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Beaty et al.

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[54] **APPARATUS FOR THREE DIMENSIONAL INSPECTION OF ELECTRONIC COMPONENTS**

[75] Inventors: **Elwin M. Beaty**, 13529 Arthur St., Minnetonka, Minn. 55305; **David P. Mork**, Plymouth, Minn.

[73] Assignee: **Elwin M. Beaty**, Minnetonka, Minn.

[\*] Notice: This patent is subject to a terminal disclaimer.

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[51] **Int. Cl.**<sup>7</sup> ..... **G06K 9/00**

[52] **U.S. Cl.** ..... **382/146**; 250/559.23; 250/559.31; 348/87; 348/94; 356/376; 382/151; 382/154; 702/152

[58] **Field of Search** ..... 382/145, 146, 382/147, 148, 150, 151, 154, 199; 348/87, 94, 95, 126, 131; 356/360, 376, 377, 237; 250/559.23, 559.31; 702/150, 152, 153

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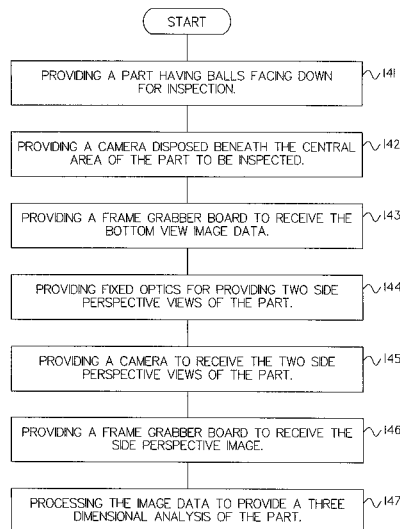
ICOS Vision Systems Product literature on BGA 3D Inspection System.

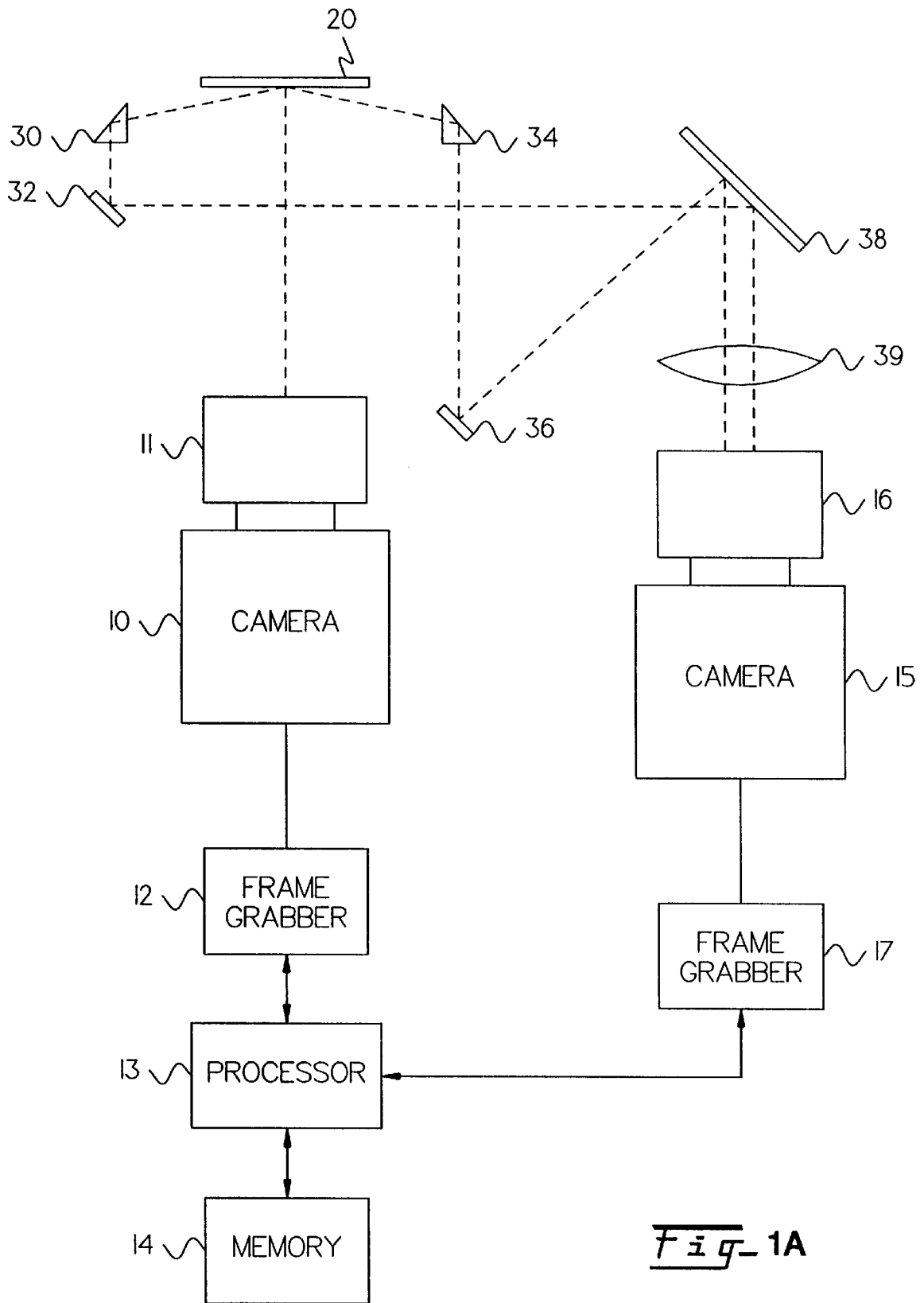
*Primary Examiner*—Bhaveshe Mehta  
*Attorney, Agent, or Firm*—George A. Leone

### [57] ABSTRACT

A three dimensional inspection apparatus for ball array devices, where the ball array device is positioned in a fixed optical system. An illumination apparatus is positioned for illuminating the ball array device. A first camera is disposed in a fixed focus position relative to the ball array device for taking a first image of the ball array device to obtain a characteristic circular doughnut shape image from a ball. A second camera is disposed in a fixed focus position relative to the ball array device for taking a second image of the ball array device to obtain a top surface image of the ball. A processor applies triangulation calculations on related measurements of the first image and the second image to calculate a three dimensional position of the ball with reference to a pre-calculated calibration plane.

**30 Claims, 26 Drawing Sheets**





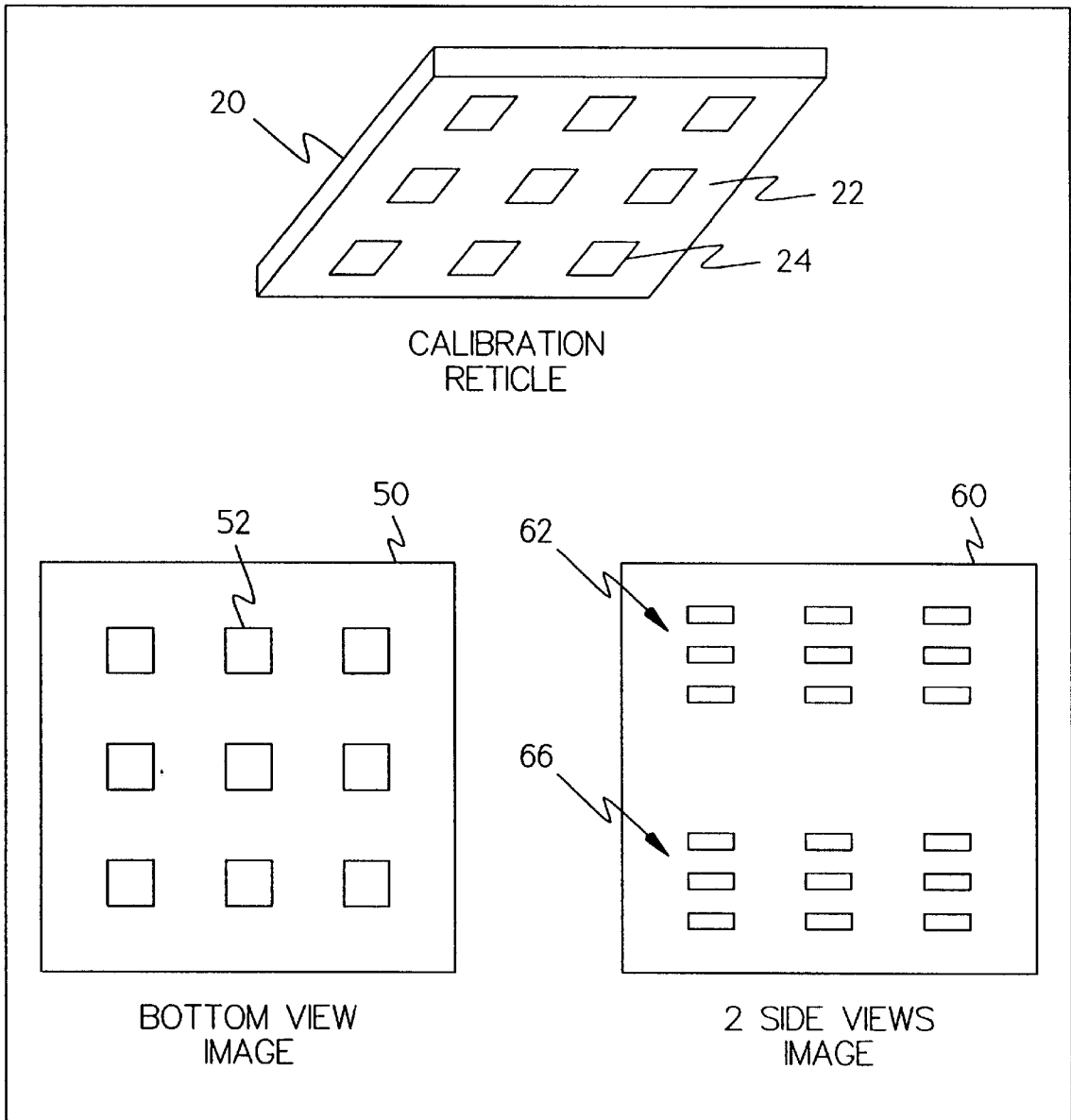


Fig. 1B

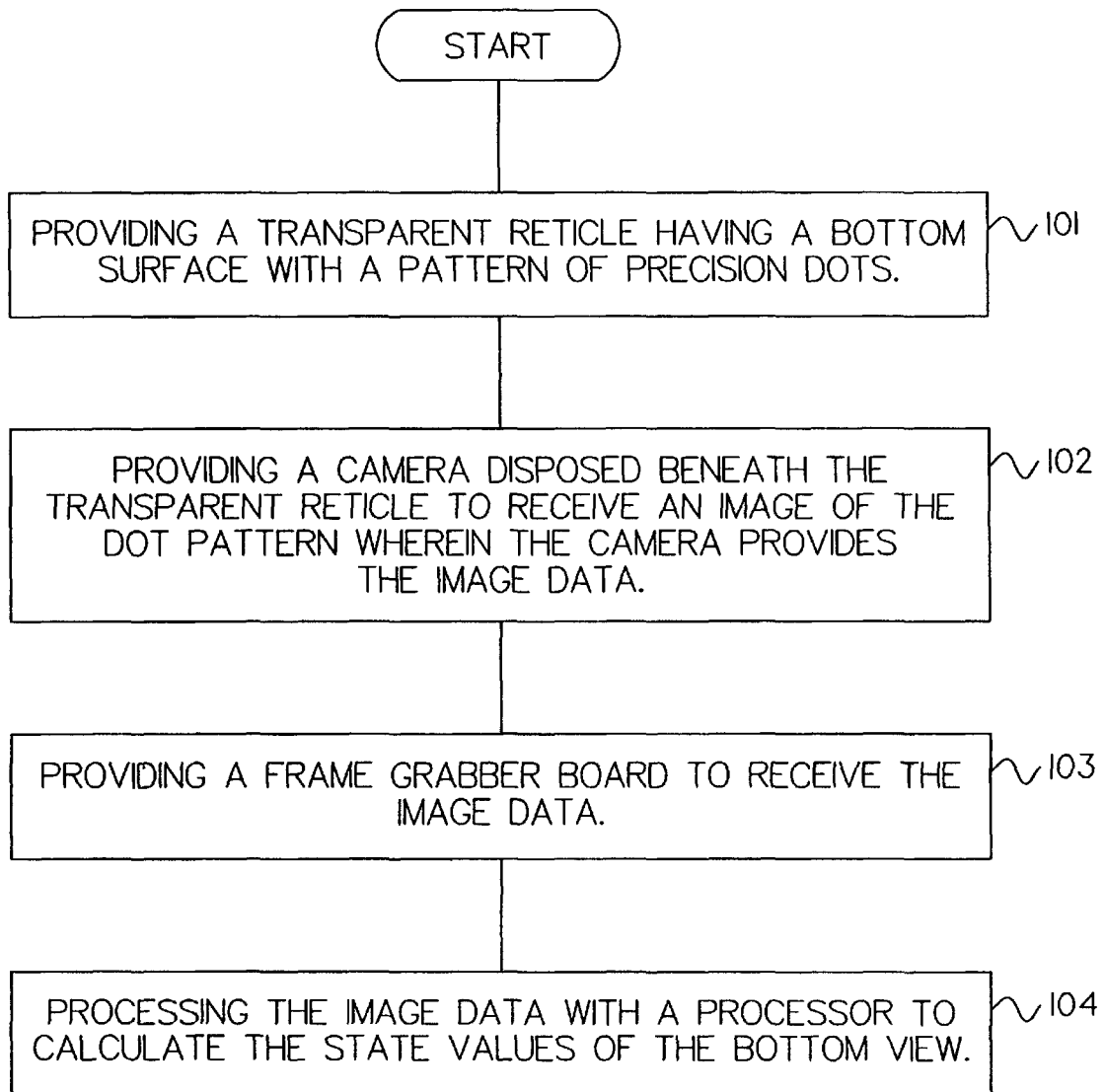


Fig. 2A

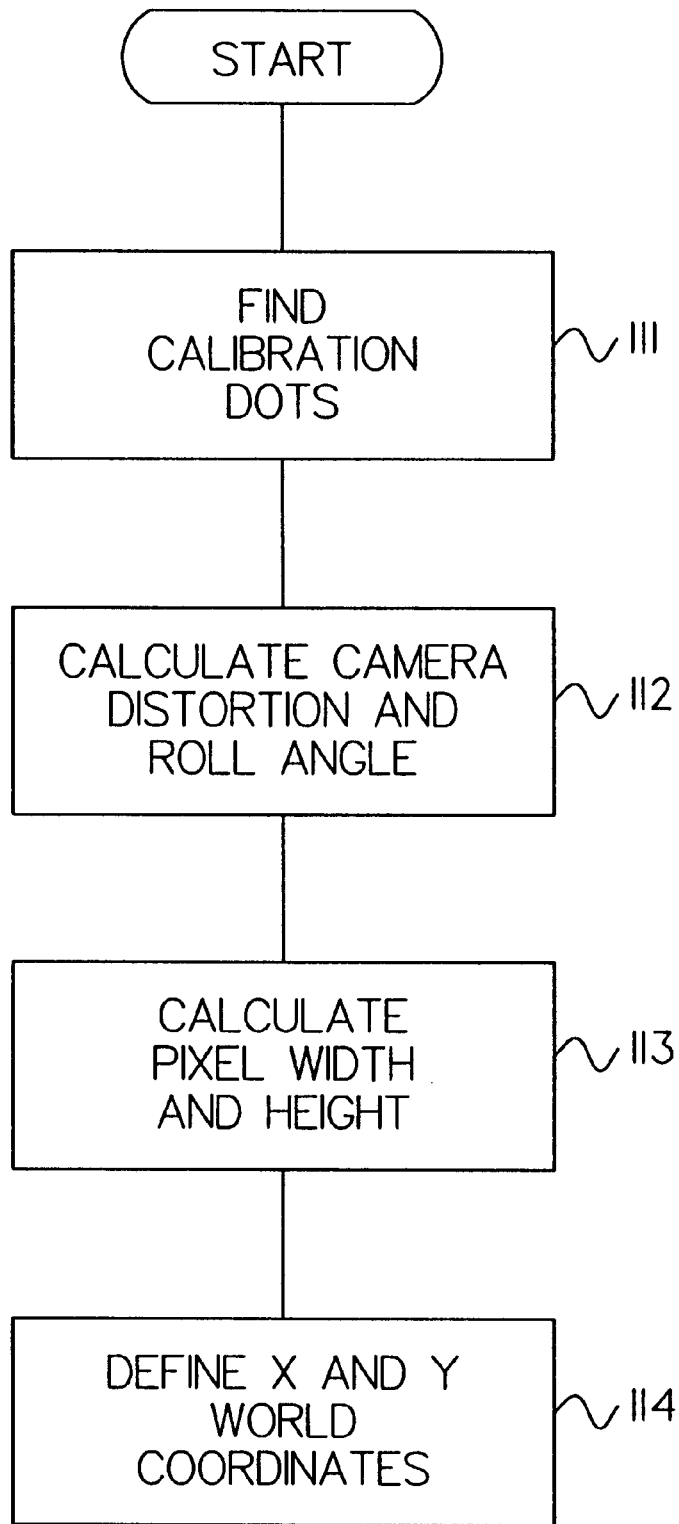


Fig. 2B

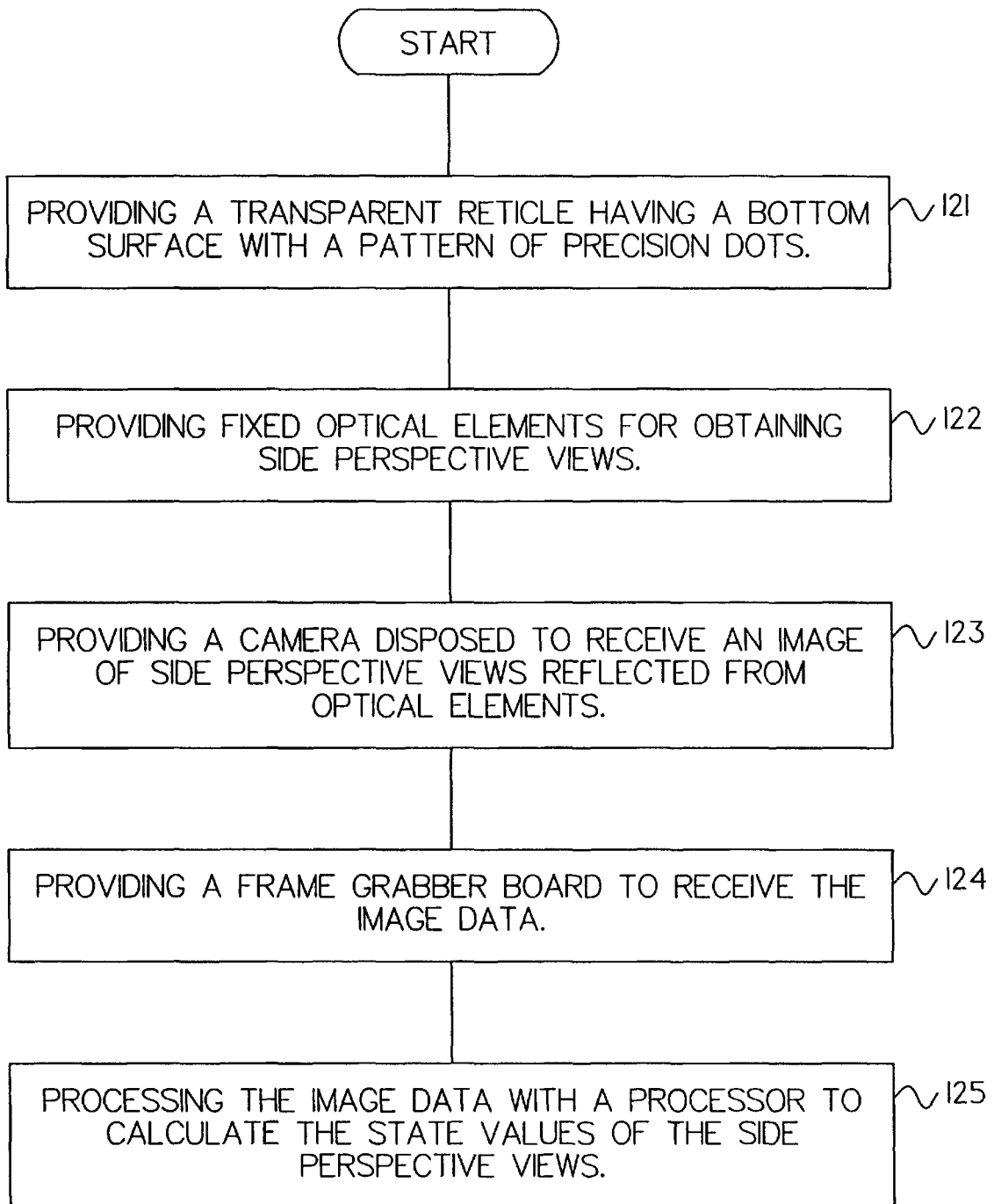


Fig-2C

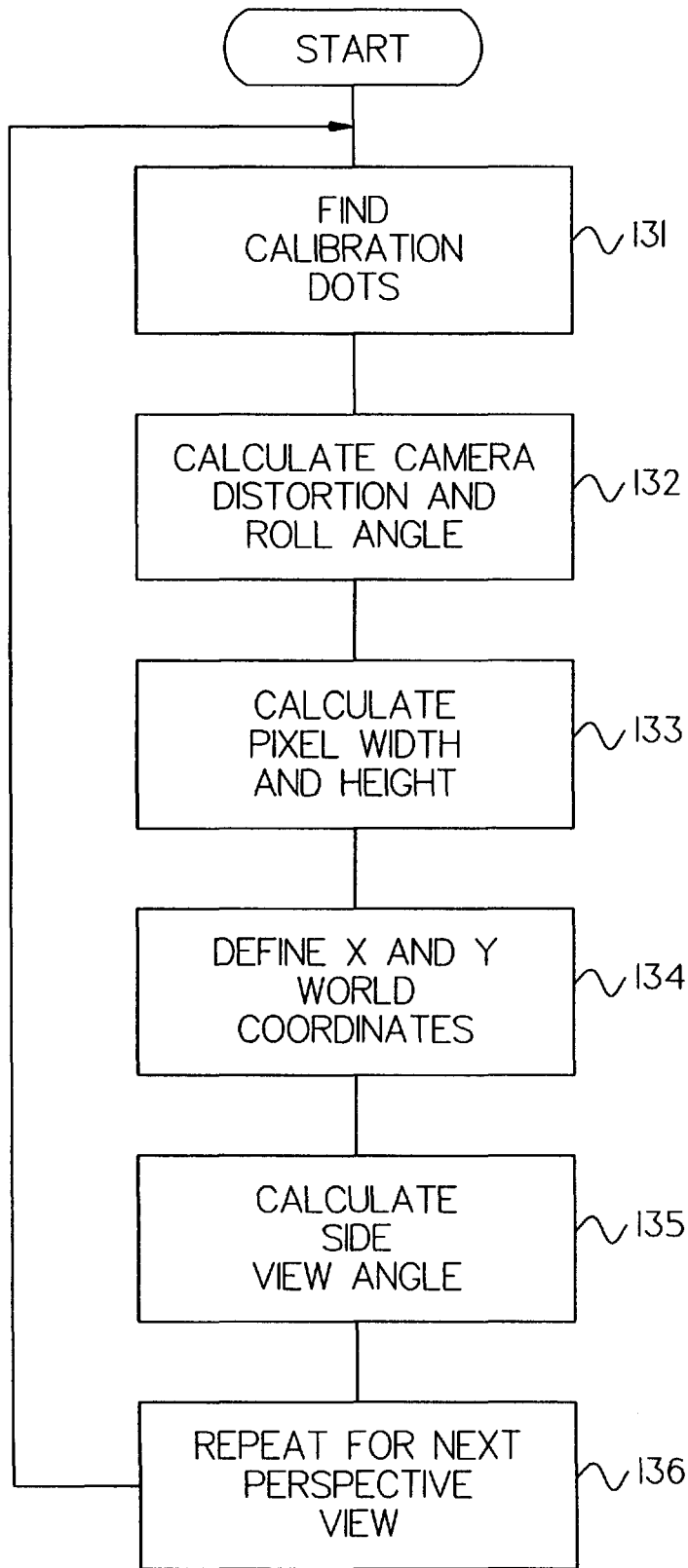


Fig. 2D





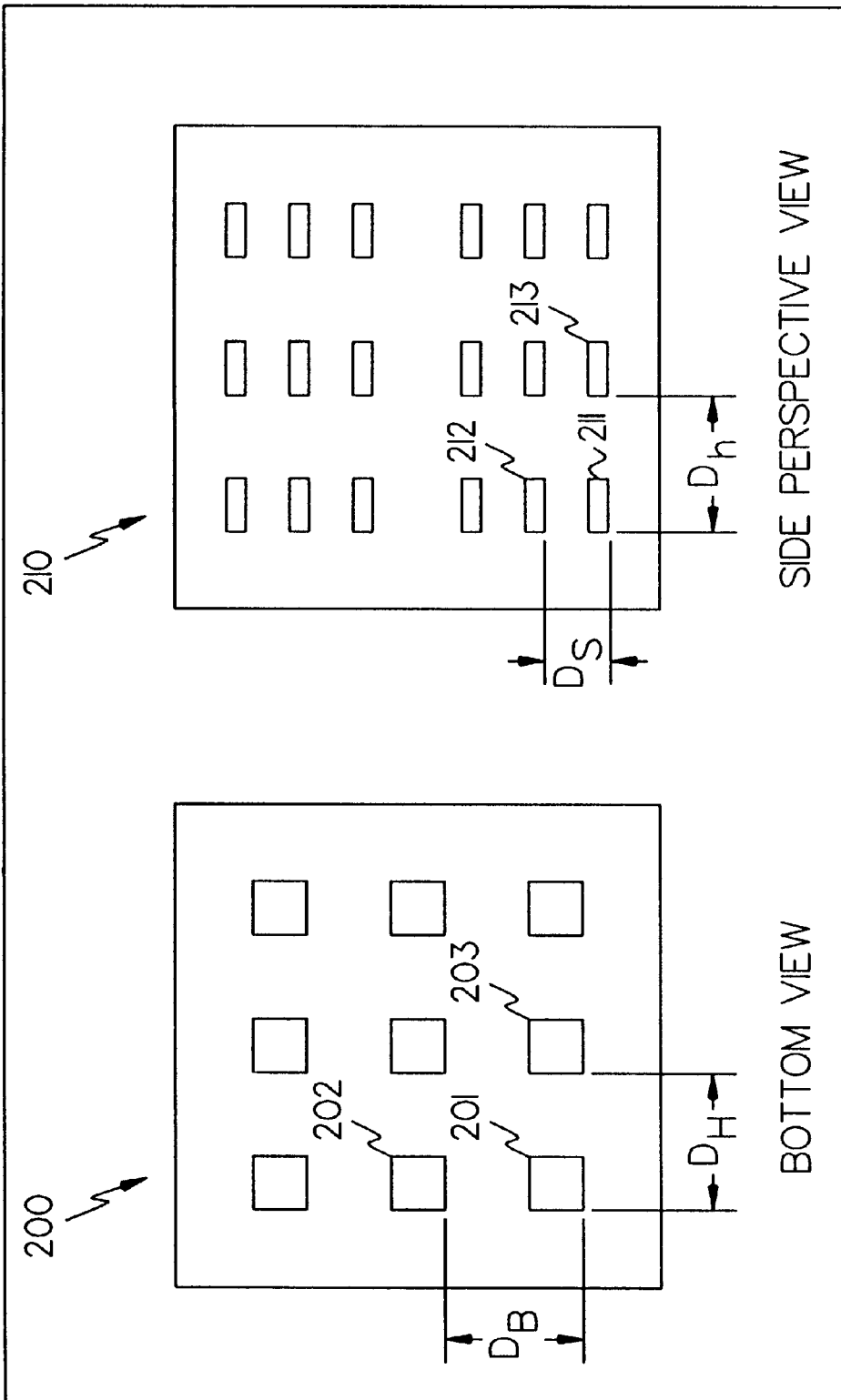
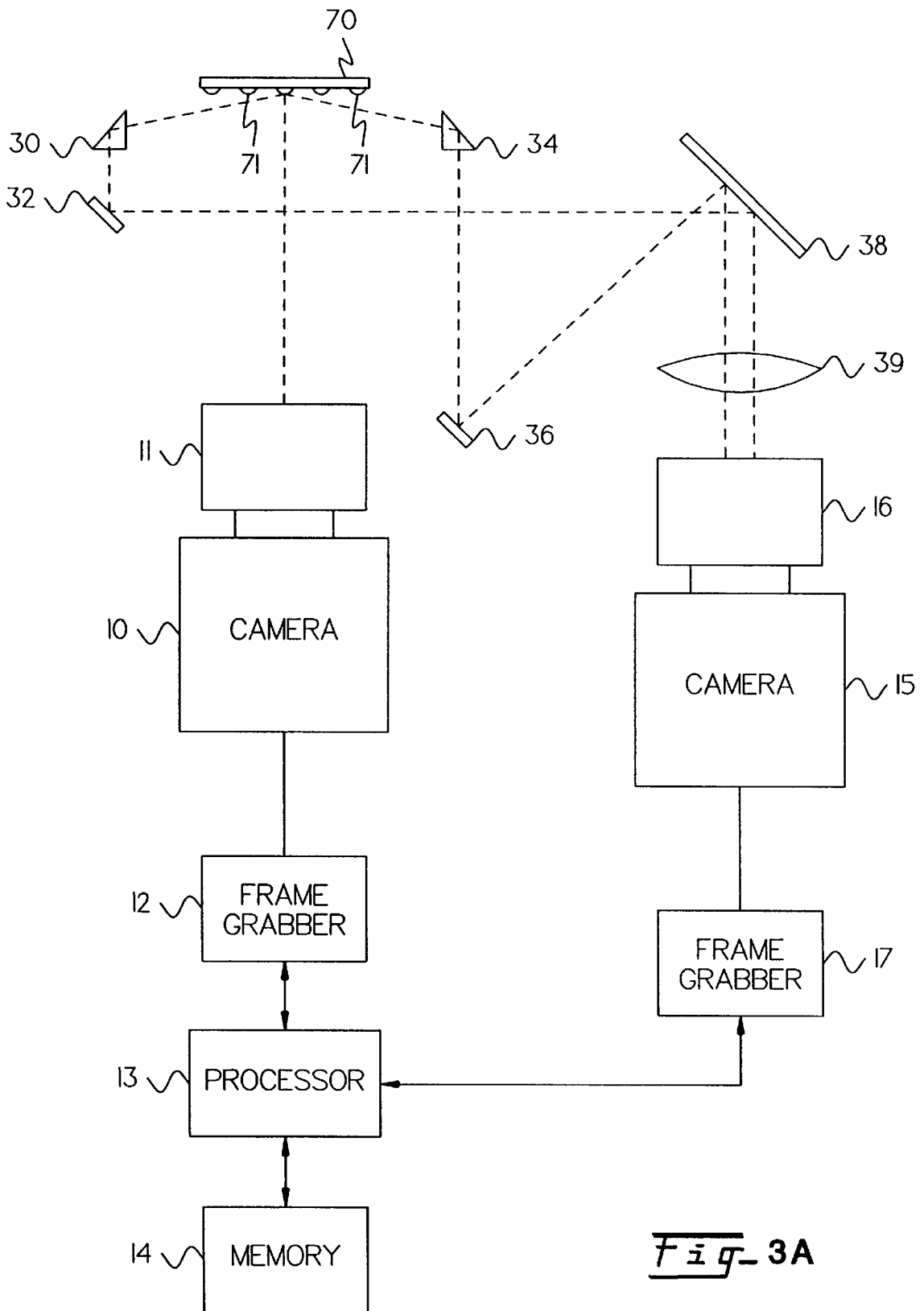


Fig-2F



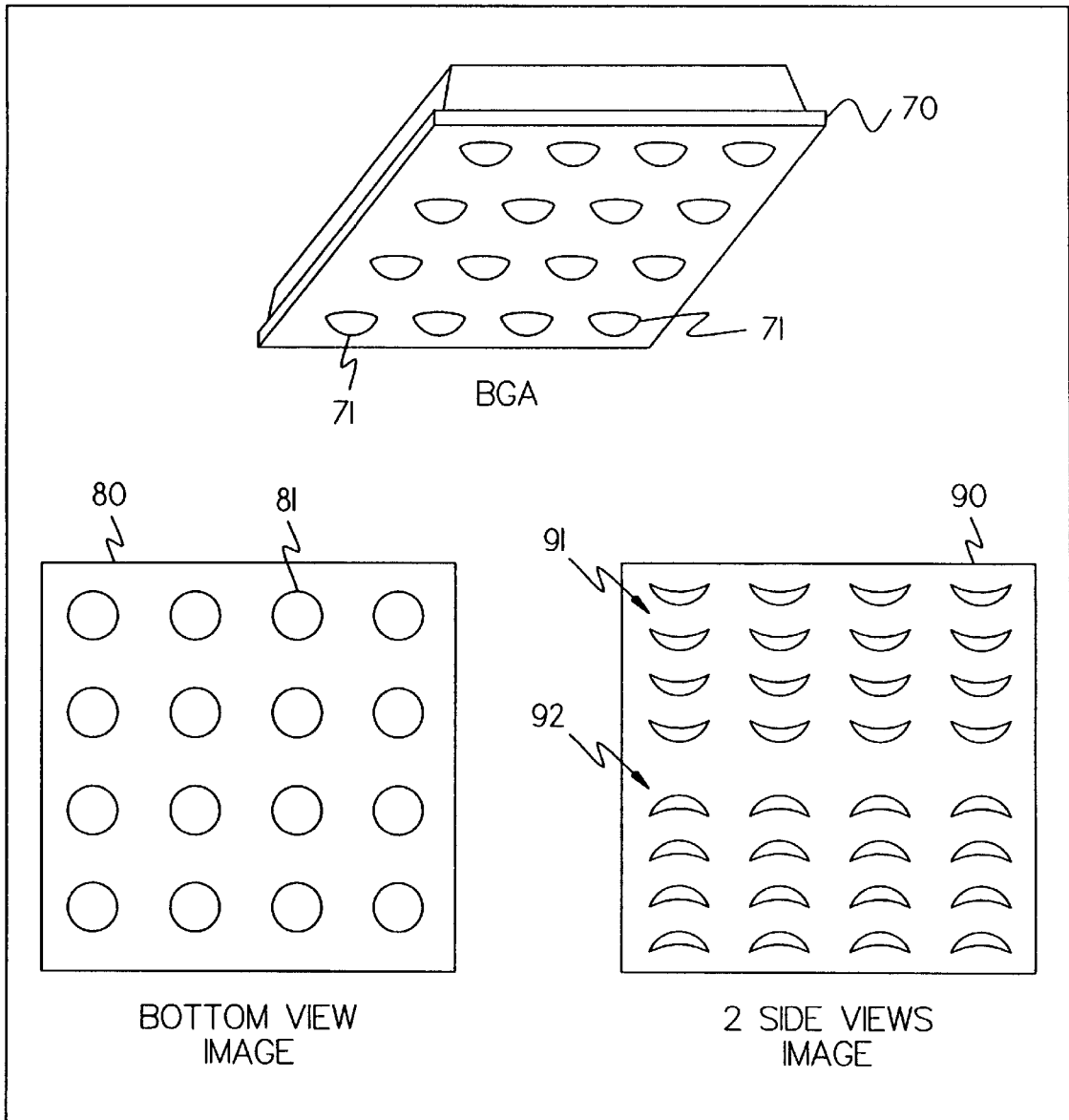


Fig- 3B

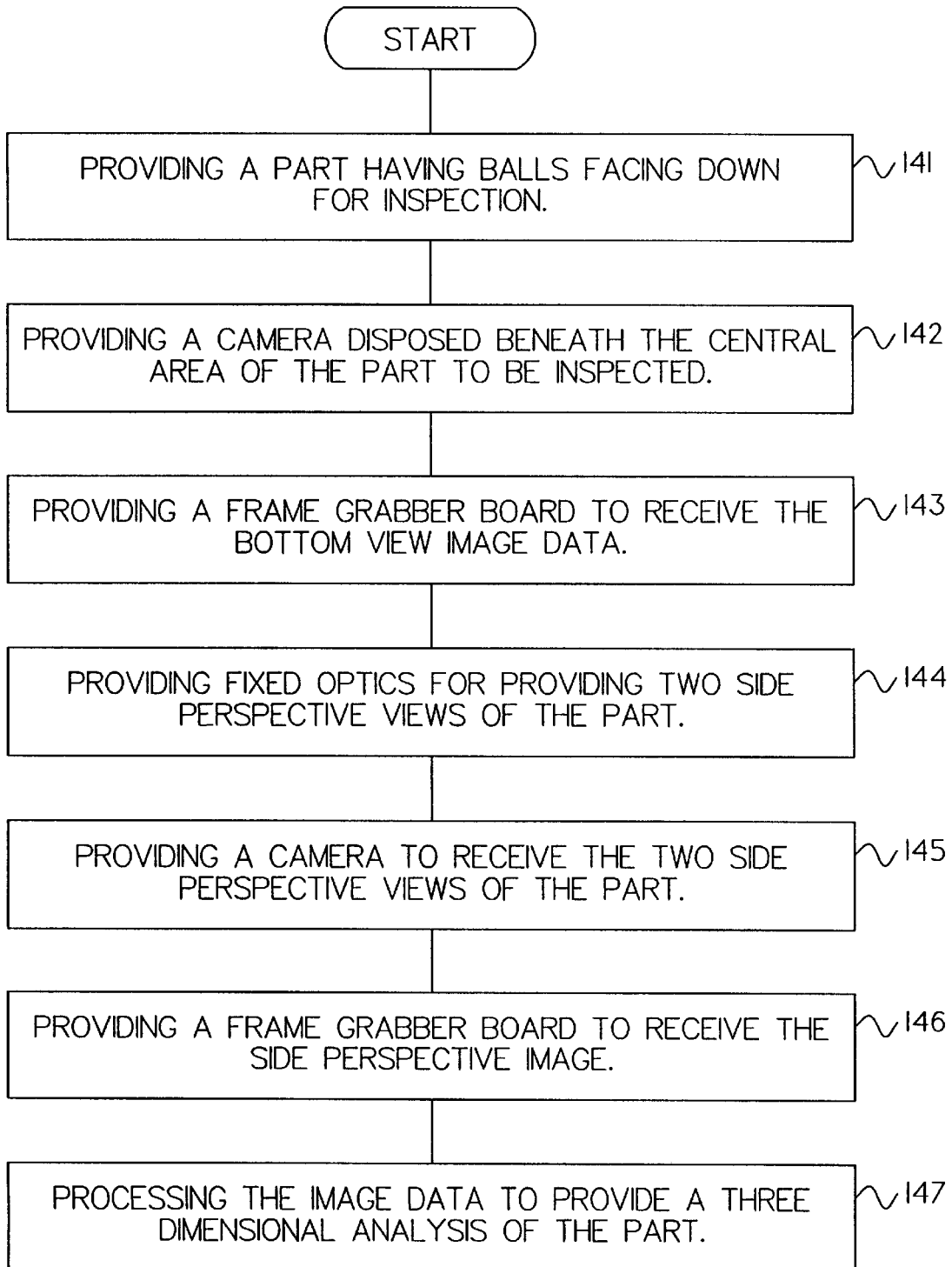


Fig-4

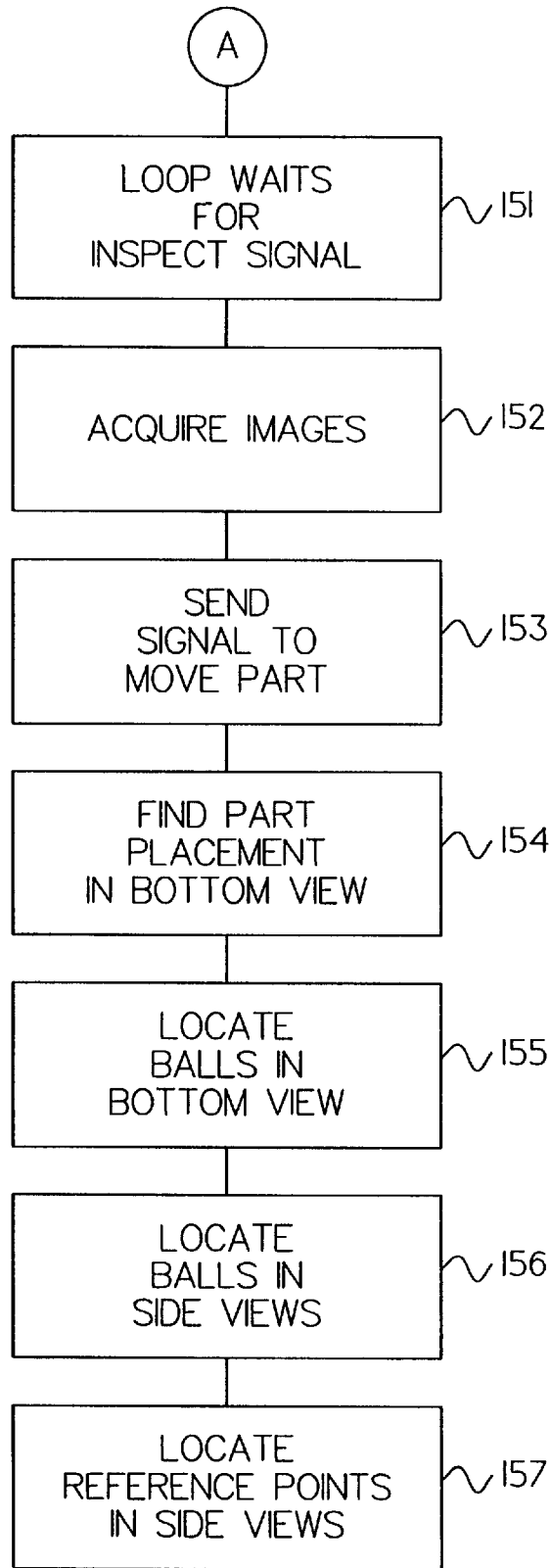


Fig- 5A

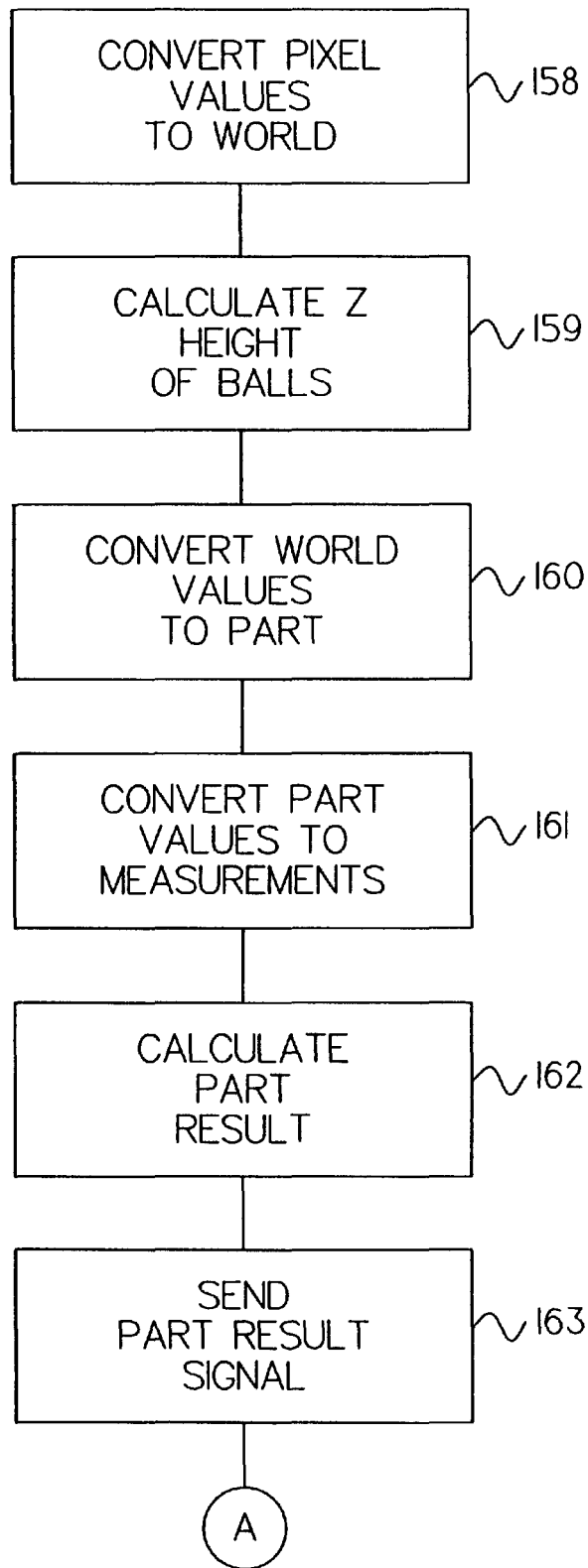


Fig. 5B



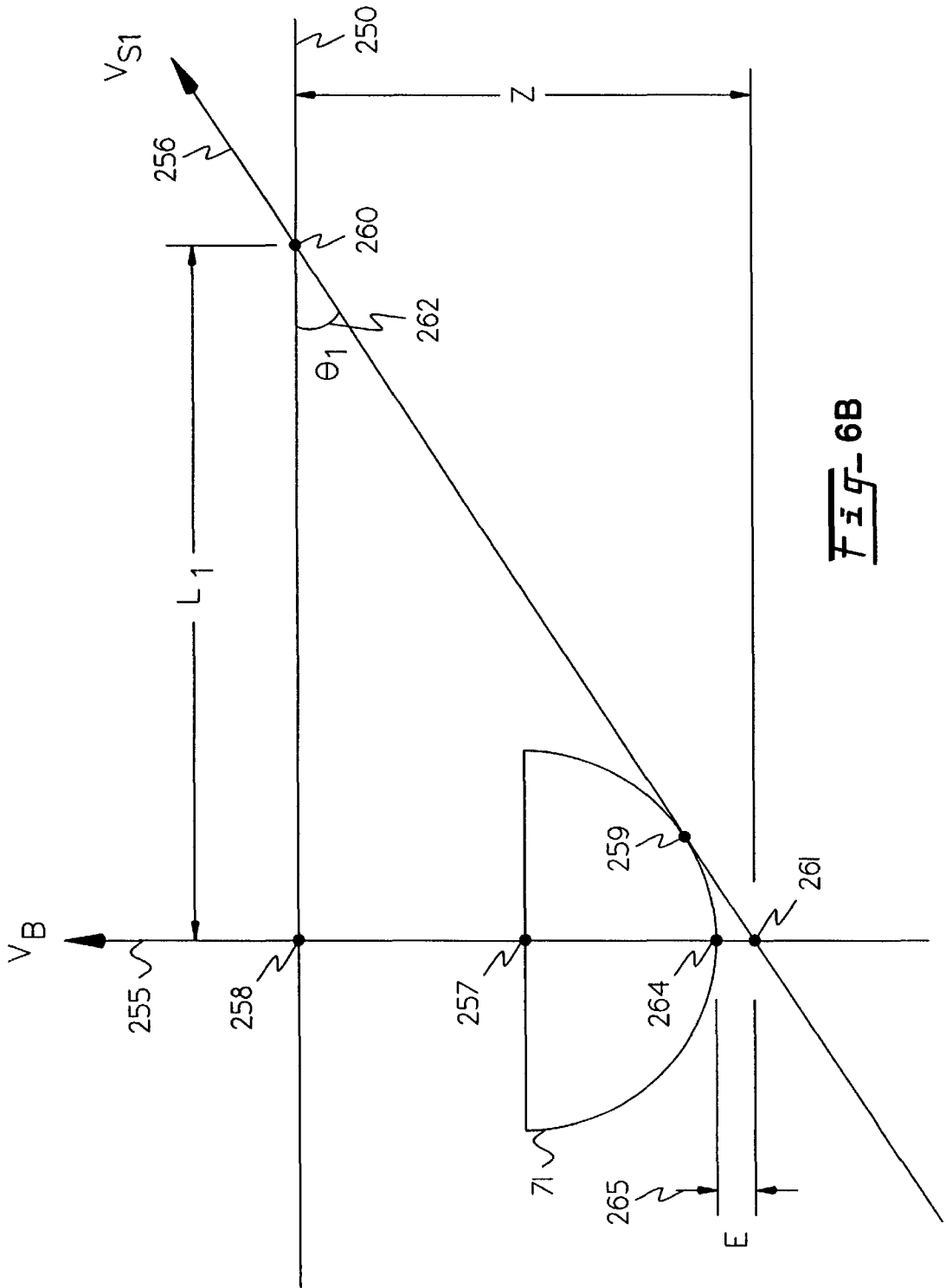


Fig- 6B



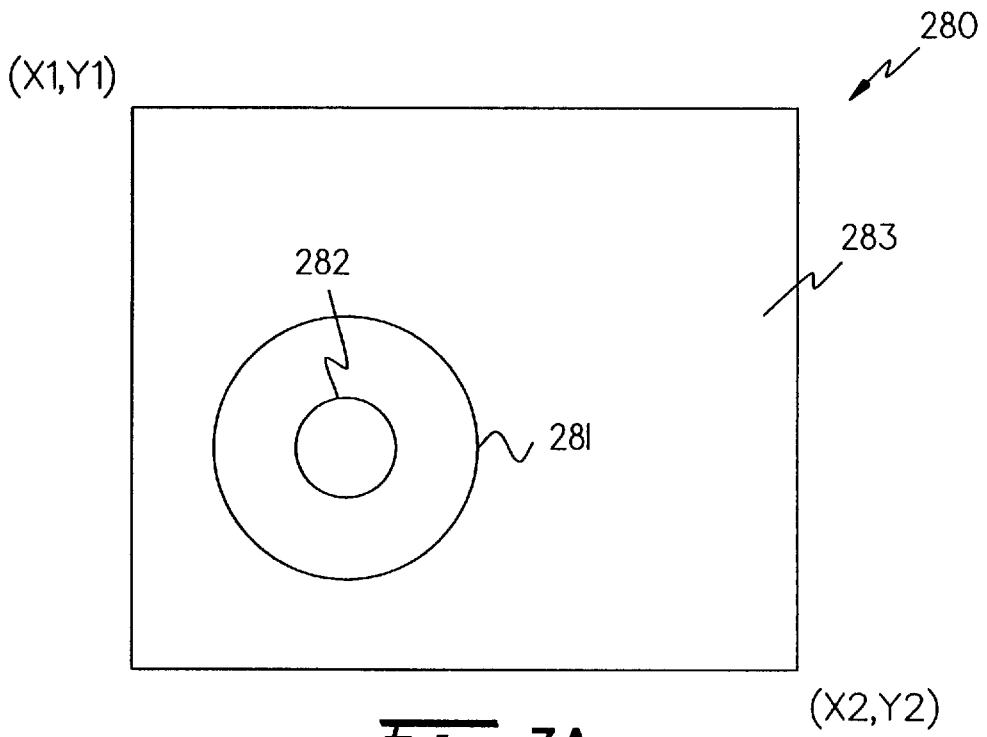


Fig-7A

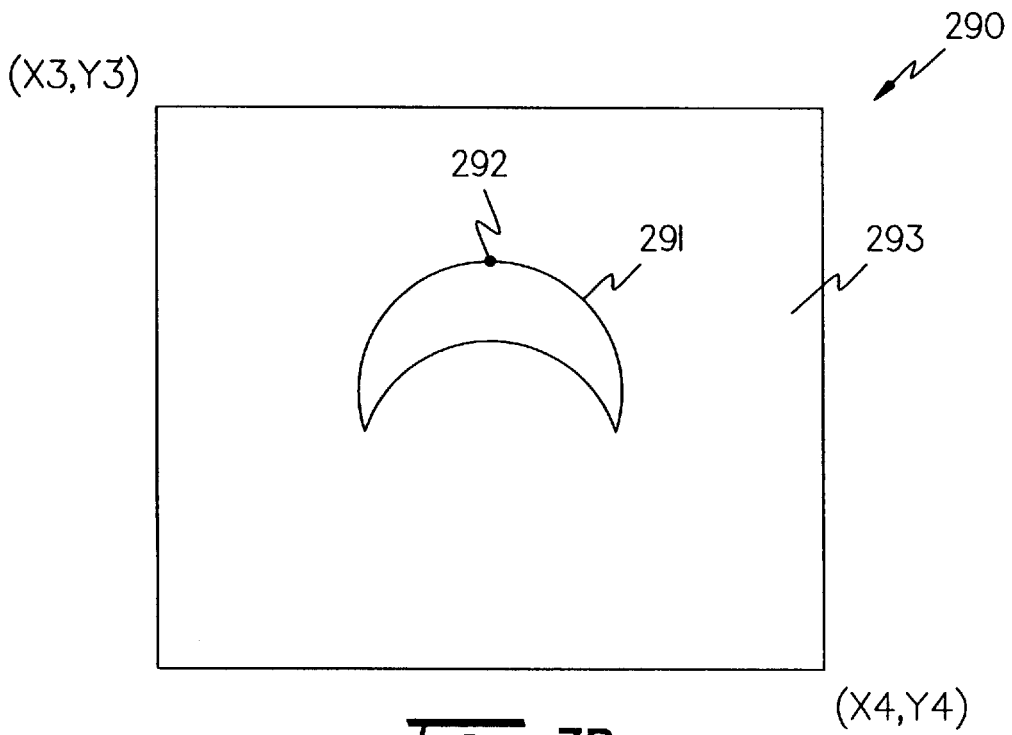
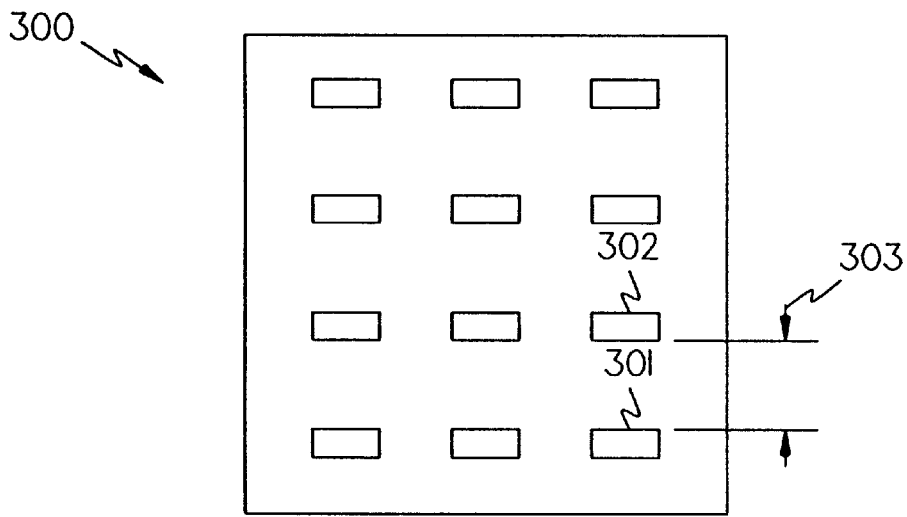
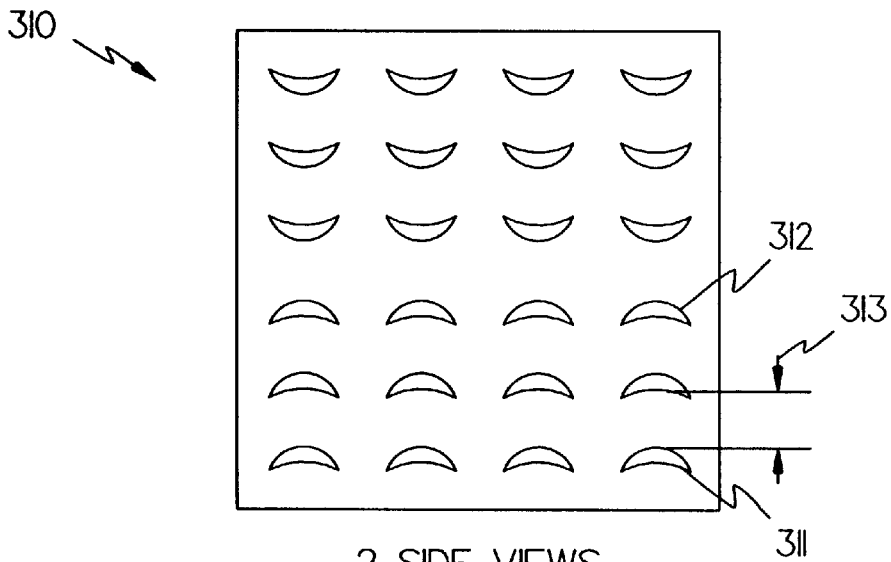


Fig-7B



2 SIDE VIEWS  
CALIBRATION PATTERN

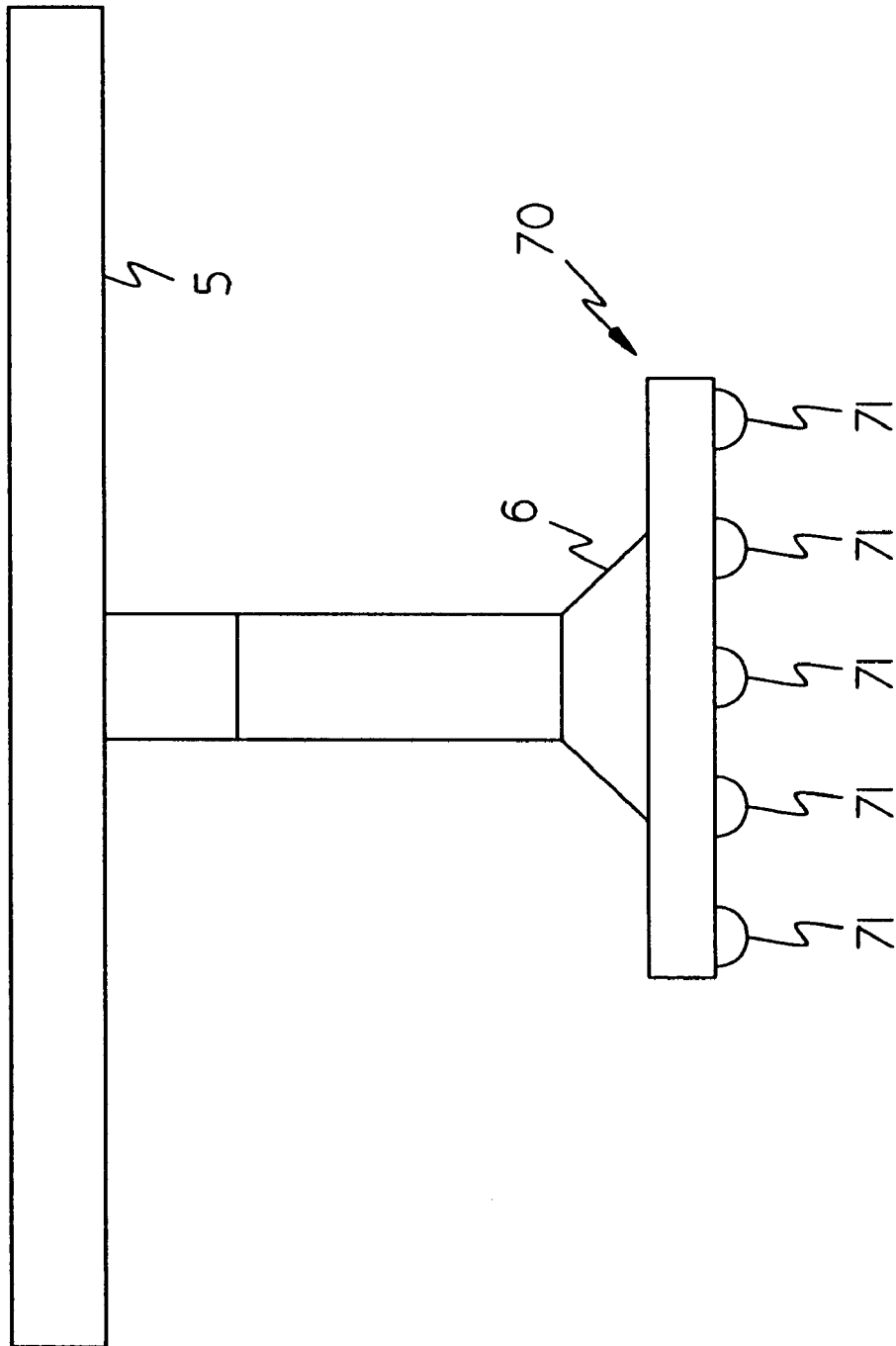
Fig- 8A



2 SIDE VIEWS  
BALLS

Fig- 8B

Fig- 9





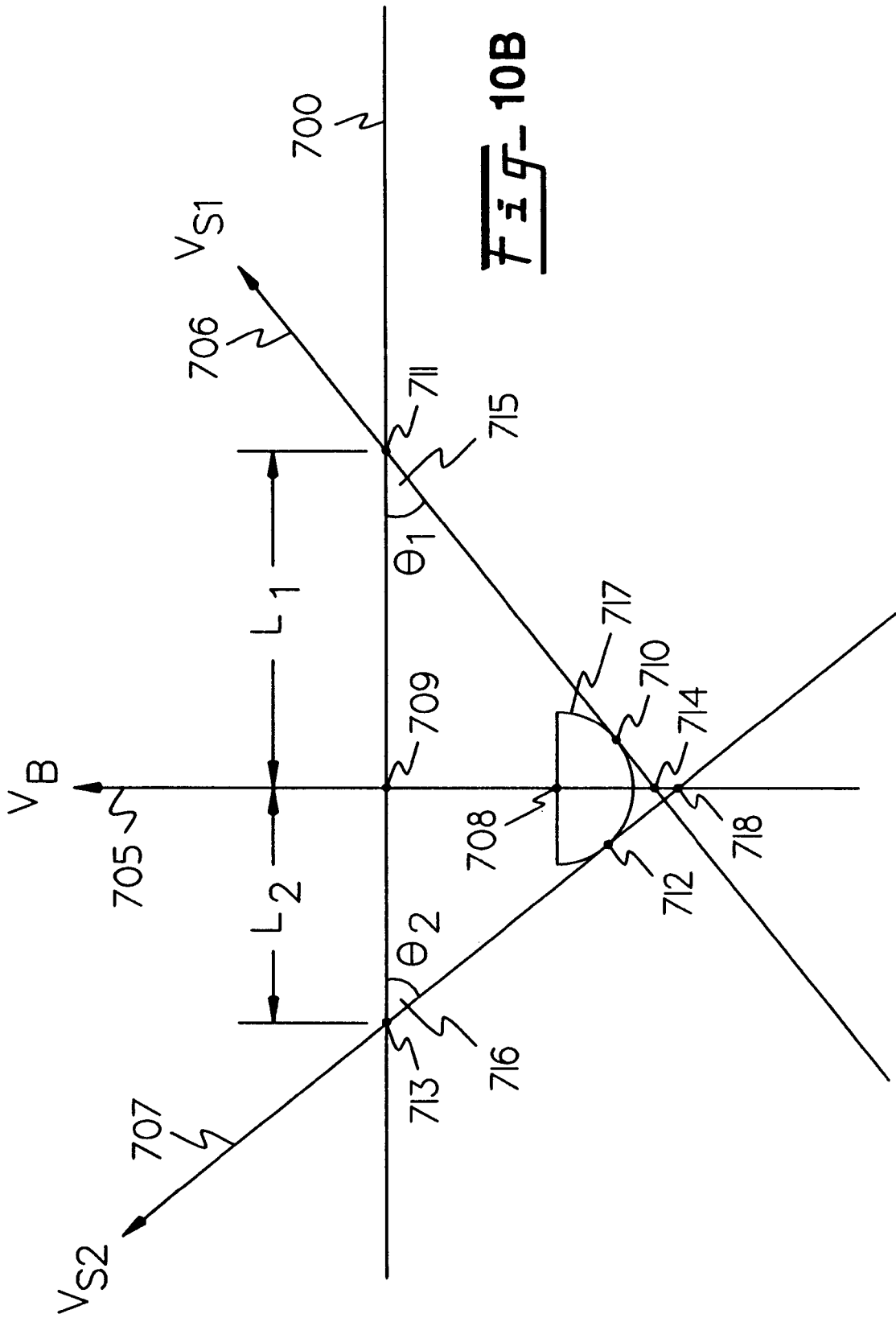


Fig-10B

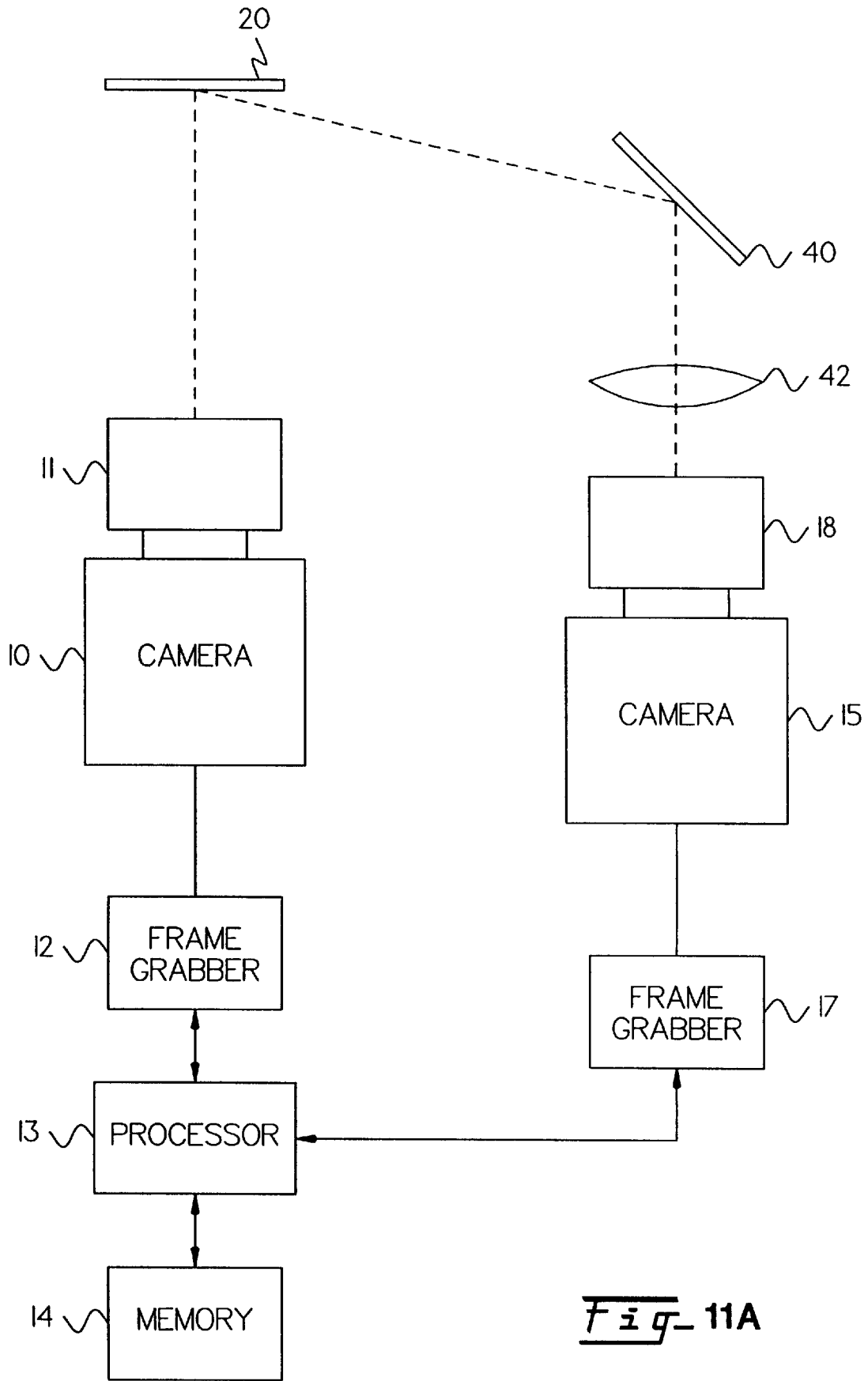


Fig. 11A

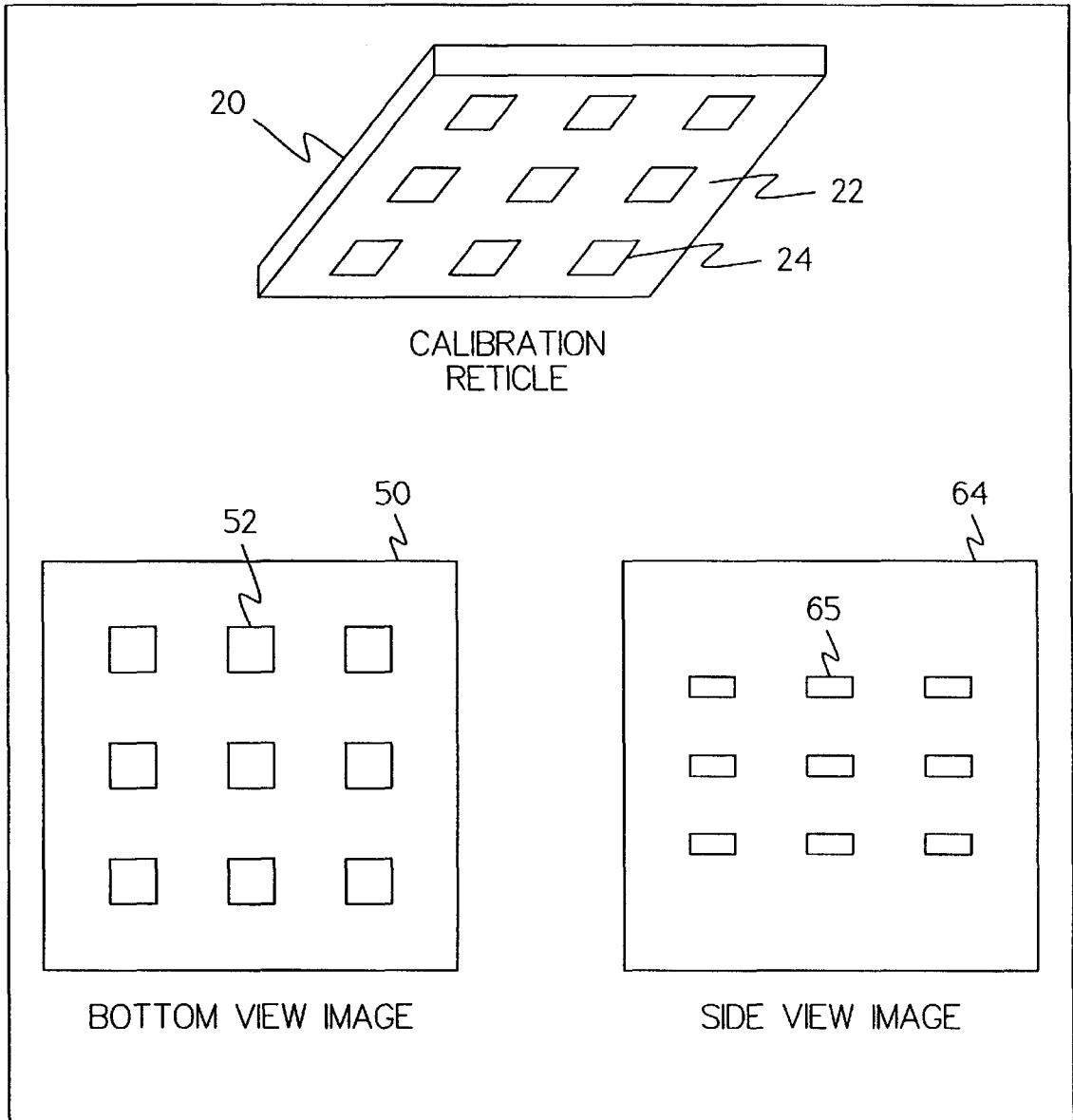


Fig- 11B

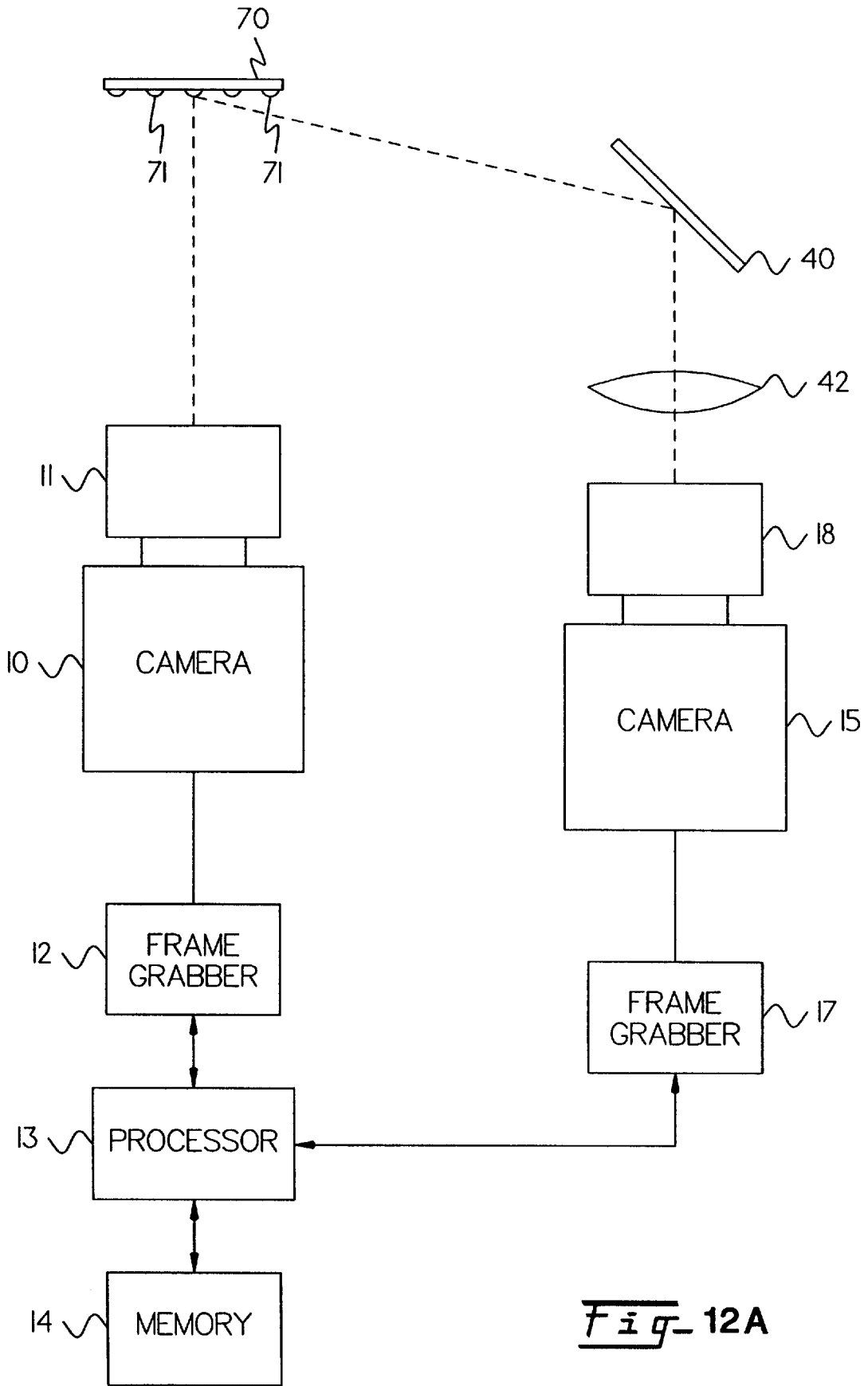


Fig-12A



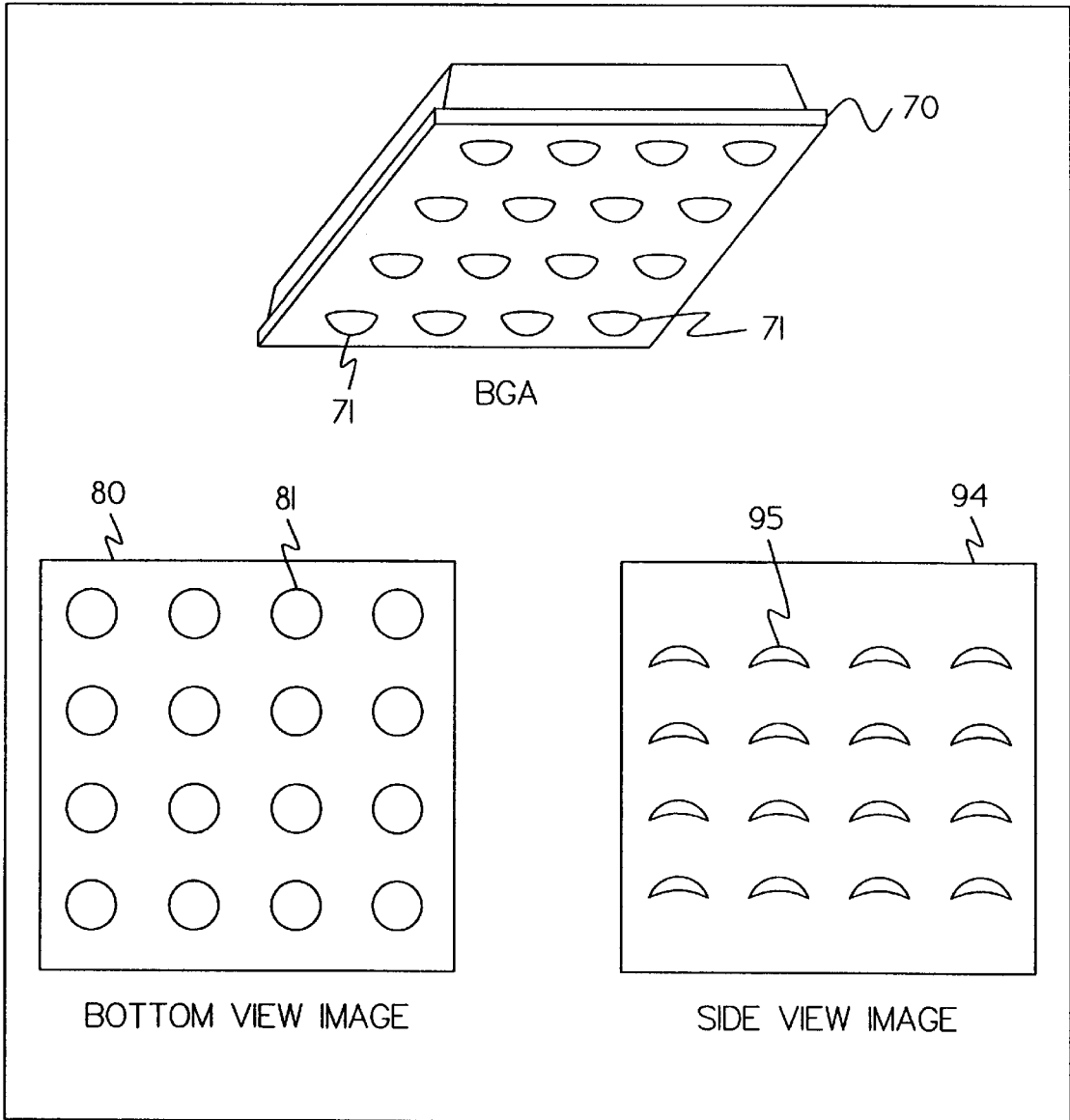
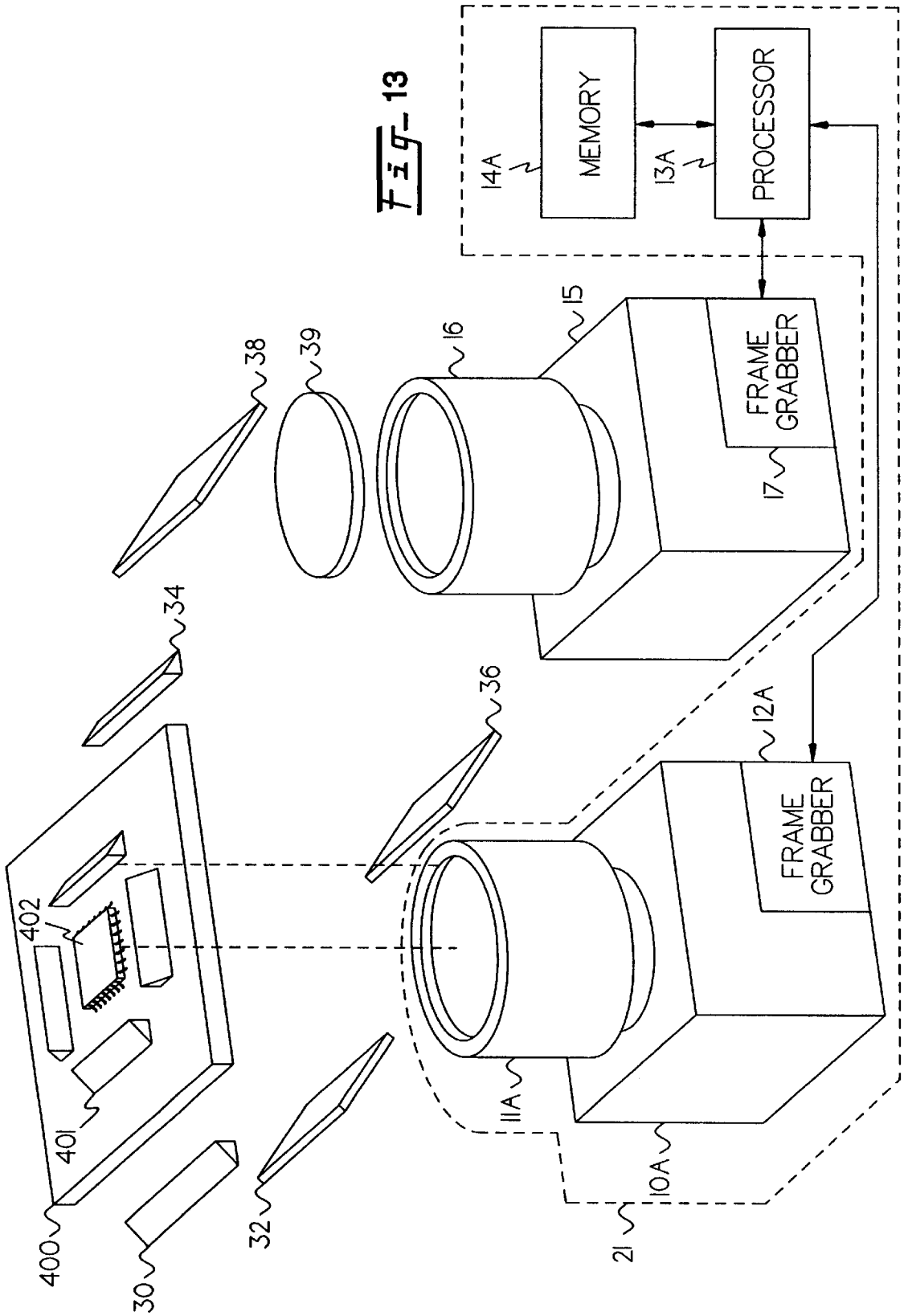
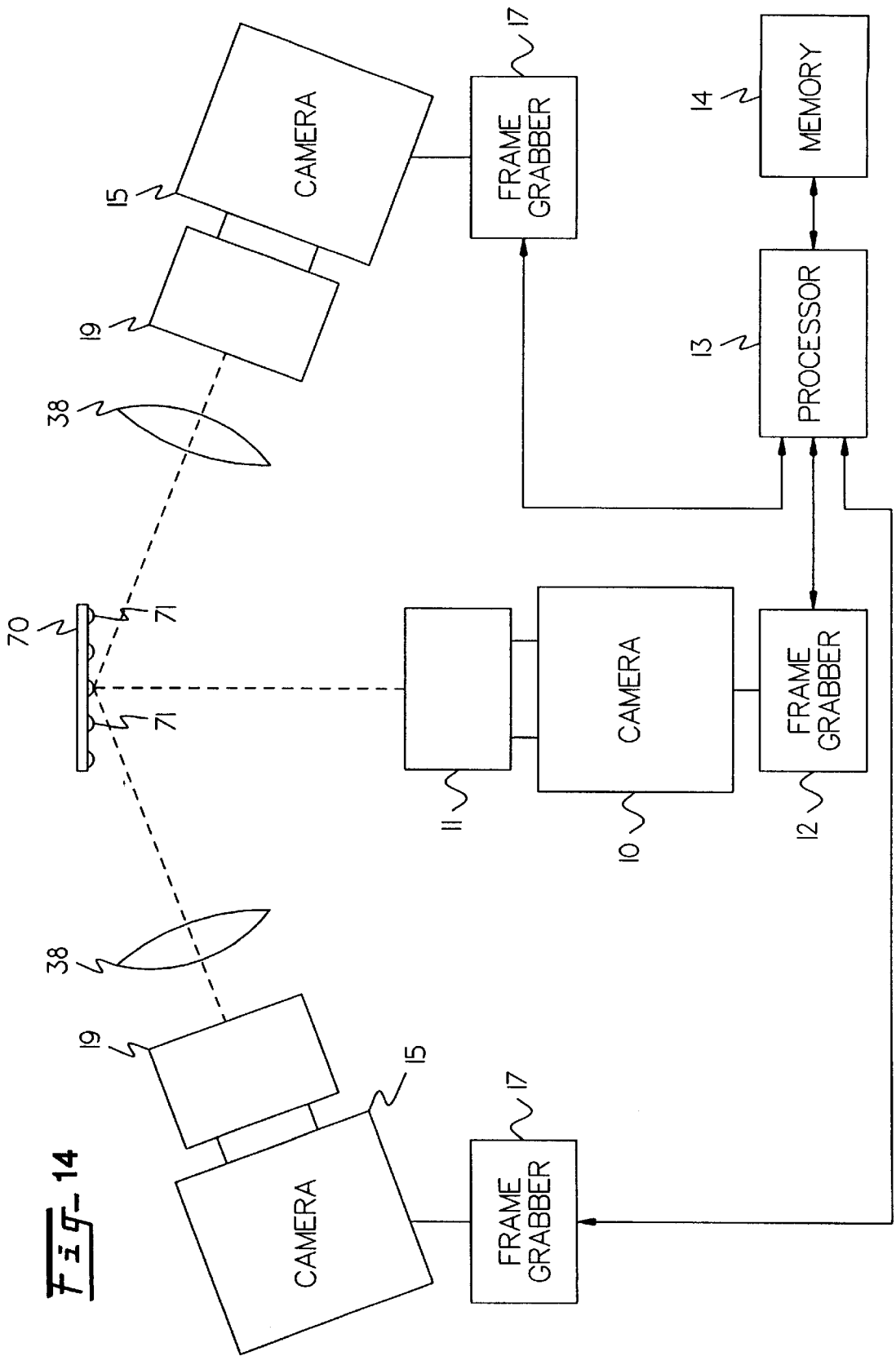


Fig. 12B





## APPARATUS FOR THREE DIMENSIONAL INSPECTION OF ELECTRONIC COMPONENTS

### CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a divisional of pending U.S. application Ser. No. 09/008,243 filed Jan. 16, 1998, entitled "Method and Apparatus for Three Dimensional Inspection of Electronic Components," incorporated by reference herein.

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### FIELD OF THE INVENTION

This invention relates to a method and apparatus for three dimensional inspection and, more particularly, a method and apparatus for three dimensional inspection of solder balls on ball grid arrays and solder bumps on wafer and die, and to a calibration method.

### BACKGROUND OF THE INVENTION

Prior art three dimensional inspection systems have involved laser range finding technology, moiré interferometry, structured light patterns or two cameras. The laser range finding method directs a focused laser beam onto the Ball Grid Array, BGA, and detects the reflected beam with a sensor. Elements of the BGA are determined in the X, Y and Z dimensions utilizing a triangulation method. This method requires a large number of measurement samples to determine the dimensions of the BGA resulting in longer inspection times. This method also suffers from specular reflections from the smooth surfaces of the solder balls resulting in erroneous data.

Moiré interferometry utilizes the interference of light waves generated by a diffraction grating to produce a pattern of dark contours on the surface of the BGA. These contours are of known distance in the Z dimension from the diffraction grating. By counting the number of contours from one point on the BGA to another point on the BGA, the distance in the Z dimension between the two points can be determined. This method suffers from the problem of low contrast contour lines resulting in missed counting of the number of contours and resulting in erroneous data. This method also suffers from the contour lines merging at surfaces with steep slopes, such as the sides of the balls on the BGA, resulting in an incorrect count of the number of contours and resulting in erroneous data.

Structured light systems project precise bands of light onto the part to be inspected. The deviation of the light band from a straight line is proportional to the distance from a reference surface. The light bands are moved across the part, or alternately the part is moved with respect to the light bands, and successive images are acquired. The maximum deviation of the light band indicates the maximum height of a ball. This method suffers from specular reflections due to the highly focused nature of the light bands resulting in erroneous delta. This method further suffers from increased inspection times due to the number of images required.

Two camera systems utilize one camera to view the BGA device in the normal direction to determine X and Y dimensions and the second camera to view the far edges of the balls from an angle. The two images are combined to determine the apparent height of each ball in the Z dimension utilizing a triangulation method. This method suffers from the need for a higher angle of view of the ball from the second camera resulting in looking at a point significantly below the top of the ball for BGA's having fine pitch. This method also suffers from limited depth of focus for the second camera limiting the size of BGA's that can be inspected. This system can only inspect BGA's and not other device types such as gullwing and J lead devices.

The prior art does not provide two separate and opposite side views permitting larger BGA's to be inspected or nonlinear optics to enhance the separation between adjacent ball images in the side perspective view.

It is therefore a motivation of the invention to improve the accuracy of the measurements, the speed of the measurements, the ability to measure all sizes and pitches of BGA's and to measure other devices including gullwing and J lead parts in a single system.

### SUMMARY OF THE INVENTION

The invention provides a calibration and part inspection method and apparatus for the inspection of BGA devices. The invention includes two cameras to image a precision pattern mask with dot patterns deposited on a transparent reticle to be inspected and provides information needed for calibration. A light source and overhead light reflective diffuser provide illumination that enhances the outline of the ball grid array. A first camera images the reticle precision pattern mask from directly below. An additional mirror or prism located below the bottom plane of the reticle reflects the reticle pattern mask from a side view, through prisms or reflective surfaces, into a second camera. A second additional mirror or prism located below the bottom plane of the reticle reflects the opposite side view of the reticle pattern mask through prisms or mirrors into a second camera. By imaging more than one dot pattern, the missing state values of the system can be resolved using a trigonometric solution. The reticle with the pattern mask is removed after calibration and a BGA to be inspected is placed with the balls facing downward, in such a manner as, to be imaged by the two cameras. The scene of the part can thus be triangulated and the dimensions of the BGA are determined.

The system optics are designed to focus images for all perspectives without the need for an additional focusing element. The optics of the side views may incorporate a nonlinear element to stretch the image in one direction to increase the apparent spacing between adjacent ball images allowing a lower angle of view and inspection of BGA's with closely spaced balls.

The invention provides an apparatus for inspecting a ball grid array, wherein the apparatus is calibrated using a precision pattern mask with dot patterns deposited on a calibration transparent reticle. The apparatus for inspecting a ball grid array comprises a means for mounting the ball grid array and a means for illuminating the ball grid array to provide an outline of the ball grid array. A first camera is positioned to image the ball grid array to provide a first image of the ball grid array. A first means for light reflection is positioned to reflect the ball grid array through a second means for light reflection into a second camera, wherein the second camera provides a second image of the ball grid array. A third means for light reflection is positioned to

reflect an opposite side view of the ball grid array into a fourth means for light reflection and into the second camera as part of the second image of the ball grid array. A means for image processing, such as a computer, microprocessor or digital signal processor, processes the first image and second image of the ball grid array to inspect the ball grid array.

The invention also provides a method for three dimensional inspection of a lead on a part mounted on a reticle. The method comprises the steps of: locating a first camera to receive an image of the lead; transmitting an image of the lead to a first frame grabber; providing fixed optical elements to obtain two side perspective views of the lead; locating a second camera to receive an image of the two side perspective views of the lead; transmitting the two side perspective views of the lead to a second frame grabber; operating a processor to send a command to the first frame grabber and second frame grabber to acquire images of pixel values from the first camera and the second camera; and processing the pixel values with the processor to obtain three dimensional data about the lead.

The invention also provides a method to inspect a ball grid array device comprising the steps of: locating a point on a world plane determined by a bottom view ray passing through a center of a ball on the ball grid array device; locating a side perspective view point on the world plane determined by a side perspective view ray intersecting a ball reference point on the ball and intersecting the bottom view ray at a virtual point where the side perspective view ray intersects the world plane at an angle determined by a reflection of the side perspective view ray off of a back surface of a prism where a value of the angle was determined during a calibration procedure; calculating a distance  $L_1$  as a difference between a first world point, defined by an intersection of the bottom view ray with a  $Z=0$  world plane, and a second world point, defined by the intersection of the side perspective view ray and the  $Z=0$  world plane, where a value  $Z$  is defined as a distance between a third world point and is related to  $L_1$  as follows:

$$\tan\theta_1 = \frac{Z}{L_1}$$

$$Z = L_1 \tan\theta_1$$

wherein  $Z$  is computed based on the angle; computing an offset  $E$  as the difference between the virtual point defined by the intersection of the bottom view ray and the side perspective view ray and a crown of a ball at a crown point that is defined by the intersection of the bottom view ray with the crown of the ball, and can be calculated from a knowledge of the angle and ideal dimensions of the ball where a final value of  $Z$  for the ball is:

$$Z_{final} = Z - E.$$

The invention also provides a method for finding a location and dimensions of a ball in a ball grid array from a bottom image comprising the steps of: defining a region of interest in the bottom image of an expected position of a ball where a width and a height of the region of interest are large enough to allow for positioning tolerances of the ball grid array for inspection; imaging the ball, wherein the ball is illuminated to allow a spherical shape of the ball to present a donut shaped image, wherein the region of interest includes a perimeter of the ball wherein the bottom image comprises camera pixels of higher grayscale values and where a center of the bottom image comprises camera pixels of lower grayscale value and wherein a remainder of the

region of interest comprises camera pixels of lower grayscale values; finding an approximate center of the ball by finding an average position of pixels having pixel values that are greater than a predetermined threshold value; converting the region of lower grayscale pixel values to higher grayscale values using coordinates of the approximate center of the ball; and finding the center of the ball.

The invention also provides a method for finding a reference point on a ball in an image of a side perspective view of a ball grid array comprising the steps of: defining a region of interest in the image from an expected position of a ball wherein a width and a height of the region of interest are large enough to allow for positioning tolerances of the ball grid array; imaging the ball, wherein the ball is illuminated to allow a spherical shape of the ball to present a crescent shaped image having camera pixels of higher grayscale values, and wherein a remainder of the region of interest comprises camera pixels of lower grayscale values; computing an approximate center of the crescent shaped image by finding an average position of pixels that are greater than a predetermined threshold value; using coordinates of the approximate center of the crescent; determining a camera pixel as a seed pixel representing a highest edge on a top of the crescent shaped image; and determining a subpixel location of the reference point based on the camera pixel coordinates of the seed pixel that define coordinates of a region of interest for the seed pixel.

#### BRIEF DESCRIPTION OF THE DRAWINGS

To illustrate this invention, a preferred embodiment will be described herein with reference to the accompanying drawings.

FIG. 1A shows the apparatus of the invention for system calibration.

FIG. 1B shows an example calibration pattern and example images of the calibration pattern acquired by the system.

FIG. 2A shows a flow chart of a method of the invention used for calibration of the bottom view.

FIG. 2B shows a flow chart of a method of the invention used for determining the state values, and the X and Y world coordinates, of the bottom view of the system.

FIG. 2C shows a flow chart of a method of the invention used for calibration of the side perspective views.

FIG. 2D shows a flow chart of a method of the invention used for determining the state values of the side perspective views of the system.

FIG. 2E shows the relationship of a side perspective angle to the ratio of the perspective dimensions to the non-perspective dimensions.

FIG. 2F shows a bottom view and a side perspective view of precision dots used in the method for determining a side perspective view angle.

FIG. 3A shows the apparatus of the invention for part inspection.

FIG. 3B shows example images of a part acquired by the system.

FIG. 4 shows a method of the invention for the three dimensional inspection of balls on a ball grid array.

FIGS. 5A and 5B together show a flow chart of the three dimensional inspection method of the invention.

FIGS. 6A and 6B show an example ball of a ball grid array and associated geometry used in a method of the invention for determining the Z position of the ball.

FIG. 7A shows one example of an image used in the grayscale blob method of the invention.

FIG. 7B shows one example of an image used with the method of the invention to perform a subpixel measurement of the ball reference point.

FIG. 8A shows a side perspective image of the calibration pattern magnified in one dimension.

FIG. 8B shows a side perspective image of the balls on a BGA, magnified in one dimension.

FIG. 9 shows an apparatus for presenting a BGA for inspection.

FIGS. 10A and 10B show an example ball of a ball grid array with associated geometry as used with a method of the invention for determining the Z position of a ball using two side perspective views.

FIG. 11A shows the apparatus of the invention for system calibration, utilizing a single side perspective view.

FIG. 11B shows an example calibration pattern and example images of a calibration pattern acquired by the system, utilizing a single side perspective view, of the invention.

FIG. 12A shows the apparatus of the invention for ball inspection utilizing a single side perspective view.

FIG. 12B shows an example ball grid array and example images of the ball grid array for three dimensional inspection, utilizing a single side perspective view.

FIG. 13 shows the apparatus of the invention for the three dimensional inspection of ball grid array devices, gullwing devices and J lead devices.

FIG. 14 shows the apparatus of the invention for the three dimensional inspection of parts utilizing three cameras.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

In one embodiment of the invention, the method and apparatus disclosed herein is a method and apparatus for calibrating the system by placing a pattern of calibration dots of known spacing and size on the bottom plane of a calibration reticle. From the precision dots the missing state values of the system are determined allowing for three dimensional inspection of balls on ball grid array devices, BGA devices or balls on wafers or balls on die. In one embodiment of the invention the system may also inspect gullwing and J lead devices as well as ball grid arrays.

Refer now to FIG. 1A which shows the apparatus of the invention configured with a calibration reticle for use during calibration of the state values of the system. The apparatus obtains what is known as a bottom image 50 of the calibration reticle 20. To take the bottom image 50 the apparatus includes a camera 10 with a lens 11 and calibration reticle 20 with a calibration pattern 22 on the bottom surface. The calibration pattern 22 on the reticle 20 comprises precision dots 24. The camera 10 is located below the central part of the calibration reticle 20 to receive an image 50 described in conjunction with FIG. 1B. In one embodiment the camera 10 comprises an image sensor. The image sensor may be a charged coupled device array. The camera 10 is connected to a frame grabber board 12 to receive the image 50. The frame grabber board 12 provides an image data output to a processor 13 to perform a two dimensional calibration as described in conjunction with FIG. 2A. The processor 13 may store an image in memory 14. The apparatus of the invention obtains an image of a pair of side perspective views and includes using a camera 15 with a lens 16 and a calibration reticle 20. The camera 15 is located to receive an

image 60, comprising a pair of side perspective views, described in conjunction with FIG. 1B. Fixed optical elements 30, 32 and 38 provide a first side perspective view and fixed optical elements 34, 36, 38 for a second side perspective view. The fixed optical elements 30, 32, 34, 36 and 38 may be mirrors or prisms. As will be appreciated by those skilled in the art additional optical elements may be incorporated. The camera 15 is connected to a frame grabber board 17 to receive the image 60. The frame grabber board 17 provides an image data output to a processor 13 to perform a two dimensional inspection as described in conjunction with FIG. 2B. The processor 13 may store an image in memory 14. In one embodiment of the invention, the apparatus may contain a nonlinear optical element 39 to magnify the side perspective image 60 in one dimension as shown in FIG. 8A. In another embodiment of the invention optical element 38 may be a nonlinear element. The nonlinear optical elements 38 and 39 may be a curved mirror or a lens.

FIG. 1B shows an example image 50 from camera 10 and an example image 60 from camera 15 acquired by the system. The image 50, a bottom view of dot pattern 22, shows dots 52 acquired by camera 10. The dot pattern contains precision dots 24 of known dimensions and spacing. The precision dots 24 are located on the bottom surface of the calibration reticle 20. The image 60 shows two side perspective views of the dot pattern 22. A first side perspective view in image 60 contains images 62 of dots 24 and is obtained by the reflection of the image of the calibration reticle dot pattern 22 off of fixed optical elements 30, 32 and 38 into camera 15. A second side perspective view in image 60 contains images 66 of dots 24 and is obtained by the reflection of the image of the calibration reticle dot pattern 22 off of fixed optical elements 34, 36 and 38 into camera 15.

Optical element 36 is positioned to adjust the optical path length of a second side perspective view to equal the optical path length of a first side perspective view. Those skilled in the art will realize that any number of perspective views can be utilized by the invention. In one embodiment of the invention, the maximum depth of focus of a side perspective view includes an area of the reticle including the center row of dots. This allows for a fixed focus system to inspect larger parts, with one perspective view imaging half of the part and the second perspective view imaging the other half of the part.

FIG. 2A shows a flow diagram for the calibration of the bottom view of the system. The method starts in step 1101 by providing a transparent reticle 20 having a bottom surface containing a dot pattern 22, comprising precision dots 24 of known dimensions and spacing. The method in step 102 provides a camera 10 located beneath the transparent reticle 20 to receive an image 50. In step 103 the processor 13 sends a command to a frame grabber 12 to acquire an image 50, comprising pixel values from the camera 10. The method then proceeds to step 104 and processes the pixel values with a processor 13.

FIG. 2B shows a flow diagram for determining the state values of the bottom view of the system. In step 111 the method begins by finding the dots 52 in image 50, corresponding to the calibration dots 24. The processor finds a dimension and position for each dot visible in image 50 in subpixel values using well known grayscale methods and stores these values in memory 14. By comparing these results to known values stored in memory, the processor calculates the missing state values for the bottom calibration in steps 112 and 113. In step 112 the processor 13 calculates

the optical distortion of lens 11 and the camera roll angle with respect to the dot pattern 22. Step 113 calculates the pixel width and pixel height by comparing the subpixel data of dots 52 with the known dimensions of the precision dot pattern 22. The pixel aspect ratio is determined from the pixel width and pixel height. In step 114 the processor defines the X and Y world coordinates and the Z=0 plane from the image 50 of the precision dot pattern 22. The processor then stores these results in memory. These results provide conversion factors for use during analysis to convert pixel values to world values.

FIG. 2C shows a flow diagram for the calibration of the side perspective views of the system. The method starts in step 121 by providing a transparent reticle 20 having a bottom surface containing a dot pattern 22, comprising precision dots 24 of known dimensions and spacing. The method in step 122 provides fixed optical elements 30, 32, 34, 36 and 38 to reflect two perspective images of the precision dot pattern 22 into camera 15. The method in step 123 provides a camera 15 located to receive an image 60. In step 124 the processor 13 sends a command to a frame grabber 12 to acquire an image 60, comprising pixel values from the camera 15. The method then proceeds to step 125 and processes the pixel values with processor 13.

FIG. 2D shows a flow diagram for determining the state values of the side perspective views of the system. In step 131 the method begins by finding dots 62 in image 60, corresponding to the calibration dots 24. The processor finds a dimension and position for each dot visible, comprising the group of dots 62, in image 60 for a first side perspective view in subpixel values and stores these values in memory 14. By comparing these results to known values stored in memory, the processor calculates the missing state values for a side perspective view, comprising the group of dots 62, in steps 132 and 133. In step 132 the processor 13 calculates the optical distortion of lens 16 and the camera roll angle with respect to the dot pattern 22. In step 133 the processor 13 calculates the pixel width and pixel height by comparing the subpixel data of dots 62 with the known dimensions of the precision dots 24. The pixel aspect ratio is determined from the pixel width and pixel height. In step 134 the processor defines the X and Y world coordinates and the Z=0 plane from the dots 62 in image 60 of the dot pattern 22. The processor then stores these results in memory. These results provide conversion factors for use during analysis to convert pixel values to world values. In step 135 the method of the invention computes the side view angle. In step 136 the method is repeated for a second side perspective view using the dots 66 in image 60.

FIG. 2E shows the relationship of a side perspective angle to the ratio of the perspective dimension to the non-perspective dimension. Ray 171, 172, and 173 defining point 181 is parallel to ray 174, 175 and 176 defining point 182. Point 181 and point 182 lie on a plane 170 parallel to a plane 180. The intersection of ray 175 and ray 176 define point 186. The intersection of ray 176 and ray 172 define point 184. The intersection of ray 173 and ray 172 define point 187. The intersection of ray 174 and ray 172 define point 183. The reflecting plane 179 intersecting plane 180 at an angle D is defined by ray 172 and ray 175 and the law of reflectance. Ray 172 and ray 175 intersect plane 170 at an angle 177. Referring to FIG. 2E it can be shown:

$$\tan\theta = \frac{C}{D_B}$$

-continued

$$\frac{C}{\sin A} = \frac{L}{\sin A} \quad \text{Therefore: } C = L$$

$$\cos\theta = \frac{D_S}{L} = \frac{D_S}{C}$$

$$C = \frac{D_S}{\cos\theta}$$

Substituting:

$$\tan\theta = \frac{\frac{D_S}{\cos\theta}}{D_B} = \frac{D_S}{D_B \cos\theta}$$

$$(\tan\theta)(\cos\theta) = \frac{D_S}{D_B} = \sin\theta$$

$$\theta = \arcsin\left(\frac{D_S}{D_B}\right)$$

FIG. 2F shows a bottom view and a side perspective view of precision dots used in the method for determining a side perspective view angle 177 as shown in FIG. 2E of the system. A bottom view image 200 comprising precision dots 201, 202 and 203 of known spacing and dimensions from the calibration method described earlier can be used to provide a reference for determination of a side perspective view angle 177. The value  $D_H$  and  $D_B$  are known from the bottom view calibration. A side perspective view image 210 comprising precision dots 211, 212 and 213, corresponding to bottom view dots 201, 202 and 203 respectively, of known spacing and dimensions  $D_S$  and  $D_h$  from the calibration method described earlier, can be used to determine the side view perspective angle. The ratio of  $(D_h/D_H)$  from the bottom image 200 and the side perspective image 210 can be used in the bottom view to calibrate  $D_B$  in the same units as the side perspective view as follows:

$$D_{Bcal} = D_B(D_h/D_H)$$

Substituting into the equation for the side perspective view angle 177 described earlier yields:

$$\theta = \arcsin\left(\frac{D_S}{D_B}\right) = \arcsin\left(\frac{D_S}{D_{Bcal}}\right)$$

$$\theta = \arcsin\left(\frac{D_S D_H}{D_B D_h}\right)$$

FIG. 3A shows the apparatus of the invention for a three dimensional inspection of the balls of a ball grid array. The apparatus of the invention includes a part 70 to be inspected. The apparatus further includes a camera 10 with a lens 11, located below the central area of part 70, to receive a bottom image 80, described in conjunction with FIG. 3B, of part 70. The camera 10 is connected to a frame grabber board 12 to receive the image 80. The frame grabber board 12 provides an image data output to a processor 13 to perform a two dimensional inspection as described in conjunction with FIG. 3A. The processor 13 may store an image in memory 14. The apparatus of the invention obtains an image of a pair of side perspective views with a camera 15 and a lens 16. The camera 15 is located to receive an image 90, comprising a pair of side perspective views, described in conjunction with FIG. 3B and utilizing fixed optical elements 30, 32 and 38 for a first side perspective view and fixed optical elements 34, 36 and 38 for a second side perspective view. In one embodiment of the invention, the apparatus may contain a nonlinear optical element 39 to magnify the side perspective

image 60 in one dimension as shown in FIG. 8B. In another embodiment of the invention optical element 38 may be the nonlinear element. The fixed optical elements 30, 32, 34, 36 and 38 may be mirrors or prisms. As will be appreciated by those skilled in the art additional optical elements may be incorporated without deviating from the spirit and scope of the invention. The camera 15 is connected to a frame grabber board 17 to receive the image 90. The frame grabber board 17 provides an image data output to a processor 13 to calculate the Z position of the balls, described in conjunction with FIG. 3B. The processor 13 may store an image in memory 14.

FIG. 3B shows an example image 80 from camera 10 and an example image 90 from camera 15 acquired by the system. The image 80 shows the bottom view of the balls located on the bottom surface of a part 70. The image 90 shows two side view perspectives of the balls located on part 70. A first side perspective view in image 90 contains images of balls 91 and is obtained by the reflection of the image of the part 70 off of fixed optical elements 30, 32 and 38 into camera 15. A second side perspective view in image 90 contains images of balls 92 and is obtained by the reflection of the image of the part 70 off of fixed optical elements 34, 36 and 38 into camera 15. Optical element 36 is positioned to adjust the optical path length of a second side perspective view to equal the optical path length of a first side perspective view. In one embodiment of the invention, the maximum depth of focus of a side perspective view just includes an area of the part including the center row of balls. This allows for a fixed focus system to inspect larger parts, with one perspective view imaging at least half of the part and the second perspective view imaging at least the other half of the part. Those skilled in the art will realize that any number of perspective views can be utilized by the invention. In another embodiment of the invention, all of the balls are in focus from both side perspective views resulting in two perspective views for each ball. This permits two Z calculations for each ball as shown in conjunction with FIGS. 10A and 10B.

FIG. 4 shows a flow diagram for the three dimensional inspection of balls on a ball grid array. The method starts in step 141 by providing a part 70 having balls 71 facing down. The method in step 142 provides a camera 10 located beneath the part 70 to receive an image 80. In step 143 a frame grabber 12 is provided to receive the image 80 from camera 10. In step 144, fixed optical elements are provided for obtaining two side perspective views of the part 70. A first optical path is provided by optical elements 30, 32 and 38. A second optical path is provided by optical elements 34, 36 and 38. A second camera 15 receives an image 90 of two side perspective views in step 145. In step 146 a second frame grabber board 17 is provided to receive the image 90 from camera 15. A processor 13 sends a command to frame grabbers 12 and 17 to acquire images 80 and 90 comprising pixel values from cameras 10 and 15. The method then proceeds to step 147 and processes the pixel values with a processor 13 to obtain three dimensional data about part 70.

The invention contemplates the inspection of parts that have ball shaped leads whether or not packaged as a ball grid array. The invention also contemplates inspection of leads that present a generally curvilinear profile to an image sensor.

FIGS. 5A and 5B together show a flow chart of the three dimensional inspection method of the invention. The process begins in step 151 by waiting for an inspection signal. When the signal changes state, the system initiates the inspection. The processor 13 sends a command to frame

grabber boards 12 and 17 to acquire images 80 and 90 respectively of part 70 having balls 71. In step 152, camera 10 captures an image 80 comprising pixel values and camera 15 captures an image 90 comprising pixel values and the processor stores the images in memory 14. The images comprise information from both a bottom view and two side perspective views as shown in FIG. 3B. In step 153, the inspection system sends a signal to a part handler shown in FIG. 9 to allow the part handler to move the part out of the inspection area and allows the next part to be moved into the inspection area. The handler may proceed with part placement while the inspection system processes the stored image data.

The inspection system processes the pixel values of the stored image 80 in step 154 to find a rotation, and X placement and Y placement of the part relative to the world X and Y coordinates. The processor determines these placement values finding points on four sides of the body of the part. In step 155, the processor employs a part definition file that contains values for an ideal part.

By using the measurement values from the part definition file and the placement values determined in step 154, the processor calculates an expected position for each ball of the part for the bottom view contained in image 80. The processor employs a search procedure on the image data to locate the balls 81 in image 80. The processor then determines each ball's center location and diameter in pixel values using grayscale blob techniques as described in FIG. 7A. The results are stored in memory 14.

The processor proceeds in step 156 to calculate an expected position of the center of each ball in both side perspective views in image 90 using the known position of each side view from calibration. The processor employs a subpixel edge detection method described in FIG. 7B to locate a reference point on each ball in step 157. The results are stored in memory 14.

Now refer to FIG. 5B. In step 158 the processor converts the stored pixel values from steps 154 and 157 into world locations by using pixel values and parameters determined during calibration. The world locations represent physical locations of the balls with respect to the world coordinates defined during calibration.

In step 159 the Z height of each ball is calculated in world coordinates in pixel values. The method proceeds by combining the location of the center of a ball from the bottom view 80 with the reference point of the same ball from a side perspective view in image 90 as described in FIGS. 6A and 6B. The processor then converts the world values to part values using the calculated part rotation, and X placement and Y placement in step 160 to define part coordinates for the ideal part. The part values represent physical dimensions of the balls such as ball diameter, ball center location in X part and Y part coordinates and ball height in Z world coordinates.

In step 161 these part values are compared to the ideal values defined in the part file to calculate the deviation of each ball center from its ideal location. In one examples embodiment of the invention the deviation values may include ball diameter in several orientations with respect to the X and Y part coordinates, ball center in the X direction, Y direction and radial direction, ball pitch in the X direction and Y direction and missing and deformed balls. The Z world data can be used to define a seating plane, using well known mathematical formulas, from which the Z dimension of the balls with respect to the seating plane can be calculated. Those skilled in the art will recognize that there are several possible definitions for seating planes from the data





-continued

```

//
long FindBlobCenter (int x1, int y1, int x2, int y2,
                    double* pX, double* pY)
{
    int x,y;
    long Found = 0;
    long SumX = 0;
    long SumY = 0;
    for (x = x1; x <= x2; x++)
    {
        for (y = y1; y <= y2; y++)
        {
            if (Pixel [x] [y] > THRESHOLD)
            {
                SumX += x;
                SumY += y;
                Found ++;
            }
        }
    }
    if (Found > 0)
    {
        *pX = (double)SumX / (double)Found;
        *pY = (double)SumY / (double)Found;
    }
    return Found;
}
//
// FillBallCenter - fills the center of the BGA "donut"
//
void FillBallCenter (double CenterX, double CenterY, double
Diameter)
{
    int x,y;
    int x1 = (int) (CenterX - Diamter / 4.0);
    int x2 = (int) (CenterX + Diamter / 4.0);
    int y1 = (int) (CenterY - Diamter / 4.0);
    int y2 = (int) (CenterY + Diamter / 4.0);
    for (x = x1; x <= x2; x++)
    {
        for (y = y1; y <= y2; y++)
        {
            Pixel[x] [y] = 255;
        }
    }
}
//
// FindBallCenter - finds the X,Y center of the a BGA ball
// using the grayscale values
//
long FindBallCenter (int x1, int y1, int x2, int y2,
                    double* pX, double* pY, double* pRadius)
{
    int x,y;
    long Found = 0;
    long Total = 0;
    long SumX = 0;
    long SumY = 0;
    for (x = x1; x <= x2; x++)
    {
        for (y = y1; y <= y2; y++)
        {
            if (Pixel [x] [y] > THRESHOLD)
            {
                SumX += x*Pixel [x] [y];
                SumY += y*Pixel [x] [y];
                Total += Pixel [x] [y];
                Found ++;
            }
        }
    }
    if (Found > 0)
    {
        *pX = (double)SumX / (double)Total;
        *pY = (double)SumY / (double)Total;

```

-continued

```

        *pRadius = sqrt ((double) Found / 3.14159279);
    }
    return Found;
}
//
// FindCrescentTop - finds the X,Y top position of a BGA
crescent
//
void FindCrescentTop(int CenterX, int CenterY, int Diameter,
                    int* pX, int* pY)
{
    int x,y,Edge,Max,TopX,TopY;
    int x1 = CenterX - Diameter / 2;
    int x2 = CenterX + Diameter / 2;
    int y1 = CenterY - Diameter / 2;
    int y2 = CenterY;
    *pY = 9999;
    for (x = x1; x <= x2; x++)
    {
        Max = -9999;
        for (y = y1; y <= y2; y++)
        {
            Edge = Pixel [x] [y] - Pixel [x] [y - 1];
            if (Edge > Max)
            {
                Max = Edge;
                TopY = y;
                TopX = x;
            }
        }
        if (TopY < *pY)
        {
            *pX = TopX;
            *pY = TopY;
        }
    }
}

```

35 FIG. 8A shows a side perspective image of the calibration pattern magnified in cone dimension. FIG. 8A shows a side perspective image 30 of a reticle calibration pattern where the space 303 between dot 301 and dot 302 is magnified, increasing the number of lower value grayscale pixels when compared to a non magnified image.

40 FIG. 8B shows a side perspective image of the balls on a BGA, magnified in one dimension. In FIG. 8B a side perspective image 310 of two views are shown where the space 313 between ball image 311 and ball image 312 is magnified, increasing the number of lower value grayscale pixels when compared to a non magnified image. The increased number of lower grayscale value pixels allows for the successful application of the subpixel algorithm.

50 In another embodiment of the invention, the method and apparatus disclosed herein is a method and apparatus for calibrating the system by placing a pattern of calibration dots of known spacing and dimensions on the bottom plane of a calibration reticle and for providing for two side perspective views of each ball for the three dimensional inspection of parts. From the precision dots the missing state values of the system are determined allowing for three dimensional inspection of balls on BGA devices or balls on wafers or balls on die.

60 FIG. 9 shows an example apparatus for presenting a BGA to the system for inspection. An overhead light reflective diffuser 5 includes a vacuum cup assembly 6. The vacuum cup assembly may attach to a BGA part 70 having balls 71 and suspend the BGA part 70 below the overhead light reflective diffuser 5.

65 FIGS. 10A and 10B show an example ball on a ball grid array and associated geometry for use with the method of the invention for determining the Z position of a ball with

respect to the world coordinates defined during calibration, using two perspective views for each ball. Using parameters determined from the calibration procedure as shown in FIGS. 2B and 2D to define a world coordinate system for the bottom view and the two side perspective views, comprising world coordinate plane 700 with world coordinate origin 701 and world coordinate axis X 702, Y 703 and Z 704 shown in FIG. 10A and FIG. 10B, and a pair of images 80 and 90 as shown in FIG. 3B, the processor computes a three dimensional location.

Now refer to FIG. 10A. The processor locates a point 709 on the world plane 700 determined by a bottom view ray 705 passing through the center 718 of a ball 717. The processor locates a first side perspective view point 711 on the world plane 700 determined by a side view ray 706 intersecting a ball reference point 710 on ball 717 and intersecting the bottom view ray 705 at a virtual point 714. Ray 706 intersects the world plane 700 at an angle 715 determined by the reflection of ray 706 off of the back surface of prism 30. The value of angle 715 was determined during the calibration procedure. The processor locates a second side perspective view point 713 on the world plane 700 determined by a side view ray 707 intersecting a ball reference point 712 on ball 717 and intersecting the bottom view ray 705 at a virtual point 718. Ray 707 intersects the world plane 700 at an angle 716 determined by the reflection of ray 707 off of the back surface of prism 34. The value of angle 716 was determined during the calibration procedure.

Now refer to FIG. 10B. The distance  $L_1$  is calculated by the processor as the distance between world point 709 and world point 711. The distance  $L_2$  is calculated by the processor as the distance between world point 713 and world point 709. The value  $Z_1$  is defined as the distance between world point 714 and 709 and is related to  $L_1$  as follows:

$$\tan\theta_1 = \frac{Z_1}{L_1}$$

$$Z_1 = L_1 \tan\theta_1$$

The value  $Z_2$  is defined as the distance between world point 718 and 709 and is related to  $L_2$  as follows:

$$\tan\theta_2 = \frac{Z_2}{L_2}$$

$$Z_2 = L_2 \tan\theta_2$$

The average of  $Z_1$  and  $Z_2$  are calculated and used as the value for Z of the ball. This method is more repeatable and accurate than methods that use only one perspective view per ball.

In still another embodiment of the invention, the method and apparatus disclosed herein is a method and apparatus for calibrating the system by placing a pattern of calibration dots of known spacing and dimensions on the bottom plane of a calibration reticle and for providing a single side perspective view for the three dimensional inspection of parts. From the precision dots the missing state values of the system are determined allowing for three dimensional inspection of balls on BGA devices or balls on wafers or balls on die.

FIG. 11A shows the apparatus of the invention for system calibration, utilizing a single side perspective view. The method and apparatus for calibration of the bottom view is identical to the method and apparatus described earlier in FIGS. 2A and 2B for the two side perspective views method. The apparatus for an image of a side perspective view

includes a camera 15 with a lens 18 and a calibration reticle 20. The camera 15 is located to receive an image 64 of a side perspective view comprising dots 65, described in conjunction with FIG. 11B, and utilizing fixed optical elements 40 and 42. The fixed optical element 40 may be a mirror or prism. The fixed optical element 42 is a nonlinear element that magnifies the image in one direction. In another embodiment fixed optical element 40 may be this nonlinear element. As will be appreciated by those skilled in the art additional optical elements may be incorporated. The camera 15 is connected to a frame grabber board 17 to receive the image 64. The frame grabber board 17 provides an image data output to a processor 13 to perform a two dimensional inspection as described in conjunction with FIG. 2B. The processor 13 may store an image in memory 14.

FIG. 1B shows an example calibration pattern and example images of a calibration pattern acquired by the system, utilizing a single side perspective view, of the invention. FIG. 11B shows an example image 50 from camera 10 and an example image 64 from camera 15 acquired by the system. The image 50 showing dot, 52 acquired by camera 10 includes a bottom view of the dot pattern 22, containing precision dots 24 of known dimensions and spacing, located on the bottom surface of the calibration reticle 20. The image 64 shows a side perspective view of the dot pattern 22, containing precision dots 24 of known dimensions and spacing, located on the bottom surface of the calibration reticle 20. A side perspective view in image 64 contains images of dots 65 and is obtained by the reflection of the image of the calibration reticle cot pattern 22 off of fixed optical element 40, passing through nonlinear element 42 and into camera 15.

The side perspective calibration is identical to the method shown in FIG. 2C except the fixed optical elements may have different properties.

The determination of the state values for the side perspective view is identical to the method shown in FIG. 2D except the fixed optical elements may be different and there is only one side perspective view. The principles and its relationships shown in FIG. 2E and FIG. 2F apply.

In still another embodiment employing a single side perspective view, the invention does not include the nonlinear element 42.

FIG. 12A shows the apparatus of the invention for ball inspection utilizing a single side perspective view. The apparatus of the invention includes a part 70 to be inspected. The apparatus further includes a camera 10 with a lens 11, located below the central area of part 70, to receive a bottom image 80, described in conjunction with FIG. 12B, of part 70. The camera 10 is connected to a frame grabber board 12 to receive the image 80. The frame grabber board 12 provides an image data output to a processor 13 to perform a two dimensional inspection as described in conjunction with FIG. 12B. The processor 13 may store an image in memory 14. The apparatus for an image of a single side perspective view includes a camera 15 with a lens 18. The camera 15 is located to receive an image 94, comprising a single side perspective view, described in conjunction with FIG. 12B and utilizing fixed optical element 40 and nonlinear, fixed optical element 42, to magnify the side perspective view in one dimension. In another embodiment of the invention optical element 40 may be the nonlinear element. The fixed optical element 40 may be a mirror or prism. As will be appreciated by those skilled in the art additional optical elements may be incorporated. The camera 15 is connected to a frame grabber board 17 to receive the image 94. The frame grabber board 17 provides an image

data output to a processor 13 to calculate the Z position of the balls, described in conjunction with FIG. 12B. The processor 13 may store an image in memory 14.

FIG. 12B shows an example ball grid array and example images of the ball grid array for three dimensional inspection, utilizing a single side perspective view. FIG. 12B shows an example image 80 from camera 10 and an example image 94 from camera 15 acquired by the system. The image 80 shows the bottom view of the balls 71 located on the bottom surface of a part 70. The image 91 shows a side perspective view of the balls 71 located on part 70. The side perspective view in image 94 contains images of balls 95 and is obtained by the reflection of the image of the part 70 off of fixed optical element 40 and passing through the nonlinear fixed element 42 into camera 15.

In an alternate embodiment of the invention, the system can be used to inspect other types of electronic parts in three dimensions, such as gullwing and J lead devices. By utilizing only one camera and adding an additional set of prisms on the reticle 400 these other devices may be inspected. The advantage of being able to inspect different devices with the same system includes savings in cost, and floor space in the factory. Additionally this design allows more flexibility in production planning and resource management.

FIG. 13 shows the apparatus of the invention for the three dimensional inspection of ball grid array devices, gullwing devices and J lead devices. The apparatus described in FIG. 13 allows the inspection of BGA, gullwing and J lead devices all on the same system. The apparatus includes a part 402 to be inspected located over the central area of a transparent reticle 400 with prisms 401 glued to the top surface to receive side perspective views of part 402. A gullwing and J lead inspection device 21 may be integrated into the ball grid array inspection device. One example embodiment of such a gullwing and J lead inspection device is the "UltraVim" scanner from Scanner Technologies of Minnetonka, Minn. The apparatus further includes a camera 10A with a lens 11A, located below the central area of part 402 and reticle 400 to receive a bottom view and side perspective views of part 402. The camera 10A is connected to a frame grabber board 12A to receive an image. The frame grabber board 12A provides an image data output to a processor 13A to perform a three dimensional inspection of part 402. The processor 13A may store an image in memory 14A. These components comprise the hardware of the gullwing and J lead inspection device 21 and are shared by the ball grid array inspection device as described herein.

The UltraVim is described in U.S. patent application Ser. No. 08/850,473 entitled THREE DIMENSIONAL INSPECTION SYSTEM by Beauty et al., filed May 5, 1997 which is incorporated in its entirety by reference thereto.

Refer now to FIG. 14. In still another embodiment of the invention, the system may use three cameras to image directly the bottom view and two side perspective views as shown in FIG. 14. FIG. 14 shows the apparatus of the invention for a three dimensional inspection of the balls of a BGA. The apparatus of the invention includes a part 70, with balls 71 to be inspected. The apparatus further includes a camera 10 with a lens 11, located below the central area of part 70, to receive a bottom image 80, described in conjunction with FIG. 12B, of part 70. The camera 10 is connected to a frame grabber board 12 to receive the image 80. The frame grabber board 12 provides an image data output to a processor 13 to perform a two dimensional inspection as described in conjunction with FIG. 12B. The processor 13 may store an image in memory 14. The apparatus for an image of a first side perspective view

includes a camera 15 with a lens 19. The camera 15 is located to receive an image 94, comprising a single side perspective view, described in conjunction with FIG. 12B and utilizing fixed optical element 38, to magnify the side perspective view in one dimension. The camera 15 is connected to a frame grabber board 17 to receive the image 94. The frame grabber board 17 provides an image data output to a processor 13 to calculate the Z position of the balls, described in conjunction with FIG. 12B. The processor 13 may store an image in memory 14. The apparatus for an image of a second side perspective view includes a camera 15 with a lens 19. The camera 15 is located to receive an image similar to 94, comprising a single side perspective view, described in conjunction with FIG. 12B and utilizing fixed optical element 38, to magnify the side perspective view in one dimension. The camera 15 is connected to a frame grabber board 17 to receive the image similar to 94. The frame grabber board 17 provides an image data output to a processor 13 to calculate the Z position of the balls, described in conjunction with FIG. 12B. The processor 13 may store an image in memory 14. In another embodiment, the nonlinear fixed optical element 38 may be missing. In still another embodiment of the invention, only one side perspective view may be utilized.

The invention has been described herein in considerable detail in order to comply with the Patent Statutes and to provide those skilled in the art with the information needed to apply the novel principles and to construct and use such specialized components as are required. However, it is to be understood that the invention can be carried out by specifically different equipment and devices, and that various modifications, both as to the equipment details and operating procedures, can be accomplished without departing from the scope of the invention itself.

What is claimed is:

1. A three dimensional inspection apparatus for ball array devices having a plurality of balls, wherein the ball array device is positioned in a fixed optical system, the apparatus comprising:

- a) an illumination apparatus positioned for illuminating the ball array device;
- b) a first camera disposed in a fixed focus position relative to the ball array device for taking a first image of the ball array device to obtain a characteristic circular doughnut shape image from at least one ball;
- c) a second camera disposed in a fixed focus position relative to the ball array device for taking a second image of the ball array device to obtain a side view image of the at least one ball; and
- d) a processor, coupled to receive the first image and the second image, that applies triangulation calculations on related measurements of the first image and the second image to calculate a three dimensional position of the at least one ball with reference to a pre-calculated calibration plane.

2. The three dimensional inspection apparatus of claim 1 wherein the second image comprises a segment having a crescent shape.

3. The three dimensional inspection apparatus of claim 1 wherein the calibration plane comprises a coordinate system having X, Y and Z axes and wherein an X measurement value is proportional to a Z measurement value.

4. The three dimensional inspection apparatus of claim 3 wherein the triangulation calculations are based on determining a center of the ball in the first image and determining a ball top location in the second image.

5. The three dimensional inspection apparatus of claim 1 wherein the pre-calculated calibration plane is defined by measuring a calibration pattern.

6. The three dimensional inspection apparatus of claim 1 wherein a mirror reflects light between the ball array device and the second camera.

7. The three dimensional inspection apparatus of claim 1 wherein the second image is obtained at a low angle of view.

8. The three dimensional inspection apparatus of claim 1 wherein the first camera and the second camera are fixed at different angles relative to the calibration plane.

9. The three dimensional inspection apparatus of claim 1 wherein the first camera and the second camera each comprise a charged coupled device array.

10. The three dimensional inspection apparatus of claim 1 wherein the measurements from the first image and the second image include grayscale edge detection to locate ball positions.

11. The three dimensional inspection apparatus of claim 1 wherein the illumination apparatus further comprises a diffuser.

12. The three dimensional inspection apparatus of claim 1 wherein the ball array devices comprise ball grid array devices.

13. The three dimensional inspection apparatus of claim 1 wherein the ball array devices comprise bump on wafer devices.

14. A three dimensional inspection apparatus for ball array devices having a plurality of balls, the apparatus comprising:

- (a) an illuminator positioned to produce reflections from the ball array device;
- (b) a first camera, for taking a first image of the ball array device, disposed in a first fixed position relative to the ball array device to obtain a circular doughnut shape view of the ball array device;
- (c) a second camera, for taking a second image of the ball array device, disposed in a second fixed position non-parallel to the first fixed position to obtain a side view of the ball array device;
- (d) a first frame grabber coupled to the first camera to acquire first image;
- (e) a second frame grabber coupled to the second camera to acquire the second image; and
- (f) a processor, coupled to the first and second frame grabbers, that applies triangulation calculations to related measurements on the first image and the second image so as to calculate a three dimensional position of at least one ball with reference to a pre-calculated calibration plane.

15. The three dimensional inspection apparatus of claim 14 wherein the second image comprises a segment having a crescent shape.

16. The three dimensional inspection apparatus of claim 14 wherein the calibration plane comprises a coordinate system having X, Y and Z axes and wherein an X measurement value is proportional to a Z measurement value.

17. The three dimensional inspection apparatus of claim 14 wherein the pre-calculated calibration plane is defined by measuring a calibration pattern.

18. The three dimensional inspection apparatus of claim 14 wherein a mirror is positioned to reflect light between the ball array device and the second camera.

19. The three dimensional inspection apparatus of claim 14 wherein the first camera and the second camera each comprise a charged coupled device array.

20. The three dimensional inspection apparatus of claim 14 wherein the illuminator further comprises a diffuser.

21. The three dimensional inspection apparatus of claim 14 wherein the ball array devices comprise ball grid array devices.

22. The three dimensional inspection apparatus of claim 14 wherein the ball array devices comprise bump on wafer devices.

23. The three dimensional inspection apparatus of claim 14 wherein the measurements from the first image and the second image include grayscale edge detection to locate ball positions.

24. A three dimensional inspection apparatus for ball array devices having a plurality of balls, the apparatus comprising:

- (a) an illuminator disposed to illuminate a ball array device;
- (b) a first camera for taking a first image of the ball array device, the first camera disposed in a first fixed position relative to the ball array device to obtain a circular doughnut shape view of the ball array device, wherein the first camera includes a charged coupled device array;
- (c) a second camera disposed for taking a second image of the ball array device, the second camera disposed in a second fixed position non-parallel to the first fixed position to obtain a side view of the ball array device, wherein a fixed mirror is interposed to reflect light between the ball array device and the second camera, and wherein the second camera includes a charged coupled device array;
- (d) a first image acquisition apparatus coupled to the first camera to acquire first image, and a second image acquisition apparatus coupled to the second camera to acquire the second image; and
- (e) a processor coupled to receive information from the first and second image acquisition apparatus, where the processor operates to make measurements from the first image and the second image so as to calculate a three dimensional position of at least one ball using a triangulation method with reference to a pre-calculated calibration plane, wherein the calibration plane comprises a coordinate system having X, Y and Z axes, and wherein an X measurement value is proportional to a Z measurement value.

25. The three dimensional inspection apparatus of claim 24 wherein the second image comprises a segment having a crescent shape.

26. The three dimensional inspection apparatus of claim 24 wherein the pre-calculated calibration plane is defined by measuring a calibration pattern.

27. The three dimensional inspection apparatus of claim 24 wherein the measurements from the first image and the second image include grayscale edge detection to locate ball positions.

28. The three dimensional inspection apparatus of claim 24 wherein the illuminator further comprises a diffuser.

29. The three dimensional inspection apparatus of claim 24 wherein the ball array devices comprise ball grid array devices.

30. The three dimensional inspection apparatus of claim 24 wherein the ball array devices comprise bump on wafer devices.

UNITED STATES PATENT AND TRADEMARK OFFICE  
**CERTIFICATE OF CORRECTION**

PATENT NO. : 6,064,756  
DATED : May 16, 2000  
INVENTOR(S) : Beaty et al.

Page 1 of 2

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 3,

Line 17, delete "flame" and substitute -- frame --.

Column 4,

Line 7, delete "he" and substitute -- the --.

Column 5,

Line 35, change "EMBODIMENT" to -- EMBODIMENTS --.

Column 6,

Line 48, change "1101" to -- 101 --.

Column 10,

Line 57, change "examples" to -- example --.

Column 11,

Line 20, change "use" to -- used --.

Line 65, in the equation change "F" to -- E --.

Column 14,

Line 9, change "FindCresentTop" to -- FindCrescentTop --.

Line 10, change "cresent" to -- "crescent --.

Line 12, change "FindCresentTop" to -- FindCrescentTop --.

Line 36, change "cone" to -- one --.

Column 16,

Line 16, change "1B" to -- 11B --.

Line 39, delete the second occurrence of "is".

Column 17,

Line 11, change "past" to -- part --.

Line 50, change "Beauty" to -- Beaty --.

Line 55, change "snows" to -- shows --.

UNITED STATES PATENT AND TRADEMARK OFFICE  
**CERTIFICATE OF CORRECTION**

PATENT NO. : 6,064,756  
DATED : May 16, 2000  
INVENTOR(S) : Beaty et al.

Page 2 of 2

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 19,

Line 40, before "first" insert -- the --.

Column 20,

Line 27, delete "he" and substitute -- the --.

Line 33, before "first" insert -- the --.

Signed and Sealed this

Thirteenth Day of November, 2001

Attest:

*Nicholas P. Godici*

Attesting Officer

NICHOLAS P. GODICI  
Acting Director of the United States Patent and Trademark Office