communication with the reference station by the communication device 40 goes bad, in this working example, as shown in FIG. 2, the measured GPS correction data is saved on a floppy disk independently at the reference station as well. That is to say, the GPS reception device 50 calculates the current location of the GPS antenna 52 from the output of the GPS antenna 52, and outputs the GPS position measurement data to a computer 54. Accurate coordinates (reference position data) of the GPS antenna 52 are measured beforehand, and this data is input to or set in the computer 54. The computer 54 computes the error of the GPS position measurement data from the GPS reception device 50 and the reference position data, and records it on a floppy disk 56 as GPS correction data. Of course, measurement-time information is also recorded at the same time. The GPS position measurement data and the error (which is to say, the GPS correction data) are displayed on the screen of the monitor 58 as necessary. The operator can input various instructions to the computer 54 by way of a keyboard 60. The computer 54 also sends the GPS correction data via a communication device 62 to (the computer 18 of) the airborne measurement system shown in FIG. 1.

**[0022]** The data measured by the airborne measurement system shown in FIG. 1 (and as necessary by the on-the-ground measurement system shown in FIG. 2) is analyzed, and three-dimensional data is calculated, by the on-the-ground analysis system shown in FIG. 3. That is to say, the high-quality VTR 70 plays back the videotape that was recorded by the airborne measurement system shown in FIG. 1, applying the image image [sic] signal to the frame buffer 74 and the reproduced time codes to an engineering workstation 76. The image data temporarily stored in the frame buffer 74 is applied to a monitor 78 and is image-displayed. Needless to say, sometimes the reproduced time codes are also displayed simultaneously on the monitor 78.

**[0023]** A personal computer 80 reads the flight data and GPS correction data that is simultaneously collected by the airborne measurement system shown in FIG. 1 (in the event of a communication breakdown, the GPS correction data measured by the on-the-ground measurement system shown in FIG. 2), corrects the GPS position measurement data with the GPS correction data and corrects the tri-axial gyroscopic data with the magnetic bearing data, and transfers this, along with other measurement data and the time codes that are recorded together, to the workstation 76. The workstation 76 controls the VTR 70 in accordance with the time codes supplied from the computer 80 and causes the VTR 70 to play back images with the same time code. In this way, the workstation 76 can correlate the conditions and imaging position when imaging with the images captured at that time, and reproduces three-dimensional data by way of computation that is described in detail below.

**[0024]** FIG. 4 shows the flow in this working example, from measurement to three-dimensional data extraction. First, the equipment shown in FIG. 1 is put on board the aircraft, the target region is imaged and the flight information is recorded while flying over the target region at as constant an altitude and speed as possible (S1). At this time, the imaging target basically moves perpendicular to the scan lines of the camera 10. The images captured by the camera 10 are recorded on videotape by the VTR 14. At the same time, information on the exact position (latitude, longitude, height) and orientation of the camera 10 is

recorded on a floppy disk 42 along with the time codes from the VTR 14. The time codes are used during analysis on the ground for synchronizing the position and orientation of the camera with the reproduced images.

**[0025]** The position of the camera is known basically from the GPS position measurement data that is output from the GPS receiver [sic] 32, and for sake of better precision undergoes differential processing with the GPS correction data from the reference station. The differential processing may be done aboard the aircraft, but in consideration of such factors as bad communication of the GPS correction data, it is preferable to record the output of the GPS receiver 32 (the GPS position measurement data) and the GPS correction data separately on a floppy disk 42, and to do the differential processing during analysis on the ground. When there has been bad communication of the GPS correction data, then the GPS position measurement data undergoes differential processing with the GPS correction data that has been recorded and saved by way of the on-the-ground measurement system shown in FIG. 2.

**[0026]** With regard to the orientation of the camera 10, values wherein the output of the gyro sensors of the anti-vibration stabilizing device 12 have been corrected by the output of the magnetic bearing sensor 28 are recorded to the floppy disk 42. Specifically, the orientation of the three axes (pitch, roll, and yaw) is recorded on the floppy disk. Of course, the orientation of the camera 10 may be fixed for sake of simplicity, or if the performance of the anti-vibration stabilizing device 12 is good, or if simplification is acceptable.

**[0027]** In this connection, the imaging altitude is set to 1000 feet, and with a Hi-Vision camera that uses a 2-million-pixel CCD image sensor, if the focal length is 8.5 mm, the imaging range is 339 m and the resolution is 17.7 cm, and if the focal length is 102.0 mm, the imaging range is 28 m and the resolution is 1.5 cm.

**[0028]** The recorded information (image and flight information) is reproduced and analyzed by the on-the-ground analysis system shown in FIG. 3. As described above, in accordance with the information during imaging from the computer 80 (the camera position and bearing, and the time codes), the workstation 76 controls the VTR 70 and causes it to play back images with the same time code. The reproduced image signals are digitized and stored in the frame buffer 74. In this way, the workstation 76 can obtain image data as well as data on the position and orientation of the camera during imaging, and outputs DEM data after going through the various processing of orientation calculation (S2), continuous mosaic image formation (S3), vertical parallax



removal (S4), parallax difference calculation, and DEM creation.

**[0029]** The orientation calculation (S2) will be described. In photogrammetry, if a three-dimensional measurement is to be made from two stereo images, it is necessary to have accurate orientation elements for each image. Orientation elements include exterior orientation elements, which are made up of the position and tri-axial orientation of the camera when capturing images, and interior orientation elements, which are made up of the camera principal point shift, lens distortion coefficient, film flatness, and the like. Interior orientation elements for which there could be individual differences from one camera to another can be measured beforehand.

**[0030]** Exterior orientation elements can be determined by general photogrammetry techniques such as the following. That is to say, based on flight information that is recorded at the same time video images are captured, and specifically, the position and orientation of the camera 10, scenes (in this working example, field images) can be extracted from the captured images so that the overlap percentage is 60% (or roughly 60%). For example, in the example shown in FIG. 5, scene #2 overlaps scene #1 by 60%, and scene #3 overlaps scene #2 by 60%. Scene #3 overlaps also scene #1 by 20%. The field number of the extracted scene is needed for the exterior orientation element interpolation processing in the vertical parallax removal processing that is described below, and is therefore recorded in an auxiliary storage device (for example, a hard disk device), which is not shown in the drawings, in association with the exterior orientation elements of each extracted scene.

**[0031]** But because sensor error and topography height influences are involved, the overlapping parts of the three scenes extracted in accordance with the flight information will seldom match exactly. Thus, in practice, the overlapping parts are established as follows. That is to say, as shown in FIG. 6, multiple matching regions are set in the overlapping parts of each scene, and points in common within the matching regions of the scenes are calculated by a matching technique such as the sequential similarity detection algorithm or the cross-correlation coefficient method or the like. This calculation can of course be automated, and these points in common are called pass points.

**[0032]** A pair consisting of two images that make up a stereoscopic image is called a model; determining the relationship of relative position and orientation from the coordinates of the pass points of the overlapping parts is called relative orientation; and joining multiple models together for transformation into a unified course coordinate system based on the pass points that a plurality of models have mutually in common is called successive orientation. The relationship between relative orientation and successive orientation is shown in FIG. 7.

**[0033]** The models can be transformed into a unified course coordinate system by repeatedly performing the above relative orientation and successive orientation with a series of captured images. The flight information recorded during video imaging (exterior orientation elements) includes measurement errors and fluctuations that depend on the measurement system, but by way of orientation calculation such as this (relative orientation and successive orientation), the values of the exterior orientation elements can be established with high precision.

**[0034]** By way of the foregoing, the orientation calculation (S2) is ended and, next, continuous mosaic images are created (S3). The relationship between the camera imaging plane (CCD plane) and the on-the-ground imaging range is as in FIG. 8. As is well known, video images are made up of 30 frames per second, and one frame consists of two fields, an odd field and an even field. Odd fields and even fields are arranged displaced from each

other so that the scan lines do not overlap, and are displayed in alternation every 1/60 second.

**[0035]** That is to say, the video images captured by the camera 10 are made up of scenes (fields) in which the imaging position is changed every 1/60 second; in this working example, as shown in FIG. 9, line data for the leading line, the middle line, and the final line of each field are extracted therefrom. The image formed from the data of the leading line of each field is called the forward view image, the image formed from the data of the middle line of each field is called the nadir view image, and the image formed from the data of the final line of each field is called the rearward view image. If the travel speed when imaging is constant, and the orientation of the camera is also constant, stereoscopic viewing is possible using this forward view image, this nadir view image, and this rearward view image. Note that lenses of short focal length may be used to emphasize height, which is to say, to increase the resolution.

**[0036]** However, in video imaging with an aircraft, there are the variable factors of changes in the flying speed, flight path deviations, changes in the flying altitude, and changes in the three axes (pitch, roll, and yaw), and it is necessary to remove the vertical parallax that arises from these influences (S4).

**[0037]** In the vertical parallax removal processing (S4), first, based on the exterior orientation elements of the images with a 60% overlap percentage obtained in the orientation calculation (S2), the values of the exterior orientation elements corresponding to each of the line data in the continuous mosaic images (forward view image, nadir view image, and rearward view image) are interpolated. For example, as shown in FIG. 10, where the exterior orientation elements, which is to say, the position and orientation of the camera, at three imaging points P, Q, R, are, respectively,  $(X_p, Y_p, Z_p, \omega_p, \phi_p, \kappa_p)$ ,  $(X_q, Y_q, Z_q, \omega_q, \phi_q, \kappa_q)$ , and  $(X_r, Y_r, Z_r, \omega_r, \phi_r, \kappa_r)$ , in the continuous mosaic image, the values of these exterior orientation elements are assigned to the lines that correspond to the nadir view image at the imaging points P, Q, R, and interpolated values are assigned to other lines. In this way, as shown in FIG. 11, exterior orientation elements  $(X_i, Y_i, Z_i, \omega_i, \phi_i, \kappa_i)$  are assigned to each line of the continuous mosaic image.

**[0038]** In this working example, because use is made of computation software [intended for] photogrammetry, the coordinate system of the video image is transformed into a coordinate system for single photographs in ordinary photogrammetry, as shown in FIG. 12. Which

**[0039]**

is to say,  $(u, v)$  in the image coordinate system is transformed to  $(x, y)$  in the photograph coordinate system, as shown in **[Num. 1]**.

**[0040]**

**[Num. 1]**

$$x = (u - u_0) \times x_C$$

$$y = (v - v_0) \times y_C$$

where  $u_0$  and  $v_0$  are middle image coordinate values of the video

image, and  $x_c$  and  $y_c$  are the lengths per pixel in the x and y directions in the CCD image formation plane.

[0041] Then, the photograph coordinate system is transformed into an on-the-ground coordinate system. Between (x, y) in the photograph coordinate system and (X, Y, Z) in the on-the-ground coordinate system is the geometric relationship shown in FIG. 13, and the conversion formula is expressed by the following formula.

[0042]

[Num. 2]

$$\begin{cases} x = -f \frac{a_{11}(X-X_0) + a_{12}(Y-Y_0) + a_{13}(Z-Z_0)}{a_{31}(X-X_0) + a_{32}(Y-Y_0) + a_{33}(Z-Z_0)} \\ y = -f \frac{a_{21}(X-X_0) + a_{22}(Y-Y_0) + a_{23}(Z-Z_0)}{a_{31}(X-X_0) + a_{32}(Y-Y_0) + a_{33}(Z-Z_0)} \end{cases}$$

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \omega & -\sin \omega \\ 0 & \sin \omega & \cos \omega \end{bmatrix} \begin{bmatrix} \cos \phi & 0 & \sin \phi \\ 0 & 1 & 0 \\ -\sin \phi & 0 & \cos \phi \end{bmatrix} \begin{bmatrix} \cos \kappa & -\sin \kappa & 0 \\ \sin \kappa & \cos \kappa & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

[0046] Therefore,

[0047]

[Num. 4]

$$\begin{cases} a_{11} = \cos \phi \cdot \cos \kappa \\ a_{12} = -\cos \phi \cdot \sin \kappa \\ a_{13} = \sin \phi \\ a_{21} = \cos \omega \cdot \sin \kappa + \sin \omega \cdot \sin \phi \cdot \cos \kappa \\ a_{22} = \cos \omega \cdot \cos \kappa - \sin \omega \cdot \sin \phi \cdot \sin \kappa \\ a_{23} = -\sin \omega \cdot \cos \phi \\ a_{31} = \sin \omega \cdot \sin \kappa - \cos \omega \cdot \sin \phi \cdot \cos \kappa \\ a_{32} = \sin \omega \cdot \cos \kappa + \cos \omega \cdot \sin \phi \cdot \sin \kappa \\ a_{33} = \cos \omega \cdot \cos \phi \end{cases}$$

[0048]

The reverse transformation formula of [Num. 2] is as follows.

That is to say,

[0049]

[Num. 5]

$$\begin{cases} X = (Z - Z_0) \frac{a_{11}x + a_{21}y - a_{31}f}{a_{13}x + a_{23}y - a_{33}f} + X_0 \\ Y = (Z - Z_0) \frac{a_{12}x + a_{22}y - a_{32}f}{a_{13}x + a_{23}y - a_{33}f} + Y_0 \end{cases}$$

[0050]

The unknown variables in [Num. 2] and [Num. 5] are the six

[0043] Here, f is the principal distance, and (X<sub>0</sub>, Y<sub>0</sub>, Z<sub>0</sub>) are the on-the-ground co

[0044] ordinates [sic] of the projection center O of the photograph.

[The expressions in] [Num. 2] are known as collinearity equations. The nine coefficients a<sub>11</sub> to a<sub>33</sub> are determined by Num. 3 from the orientation (ω, φ, κ) of the camera projection axes. [The symbols], ω, φ, κ denote the angles of rotation about the X axis, the Y axis, and the Z axis, respectively, and a rightward turning toward the positive direction of each axis is taken as positive.

[0045]

[Num. 3]

[variables consisting of] the on-the-ground coordinates (X<sub>0</sub>, Y<sub>0</sub>, Z<sub>0</sub>) of the projection center of the photograph, and the orientation (ω, φ, κ) of the imaging axis. These six unknown variables are exterior orientation elements, and for each line the photograph coordinate system can be transformed into the on-the-ground coordinate system based on the exterior orientation elements for each line that were determined above.

[0051] [Num. 5] is applied to continuous mosaic images that have been transformed in this way to the on-the-ground coordinate system, and as shown in FIG. 14, an image is created from which the vertical parallax has been removed (S4). That is to say, using the exterior orientation elements that were determined above for each line, the coefficients a<sub>11</sub> to a<sub>33</sub> are determined, and by applying

[Num. 5] to the continuous mosaic im

[0052] age [sic] forward view image, nadir view image, and rearward view image, images are created that are projected onto an elevation of 0 m. At this time, the size of one pixel of the image that is created is set to an optimum value, calculating from the imaging altitude, the camera focal length, the CCD length of one pixel in the video image, and the like.

[0053] Even if the size of one pixel in the output image is set to the optimum value, there are cases in which a missing-pixel spot will occur due to changes in the flight speed or imaging direction during video imaging. This is interpolated (*naisou*) or interpolated (*hokan*)<sup>1</sup> from neighboring pixels by filter processing. Interpolation techniques include nearest-neighbor interpolation, in which the value of the observation point that is closest to the point to be interpolated is used as-is, bilinear interpolation, which takes the value [resulting from] determining

<sup>1</sup> Two exact synonyms, both meaning "interpolation" are used in the original Japanese text. -- trans.



the mean value of the values of four observation points around the point to be interpolated, and cubic convolution interpolation, in which cubic convolution processing is applied to the values of 16 observation points around the point to be interpolated.

**[0054]** Nearest-neighbor interpolation gives rise to position errors of up to half a pixel, but has the advantage that no original image data is destroyed, and the algorithm is simple. Bilinear interpolation has the disadvantage that original data is destroyed but has the advantage that the averaging produces a smoothing effect. Cubic convolution interpolation has the disadvantage that original data is destroyed, but has the advantage that the image can be made both smoother and sharper. Which interpolation method to apply, either overall or in part, may be selected according to the purpose, and by looking at the final result.

**[0055]** The parallax difference is calculated from the images from which vertical parallax has been removed (S5). In calculating the parallax difference, an automatic stereo matching technique is used. In this working example, as shown in FIG. 15, the images from which vertical parallax has been removed are rearranged so that the imaging direction of the images from which vertical parallax has been removed becomes a direction that is orthogonal to the horizontal scan lines, then images for stereo matching, which is to say, matching images, are created. By doing so, not only can the following processing be speeded up, but the volume of memory needed for the processing can be reduced as well.

**[0056]** A template image (for example,  $N \times N$  pixels) for calculating height is set on the forward view image of the matching images that were obtained by the above processing, and an image that is similar to this template image is searched for among other matching images, which is to say, within a prescribed search range in the rearward view image or the nadir view image. In this working example, the vertical parallax is removed beforehand, so it suffices that the search range be only in the direction orthogonal to the horizontal scan lines. If a match is found, the difference in the positions, which is to say, the parallax difference, is calculated.

**[0057]** Mosaic images that are formed from data from lines that are adjacent in the video image field will be extremely similar, but the farther apart the extracted lines are, the more different the viewing directions of the resulting mosaic images will be, and the greater the matching error will be, even with an optimal match. Thus, in this working example, even in cases where stereo matching is done between the forward view image and the rearward view image, mosaic images are formed from intermediate lines (of course, the vertical parallax is removed as well), and corresponding points are sequentially searched for. In this way, the effect of occlusion can be eliminated, and corresponding points can be detected with high precision.

**[0058]** This is explained taking as an example the object shown in FIG. 17, which has the shape of the frustum a square pyramid. FIG. 18 shows the correspondence between the extracted lines in the captured image when this object is video imaged, and the mosaic images (vertical parallax already removed) that result from combining the lines. FIG. 18 (1) is the case in which the leading line and final line are extracted; (2) in the same is the case in which lines that are farther inward are extracted; (3) in the same is the case in which lines even farther inward are extracted; and (4) in the same is the case in which adjacent lines in the approximate center are extracted. Thus, in this working example, in addition to the original forward view image F1 and rearward view image R1, there are intermediate forward view images F2, F3, F4 and rearward view images R2, R3, R4. The nadir view image may be used

instead of the intermediate forward view picture [sic] F4 and the rearward view image R4.

**[0059]** Needless to say, either fewer or more intermediate images F2, F3, F4, R2, R3, R4 may be set, as needed. The appropriate number may be set according to the results of trial matching computations.

**[0060]** When searching in the rearward view image R1 for a point that corresponds to point A in the forward view image F1, first, a search is made for a point corresponding to point A in the intermediate forward sight line [sic] image F2. Because the sight lines of image F1 and image F2 are only slightly shifted, the corresponding points can be searched for with high precision, even with automatic stereo matching. The template that includes the corresponding point searched for in image F2 [is] set [as] an image, and the corresponding point is searched for in image F3. Then, stereo matching computation is successively performed for image F4, image R4, image R3, image R2, and image R1. In this way, the point corresponding to point A in image F1 can be detected in the image R1 with high precision. If image F1 and image R1 were stereo-matched directly, because of the effect of occlusion, it would be impossible to avoid large errors caused by objects, but in this working example the effect of occlusion can be completely removed by such successive searching.

**[0061]** Here the intermediate images were created beforehand, but a corresponding point may also be searched for, by way of binary searching, by successively creating intermediate images while executing matching computation for parallax difference calculation, until the matching error goes to or below an allowable value. For example, if in matching processing with a rearward view image there is a matching error greater than or equal to the allowable value, a mosaic image extracted from intermediate lines is formed (of course, the vertical parallax is removed as well), and matching computation is done on that mosaic image. Here, if the corresponding point is found with no less than a certain precision, then taking this corresponding point that has been found as a reference, the corresponding point is searched for by way of matching processing in the rearward view image. If there is a matching error at or above the allowable value, even in the intermediate mosaic image, then a mosaic image is made that is extracted from further intermediate lines, and matching computation is done on this mosaic image. By such repeated processing, a corresponding point is ultimately detected between the forward view image and the rearward view image. By operating in [this manner<sup>2</sup>], the effect of occlusion is completely eliminated, and corresponding points can be detected with high precision.

**[0062]** In any case, for the intermediate images, one may form only the parts that are needed for matching computation. In this manner, the time for matching computation can be shortened, and a small memory capacity will suffice for storing intermediate image data.

**[0063]** Next, in order to create a DEM (Digital Elevation Model), the height can be calculated from the parallax difference according to the following formula. That is to say,

**[0064]**

**[Num. 6]**  $h = d \times H / B$

where  $h$  is the height (m) to be determined,  $d$  is the parallax difference (m),  $B$  is the base length (m), and  $H$  is the imaging

<sup>2</sup> *There is an untranslatable typographical error in the original Japanese text. -- trans.*

altitude (m). FIG. 19 shows the relationship between parallax difference and height.

**[0065]** Where the length of the image formation plane of the CCD imaging elements of the camera 10 is  $c_1$  (mm), the length per pixel in the CCD image formation plane is  $dc$  (mm), and the focal length is  $f$  (m), when the height is determined from the parallax difference based on the forward view image and the rearward view image, this is

**[0066]**

**[Num. 7]**  $h = dx \cdot f / (c_1 - dc)$ ,

and when the height is determined from the parallax difference based on the forward view image, or rearward view image, and the nadir view image, this is

**[0067]**

**[Num. 8]**  $h = dx \cdot 2 \cdot f / (c_1 - dc)$ .

**[0068]** The precision of the height is determined by the B/H ratio, but can be freely set by varying the focal length of the camera 10 during imaging.

**[0069]** When the height data has been obtained, data is detected, by a median filter or the like, which has particularly more ups-and-downs than the surrounding data, and this is corrected by way of the surrounding data.

**[0070]** By way of the above processing, height data can be computed, and three-dimensional data can be obtained, for desired regions within the imaging target.

**[0071]** In this working example, there is no need to set up air-photo signals and perform survey work to measure the positions of the same, and thus exploration can be conducted rapidly in any region. Also, three-dimensional topographical maps can be made even for regions of danger where people cannot enter (such as areas subject to landslides, rockslides, and volcanic eruptions). And because the orientation calculation is automated, analysis processing can proceed quickly. The height precision can be freely set by varying the focal length of the camera 10.

**[0072]** The present invention can be used not just for preparing three-dimensional topographical maps but also for such purposes as disaster prevention information collection systems, route planning for railroads, highways, and the like, and erosion studies along seashores and riverbanks.

**[0073]** A brief description will be given of the matching method used in orientation calculation (S2) and parallax difference calculation (S5). As described above, conventionally used matching methods include the sequential similarity detection algorithm and the cross-correlation coefficient method.

**[0074]** First, a description will be given of the sequential similarity detection algorithm. As shown in FIG. 20, an  $N \times N$ -pixel template image is moved in a search range  $(M - N + 1)$

**[0075]** <sup>2</sup> [sic] within a larger  $M \times M$ -pixel input image, and it is deemed that superimposition has been reached at the position where the remainder of **[Num. 9]** is minimal

**[0076]**

**[Num. 9]**

$$R(a, b) = \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} |I(a, b)(m, n) - T(m, n)|$$

**[0077]** Here,  $(a, b)$  indicates the upper left position of the template image within the input image,  $I(a, b)(m, n)$  is a partial image of the input image,  $T(m, n)$  is the template image, and  $R(a, b)$  is the remainder of the input image partial image and the template image.

**[0078]** If the superimposition is off, the remainder suddenly increases when sequential addition is performed for each pixel.

Thus, if the remainder exceeds a given threshold value during addition, it is judged that the superimposition is not good, the addition is discontinued, and the next  $(a, b)$  is moved on to. This is the sequential similarity detection algorithm (hereafter abbreviated to the SSDA method). In the SSDA method, which was proposed by Barnea *et al.*, the problem was how to give the threshold value. On this point, Onoue *et al.* have proposed an automatic threshold value determination method, which is discussed below.

**[0079]** In the automatic threshold value determination method proposed by Onoue *et al.*, the minimum value of past remainders is adopted as a provisional threshold value. Note that, initially, with no threshold value, addition is carried out until the end, and the resulting remainder is taken as the initial threshold value. Thereafter, and until the end, every time addition is carried out without exceeding a threshold value, the remainder is taken as the new threshold value. This method guarantees that the true minimum value is reached at all times.

**[0080]** The SSDA method can greatly shorten the calculation time, because it consists only of additions, which are often discontinued midway. Onoue *et al.* obtained very good results in applying this to tracking the movement of clouds, obtaining the same precision as with a method by cross-correlation coefficients, and a reduction in processing time by a factor of ten or more.

**[0081]** The cross-correlation coefficient method is described. The cross-correlation coefficient method determines the upper left position  $(a, b)$  of the template image within the input image where **[Num. 10]** is maximal.

**[0082]**

**[Num. 10]**

$$C(a,b) = \frac{\sum_{m=0}^{N-1} \sum_{n=0}^{N-1} \{I(a,b)(m,n) - \bar{I}\} \{T(m,n) - \bar{T}\}}{\sqrt{I\sigma_{ab}T\sigma}}$$

where

$$\bar{I} = \frac{1}{N^2} \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} I(a,b)(m,n)$$

$$\bar{T} = \frac{1}{N^2} \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} T(m,n)$$

$$I\sigma_{ab} = \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} \{I(a,b)(m,n) - \bar{I}\}^2$$

$$T\sigma = \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} \{T(m,n) - \bar{T}\}^2$$

**[0083]** The calculation time cannot be shortened very much with this method, because there is no discontinuation of the calculation as there is in the SSDA method. But in the field of photogrammetry, when the elevations of lattice points are measured from digital images of stereo aerial photographs and contour lines are drawn, the cross-correlation coefficient method is convenient, and is therefore often used as a method for finding corresponding points in left and right images.

**[0084]** According to this working example, three-dimensional topographical maps and the like can be created from images recorded by a high-resolution video camera instead of from the conventionally used aerial photographs, and therefore can be used in a very wide range of applications. For example, this can be used in various types of management, of roads, rivers, railroads, and the like, and if only the parts that have changed are extracted, by way of image processing, this can be used in surveys of the state of development of urban areas and the like. Furthermore, this can be used in creating three-dimensional bird's-eye views and in simulating new route plans in the completed state.

**[0085]** The description has taken as an example the imaging of the ground from a helicopter, but needless to say the present invention may also be applied to aircraft other than helicopters, and to cases in which imaging is done from an observation satellite and from vehicles that travel over the ground.

**[0086]** Also, in the above working example the forward view image was formed from the leading line of the field images while the rearward view image was formed from the final line, but it is a matter of course that these may, respectively, be the second or subsequent line, and a line that is 1 or 2 before the final line.

**[0087]**

**[Effect of the Invention]** As can easily be understood from the above description, by virtue of the present invention, basic data can be collected from video imaging while moving, and height data can be collected by way of image processing thereof. Because all or almost all of the post-imaging analysis processing can be automated, the desired three-dimensional data can be obtained quickly. Also, the three-dimensional data can be obtained at lower cost than heretofore.

**[Brief Description of the Drawings]**

**[FIG. 1]** is a schematic block diagram of the airborne measurement system of one working example of the present invention.

**[FIG. 2]** is a schematic block diagram of the on-the-ground measurement system of this working example.

**[FIG. 3]** is a schematic block diagram of the on-the-ground analysis system of this working example.

**[FIG. 4]** is a flowchart from measurement to three-dimensional data extraction in this working example.

**[FIG. 5]** is an explanatory diagram of 60% overlap scenes for orientation calculation.

**[FIG. 6]** is an explanatory diagram of relative orientation and pass points.

**[FIG. 7]** is an explanatory diagram of relative orientation and successive orientation.

**[FIG. 8]** is a diagram of the relationship between the camera imaging plane and the on-the-ground imaging range.

**[FIG. 9]** is a conceptual diagram of creating continuous mosaic images.

**[FIG. 10]** is a diagram of the relationship between continuous mosaic images and exterior orientation elements.

**[FIG. 11]** is a diagram explaining the interpolation of exterior orientation elements.

**[FIG. 12]** is a diagram describing the image coordinate system of the imaging plane and the photograph coordinate system.

**[FIG. 13]** is a diagram of the relationship between the photograph coordinate system and the on-the-ground coordinate system.

**[FIG. 14]** is an example of images before and after vertical parallax removal.

**[FIG. 15]** is an explanatory diagram of matching images for parallax difference calculation.

**[FIG. 16]** is an explanatory diagram of stereo matching for parallax difference calculation.

**[FIG. 17]** is an object model in the shape of a square pyramid frustum that is to be measured.

**[FIG. 18]** is a diagram showing the correspondence between extracted lines within an imaging screen when the object shown in FIG. 17 is video imaged, and the mosaic images (vertical parallax having been removed) that are obtained by combining the lines.

[FIG. 19] is an explanatory diagram of the relationship between parallax difference and height.

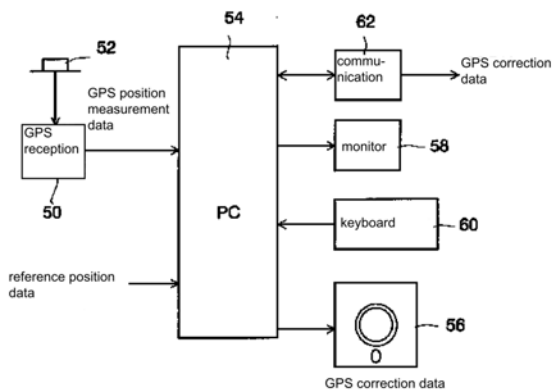
[FIG. 20] is a basic diagram of matching of input images and template images.

**[Explanation of the Reference Symbols]**

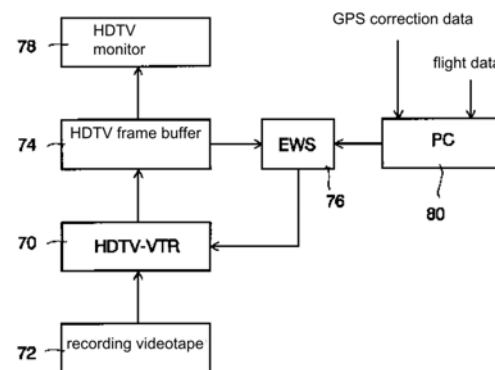
10: high-quality camera  
 12: high-precision anti-vibration stabilizing device (anti-vibration device)  
 14: high-quality video tape recorder  
 16: high-quality monitor  
 18: personal computer  
 20: three-axis control device  
 22: camera control device  
 24: VTR control device  
 26: height above ground sensor  
 28: magnetic bearing sensor  
 30: GPS antenna  
 32: GPS reception device  
 34: navigation system  
 36: floppy disk  
 38: monitor

40: communication device  
 42: floppy disk  
 44: monitor  
 46: keyboard  
 50: GPS receiver  
 52: GPS antenna  
 54: computer  
 56: floppy disk  
 58: monitor  
 60: keyboard  
 62: communication device  
 70: high-quality VTR  
 74: frame buffer  
 76: engineering workstation  
 78: monitor  
 80: personal computer  
 F1: forward view image  
 F2, F3, F4: intermediate forward view images  
 R1: rearward view image  
 R2, R3, R4: intermediate rearward view images

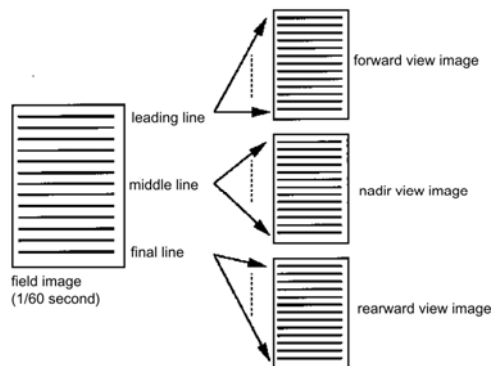
**[FIG.2]**



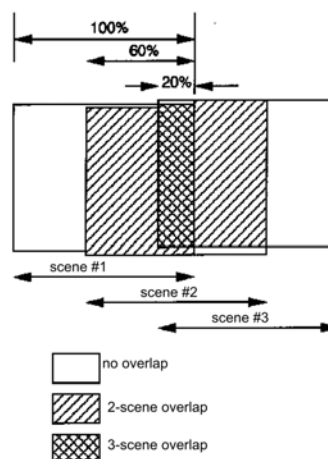
**[FIG.3]**



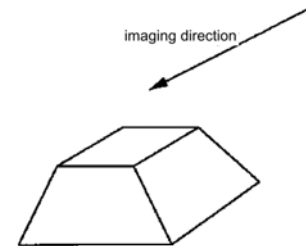
**[FIG.9]**



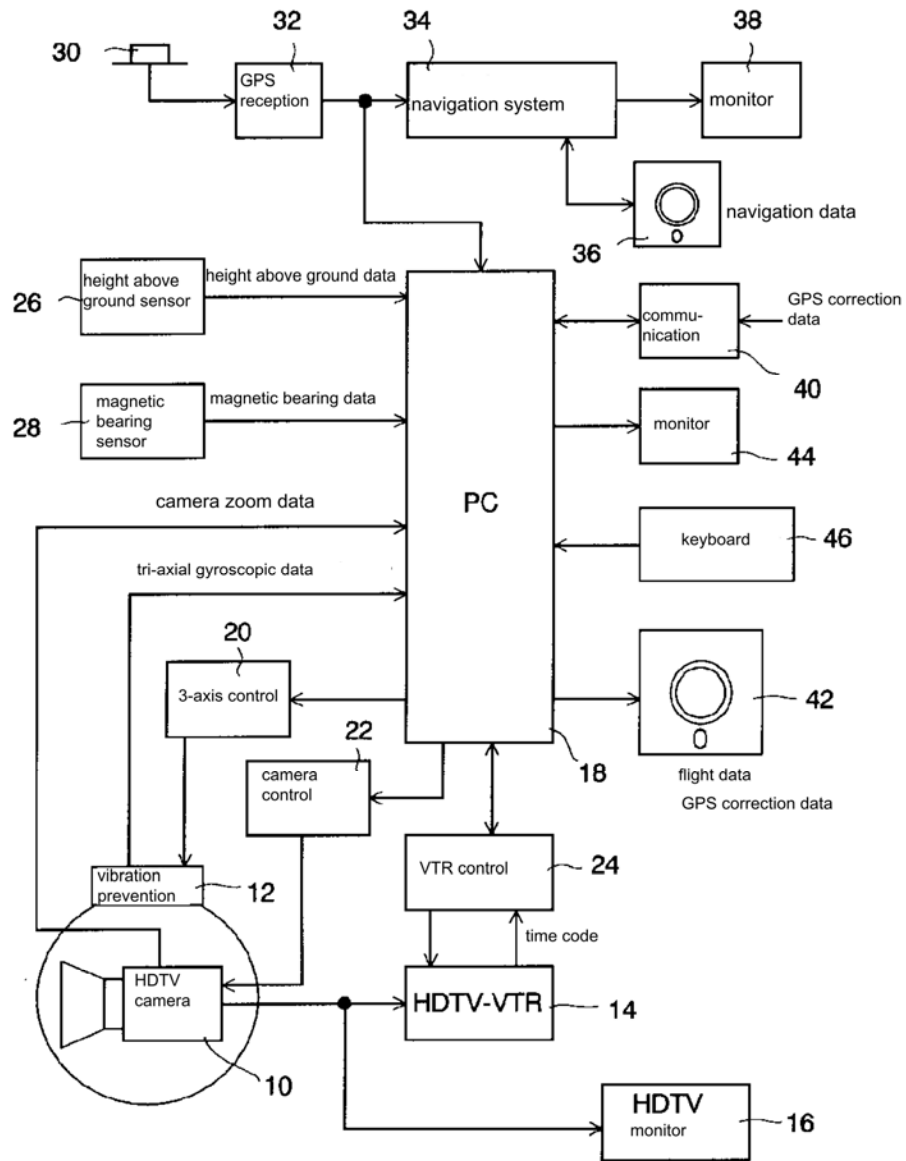
**[FIG.5]**



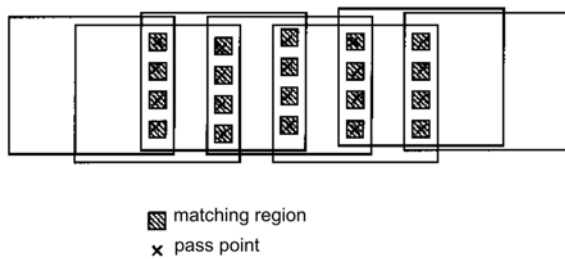
**[FIG.17]**



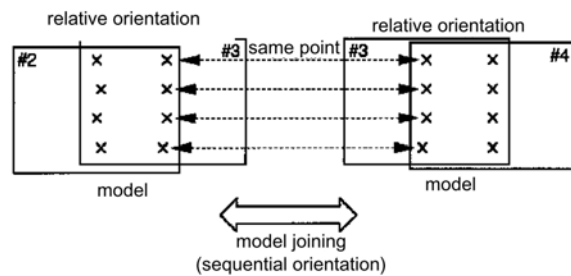
[FIG.1]



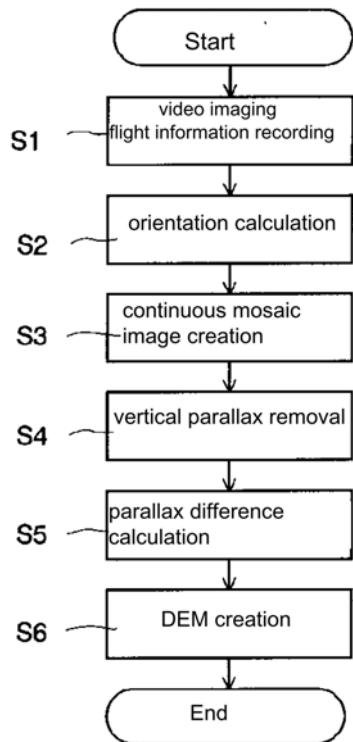
[FIG.6]



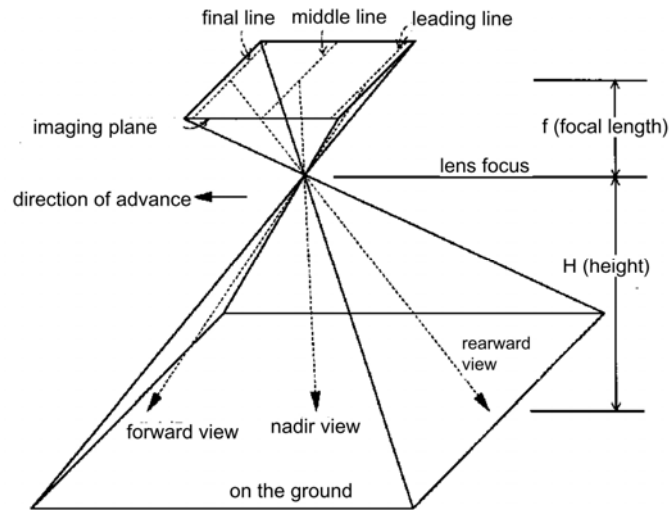
[FIG.7]



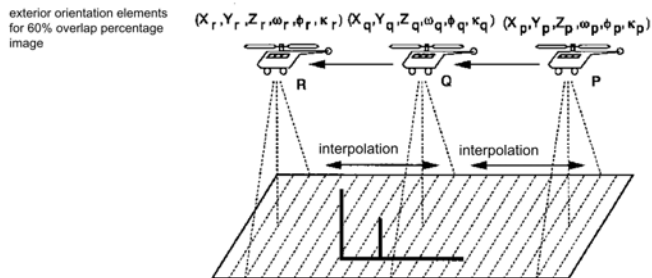
[FIG.4]



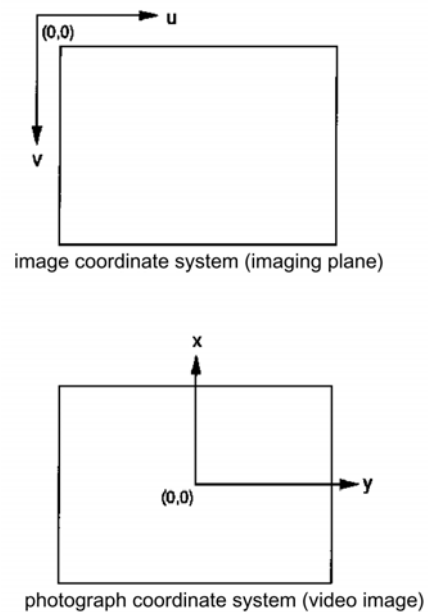
[FIG.8]



[FIG.10]

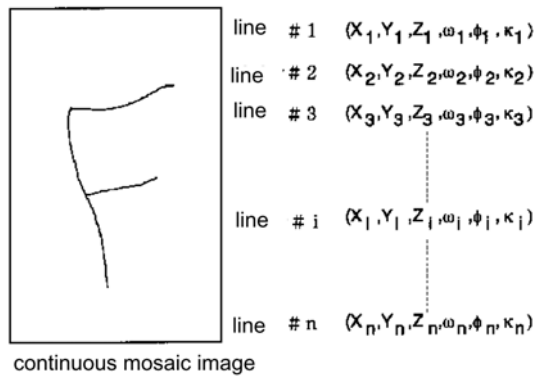


[FIG.12]

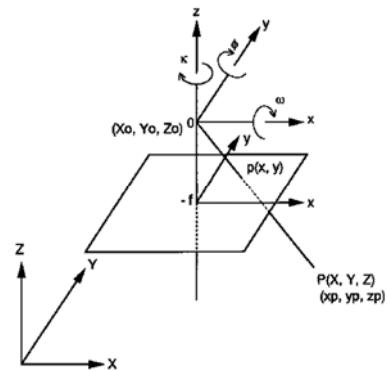




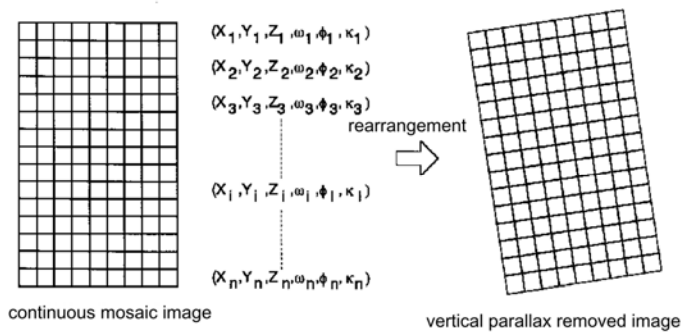
[FIG.11]



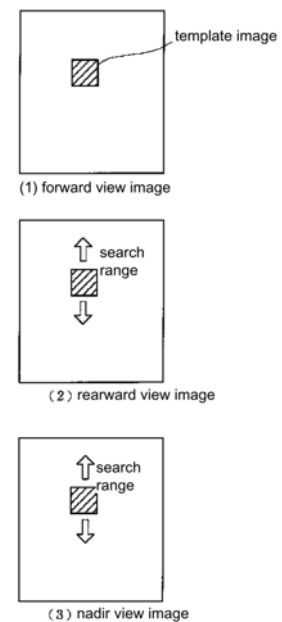
[FIG.13]



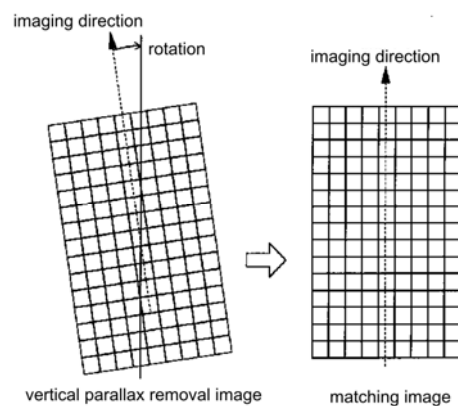
[FIG.14]

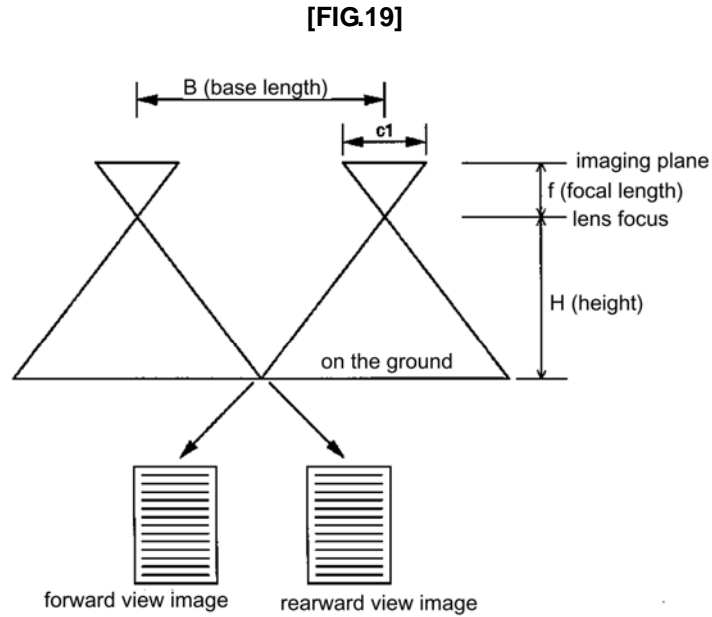
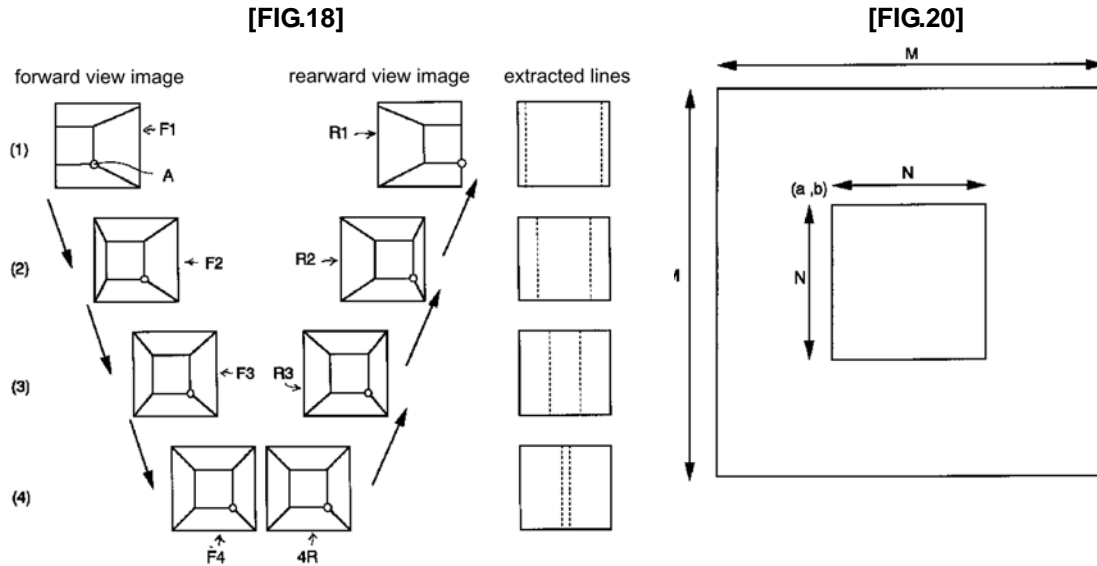


[FIG.16]



[FIG.15]





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G06T 17/00  
7/00

Identification Code

Internal File No.

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Tech. Indic.