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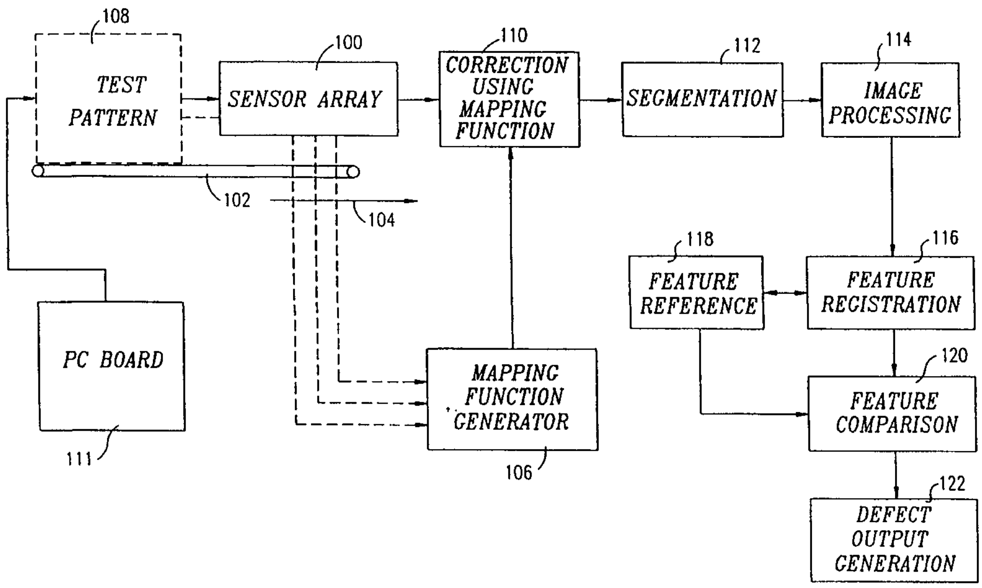

(57) Abstract

An image acquisition system including a plurality of sensors each including a multiplicity of sensor elements, pre–scan calibration subsystem, employing a predetermined test pattern (108), which is sensed by the plurality of sensors (100), for providing an output indication in two dimensions of distortions in the output of the plurality of sensors, the output indication being employed to generate a function which maps the locations viewed by the sensor elements in at least two dimensions and a distortion subsystem operative during scanning of an article by the plurality of sensors to correct the distortions by employing the output indication.

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METHOD AND APPARATUS FOR INSPECTION OF PRINTED CIRCUIT BOARDS

FIELD OF THE INVENTION

The present invention relates to article inspection systems and methods generally and more particularly to systems and methods for inspecting generally two dimensional articles, such as printed circuit boards.

BACKGROUND OF THE INVENTION

There are known in the patent and professional literature various article inspection systems and methods. One well known problem with existing article inspection systems is that they encounter great difficulty strictly arranging multiple line image sensors such that they collectively acquire an image of a single line of an article being inspected. Other problems relate to the stretching of pixels due to the angle of the camera, the difficulty in combining overlapping images from multiple cameras, and the shifting of color components of an image due to factors such as the physical separation between diodes in a line sensor, chromatic aberrations, and varying intensities of different wavelengths of light.

The following patent documents are believed to represent the current state of the art:

U.S. Patent Nos.: RE33,956, 3,814,520, 3,956,698, 4,100,570, 4,152,723, 4,167,728, 4,185,298, 4,223,346, 4,269,515, 4,277,175, 4,277,802, 4,326,792, 4,347,001, 4,389,655, 4,421,410, 4,448,532, 4,449,818, 4,459,619, 4,465,939, 4,506,275, 4,532,650, 4,538,909, 4,556,317, 4,585,351, 4,589,140, 4,590,607, 4,594,599, 4,597,455, 4,618,938, 4,633,504, 4,635,289, 4,653,109, 4,675,745, 4,692,812, 4,701,859, 4,712,134, 4,751,377, 4,758,782, 4,758,888, 4,762,985, 4,771,468, 4,772,125, 4,783,826, 4,794,647, 4,799,175, 4,805,123, 4,805,123, 4,811,410, 4,821,110, 4,821,110, 4,870,505, 4,870,505, 4,877,326, 4,878,736, 4,893,346, 4,894,790, 4,897,737, 4,897,795, 4,929,845, 4,930,889, 4,938,654, 4,958,307, 4,969,038, 4,969,198, 4,978,974, 4,978,974, 4,979,029, 4,984,073, 4,989,082, 4,989,082, 5,023,714, 5,023,917, 5,067,012, 5,067,162, 5,085,517, 5,091,974, 5,103,105, 5,103,257, 5,114,875, 5,119,190, 5,119,439, 5,125,040, 5,127,726, 5,128,753, 5,129,014, 5,131,755, 5,136,149, 5,144,132, 5,144,132, 5,144,448, 5,150,422, 5,150,423, 5,161,202, 5,162,866, 5,162,867, 5,163,128, 5,170,062, 5,175,504, 5,181,068, 5,198,778, 5,204,918, 5,220,617, 5,245,421, 5,253,307, 5,258,706, 5,285,295, 5,303,064, 5,305,080, 5,331,397, 5,373,233, 5,379,350, 5,414,534, 5,414,534, 5,444,478, 5,450,204, 5,483,359, 5,483,603, 5,495,535, 5,500,746, 5,539,444;

European patent documents: EP 094,501 A2, EP 598,582 A2, EP 426,182 A2, EP 426,166 A2, EP 247,308 A2, EP 243,939 A2, EP 206,713 A2, EP 128,107 A1, EP 126,492 A2, EP 426,166 A2, EP 533,348 A2, EP 209,422 A2, EP 536,918 A2, EP 92306649.2; and

British patent documents GB 2,201,804 A and GB 2,124,362 A.

The following patent documents are believed to be most relevant:

U.S. Patent Nos.: 4,459,619, 4,465,939, 4,675,745, 4,692,812, 4,821,110, 4,870,505, 5,144,132, 5,144,448, 5,438,359, and 5,500,746.

SUMMARY OF THE INVENTION

The present invention seeks to provide an improved system and method for article inspection which are characterized by substantially enhanced accuracy.

There is thus provided in accordance with a preferred embodiment of the present invention an image acquisition system including a plurality of sensors each including a multiplicity of sensor elements, a pre-scan calibration subsystem, employing a predetermined test pattern, which is sensed by the plurality of sensors, for providing an output indication in two dimensions of distortions in the output of the plurality of sensors, the output indication being employed to generate a function which maps the locations viewed by the sensor elements in at least two dimensions, and a distortion correction subsystem operative during scanning of an article by the plurality of sensors to correct the distortions by employing the output indication.

Further in accordance with a preferred embodiment of the present invention the plurality of sensors include plural sensors having different spectral sensitivities.

Still further in accordance with a preferred embodiment of the present invention the plurality of sensors include at least two sensors having generally the same spectral sensitivity.

Additionally in accordance with a preferred embodiment of the present invention the plurality of sensors include at least two sensors which at least partially overlap in at least one dimension.

Moreover in accordance with a preferred embodiment of the present invention the pre-scan calibration subsystem is operative to sub-pixel accuracy.

Further in accordance with a preferred embodiment of the present invention the distortion correction subsystem performs non-zero'th order interpolation of pixels in the outputs of the plurality of sensors.

Still further in accordance with a preferred embodiment of the present invention the distortion correction subsystem compensates for variations in pixel size in the plurality of sensors.

Additionally in accordance with a preferred embodiment of the present invention the distortion correction subsystem compensates for variations in magnification in the plurality of sensors.

Further in accordance with a preferred embodiment of the present invention the distortion correction subsystem compensates for chromatic aberrations in the plurality of sensors.

Moreover in accordance with a preferred embodiment of the present invention the plurality of sensors include sensors having differing spectral sensitivities and the function is dependent on differing accumulation times employed for the sensors having differing spectral sensitivities.

Further in accordance with a preferred embodiment of the present invention the distortion correction subsystem compensates for variations in pixel shape in the plurality of sensors.

Still further in accordance with a preferred embodiment of the present invention the distortion correction subsystem is operative to an accuracy of better than 5% of pixel size of the multiplicity of sensor elements.

There is additionally provided in accordance with a preferred embodiment of the present invention an image acquisition system including a plurality of sensors each including a multiplicity of sensor elements, a pre-scan calibration subsystem, employing a predetermined test pattern, which is sensed by the plurality of sensors, for providing an output indication of distortions in the output of the plurality of sensors, the output indication being employed to generate a correction function, and a distortion correction subsystem operative during scanning of an article by the plurality of sensors to correct the distortions by employing the correction function, the distortion correction subsystem being operative to an accuracy of better than 5% of pixel size of the multiplicity of sensor elements.

There is also provided in accordance with a preferred embodiment of the present invention an image acquisition system including a plurality of sensors, a pre-scan calibration subsystem, employing a predetermined test pattern, which is sensed by the plurality of sensors while being moved relative to the plurality of sensors in a direction of relative movement, for providing an output indication of distortions in the output of the plurality of sensors, the pre-scan calibration system being operative to correlate images of at least one target on the test pattern as seen by the plurality of sensors, thereby to determine the relative orientation of the plurality of sensors, and a distortion correction subsystem operative to correct the distortions by employing the output indication.

Further in accordance with a preferred embodiment of the present invention the pre-scan calibration subsystem also is operative to provide an output indication of the orientation of the plurality of sensors relative to the scan direction.

Still further in accordance with a preferred embodiment of the present invention each of the plurality of sensors includes a multiplicity of sensor elements, and the pre-scan calibration subsystem also is operative to determine the pixel size characteristic of each of the multiplicity of sensor elements of each of the plurality of sensors.

Additionally in accordance with a preferred embodiment of the present invention the pre-scan calibration subsystem is operative to determine the pixel size characteristic of each of the multiplicity of sensor elements of each of the plurality of sensors by causing the plurality of sensors to view a grid formed of a multiplicity of parallel uniformly spaced lines, formed on the test pattern.

There is additionally provided in accordance with a preferred embodiment of the present invention an image acquisition system including a plurality of sensors each including a multiplicity of sensor elements, a pre-scan calibration subsystem, employing a predetermined test pattern, which is sensed by the plurality of sensors, for providing an output indication in two dimensions of distortions in the output of the plurality of sensors, the output indication being employed to generate a function which maps the locations viewed by the sensor elements in at least two dimensions, and an distortion correction subsystem operative during scanning of an article by the plurality of sensors to correct the distortions by employing the output indication.

Further in accordance with a preferred embodiment of the present invention the distortion correction subsystem is operative using a pixel size which is user selectable.

There is additionally provided in accordance with a preferred embodiment of the present invention an article inspection system including an image acquisition subsystem operative to acquire an image of an article to be inspected, an image analysis subsystem for identifying at least one predetermined characteristic of the article from the image, and an output indication subsystem for providing an output indication of the presence of the at last one predetermined characteristic of the article, characterized in the camera assembly includes a plurality of sensor assemblies, self calibration apparatus for determining a geometrical relationship between the sensor assemblies, and sensor output modification apparatus for modifying outputs of the plurality of sensor assemblies based on the geometrical relationship between the sensor assemblies, the sensor output modification apparatus including electronic interpolation apparatus operative to perform non-zero'th order interpolation of pixels in the outputs of the plurality of sensor assemblies.

There is additionally provided in accordance with a preferred embodiment of the present invention an article inspection system including an image acquisition subsystem operative to acquire an image of an article to be inspected, an image analysis subsystem for identifying at least one predetermined characteristic of the article from the image, and an output indication subsystem for providing an output indication of the presence of the at least one predetermined characteristic of the article, characterized in the camera assembly includes a plurality of sensor assemblies, self calibration apparatus for determining a geometrical relationship between the sensor assemblies, and sensor output modification apparatus for modifying outputs of the plurality of sensor assemblies based on the geometrical relationship between the sensor assemblies, the sensor output modification apparatus being operative to modify the outputs of the plurality of sensor assemblies to sub-pixel accuracy.

There is additionally provided in accordance with a preferred embodiment of the present invention an article inspection system including an image acquisition subsystem operative to acquire an image of an article to be inspected, an image analysis subsystem for identifying at least one predetermined characteristic of the article from the image, and an output indication subsystem for providing an output indication of the presence of the at least one predetermined characteristic of the article, characterized in the camera assembly includes at least one sensor assembly, and sensor output modification apparatus for modifying at least one output of the at least one sensory assembly based at least in part on an optical distortion associated with the at least one sensor assembly.

Further in accordance with a preferred embodiment of the present invention the optical distortion includes pixel size distortion.

Still further in accordance with a preferred embodiment of the present invention the optical distortion includes magnification distortion.

Additionally in accordance with a preferred embodiment of the present invention the optical distortion includes chromatic aberration.

Moreover in accordance with a preferred embodiment of the present invention the optical distortion includes overlap misadaptation.

Further in accordance with a preferred embodiment of the present invention the optical distortion includes pixel shift due to sensor separation.

Still further in accordance with a preferred embodiment of the present invention the optical distortion includes focus inconsistencies across color components.

Additionally in accordance with a preferred embodiment of the present invention the optical distortion includes color accumulation shift.

There is additionally provided in accordance with a preferred embodiment of the present invention an article inspection system including an image acquisition subsystem operative to acquire an image of an article to be inspected, an image analysis subsystem for identifying at least one predetermined characteristic of the article from the image, and an output indication subsystem for providing an output indication of the presence of the at least one predetermined characteristic of the article, characterized in the camera assembly includes at least one sensor assembly, sensor output modification apparatus for modifying at least one output of the at least one sensory assembly, the sensor output modification apparatus including a function generator which generates a function which maps locations on the sensor assembly to a collection of scan locations.

There is additionally provided in accordance with a preferred embodiment of the present invention an article inspection system including a camera assembly operative to acquire an image of an article to be inspected, an image analysis subsystem for identifying at least one predetermined characteristic of the article from the image, and an output indication subsystem for providing an output indication of the presence of the at last one predetermined characteristic of the article, characterized in the camera assembly includes a user interface which enables a user to select resolution of the image acquired by the camera assembly, an electro-optical sensor assembly, and an electronic resolution modifier operative downstream of the electro-optical sensor assembly.

Further in accordance with a preferred embodiment of the present invention the camera assembly is operative in response to resolution selection at the user interface to determine the pixel size of the image.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be understood and appreciated more fully from the following detailed description taken in conjunction with the drawings in which:

Fig. 1 is a simplified block diagram illustration of an article inspection system constructed and operative in accordance with a preferred embodiment of the present invention;

Fig. 2 is a simplified illustration of parts of a preferred test pattern, certain portions of which are not drawn to scale, along with a simplified indication of the fields of view of individual line sensors viewing the test pattern;

Fig. 3 is a simplified block diagram illustration of mapping function generator circuitry forming part of the system of Fig. 1;

Fig. 4A is a simplified flow chart illustrating operation of pixel size and shape determination functionality of the mapping function generator circuitry of Fig. 3;

Fig. 4B is a simplified illustration of geometrical distortion addressed by the functionality of Fig. 4A;

Fig. 4C is a simplified semi-pictorial, semi-graphical illustration of the functionality described in the flowchart of Fig. 4A;

Fig. 5A is a simplified flow chart illustrating operation of test pattern angle determination functionality of the mapping function generator circuitry of Fig. 3;

Fig. 5B is a simplified illustration of the geometrical distortion addressed by the functionality of Fig. 5A;

Fig. 5C is a simplified semi-pictorial, semi-graphical illustration of the functionality described in the flowchart of Fig. 5A;

Fig. 6A is a simplified flow chart illustrating operation of Determination of Relative Orientation of Sensors by Correlating Images of Test Pattern Targets at Edges of the Field of View of Sensors functionality of the mapping function generator circuitry of Fig. 3;

Fig. 6B is a simplified illustration of the geometrical distortion addressed by the functionality of Fig. 6A;

Fig. 6C is a simplified semi-pictorial, semi-graphical illustration of the functionality described in the flowchart of Fig. 6A;

Fig. 7A is a simplified flow chart illustrating operation of Determination of X Overlap and Y Offset of Sensors by Correlation of Adjacent Images functionality of the mapping function generator circuitry of Fig. 3;

Fig. 7B is a simplified illustration of the geometrical distortion addressed by the functionality of Fig. 7A;

Fig. 7C is a simplified illustration of the functionality described in the flowchart of Fig. 7A;

Fig. 8A is a simplified flow chart illustrating operation of Determination of X and Y Offsets for Multiple Colors functionality of the mapping function generator circuitry of Fig. 3;

Fig. 8B is a simplified illustration of the geometrical distortion addressed by the functionality of Fig. 8A;

Fig. 8C is a simplified illustration of the functionality described in the flowchart of Fig. 8A;

Figs. 9A and 9B, taken together, are simplified flowchart illustrations of a preferred method of implementing mapping function generator circuitry forming part of the system of Fig. 1;

Fig. 10A is a simplified illustration of acquisition of a target image by multiple cameras under ideal conditions;

Fig 10B is a simplified illustration of image buffers for storing the acquired image of 10A;

Fig. 11A is a simplified illustration of multiple cameras acquiring an image of a target where the camera fields of view are mutually skewed and overlapped;

Fig 11B is a simplified illustration of image buffers for storing the acquired image of 11A;

Fig. 12 is a simplified illustration useful in understanding Y-resampling functionality of the image correction circuitry 110 of Fig. 1;

Figs. 13 and 14, taken together, are simplified illustrations useful in understanding overlap correction functionality of the image correction circuitry 110 of Fig. 1;

Figs. 15 and 16, taken together, are simplified illustration useful in understanding X-resampling functionality of the image correction circuitry 110 of Fig. 1;

Fig. 17 is a simplified illustration useful in understanding aspects of accumulation shift correction functionality of the image correction circuitry 110 of Fig. 1;

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

Reference is now made to Fig. 1 which is a simplified block diagram illustration of an inspection system constructed and operative in accordance with a preferred embodiment of the present invention. The inspection system of Fig. 1 comprises a sensor array 100, typically comprising multiple multi-pixel line sensors oriented such that their fields of view are in partially overlapping, mutually skewed arrangement and, therefore, require correction. The multi-pixel line sensors are typically housed within a camera, such as a CCD camera, having electronic shutters.

A conveyor 102 is arranged to transport an article to be inspected past the sensor array 100 in a transport direction indicated by an arrow 104. Alternatively, sensor array 100 could be moved for providing scanning of the entire article to be inspected. A mapping function generator 106 is arranged to receive outputs from the sensor array 100 when a test pattern 108 is being inspected by the sensor array. The mapping function generator 106 provides an correction output to correction circuitry 110 which employs the mapping function generated by mapping function generator 106. Circuitry 110 receives outputs from the sensor array 100 when an article to be inspected, such as a printed circuit board 111, is being inspected by the sensor array 100.

It is noted that normally, at beginning of an inspection operation series, test pattern 108 is inspected by the sensor array 100 in order whereupon mapping function generator 106 generates the information required to correct the output of circuitry 110. Multiple articles to be inspected may then be inspected and thereafter, intermittently during the inspection of such articles, test pattern 108 may again be inspected by the sensor array 100 to provide updated calibration. Typically test pattern 108 is preferably inspected about once per month of continuing operation of the inspection system.

Image correction circuitry 110 is operative to employ the correction input received from mapping function generator 106 to correct the outputs received from sensor array 100 and provides a corrected sensor array output to segmentation circuitry 112. Segmentation circuitry 112 provides a segmentation output indication dividing all areas on the image of the article represented by the corrected sensor array output into one of typically two categories. For example, in the case of inspection of printed circuit boards, every location on the image represented by the corrected sensor array output is identified by the segmentation output indication as being either laminate or copper.

The segmentation output indication from segmentation circuitry 112 is supplied to image processing circuitry 114. Image processing circuitry 114 is preferably a morphology-based system, but may alternatively be based on a bit map, a net list, or any other suitable input. Circuitry 114 provides an image processing output which identifies various features of the image represented by the corrected sensor array output and the locations of such features. In the case of printed circuit boards, the features are typically pads, conductor junctions, open ends, and other printed circuit board elements.

The image processing output of circuit 114 is supplied to feature registration circuitry 116, which maps the coordinate system of the image processing output of circuitry 114 onto a feature reference coordinate system, in accordance with information supplied by a reference input source 118.

The output of registration circuitry 116 and an output of reference input source 118 are supplied to feature comparison circuitry 120, which compares the mapped image processing output of circuitry 114 with a reference stored in source 118 and provides a defect indication which is supplied to a defect indication output generator 122.

Reference is now made to Fig. 2 which is a simplified illustration of parts of a preferred test pattern 108, certain portions of which are not drawn to scale, along with a simplified indication of the fields of view of individual line sensors 124 in sensor array 100 (Fig. 1) viewing test pattern 108. Test pattern 108 typically comprises a row 130 of parallel uniformly spaced inclined lines 132, an angular orientation determinator 134 having an inclined edge 182, and an array of LORs 136, preferably positioned at the edges of the field of view of each camera 124. The term "LOR" stands for Lots of Rectangles and is used to designate a multiplicity of differently sized rectangles as shown in enlarged form at reference numeral 138. LORs 136 are employed to facilitate the relative positioning of images of an object as seen by sensor array 100 (Fig. 1).

The uniformly spaced parallel inclined lines 132 are preferably angled at a small angle ψ having a tangent of about 0.05 with respect to the transport direction 104. The angular orientation determinator 134 is preferably nearly rectangular in shape, however one of the edges of the angular orientation determinator is preferably angled at a small angle β having a tangent of about 0.0156 with respect to the transport direction 104.

Reference is now made to Fig. 3, which is a simplified block diagram illustration of the mapping function generator 106 of Fig. 1. Outputs 200 representing images of targets on test pattern 108 (Figs. 1 and 2) which is being inspected by the sensor array 100 (Fig 1) are supplied to the mapping function generator 106 which carries out the following functions:

Pixel Size and Shape Function Determination for a Single Color 202;

Determination of Test Pattern Angle 204;

Determination of Relative Orientation of Sensors by Correlating Images of Test Pattern Targets, preferably LORs 136 (Fig. 2), at Edges of the Field of View of Sensors 206;

Determination of X Overlap and Y Offset of Sensors by Correlation of Adjacent Images 208; and

Determination of X and Y Offsets for Multiple Colors 210.

The parameters thus determined are supplied to a geometric polynomial generator 212 which preferably provides a function which maps the locations viewed by individual elements of sensor array 100 (Fig. 1) in at least two dimensions.

The output of geometric polynomial generator 212 is provided to image correction circuitry 110.

Reference is now made to Fig. 4A, which is a simplified flow chart illustrating operation of the Pixel Size and Shape Function Determination circuitry 202 of Fig. 3 and to Fig. 4B which illustrates a distortion sought to be overcome by the functionality of circuitry 202.

As seen in Fig. 4B, the apparent dimensions of identical features as seen by camera 124 may vary depending on the position of the feature in the field of view of the camera for a given field of view angle ϕ. Thus, an "on-axis" feature 140 which is directly in front of the camera and in the illustration spans the field of view of camera 124 is perceived to have a width of "d" pixels, while an identical feature 142 when located at the edge of the field of view does not span the field of view of camera 124 and is perceived to have a width "$d - \Delta$" pixels.

Considering now Fig. 4A with further reference to Fig. 4C, it is seen that row 130 of parallel uniformly spaced inclined lines 132 of test pattern target 108 (Fig. 2) is viewed by a plurality of cameras 124, of which only one is shown in Fig. 4C. Each camera 124 acquires an image of a part of row 130, an enlarged part of which is shown at reference numeral 150. For the purpose of calculating the size and pixel shape function, the image is preferably acquired in a single color, such as red.

Alternatively, the image may be acquired in several colors, one of which may be used for the purpose of calculating the size and pixel shape. For each image, the angle ψ, at which images of the lines 132 are inclined with respect to the transport direction 104, is measured. The images of the lines are indicated by reference numerals 152. The separation between each adjacent line 132 in row 130 is fixed and predetermined, and the location of each line 132 in row 130 along an axis 105 that is perpendicular to transport direction 104 is known with respect to an arbitrarily chosen one of lines 132. The location of a typical line is designated by reference numeral 154.

A graph 160 represents the summation of the outputs of the cameras 124 as they scan row 130 in a direction angled by angle ψ with respect to direction 105, i.e. the image is projected onto the x-axis at angle ψ. It can be seen that each line 152 produces a local minimum in graph 160. The separation of adjacent lines 152 in the camera output may be determined by measuring the distance between adjacent points of inflection before each local minimum. 154' indicated the point of inflection corresponding to line location 154. The X-axis of graph 160 represents the number of each initial individual diode in a linear array of diodes in camera 124, while the Y-axis in graph 160 represents the summation of the intensity L of the image scanned in a direction angled by angle ψ with respect to direction 105.

By utilizing the knowledge that lines 132 in the test pattern are uniformly spaced, the variations in the position of lines 152 can be mapped as a function of diode number to indicate the distortion present in the image output of the camera 124 and thus the correction which is required. This mapping is provided in a graph 170 which illustrates a least square fit to a cubic function which represents a size and shape function, where the Y-axis is labeled "POS" and 154'' represents the distance of the line position 154 from the arbitrarily chosen line 132 and the X-axis represents the diode number in camera 124. This function may be expressed as:

$$S_n(d)=s_1d+s_2d^2+s_3d^3$$

where n indicates the number of the camera, s_1 to s_3 are coefficients that are to be determined, and d is the diode number corresponding to an enumeration of the diodes of each camera n.

Reference is now made to Fig. 5A, which is a simplified flow chart illustrating operation of the Test Pattern Angle Determination circuitry 204 of Fig. 3 and to Fig. 5B which illustrates the distortion sought to be overcome by the functionality of circuitry 204.

As seen in Fig. 5B, the entire test pattern 108 is normally, in reality, not perfectly aligned with the transport direction 104, but rather is offset therefrom by an angle α.

Considering now Fig. 5A with further reference to Fig. 5C, it is seen that test pattern target 108 comprising angular orientation determinator 134, having edge 182 of known aspect angle β relative to additional objects in the test pattern, is viewed by camera 124. The camera 124 acquires an image of angular orientation determinator 134, an enlarged portion of which is shown at reference numeral 184 in Fig. 5C.

An aspect angle β^* of an inclined edge 186 of the image of the determinator 134 is calculated by conventional techniques based on measurements carried out on each raster line of the image. The deviation of this calculated aspect angle β^* from the angle β represents the value of the angle α and is expressed as $\beta^*-\beta=\alpha$. The thus-determined deviation is employed for correction in circuitry 110 (Fig. 1).

Reference is now made to Fig. 6A, which is a simplified flow chart illustrating operation of the Determination of Relative Orientation of Sensors by Correlating Images of Test Pattern Targets at Edges of the Field of View of Sensors circuitry 206 of Fig. 3 and to Fig. 6B which illustrates the distortion sought to be overcome by the functionality of circuitry 206.

As seen in Fig. 6B, rather than being aligned in a single row or "collinearly", the fields of view 162 of various cameras 124 are seen, in an exaggerated view, to be mutually skewed and partially overlapping. These are shown as angles θ_1 through θ_3 between the axis of the field of view of each camera 124 and an axis 308 perpendicular the direction of motion 104. The calculation of θ_1 through θ_3 is described in greater detail hereinbelow with reference to Figs. 9A and 9B. The functionality described here with reference to Figs. 6A - 6C deals with the distortion of relatively skewed fields of view of the cameras, while the functionality described hereinbelow with reference to Figs. 7A - 7C and circuitry 208 (Fig. 3) deals with the problem of partial X overlap and Y offset as determined by the direction of motion 104.

Considering now Fig. 6A with further reference to Fig. 6C, it is seen that a test pattern target preferably comprising a row 300 of LORs 136 of known angular orientation relative to edge 182 of angle determinator 134 is viewed by a plurality of cameras 124. The LORs 136 of row 300 preferably collinear, and row 300 is preferably parallel to the front edge of the target 108. Each camera 124 acquires an image of part of row 300. Preferably the LORs are seen at the edges of the respective fields of view of each camera 124.

Enlargements of two image regions 253, each shown in dashed lines and comprising a different LOR 136, as viewed by one of the cameras 124, such as CAM 1, are shown in Fig. 6C at reference numerals 304 and 306. It is noted that due to the angle of the field of view of CAM 1 there results an offset relationship between the images 304 and 306 including a y offset, Δy_{ANG}, as seen in Fig. 6C. This offset is determined and used to calculate the angle θ^* between the axis of the field of view of CAM 1 and the row of LORs 300. θ^* is determined by the relationship $\theta^* = \arctan(\Delta y_{ANG} / L_x)$ where L_x is the longitudinal separation between adjacent LORs. The angles θ^* for each camera 124 may be calculated in this manner and stored for later reference.

Reference is now made to Fig. 7A, which is a simplified flow chart illustrating operation of the Determination of X Overlap and Y Offset of Sensors by Correlation of Adjacent Images 208 of Fig. 3 and to Fig. 7B which illustrates the distortion sought to be overcome by the functionality of circuitry 208.

As seen in Fig. 7B, and similar to that which is seen in Fig. 6B, rather than being aligned in a single row or "collinearly", the fields of view 162 of various cameras 124 are seen, in an exaggerated view, to be mutually skewed and shifted in what is referred to herein as the Y direction, being the same as direction 104, and partially overlapping in what is referred to herein as the X direction, being perpendicular to direction 104. The functionality described here with reference to

Figs. 7A - 7C deals with the problem of offset of the fields of view of the cameras 124. An overlap in the fields of view of two adjacent cameras is shown at reference numeral 348.

Considering now Fig. 7A with further reference to Fig. 7C, it is seen that test pattern target 108, preferably comprising row 300 of LORs 136 as in Fig. 6C, is viewed by multiple cameras 124. Each camera 124 acquires an image of part of row 300 which includes the same LORs.

The X overlap and Y offset may be determined by using an image region 253 that is acquired by two adjacent cameras 124. Two enlarged images of one image region 253 of a LOR 136, as seen by two adjacent cameras 124, are shown in Fig. 7C at reference numeral 354. The two enlarged images of LOR 136 are shown in mutually offset, overlapping relationship, such that the LORs seen in both images are in precise overlapping registration. It is noted that due to this overlapping relationship between the images a y offset, Δy_{OV}, and an x offset, Δx_{OV}, are produced, the offsets being expressed in pixel units. Δx_{OV} may then be converted to metric units and expressed as $m\Delta x_{OV}$ by employing the pixel size and shape function as described hereinabove with reference to Figs. 4A - 4C. An overlap in the x direction, OV_x, may then be calculated as $w-m\Delta x_{OV}$, where w is the metric width of each image. Δy_{OV} may be converted to metric units by multiplying Δy_{OV} by a predetermined pixel size in the Y direction 104

Reference is now made to Fig. 8A, which is a simplified flow chart illustrating operation of the Determination of X and Y Offsets for Multiple Colors circuitry 210 of Fig. 3 and to Fig. 8B which illustrates a distortion sought to be overcome by the functionality of circuitry 210.

As seen in Fig. 8B, a three-color CCD camera 380 is shown. Camera 380 typically includes a multi-pixel line sensor 382 comprising three line sensors such as 384, 386, and 388, with the line sensor being arranged in parallel and each comprising a plurality of single-color sensing diodes 390 arranged linearly. The diodes 390 of the multi-pixel line sensor 382 may be logically arranged into groupings of three diodes, one from each of line sensors 384, 386, and 388, with each diode sensing a different color. Three such groupings 392, 394, and 396 are shown, at the center and both edges of camera 380.

Camera 380 is shown viewing elements 398 of a target 400 moving in direction 104. The image acquired by the multi-pixel line sensor 382 is typically stored in three buffers 402, 404, and 406, with each buffer corresponding to a particular color, such as red, green, and blue respectively. A combined view of buffers 402, 404, and 406 is shown at reference numeral 408. Combined buffer 408 shows the acquired images 399, 401, and 403 of elements 398. The images 399, 401, and 403 of combined buffer 408 demonstrate the pixel size and shape distortion in the X direction due to chromatic aberration, as shown at 410, as well as the Y direction displacement, as shown at 412, due to the physical separation of the R, G and B line sensors.

Considering now Fig. 8A with further reference to Fig. 8C, it is seen that test pattern target 108, preferably comprising row 300 of LORs 136 as seen in Figs. 6C and 7C, is viewed by multiple cameras 124. Each camera 124 preferably acquires a multicolored image at either edge of the camera, with one edge of camera 124 acquiring an image of one LOR 136, and the other edge acquiring an image of an adjacent LOR 136.

Each color of each multicolored image acquired at each edge of one of the cameras 124 is preferably related to separately. A single color, such as red, may be selected as a reference color to which the other two color components of the multicolored image are compared. In the example shown, the red and green components of image region 253 at one edge of the field of view of CAM 1 are shown enlarged at reference numeral 360. The two enlarged images of LOR 136 are shown in mutually offset, overlapping relationship, such that the LORs seen in both images are in precise overlapping registration. It is noted that due to this overlapping relationship between the images a y offset, Δy_{COL}, resulting from the physical shift between line sensors of different colors, and an x offset, Δx_{COL}, resulting from the shift due to chromatic aberration, are produced, the offsets being expressed in pixel units. Δx_{COL} and Δy_{COL} may then be converted to metric units in the same manner as is described hereinabove with reference to Fig. 7C. The red and blue components of image region 253 at one edge of the field of view of CAM 1 may likewise be compared, as may the red and green components and the red and blue components of the multicolored image of the adjacent LOR acquired at the other edge of the field of view of CAM 1 (not shown).

Reference is now made to Figs. 9A and 9B, which, taken together, are simplified flow charts illustrating operation of the geometric polynomial generator 212 of Fig. 3. A cubic function may be constructed to determine the positions of the diodes of cameras 124 in space using the outputs of 202 – 210 described hereinabove with reference to Figs. 4A – 8C. Two sets of polynomials are constructed for each camera 124, an X-polynomial for determining the position of a diode in the X direction and a Y-polynomial for determining the position in the Y direction. The X-polynomial may be expressed as

$$P_x(d) = a_0 + a_1 d + a_2 d^2 + a_3 d^3$$

where a_0 through a_3 are the coefficients of the X-polynomial. The Y-polynomial may be expressed as

$$P_y(d) = b_0 + b_1 d$$

where b_0 and b_1 are the coefficients of the Y-polynomial.

It has been found through experimentation that expressing the Y-polynomial linearly provides a sufficient approximation of a diode's Y position.

Methods for determining the X-polynomial are now described in greater detail.

In Fig. 9A the X-overlap, OV_X, as determined in 208 (Fig. 3), is used to find a0[n] first for one color, such as red, of each camera n in a row of cameras, such as cameras designated CAM 1, CAM 2, and CAM 3 in Fig. 7C. The X-polynomials may then be derived for the other colors, such as blue and green, based on the X-polynomial for the first color as follows:

1) Let $a_0[1] = 0$ for CAM 1

2) Proceeding along the row of cameras, for each subsequent camera n determine a0 as follows:

$$a_0[n] = a_0[n-1] + (Sn-1(ND) - W) + OV_x[n,n-1]$$

where:

- ND is the number of diodes in the preceding camera n-1;

- $S_{n-1}(ND)$ is the value of the pixel size and shape function output determined in 202 as evaluated for the last pixel of camera n-1;

- w is the width of the image in metric units containing the LOR; and

- OVx is the measured overlap in the X-direction as determined in 206.

3) The coefficients s1, s2, s3 as expressed in the size and shape function output determined by circuitry 202 (Fig. 3) are assigned to a1, a2, and a3 respectively of the X-polynomial.

The red-green and red-blue X-offsets, Δx_{COL} as determined by circuitry 210 (Fig. 3) is combined with the result of the X-polynomial determined for the red color component, designated $(a_0, a_1, a_2, a_3)^{red}$, to yield a0 and a1 values for the X-polynomial for the green color as follows:

a0[green] = a0[red] + (dr * rg_xl - dl * rg_xr) / (dr - dl)

a1[green] = a1[red] + (rg_xr-rg_xl)/(dr-dl)

a2[green] = a2[red]

a3[green] = a3[red]

where:

- dr is the diode position of the LOR used for the overlapping at the right edge of the camera;

- dl is the position in metric units of the LOR used at the left edge of the camera;

- rg_xl is the Δx_{col} difference measured between the red and the green component at the left edge of camera; and

- rg_xr is the Δx_{col} difference measured at the right edge of the camera.

The "left" and "right" edges of the field of view of a camera refer respectively to the edge of the camera closest to camera n-1 and the edge closest to camera n+1, except for the first and last cameras 1 and n, where the edges are defined with respect only to cameras n+1 and n-1 respectively. The same procedure may be used to calculate a0[blue] through a3[blue].

Methods for determining the Y-polynomial are now described in greater detail with particular reference to Fig. 9B.

Referring again to Fig. 6B, an angle $\theta_{1\text{-}3}$ may be determined for each camera 124 relative to the axis 162 of the field of view of each camera 124 and the axis 308 which is perpendicular the direction of motion 104. $\theta_{1\text{-}3}$ may then be determined by the relationship $\theta = \theta^* - \alpha$ where α is the correction angle determined by circuitry 204 (Fig. 3).

In Fig. 9B the Y-polynomial is determined initially for one color, such as red, of each camera n in a row of cameras, such as cameras designated CAM 1, CAM 2, and CAM 3. The Y-polynomials may then be derived for the other colors, such as blue and green, based on the Y-polynomial for the first color.

The coefficient b1 of the Y-polynomial may be derived as $b1 = \tan(\theta)$. The coefficient b0 of the Y-polynomial may be calculated in two stages. In the first stage b0 of the first camera CAM 1 is set b0[1] = 0. b0 for each subsequent camera may be calculated as follows:

$$b0[n] = b0[n-1] + b1[n-1]*(S_{n-1}(ND)-OVx) + \Delta y_{ov}[n, n-1]$$

In the second stage the minimum value of the three Y-polynomials referring to the three cameras is determined. Since the approximation is linear it is sufficient to look for the minimum value at the edges of the fields of view the respective cameras as follows:

$$\min(P_{y1}(0), P_{y1}(ND), P_{y2}(0), P_{y2}(ND), P_{y3}(0), P_{y3}(ND))$$

where each of the subscripts of P_y identify a specific one of several cameras. This minimum is subtracted from b0 for each camera, ensuring that $P_y >= 0$ for all diodes.

The red-green and red-blue y-offsets , Δy_{col} as determined by circuitry 210 (Fig. 3) is combined with the result of the Y-polynomial determined for the red color component to yield b0 and b1 values for the green and the blue Y-polynomials. This is done as follows:

b0[green] = b0[red] + 0.5 * (rg_ly + rg_ry)

b1[green] = b1[red]

where rg_ly is the Δy_{col} shift measured between the red and green components at the left edge of the camera, and rg_ry is the Δy_{col} shift measured at the right edge of the field of view of the camera. b0[green] and b0[blue] are also preferably modified to accommodate the different accumulation times for each color component as is described in greater detail hereinbelow with reference to Fig. 17.

Reference is now made to Fig. 10A which is a simplified illustration of multiple cameras 500 and 502 acquiring an image of a target 504 under ideal conditions, and Fig. 10B which is a simplified illustration of image buffers for storing the acquired image of target 504. Cameras 500 and 502 are typically in fixed positions, each having a static field-of-view, and are arranged such that target 504 passes through the fields-of-view of cameras 500 and 502 in the direction of motion 104. Cameras 500 and 502 each acquire an image of target 504 one image line at a time by employing a multi-pixel line sensor as is described hereinabove.

Each diode of the multi-pixel line sensor acquires a single-pixel image of a specific location on target 504, and the pixels acquired by each diode collectively form an image line. An image line portion 512 is shown comprising a plurality of pixels 514. As target 504 moves in the direction of motion 104, the field-of-view of cameras 500 and 502 "moves" in the direction designated by arrows 508, and thus the image lines are acquired in the direction of 508 as well.

Referring to a time index 510 ranging from t_0 to t_1, camera 500 begins acquiring an image at t_0 to yield an image line 516 shown in dashed lines. Image line portion 512 is acquired at time index t_x, shown intersecting a portion of a target element 518. Target 504 continues to move in the direction of arrow 506, and the acquired image lines approach t_1 as is shown in dashed lines by an image line portion 520.

The conditions under which cameras 500 and 502 acquire the image of target 504 are ideal in that the fields of view of both cameras are aligned in a single row and are non-overlapping. As shown in Fig. 10A, image line portion 512 associated with camera 500 is aligned in a single row with an image line portion 522 associated with camera 502 at time index t_x, with image line portions 512 and 522 meeting at a boundary line 524.

The image lines scanned by cameras 500 and 502 are typically stored in buffers, such as buffers 530 and 532 of Fig. 10B. Since the scan lines of both buffers are aligned in a single row for each corresponding time index, buffers 530 and 532 may be combined to form a non-distorted composite image of target element 518, a portion of which is shown as 534.

Additional reference is now made to Figs. 11A and 11B which illustrate the effect cameras 500 and 502 have when acquiring an image of target 504 under less than ideal conditions in contrast to Figs. 10A and 10B, specifically when the fields of view of both cameras are mutually skewed and are overlapping. Figs. 11A and 11B are intentionally provided as an oversimplified illustration of some difficulties encountered, and are merely intended to review what was described in greater detail hereinabove and are not intended to supersede the descriptions of Figs. 1 - 9B.

The image lines acquired are shown not aligned in a single row for a given time index t_x, such as is shown with reference to buffers 560 and 562 and image line portions 564 and 566 of Fig. 11B. Combining buffers 560 and 562 would produce a distorted composite image 568 of target element 518, as is shown in Fig. 11B. In addition, simply combining the buffer images would neither correct for image overlap, discussed hereinabove with reference to Figs. 7A - 7C, nor for the viewing angle distortion, discussed hereinabove with reference to Figs. 4A - 4C.

Techniques for deriving a corrected composite image from buffers 560 and 562 are now described with additional reference to Figs.12 - 16.

A FIFO buffer, such as a FIFO buffer 600 of Fig. 12, may be defined by defining a window having a height expressed in a fixed number of image buffer rows, such as 40, beginning with the first row of pixels acquired. This window is then typically advanced to a new position one row at a time as each new row of pixels is acquired. Alternatively, an image buffer may initially be filled with row of pixels, at which point the FIFO buffer window may be defined as a subset of the image buffer rows and advanced along the image buffer in the manner just described.

Before the X and Y polynomials determined with reference to Figs. 9A and 9B can be used for correcting the image they may be translated into another type of polynomial referred to herein as a "diode compensating polynomial". This polynomial maps the relationship between a diode and a pixel position of a corrected image constructed using a pixel size chosen by the user. The diode compensating polynomials $Q_x(d)$ and $Q_y(d)$ may be derived from the X and Y-polynomials through the transformation:

$$Q_x(d) = Px(d)/p$$

$$Q_y(d) = Py(d)/p$$

where p is the pixel size chosen by the user and is expressed in the same metric units as Px(d). The pixel size p chosen by the user must be a multiple of the minimum measurable distance of travel in the scan direction 104, typically one pulse unit of a drum encoder. The diode compensating polynomial Q_y may be additionally be adjusted for the shift introduced by different color component accumulation times as is described in greater detail hereinbelow with reference to Fig. 17.

Each pixel or grid point in the FIFO buffer represents the sampling of a corresponding target acquired by a diode. A process of "resampling" is used whereby calculations are performed to determine a gray level g at an arbitrary position "between" grid points of the buffer grid. A four point convolution may be used to interpolate a value for g as follows:

$$g = c_1 g_1 + c_2 g_2 + c_3 g_3 + c_4 g_4$$

where c_1 through c_4 are the convolution cofficients, and g_1 through g_4 are four grey levels at four adjacent grid points.

A method for determining the four interpolation coefficients c_1 through c_4, collectively designated c_i, and the four gray levels g_1 through g_4, collectively designated g_i, is now described.

The four gray levels g_i may be selected from four contiguous grid points of the FIFO buffer. These four points are referred to herein as a "quartet". The method of determining which four grid points are selected from the buffer grid is described in detail below.

Resampling may be performed in two stages corresponding to the X and Y directions described hereinabove. The stages are referred to herein as X-resampling and Y-resampling. Y-resampling is now described in greater detail with reference to Fig. 12. Two FIFO buffers 600 and 602 are shown corresponding to two cameras. The set of all pixels 604 in the FIFO buffers scanned by a diode d may be referred to as diode d's "gray level column," such as a column 606. Virtual scan lines 608 and 610 are shown to indicate the correction angles needed for each buffer to compensate for the misalignment angles of each corresponding camera. A quartet 612 is shown as a group of four pixels within the gray level column 606 closest to scan line 608.

The following steps are performed:

1. For each diode d the value of the resampling polynomial Qy(d) is calculated.

2. The quartet index q(d) denotes the first grid point belonging to the quartet of pixels that lie within the diode's gray level column. The other three grid points in the quartet are the previous three grid points in the diode's gray level column, that is the three grid points most recently acquired by diode d just prior to the grid point at index q(d). q(d) is determined as follows:

$$q(d) = \mathrm{floor}(Qy(d)-1/2)-1$$

The index q(d) for each quartet is preferably stored in a quartet look-up table in a position corresponding to the diode d.

3. The four convolution coefficients c1 through c4 are calculated based on the distance of the polynomial Qy from the nearest quartet index. This distance is called $\xi(d)$ and is expressed as:

$$\xi(d) = Qy(d) - (q(d) + 1)$$

Preferably $-1/2 <= \xi < 1/2$.

4. For a given ξ the four convolution coefficients c_1, c_2, c_3, and c_4 may be calculated as follows:

$$c_1 = -14 + 10\xi - 3\xi^2 + 0.5\xi^3$$

$$c_2 = -1 + 0.5\,\xi + 2\xi^2 - 1.5\,\xi^3$$

$$c_3 = 1 - 2.5\xi^2 + 1.5\xi^3$$

$$c_4 = -5/2 - 5.5\xi - 1.5\xi^2 - 0.5\,\xi^3$$

where ξ is dependent on d as explained above.

The use of convolution coefficients c1 through c4 is described in greater detail in "Image Reconstruction by Parametric Cubic Convolution", Stephen K. Park and Robert A. Schowengerdt, Computer Vision Graphics and Image Processing 23, 258-272, the disclosure of which is incorporated herein by reference.

For each diode d these four coefficients c1, c2, c3, and c4 are preferably encoded in such a manner that when decoded and summed the summed value equals 1.0, although the accuracy of any single coefficient may be diminished. The encoded values are preferably stored in a coefficients look-up table in a position corresponding to d.

Overlap correction functionality is now described in further detail with reference to Fig. 13 which shows outputs 620 and 622 from two adjacent cameras 1 and 2 after Y-resampling and prior to being combined. An image overlap region 624 between the two cameras must be corrected when combining the outputs thereof to provide a single image. In a preferred embodiment the image outputs are not combined by simply using the output of camera 1 until an arbitrarily chosen pixel position in the overlap region and then switching to the output of camera 2 starting from a corresponding pixel position. Rather, a "blending region" 626 of a predefined number of pixels B, typically 100 pixels, is defined within the overlap region 624 between cameras 1 and 2 where corresponding pixels from both cameras within the blending region are blended to yield a single pixel value which is then used to form the combined image 630. The blending region preferably begins after allowing for a pixel margin 628 of a predefined number of pixels M, typically 20 pixels, in order to accommodate lower-quality output often encountered at the ends of a diode array.

It is appreciated that the two diode resampling polynomials $Q_x^{(1)}(d)$ and $Q_x^{(2)}(d)$ of the two adjacent cameras may be used to determine the amount of overlap between the cameras.

To correct for overlap, the following steps may be performed:

1. Defining $Q_x^{(2)}(1)$ to refer to the pixel position r of the first pixel of X and Y-resampled output of camera 2 (X-resampling is described in greater detail hereinbelow with reference to Fig. 15). The leading edge of the blending region may be determined by adding the predetermined number of pixels defined for the pixel margin described above.

2. As shown in Fig. 14, determining a weight w(i) for each position i in the blending region where w(i)=i/B. The use of this weight aids in combining the outputs of cameras 1 and 2 as a linear mixture of the outputs of both of the adjacent cameras, where the contribution of camera 1 is expressed as 1-w(i) and camera 2 as w(i). For example, where the blending region comprises 100 pixels, the first pixel in the blending region contains 99% of the information from the pixel of camera 1 and 1% from the corresponding pixel of camera 2, and the last pixel in the blending region being inversely proportionate. This solution enables a smooth transition between the cameras.

3. Expressing the gray-level output g of two corresponding pixels of camera 1 and 2 within the blending region as:

$$g(i) = (1-w(i)) * g1(i) + w(i) * g2(i)$$

where B is the number of pixels in the blending region, i is the index of the position in the region, and g1(i) and g2(i) are the gray levels of the corresponding pixels in the region of camera 1 and 2 respectively.

X-resampling is now described in greater detail with reference to Fig. 15. Due to optical distortions, and in order to accommodate a user-defined pixel size, an output 640 of the Y-resampling must be resampled in the X direction, thereby creating a X-corrected image row 642 with pixels having the desired pixel size. Each pixel position r on the X-corrected image row corresponds to a position d(r) on the diode array.

d(r) may be calculated using the diode resampling polynomial $Q_x(d)$. This involves finding the inverse function $Q^{-1}(r)$ of $Q_x(d)$. This inverse function allows the mapping of the pixel position r on the X-corrected image row to a corresponding position d(r)on the diode array. It is appreciated that this position might not correspond to a integer position of a specific diode, but rather may be expressed in fractional terms along the diode array. Once the diode position d_p has been found, an X-quartet of pixels corresponding to four diodes is determined in a fashion similar to the method described above for Y-resampling. The gray levels of these four pixels are subsequently convolved with four correlation coefficients to interpolate a gray level value at a position r on the X-corrected image row.

An index q(r) is maintained to denote the position of the current quartet being used.

Additional reference is now made to Fig. 16 which illustrates the steps to be performed for each pixel in the X-corrected image row as follows:

1. Assigning an index r_p to correspond to the first pixel 650 in an X-corrected image row 652.

2. Stepping index r_p through each pixel position in the X-corrected image row 652 corresponding to an overlap region 654 to the end of the field of view 656 of the current camera, CAM 1, and find the diode position $d_p^{(1)}$ such that $r_p^{(1)}=Qx(d_p^{(1)})$. Since Qx is a monotonically increasing function, d_p advances as r_p advances. When d_p reaches the end 656 of the field of view of CAM 1, r_p is returned to the pixel position corresponding to the start of the overlap region 658 of the next camera, CAM 2, assigning to r_p the value of the diode compensating polynomial evaluated for the first diode of camera CAM 2, i.e. $r_p \leftarrow Q_x^{(2)}(1)$.

3. Stepping index r_p through each pixel position in the X-corrected image row 652 for CAM 2, finding the diode position $d_p^{(2)}$ such that $r_p^{(2)}=Qx(d_p^{(2)})$, and continuing as in step 2.

Steps 2 and 3 are performed for each subsequent pair of cameras.

Finding the diode position d_p may either be done through a one-time inversion of the function $Qx(d_p)$ or through a numerical solution. Once the diode position d_p has been found, the index of the first pixel in the X-quartet, as well as ξ, may be expressed as follows:

$$q(r) = FLOOR(Q^{-1}_x(r)-1/2)-1$$

$$\xi(r) = Q^{-1}_x(r) - (q(r) + 1)$$

as was similarly done in the case of Y-resampling.

q(r) thus defines the X-quartet, and the convolution coefficients c1 through c4 may be calculated based on ξ using the formulae described above for Y-resampling.

4. Storing q(r) in a X-quartet look-up table corresponding to the pixel position r. Alternatively, calculating an offset relative to the position of q(r-1) by subtracting the value of the previous quartet position q(r-1) from the current quartet position q(r) and storing the offset.

5. Encoding the four convolution coefficients c1 through c4 as was described above for the Y-resampling and store in an X-coefficients look-up table in a position corresponding to pixel position r_P.

Image correction employing Y-Resampling, X-Resampling, and Overlap correction are preferably performed by circuitry 110 of Fig. 1, now summarized hereinbelow.

During Y-Resampling, an image may be corrected for camera field-of-view misalignment as follows. For a given position of the FIFO window the quartet index is retrieved for each diode from the Y-quartet look-up table. The four gray level values g1 through g4 of the corresponding quartet may then be extracted from the FIFO buffer, and the four correlation coefficients c1 through c4 may be retrieved from the Y-coefficients look-up table. The final interpolated gray level for each diode may then be calculated as was previously described by:

$$g = c_1 * g_1 + c_2 * g_2 + c_3 * g_3 + c_4 * g_4$$

and stored in a Y-corrected gray level buffer.

During X-Resampling, the Y-Resampled output is processed further to correct pixel shape and size. The gray level is processed one pixel row at time. For each pixel in the X-corrected image row, the X-quartet index is retrieved from the X-quartet look-up table and the four convolution coefficients c_1 through c_4 are retrieved from the X-coefficients look-up table. The four gray level values $g_{1'}$ through $g_{4'}$ of the corresponding X-quartet may then be retrieved from the Y-corrected gray level buffer. The final interpolated gray level for each pixel position r_P may then be calculated as was previously described by:

$$g' = c'_1 * g_{1'} + c'_2 * g_{2'} + c'_3 * g_{3'} + c'_4 * g_{4'}$$

During overlap correction the X-Resampled image row outputs from the various cameras are combined to form a single image row as described above with reference to Fig. 16.

It is well known in color image acquisition systems that both the nature of the light sources illuminating a target as well as the spectral reflective properties of the target may result in uneven color intensity of the image acquired. Thus, for example, a diode in the multi-line sensor array which detects red may receive a different amount of light for a white area of the target than a diode which detects blue receives for the same white area. Uneven color intensity may be corrected by varying the accumulation times of each color component of the multi-line sensor array in an inverse relationship to the intensity of light received by the color component.

In the present invention, when acquisition of an image line of a target begins, the electronic shutters of the camera are all opened, and each color component of the multi-line sensor array begins to accumulate the charge corresponding to its respective color. The exposure of each color component of the multi-line sensor array is then varied by closing the electronic shutters of each color component at different times. However, the center of the acquired pixel for each color component may be different than the geometric center of the pixel. Thus when measuring the overlap in the Y-direction 104, Δy_{col}, as described in Fig. 8C, an "accumulation shift" Δy_{acc} is introduced that may be corrected by subtracting the center of the acquired pixel from the geometric center of the pixel for each color component by the formula

$$\Delta y_{acc}[green] = (AT[green]-AT[red])/(2*IT)$$

$$b0^*[green] = b0[green] + \Delta y_{acc}[green]$$

where AT represents the accumulation time, IT represents the integration time, i.e. the time between the start of two subsequent image rows, , and b0*[green] is the modified 0^{th} coefficient of Q_y. The blue coefficient is modified similarly.

This accumulation shift is preferably determined during acquisition of the test target, and is used to adjust the b0 component of the Y-polynomial P_y. The diode compensating polynomial Q_y described in Fig. 9B may also be adjusted for the accumulation shift according to the different exposure times chosen for the various color components.

Fig. 17 illustrates the problem of accumulation shift in greater detail. As was described hereinabove with reference to Fig. 8C, a multi-line sensor array 700 is shown acquiring three pixels 702, 704, and 706, each pixel being acquired by a different line sensor 708, 710, and 712, with each line sensor comprising a plurality of single-color sensing diodes. Due to the different acquisition times of each of each line sensor, the relative areas of each of the three pixels acquired vary, as is shown by accumulation areas 714, 716, and 718. A geometric center may be defined for each of the three pixels at 720, 722, and 724. The center of each accumulation area may be defined at 726, 728, and 730. The distances between the centers of each accumulation area and its corresponding geometric center 732, 734, and 736 represent the accumulation shift for each color component and may be used to correct for the overlap in the Y-direction 104 as described above.

It is appreciated that various features of the invention which are, for clarity, described in the contexts of separate embodiments may also be provided in combination in a single embodiment. Conversely, various features of the invention which are, for brevity, described in the context of a single embodiment may also be provided separately or in any suitable subcombination.

It will be appreciated by persons skilled in the art that the present invention is not limited by what has been particularly shown and described hereinabove. Rather the scope of the present invention includes both combinations and subcombinations of the features described hereinabove as well as modifications and variations thereof which would occur to a person of skill in the art upon reading the foregoing description and which are not in the prior art.

CLAIMS

What is claimed is:

1. An image acquisition system comprising:

a plurality of sensors each including a multiplicity of sensor elements;

a pre-scan calibration subsystem, employing a predetermined test pattern, which is sensed by the plurality of sensors, for providing an output indication in two dimensions of distortions in the output of said plurality of sensors, said output indication being employed to generate a function which maps the locations viewed by said sensor elements in at least two dimensions; and

a distortion correction subsystem operative during scanning of an article by said plurality of sensors to correct said distortions by employing said output indication.

2. An image acquisition system according to claim 1 and wherein said plurality of sensors include plural sensors having different spectral sensitivities.

3. An image acquisition system according to claim 2 and wherein said plurality of sensors include at least two sensors having generally the same spectral sensitivity.

4 An image acquisition system according to claim 1 and wherein said plurality of sensors include at least two sensors which at least partially overlap in at least one dimension.

5. An image acquisition system according to claim 1 and wherein said pre-scan calibration subsystem is operative to sub-pixel accuracy.

6. An image acquisition system according to claim 1 and wherein said distortion correction subsystem performs non-zero'th order interpolation of pixels in the outputs of said plurality of sensors.

7. An image acquisition system according to claim 1 and wherein said distortion correction subsystem compensates for variations in pixel size in said plurality of sensors.

8. An image acquisition system according to claim 1 and wherein said distortion correction subsystem compensates for variations in magnification in said plurality of sensors.

9. An image acquisition system according to claim 1 and wherein said distortion correction subsystem compensates for chromatic aberrations in said plurality of sensors.

10. An image acquisition system according to claim 1 wherein said plurality of sensors include sensors having differing spectral sensitivities and wherein said function is dependent on differing accumulation times employed for said sensors having differing spectral sensitivities.

11. An image acquisition according to claim 1 and wherein said distortion correction subsystem compensates for variations in pixel shape in said plurality of sensors.

12. An image acquisition system according to claim 1 and wherein said distortion correction subsystem is operative to an accuracy of better than 5% of pixel size of said multiplicity of sensor elements.

13. An image acquisition system comprising:

a plurality of sensors each including a multiplicity of sensor elements;

a pre-scan calibration subsystem, employing a predetermined test pattern, which is sensed by the plurality of sensors, for providing an output indication of distortions in the output of said plurality of sensors, said output indication being employed to generate a correction function; and

a distortion correction subsystem operative during scanning of an article by said plurality of sensors to correct said distortions by employing said correction function, said distortion correction subsystem being operative to an accuracy of better than 5% of pixel size of said multiplicity of sensor elements.

14. An image acquisition system comprising:

a plurality of sensors;

a pre-scan calibration subsystem, employing a predetermined test pattern, which is sensed by the plurality of sensors while being moved relative to the plurality of sensors in a direction of relative movement, for providing an output indication of distortions in the output of said plurality of sensors, said pre-scan calibration system being operative to correlate images of at least one target on said test pattern as seen by said plurality of sensors, thereby to determine the relative orientation of said plurality of sensors; and

a distortion correction subsystem operative to correct said distortions by employing said output indication.

15. An image acquisition system according to claim 14 and wherein said pre-scan calibration subsystem also is operative to provide an output indication of the orientation of said plurality of sensors relative to said scan direction.

16. An image acquisition system according to claim 14 and wherein

each of said plurality of sensors includes a multiplicity of sensor elements; and

said pre-scan calibration subsystem also is operative to determine the pixel size characteristic of each of said multiplicity of sensor elements of each of said plurality of sensors.

17. An image acquisition system according to claim 16 and wherein said pre-scan calibration subsystem is operative to determine the pixel size characteristic of each of said multiplicity of sensor elements of each of said plurality of sensors by causing said plurality of sensors to view a grid formed of a multiplicity of parallel uniformly spaced lines, formed on said test pattern.

18. An image acquisition system comprising:

a plurality of sensors each including a multiplicity of sensor elements;

a pre-scan calibration subsystem, employing a predetermined test pattern, which is sensed by the plurality of sensors, for providing an output indication in two dimensions of distortions in the output of said plurality of sensors, said output indication being employed to generate a function which maps the locations viewed by said sensor elements in at least two dimensions; and

an distortion correction subsystem operative during scanning of an article by said plurality of sensors to correct said distortions by employing said output indication.

19. An image acquisition system according to claim 18 and wherein said distortion correction subsystem is operative using a pixel size which is user selectable.

20. An article inspection system comprising:

an image acquisition subsystem operative to acquire an image of an article to be inspected;

an image analysis subsystem for identifying at least one predetermined characteristic of the article from said image; and

an output indication subsystem for providing an output indication of the presence of said at last one predetermined characteristic of the article,

characterized in said camera assembly includes:

a plurality of sensor assemblies;

self calibration apparatus for determining a geometrical relationship between said sensor assemblies; and

sensor output modification apparatus for modifying outputs of said plurality of sensor assemblies based on said geometrical relationship between said sensor assemblies, said sensor output modification apparatus comprising electronic interpolation apparatus operative to perform non-zero'th order interpolation of pixels in the outputs of said plurality of sensor assemblies.

21. An article inspection system comprising:

an image acquisition subsystem operative to acquire an image of an article to be inspected;

an image analysis subsystem for identifying at least one predetermined characteristic of the article from said image; and

an output indication subsystem for providing an output indication of the presence of said at least one predetermined characteristic of the article,

characterized in said camera assembly includes:

a plurality of sensor assemblies;

self calibration apparatus for determining a geometrical relationship between said sensor assemblies; and

sensor output modification apparatus for modifying outputs of said plurality of sensor assemblies based on said geometrical relationship between said sensor assemblies, said sensor output modification apparatus being operative to modify the outputs of said plurality of sensor assemblies to sub-pixel accuracy.

22. An article inspection system comprising:

an image acquisition subsystem operative to acquire an image of an article to be inspected;

an image analysis subsystem for identifying at least one predetermined characteristic of the article from said image; and

an output indication subsystem for providing an output indication of the presence of said at least one predetermined characteristic of the article, characterized in said camera assembly includes:

at least one sensor assembly; and

sensor output modification apparatus for modifying at least one output of said at least one sensory assembly based at least in part on an optical distortion associated with said at least one sensor assembly.

23. An article inspection system according to claim 22 wherein said optical distortion comprises pixel size distortion.

24. An article inspection system according to claim 22 wherein said optical distortion comprises magnification distortion.

25. An article inspection system according to claim 22 wherein said optical distortion comprises chromatic aberration.

26. An article inspection system according to claim 22 wherein said optical distortion comprises overlap misadaptation.

27. An article inspection system according to claim 22 wherein said optical distortion comprises pixel shift due to sensor separation.

28. An article inspection system according to claim 22 wherein said optical distortion comprises focus inconsistencies across color components.

29. An article inspection system according to claim 22 wherein said optical distortion comprises color accumulation shift.

30. An article inspection system comprising:

an image acquisition subsystem operative to acquire an image of an article to be inspected;

an image analysis subsystem for identifying at least one predetermined characteristic of the article from said image; and

an output indication subsystem for providing an output indication of the presence of said at least one predetermined characteristic of the article,

characterized in said camera assembly includes:

at least one sensor assembly;

sensor output modification apparatus for modifying at least one output of said at least one sensory assembly, said sensor output modification apparatus comprising a function generator which generates a function which maps locations on said sensor assembly to a collection of scan locations.

31. An article inspection system comprising:

a camera assembly operative to acquire an image of an article to be inspected;

an image analysis subsystem for identifying at least one predetermined characteristic of the article from said image; and

an output indication subsystem for providing an output indication of the presence of said at last one predetermined characteristic of the article,

characterized in said camera assembly includes:

a user interface which enables a user to select resolution of the image acquired by the camera assembly;

an electro-optical sensor assembly; and

an electronic resolution modifier operative downstream of said electro-optical sensor assembly.

32. An article inspection system according to claim 31 and wherein camera assembly is operative in response to resolution selection at said user interface to determine the pixel size of said image.

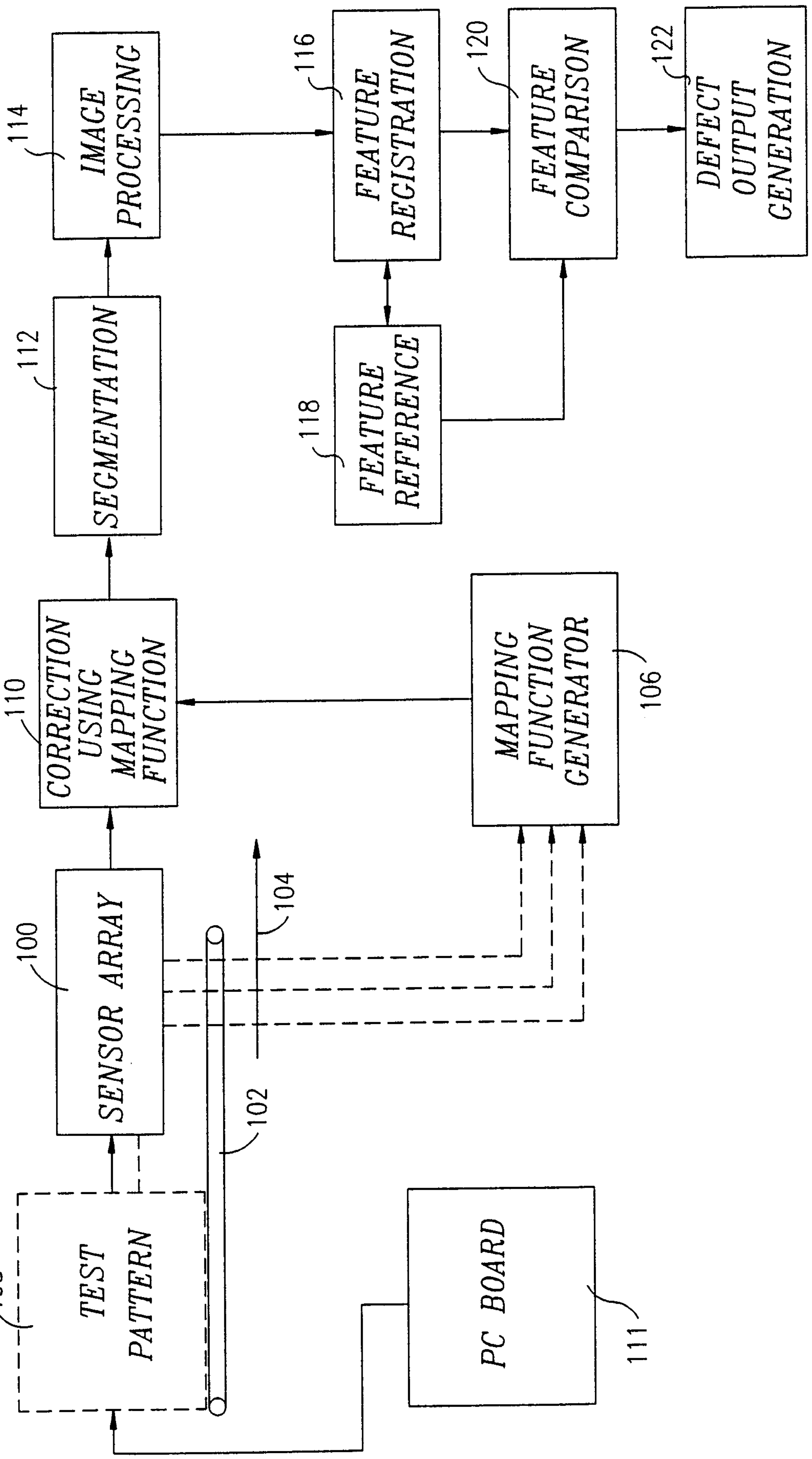

TEST PATTERN
108
SENSOR ARRAY
100
102
104
CORRECTION USING MAPPING FUNCTION
110
SEGMENTATION
112
IMAGE PROCESSING
114
FEATURE REGISTRATION
116
FEATURE REFERENCE
118
FEATURE COMPARISON
120
DEFECT OUTPUT GENERATION
122
MAPPING FUNCTION GENERATOR
106
PC BOARD
111

FIG. 1

FIG. 2

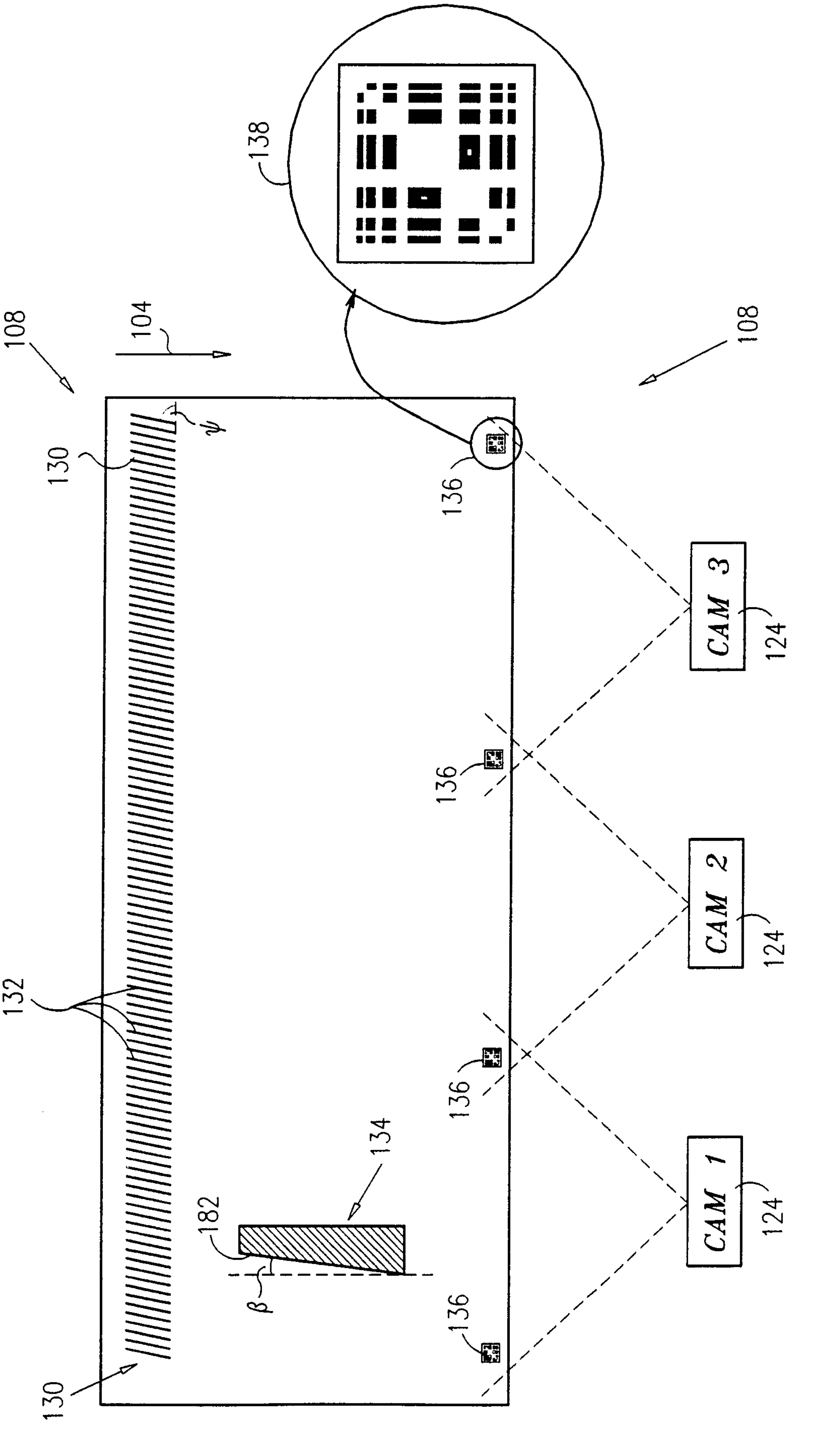

108
104
108
138
130
ψ
136
CAM 3
124
136
CAM 2
124
132
136
CAM 1
124
134
182
β
136
130

FIG. 3

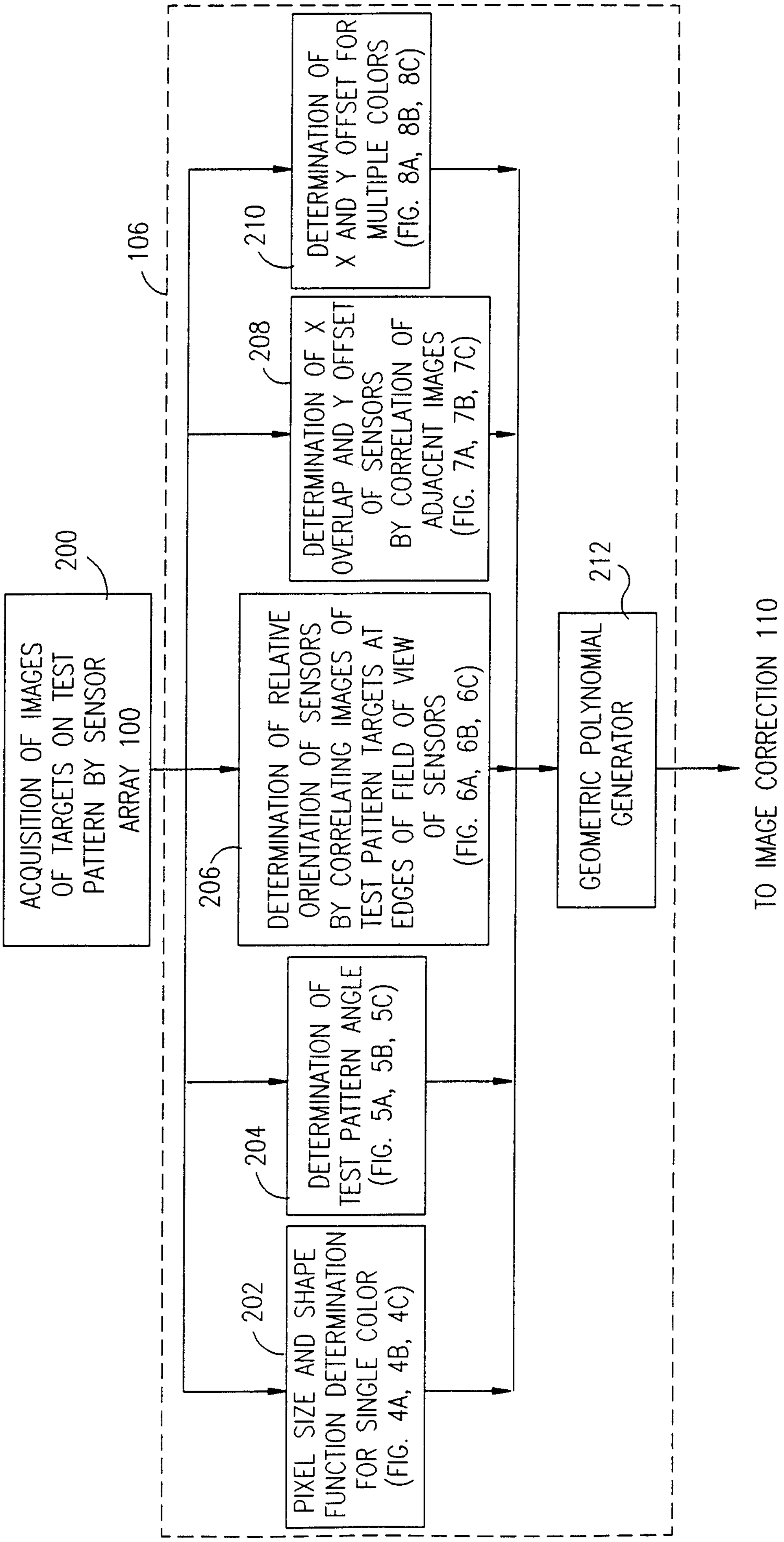
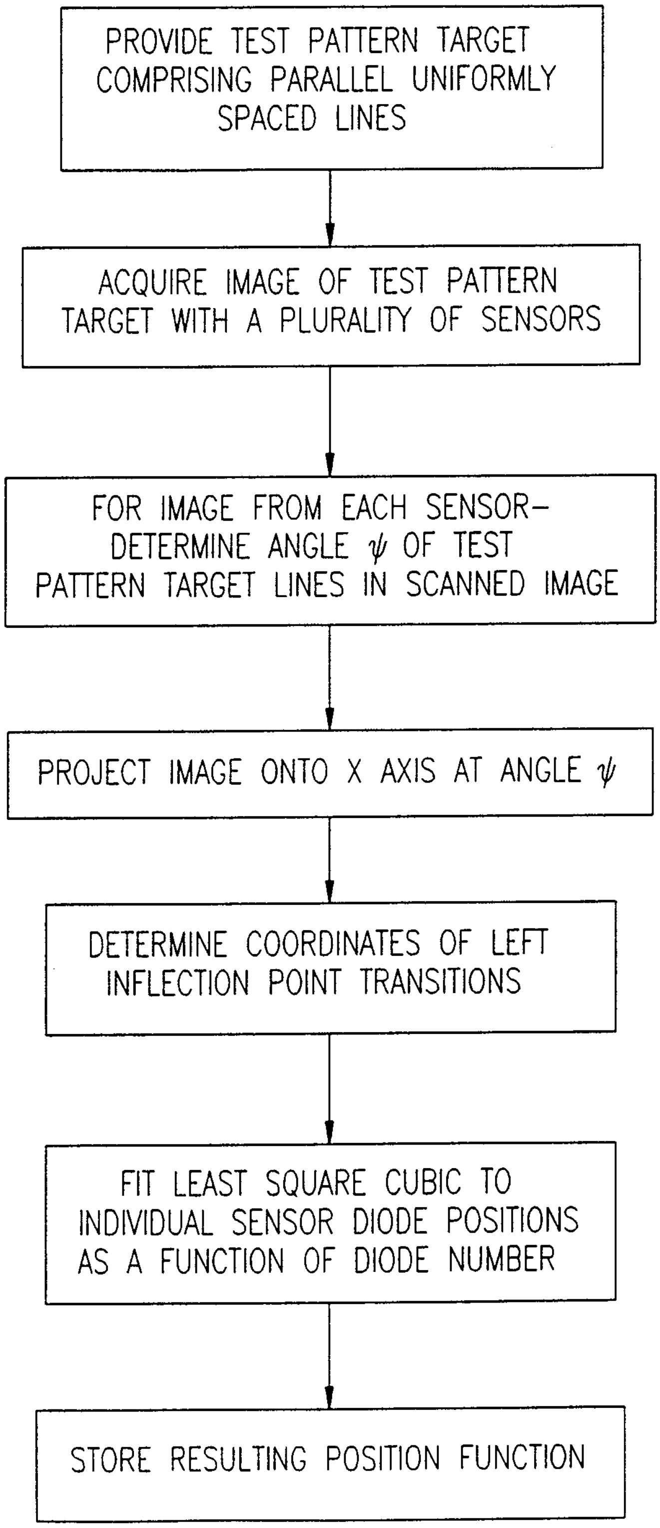

ACQUISITION OF IMAGES OF TARGETS ON TEST PATTERN BY SENSOR ARRAY 100
200
106
PIXEL SIZE AND SHAPE FUNCTION DETERMINATION FOR SINGLE COLOR (FIG. 4A, 4B, 4C)
202
DETERMINATION OF TEST PATTERN ANGLE (FIG. 5A, 5B, 5C)
204
DETERMINATION OF RELATIVE ORIENTATION OF SENSORS BY CORRELATING IMAGES OF TEST PATTERN TARGETS AT EDGES OF FIELD OF VIEW OF SENSORS (FIG. 6A, 6B, 6C)
206
DETERMINATION OF X OVERLAP AND Y OFFSET OF SENSORS BY CORRELATION OF ADJACENT IMAGES (FIG. 7A, 7B, 7C)
208
DETERMINATION OF X AND Y OFFSET FOR MULTIPLE COLORS (FIG. 8A, 8B, 8C)
210
GEOMETRIC POLYNOMIAL GENERATOR
212
TO IMAGE CORRECTION 110

FIG. 4A


PROVIDE TEST PATTERN TARGET COMPRISING PARALLEL UNIFORMLY SPACED LINES
ACQUIRE IMAGE OF TEST PATTERN TARGET WITH A PLURALITY OF SENSORS
FOR IMAGE FROM EACH SENSOR– DETERMINE ANGLE ψ OF TEST PATTERN TARGET LINES IN SCANNED IMAGE
PROJECT IMAGE ONTO X AXIS AT ANGLE ψ
DETERMINE COORDINATES OF LEFT INFLECTION POINT TRANSITIONS
FIT LEAST SQUARE CUBIC TO INDIVIDUAL SENSOR DIODE POSITIONS AS A FUNCTION OF DIODE NUMBER
STORE RESULTING POSITION FUNCTION

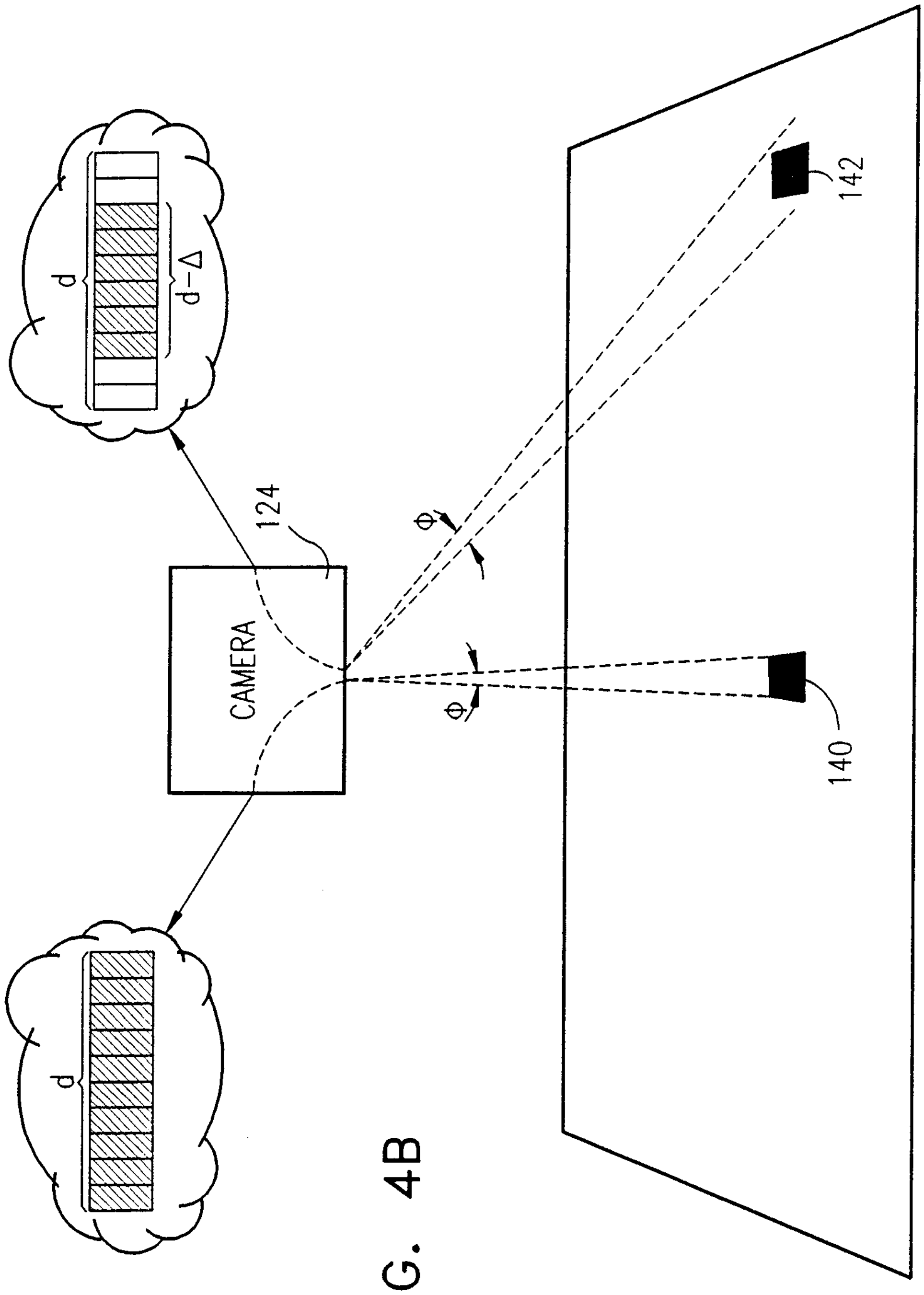


FIG. 4B

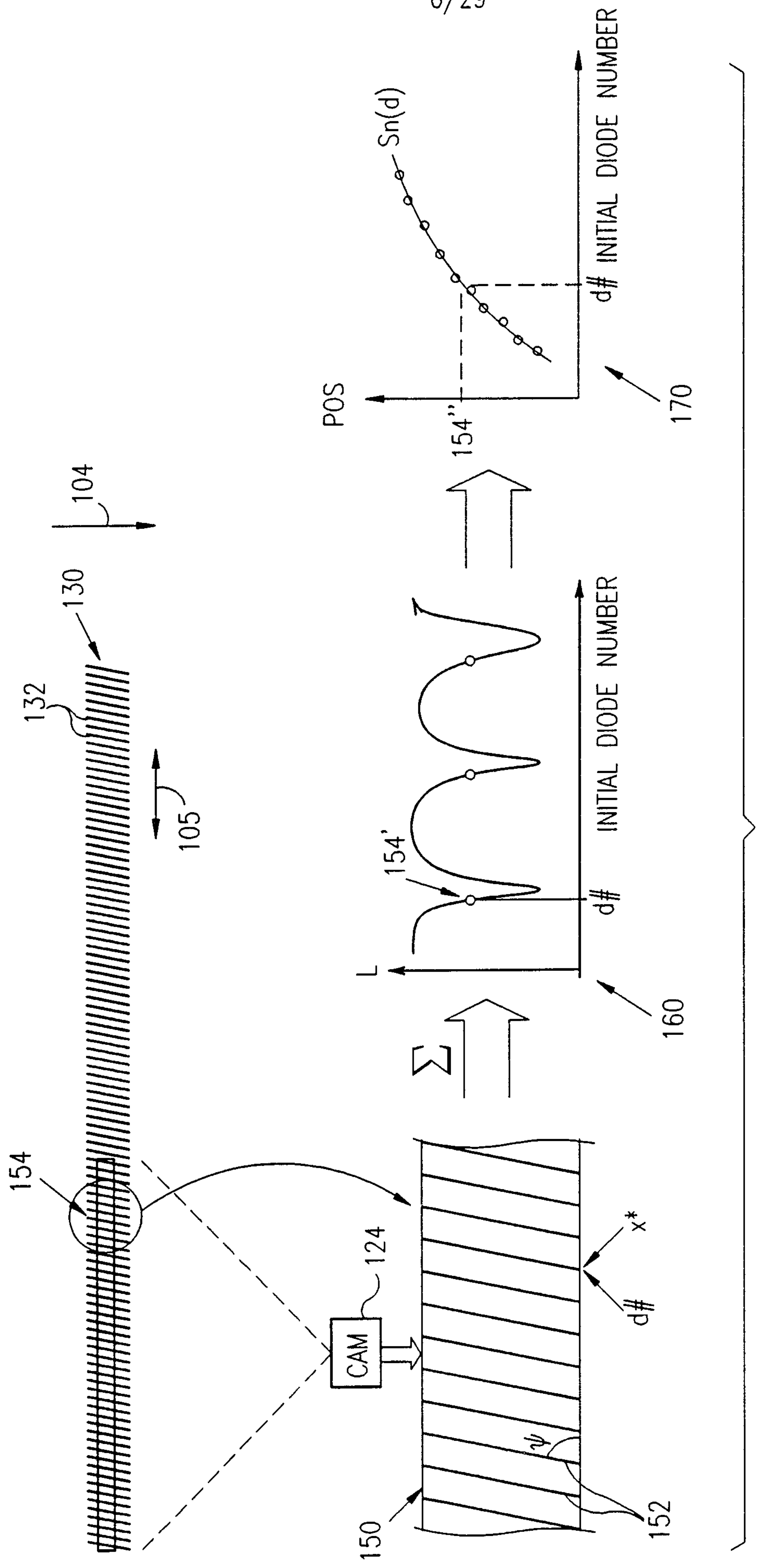
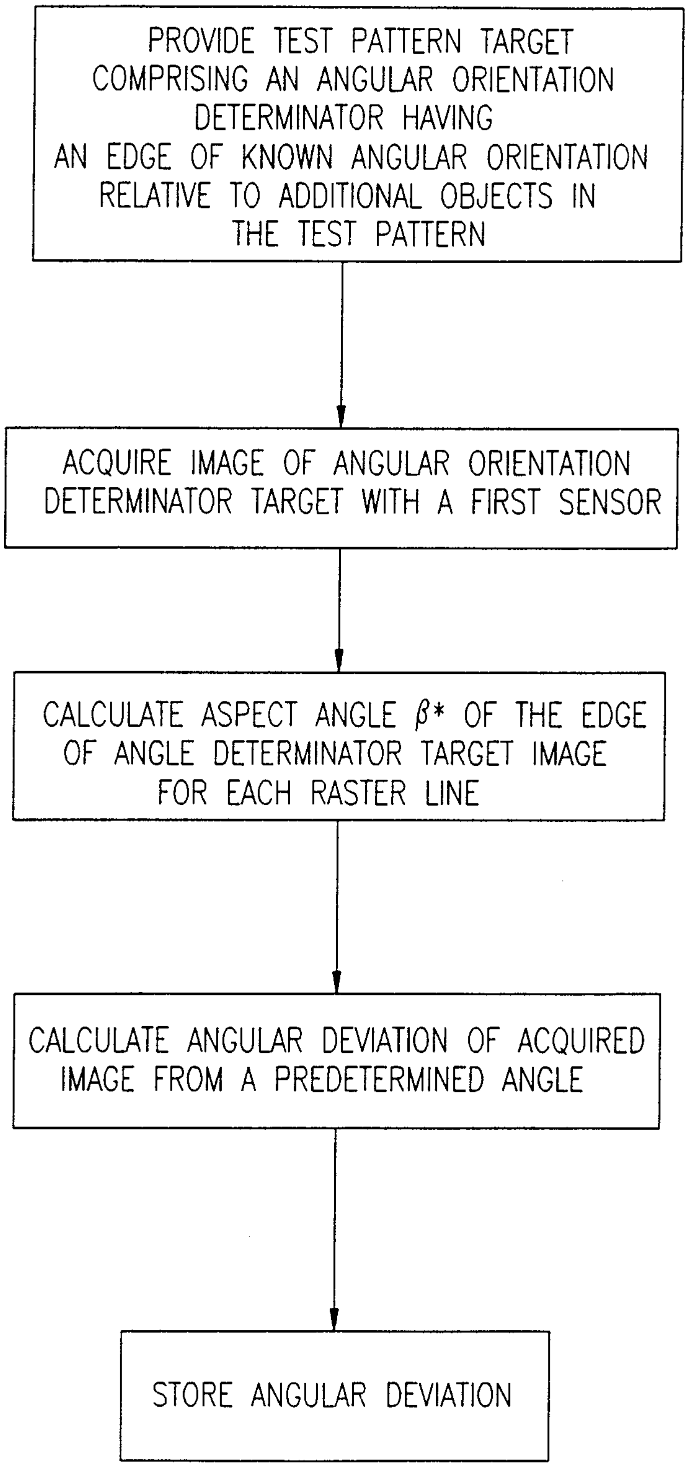

154
132
130
104
105
124
CAM
150
152
ψ
x*
d#
Σ
L
154'
d#
INITIAL DIODE NUMBER
160
POS
154''
Sn(d)
d#
INITIAL DIODE NUMBER
170

FIG. 4C

FIG. 5A


PROVIDE TEST PATTERN TARGET COMPRISING AN ANGULAR ORIENTATION DETERMINATOR HAVING AN EDGE OF KNOWN ANGULAR ORIENTATION RELATIVE TO ADDITIONAL OBJECTS IN THE TEST PATTERN
ACQUIRE IMAGE OF ANGULAR ORIENTATION DETERMINATOR TARGET WITH A FIRST SENSOR
CALCULATE ASPECT ANGLE β* OF THE EDGE OF ANGLE DETERMINATOR TARGET IMAGE FOR EACH RASTER LINE
CALCULATE ANGULAR DEVIATION OF ACQUIRED IMAGE FROM A PREDETERMINED ANGLE
STORE ANGULAR DEVIATION

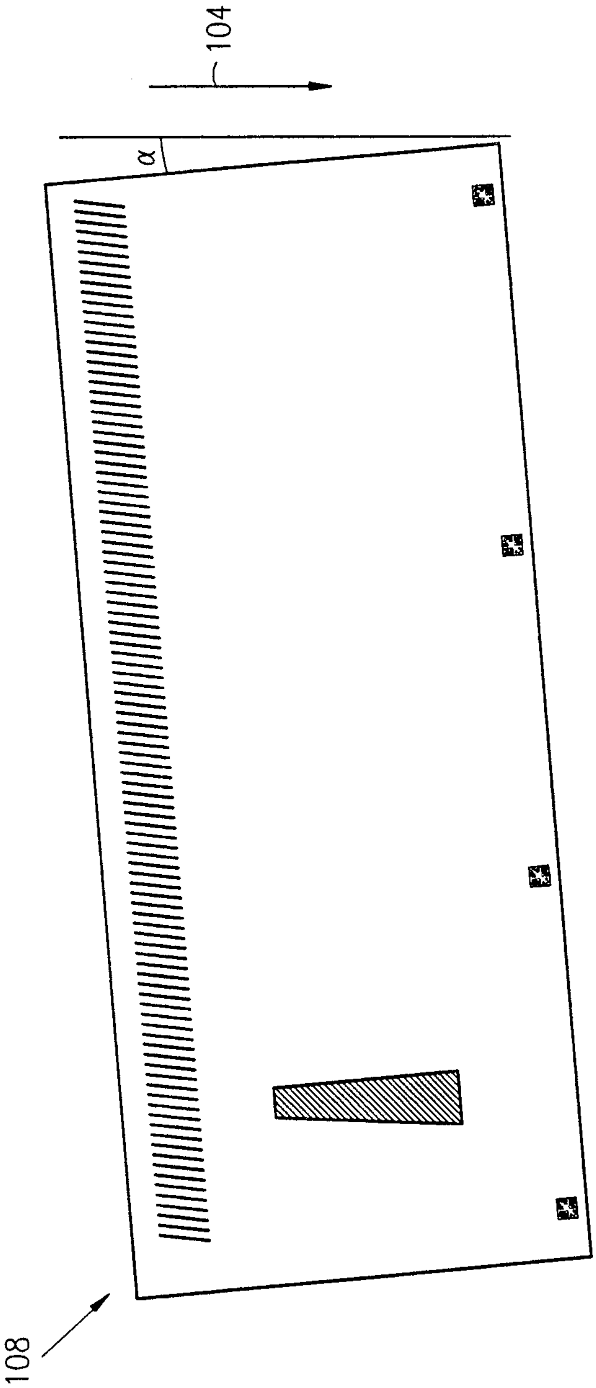


FIG. 5B

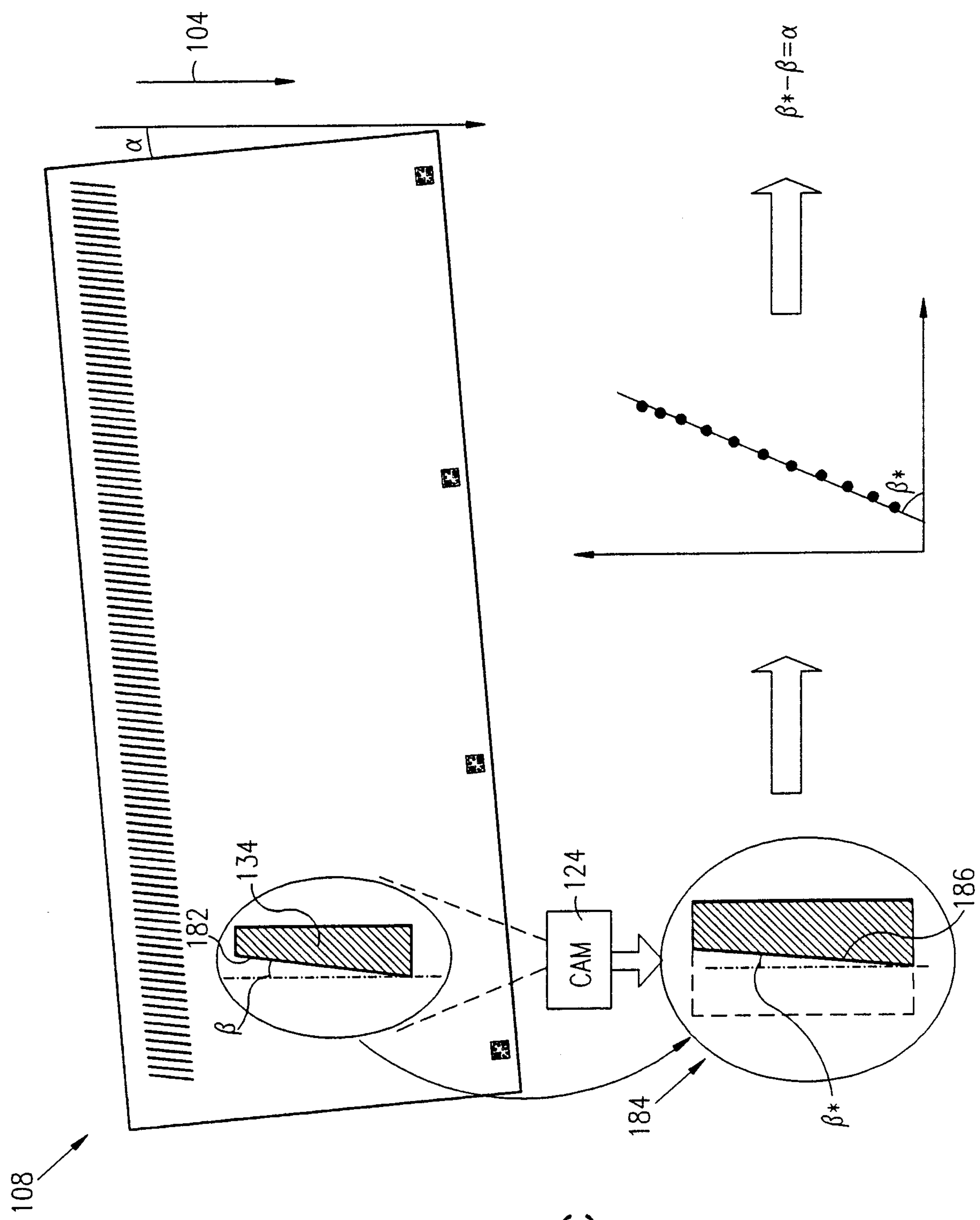
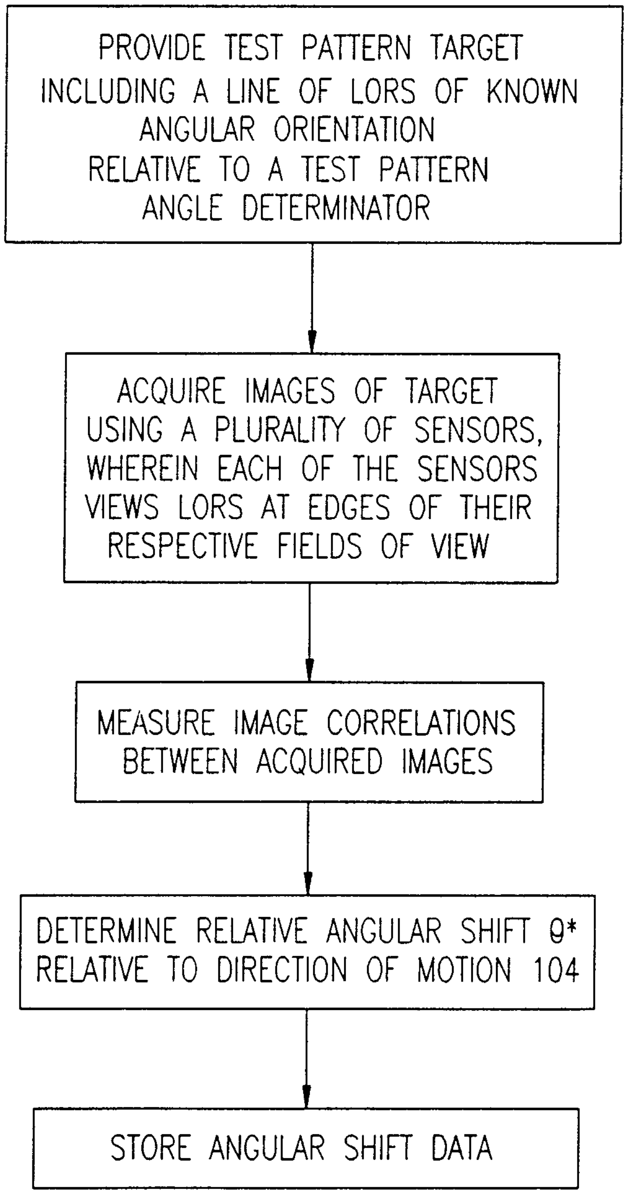


FIG. 5C

FIG. 6A


PROVIDE TEST PATTERN TARGET INCLUDING A LINE OF LORS OF KNOWN ANGULAR ORIENTATION RELATIVE TO A TEST PATTERN ANGLE DETERMINATOR
ACQUIRE IMAGES OF TARGET USING A PLURALITY OF SENSORS, WHEREIN EACH OF THE SENSORS VIEWS LORS AT EDGES OF THEIR RESPECTIVE FIELDS OF VIEW
MEASURE IMAGE CORRELATIONS BETWEEN ACQUIRED IMAGES
DETERMINE RELATIVE ANGULAR SHIFT θ* RELATIVE TO DIRECTION OF MOTION 104
STORE ANGULAR SHIFT DATA

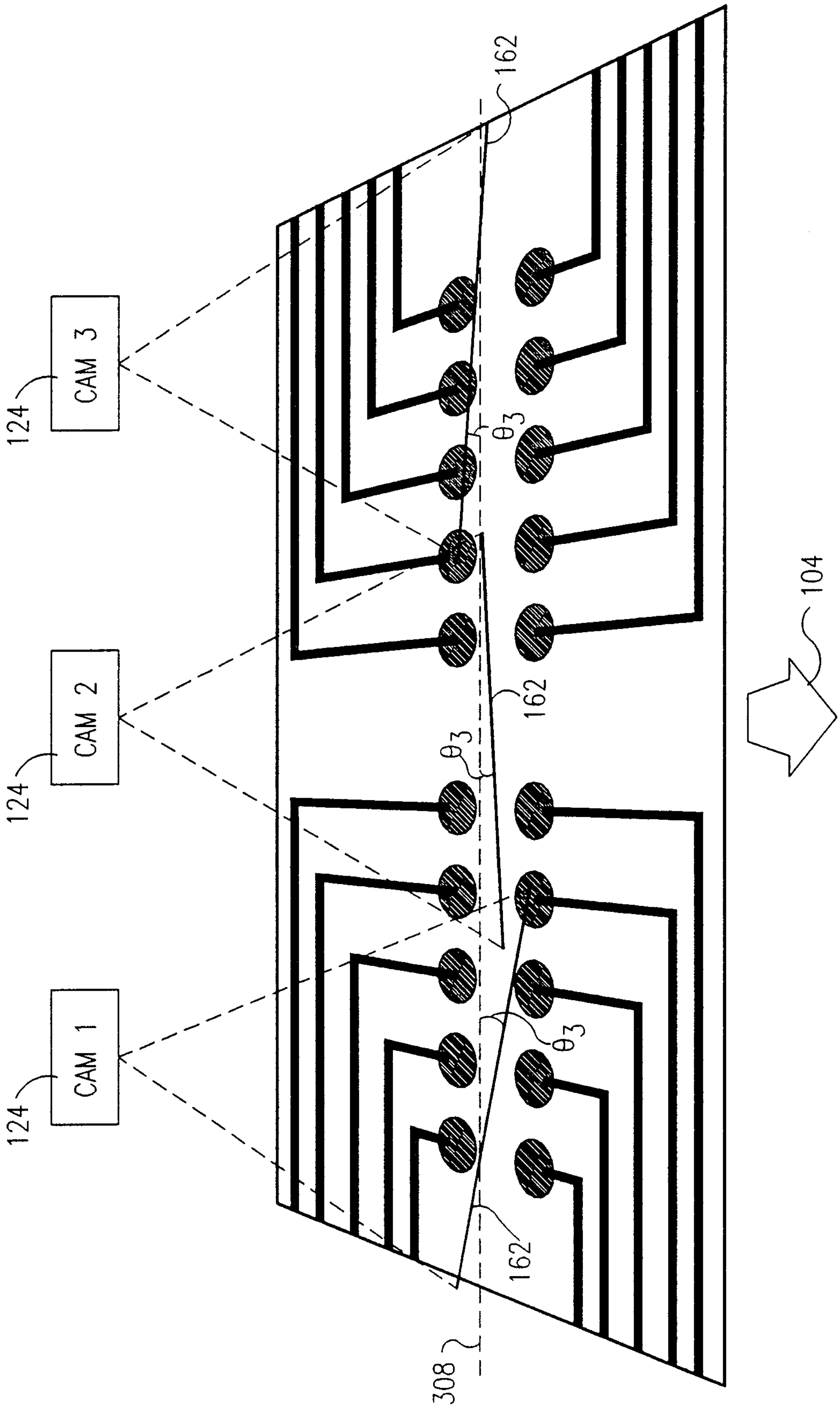


FIG. 6B

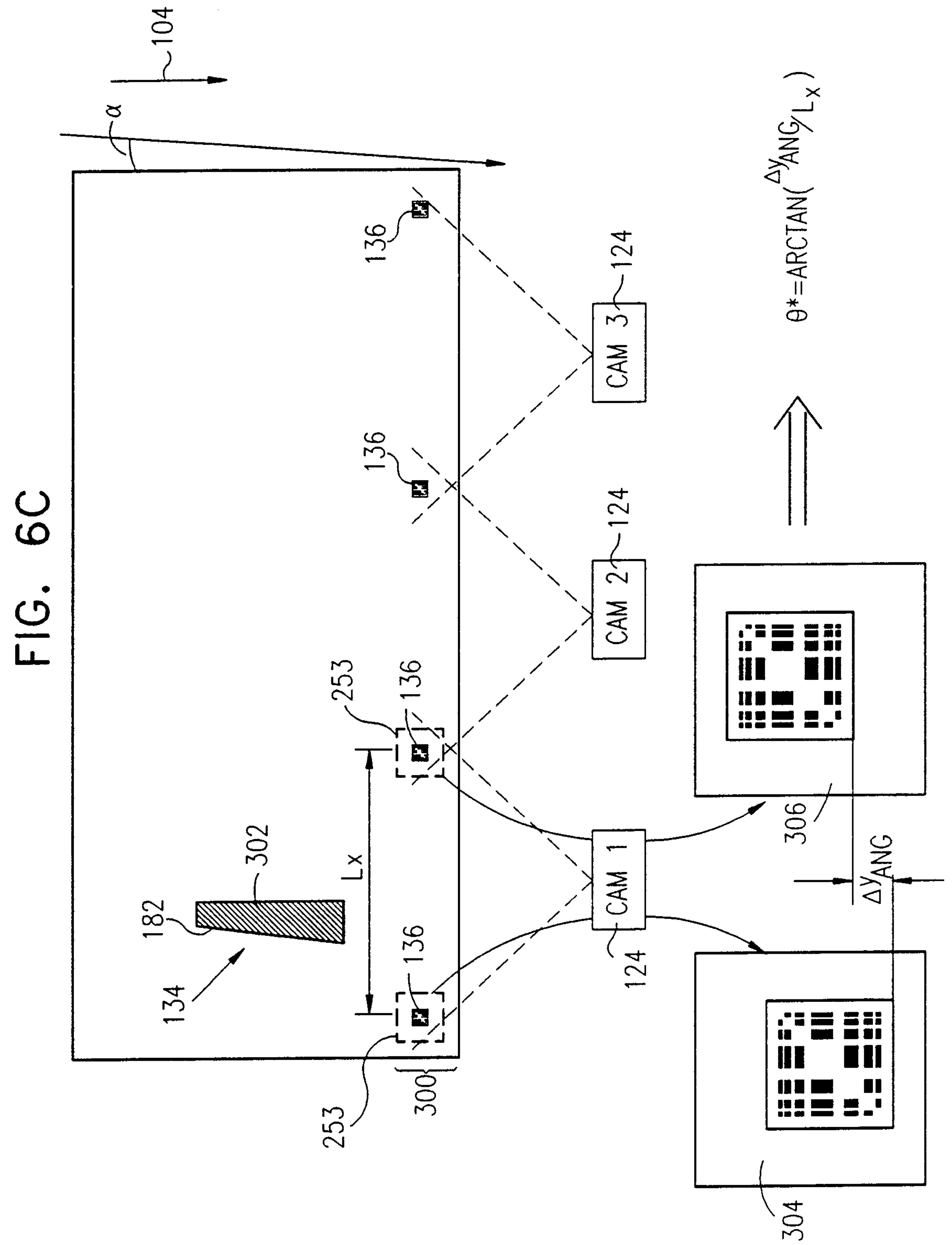

104
α
136
136
CAM 3
CAM 2
CAM 1
124
124
124
253
136
253
136
302
182
134
Lx
300
306
304
ΔY_ANG
θ*=ARCTAN(ΔY_ANG/L_x)

FIG. 6C

FIG. 7A

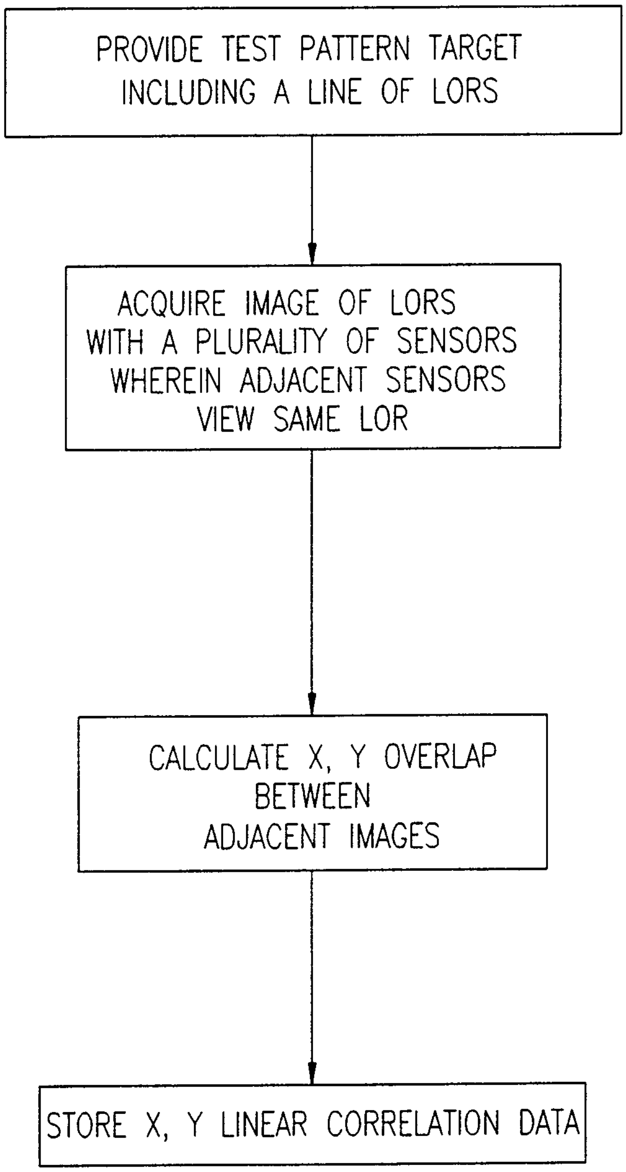
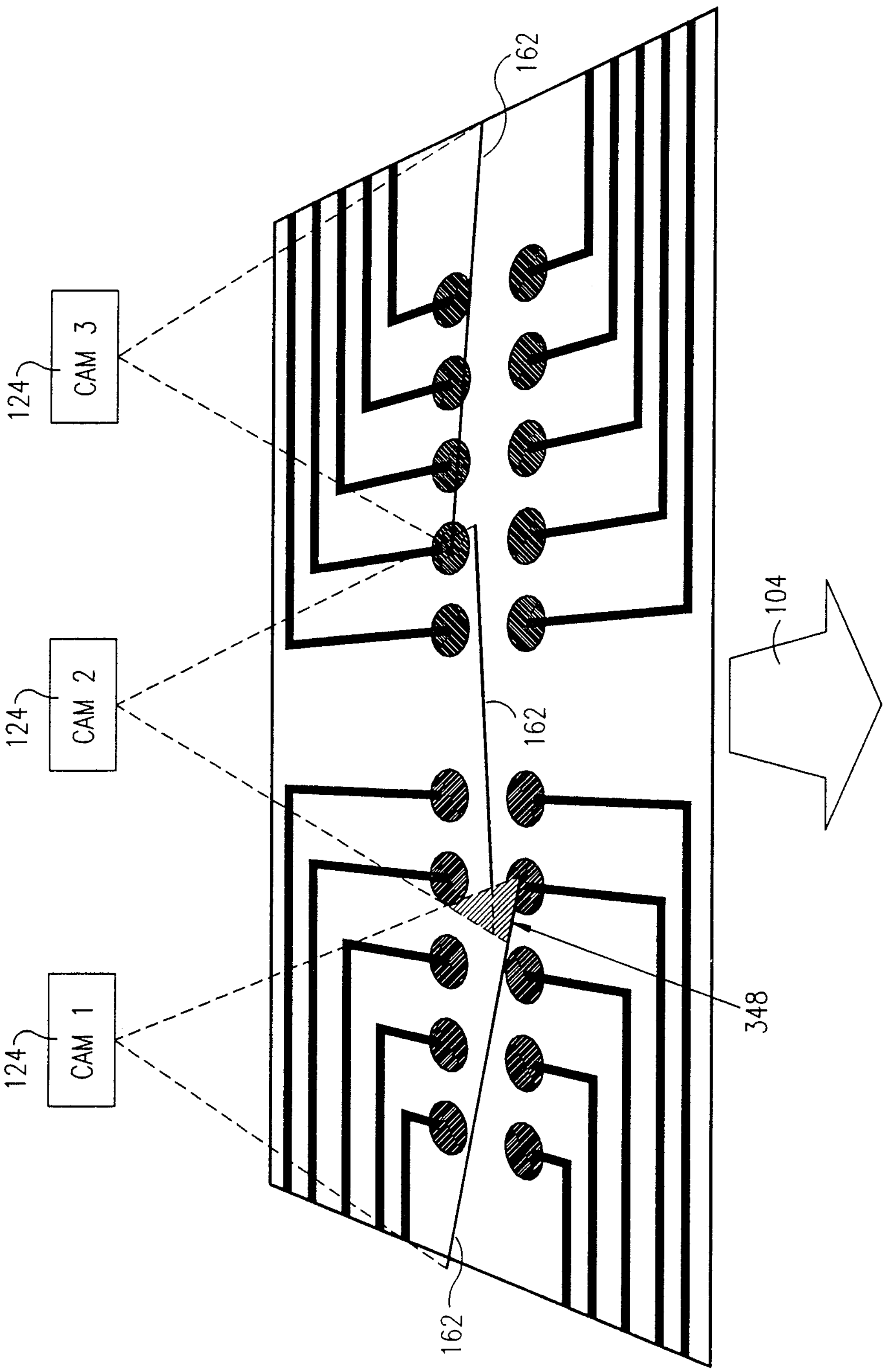

PROVIDE TEST PATTERN TARGET INCLUDING A LINE OF LORS
ACQUIRE IMAGE OF LORS WITH A PLURALITY OF SENSORS WHEREIN ADJACENT SENSORS VIEW SAME LOR
CALCULATE X, Y OVERLAP BETWEEN ADJACENT IMAGES
STORE X, Y LINEAR CORRELATION DATA

FIG. 7B



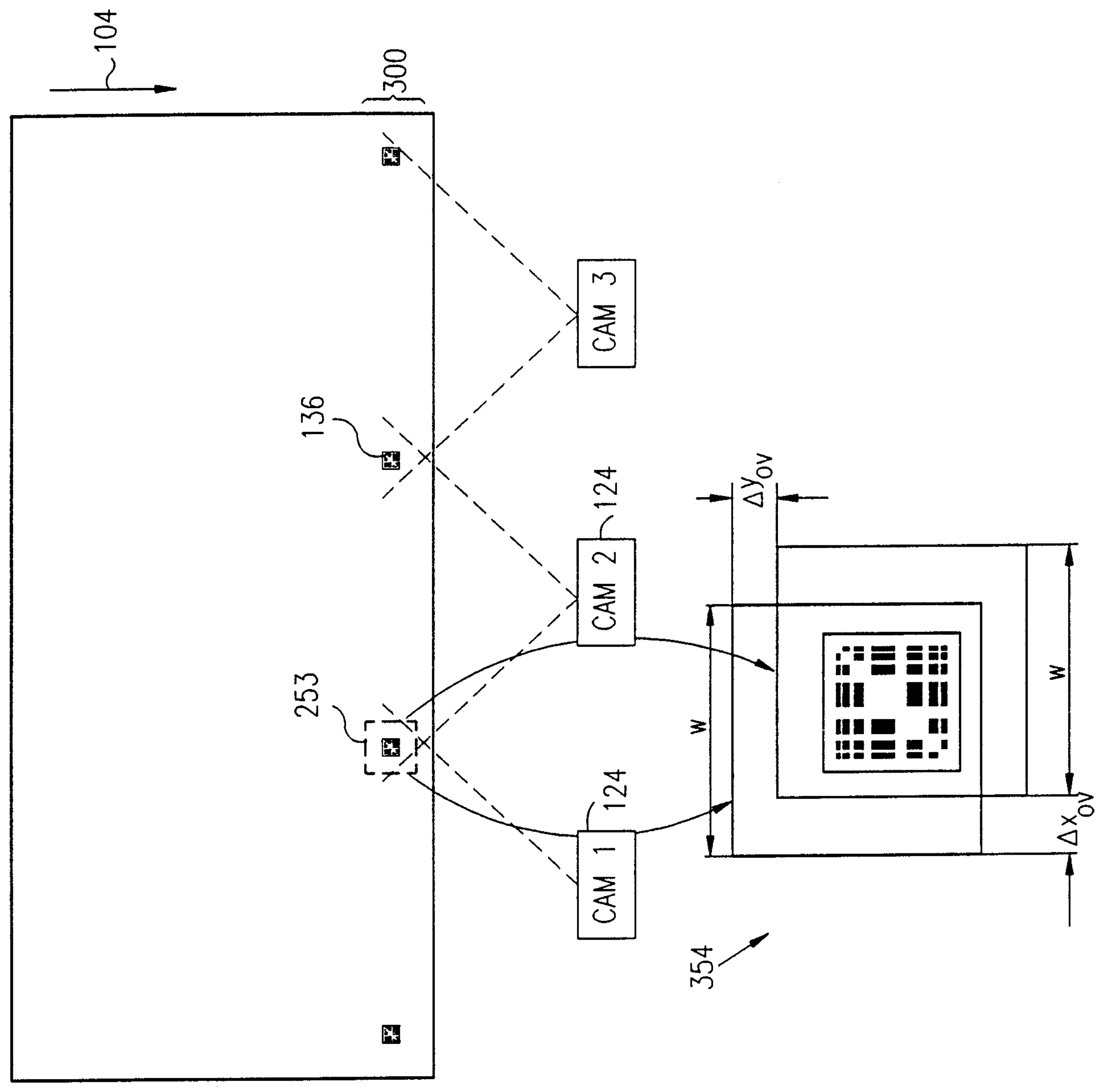
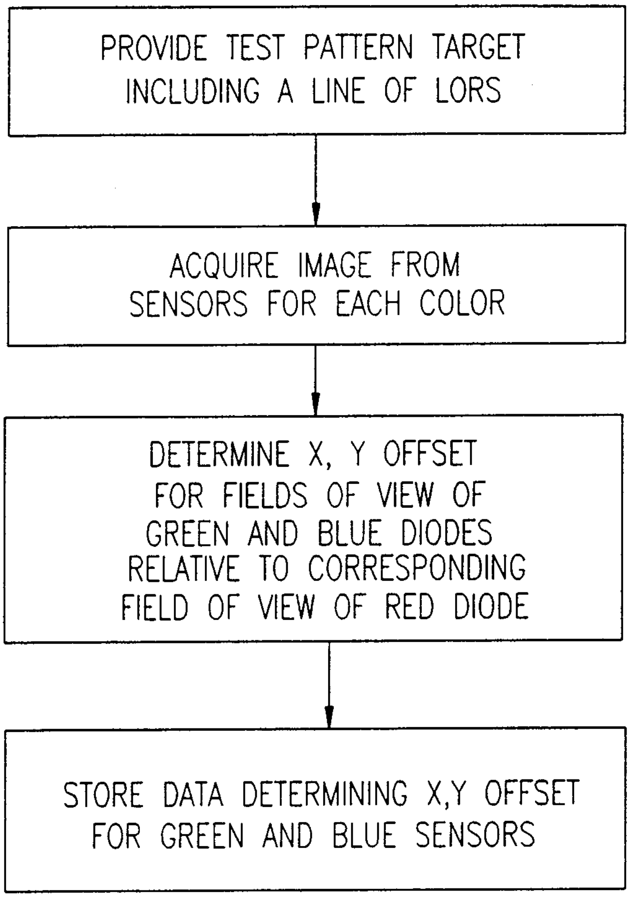


FIG. 7C

FIG. 8A


PROVIDE TEST PATTERN TARGET INCLUDING A LINE OF LORS
ACQUIRE IMAGE FROM SENSORS FOR EACH COLOR
DETERMINE X, Y OFFSET FOR FIELDS OF VIEW OF GREEN AND BLUE DIODES RELATIVE TO CORRESPONDING FIELD OF VIEW OF RED DIODE
STORE DATA DETERMINING X,Y OFFSET FOR GREEN AND BLUE SENSORS

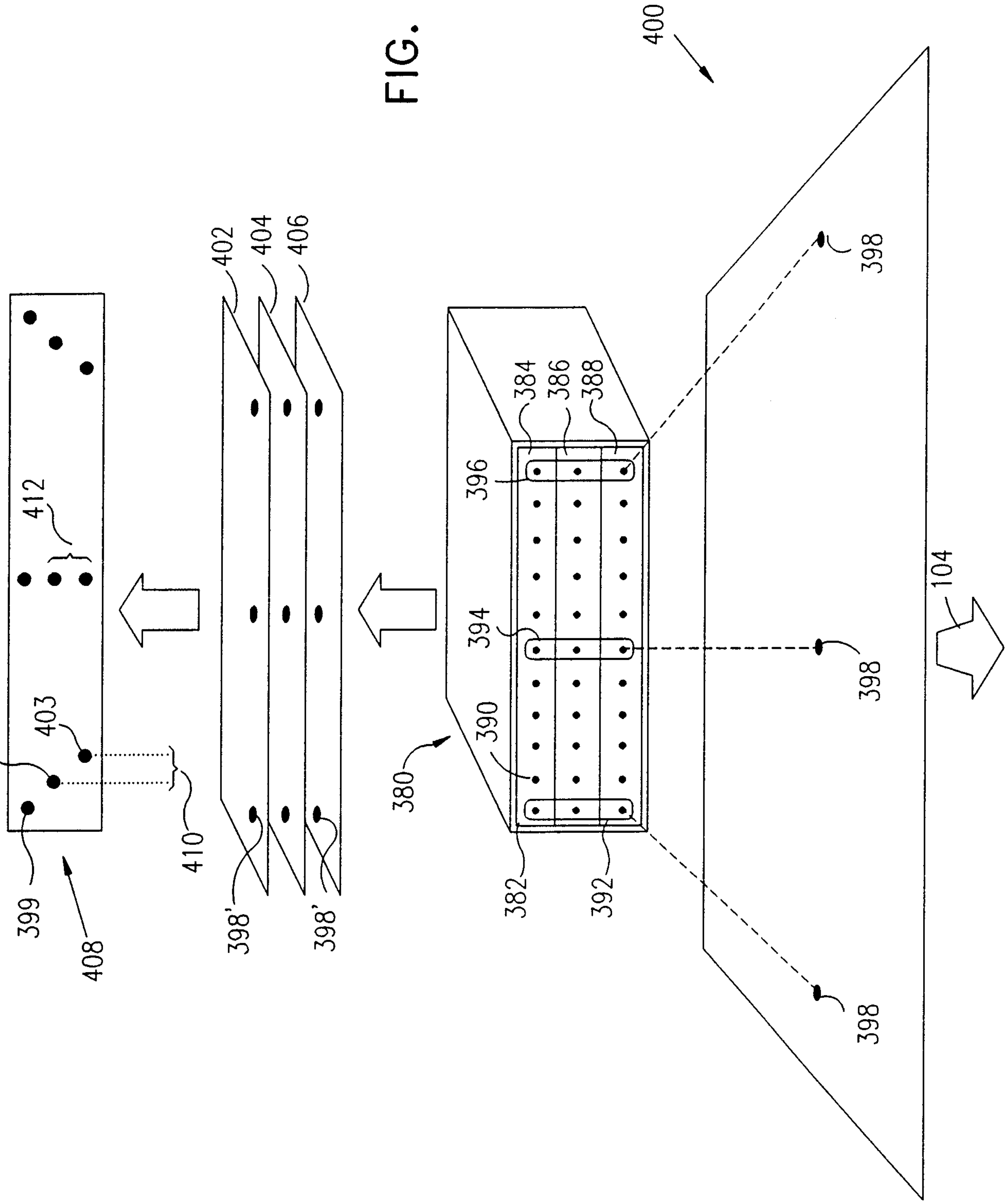

400
398
398
398
104
380
382
384
386
388
390
392
394
396
402
404
406
398'
398'
399
401
403
408
410
412

FIG. 8B

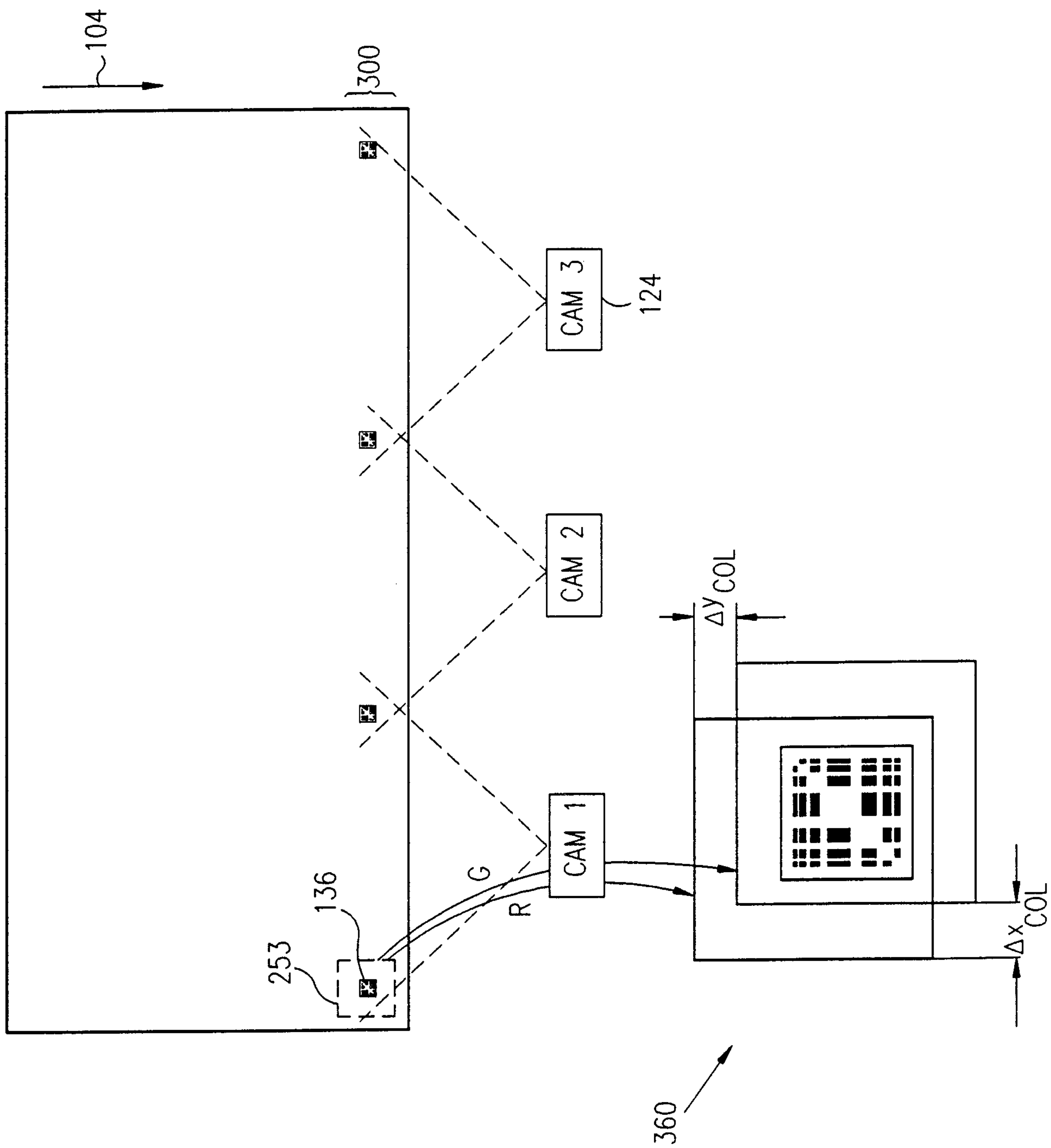


FIG. 8C

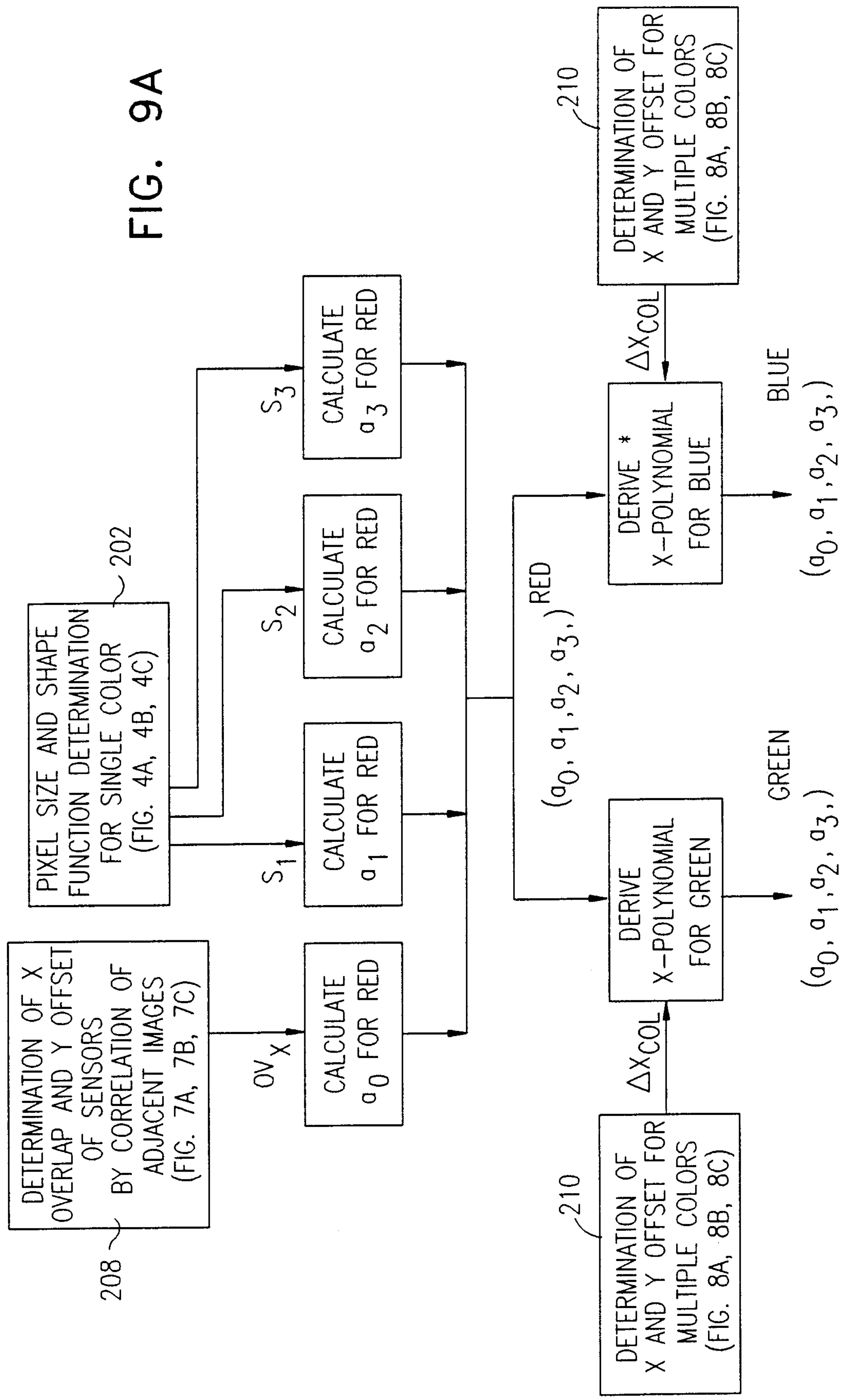
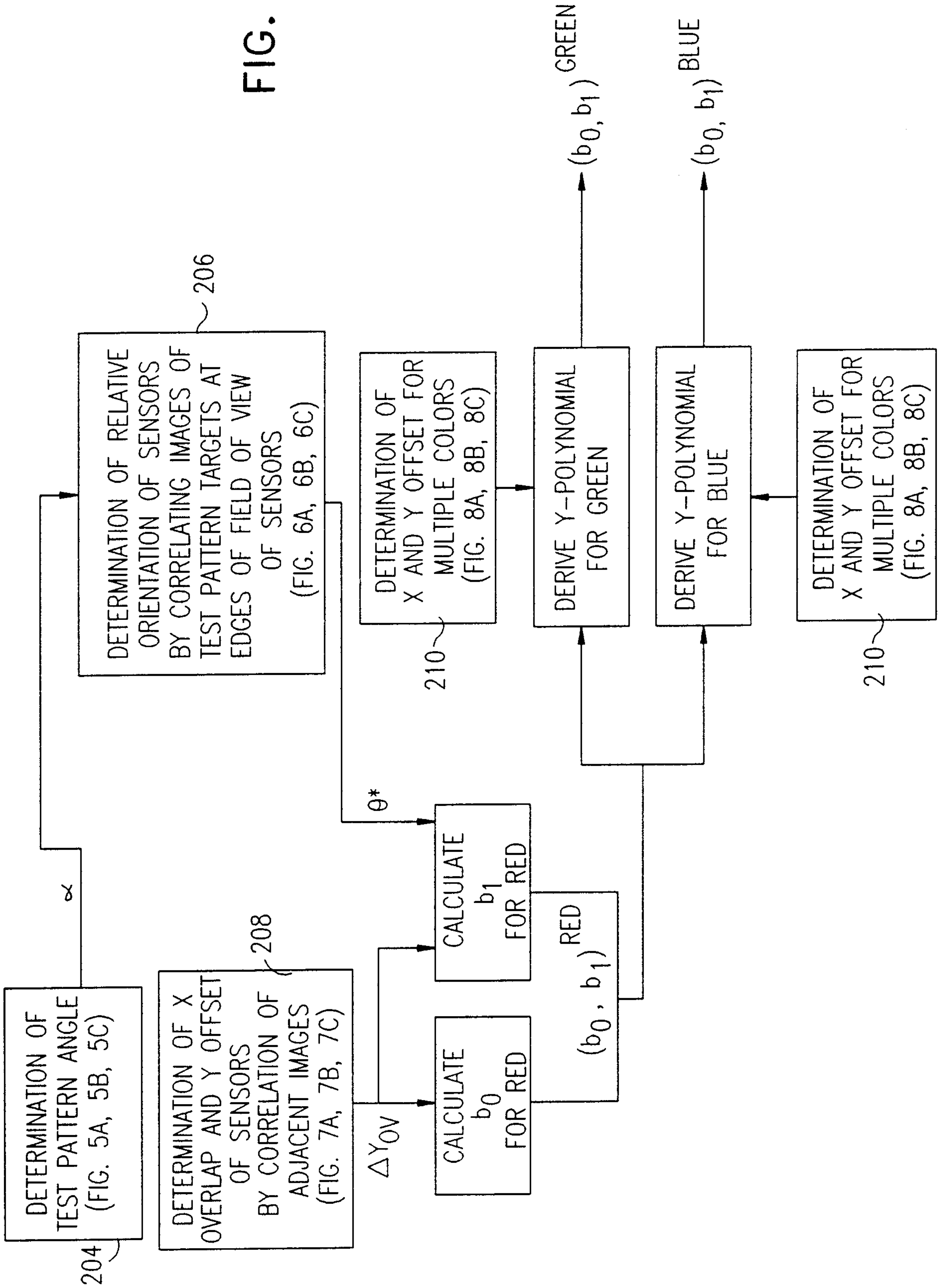

DETERMINATION OF X OVERLAP AND Y OFFSET OF SENSORS BY CORRELATION OF ADJACENT IMAGES (FIG. 7A, 7B, 7C)
208
PIXEL SIZE AND SHAPE FUNCTION DETERMINATION FOR SINGLE COLOR (FIG. 4A, 4B, 4C)
202
OV X
S 1
S 2
S 3
CALCULATE a 0 FOR RED
CALCULATE a 1 FOR RED
CALCULATE a 2 FOR RED
CALCULATE a 3 FOR RED
(a0, a1, a2, a3,) RED
DERIVE X-POLYNOMIAL FOR GREEN
DERIVE * X-POLYNOMIAL FOR BLUE
ΔX COL
ΔX COL
(a0, a1, a2, a3,) GREEN
(a0, a1, a2, a3,) BLUE
DETERMINATION OF X AND Y OFFSET FOR MULTIPLE COLORS (FIG. 8A, 8B, 8C)
210
DETERMINATION OF X AND Y OFFSET FOR MULTIPLE COLORS (FIG. 8A, 8B, 8C)
210

FIG. 9A

FIG. 9B


DETERMINATION OF TEST PATTERN ANGLE (FIG. 5A, 5B, 5C)
204
∝
DETERMINATION OF RELATIVE ORIENTATION OF SENSORS BY CORRELATING IMAGES OF TEST PATTERN TARGETS AT EDGES OF FIELD OF VIEW OF SENSORS (FIG. 6A, 6B, 6C)
206
DETERMINATION OF X OVERLAP AND Y OFFSET OF SENSORS BY CORRELATION OF ADJACENT IMAGES (FIG. 7A, 7B, 7C)
208
ΔY_{OV}
θ^*
CALCULATE b_0 FOR RED
CALCULATE b_1 FOR RED
$(b_0, b_1)^{RED}$
DETERMINATION OF X AND Y OFFSET FOR MULTIPLE COLORS (FIG. 8A, 8B, 8C)
210
DERIVE Y-POLYNOMIAL FOR GREEN
DERIVE Y-POLYNOMIAL FOR BLUE
DETERMINATION OF X AND Y OFFSET FOR MULTIPLE COLORS (FIG. 8A, 8B, 8C)
210
$(b_0, b_1)^{GREEN}$
$(b_0, b_1)^{BLUE}$

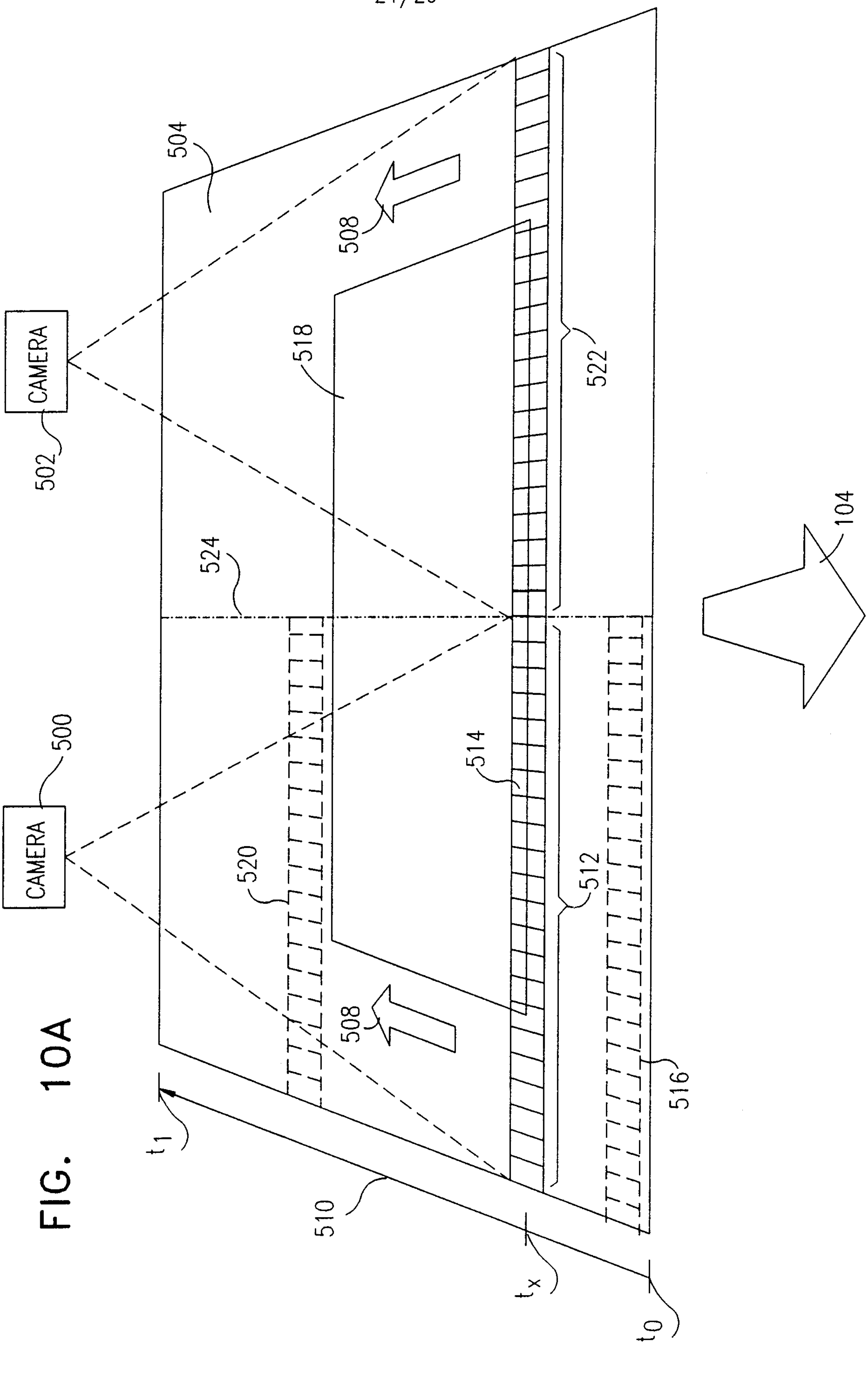

CAMERA
CAMERA
500
502
504
508
508
510
512
514
516
518
520
522
524
104
t_1
t_x
t_0

FIG. 10A

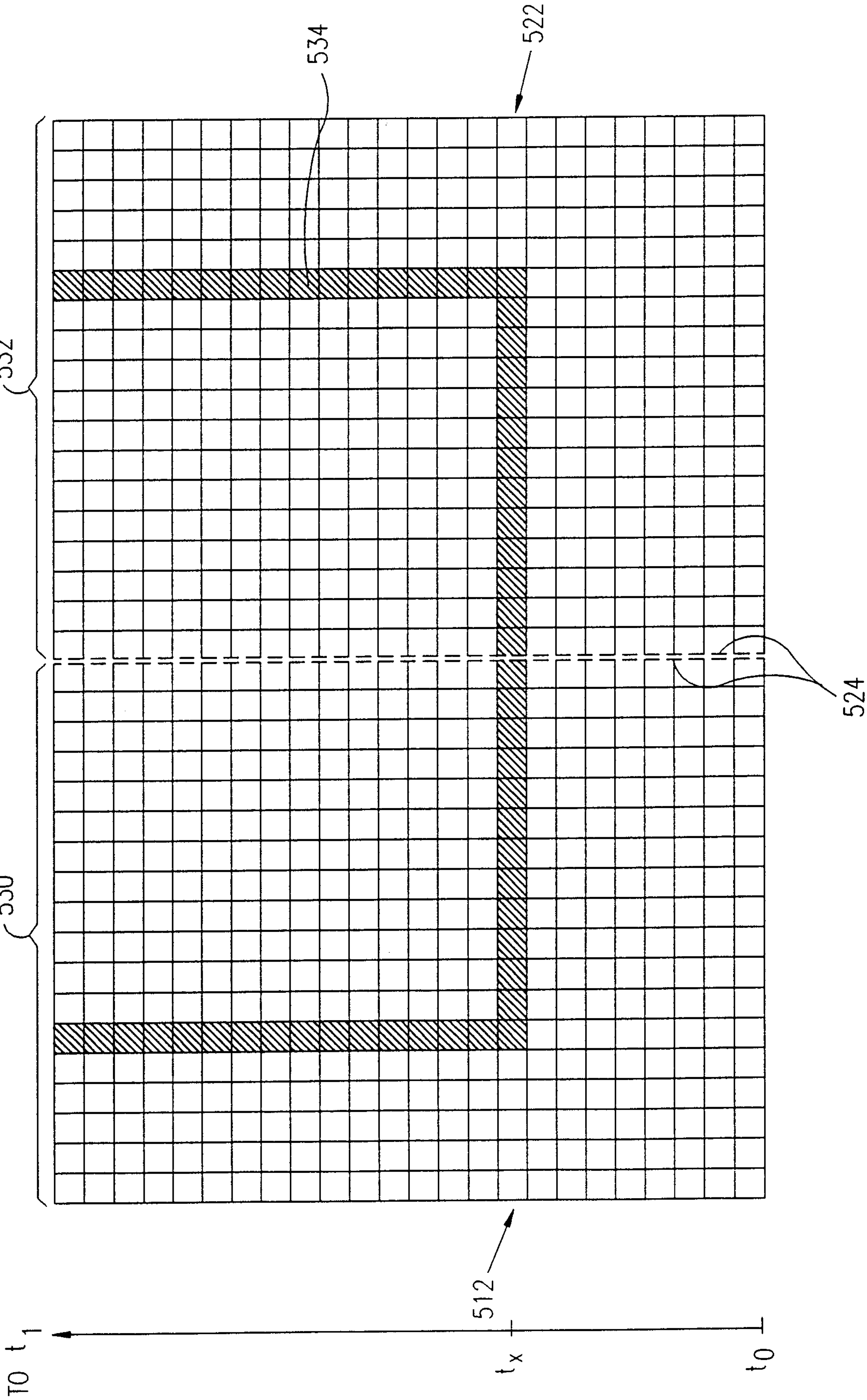


FIG. 10B

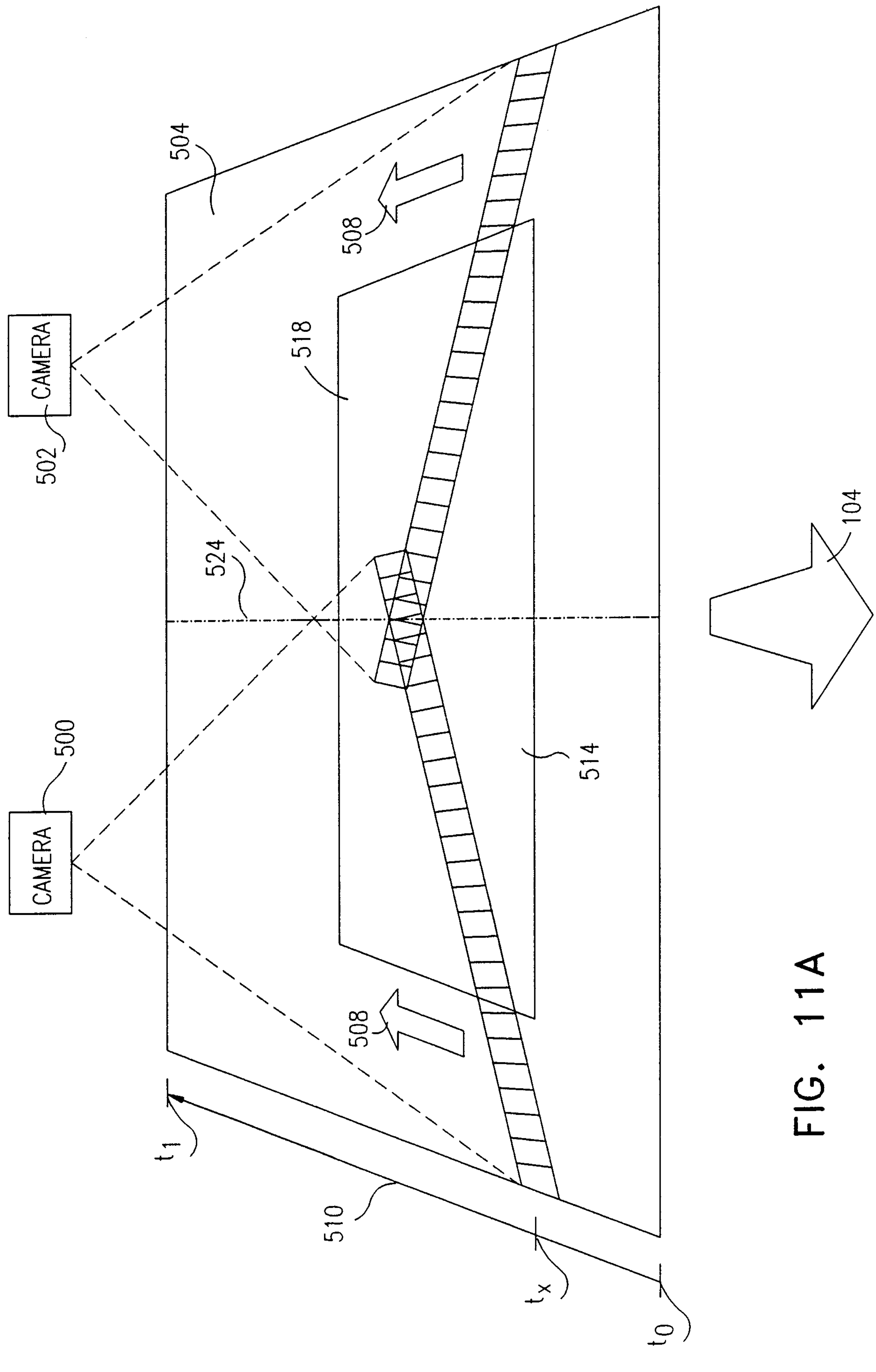


FIG. 11A

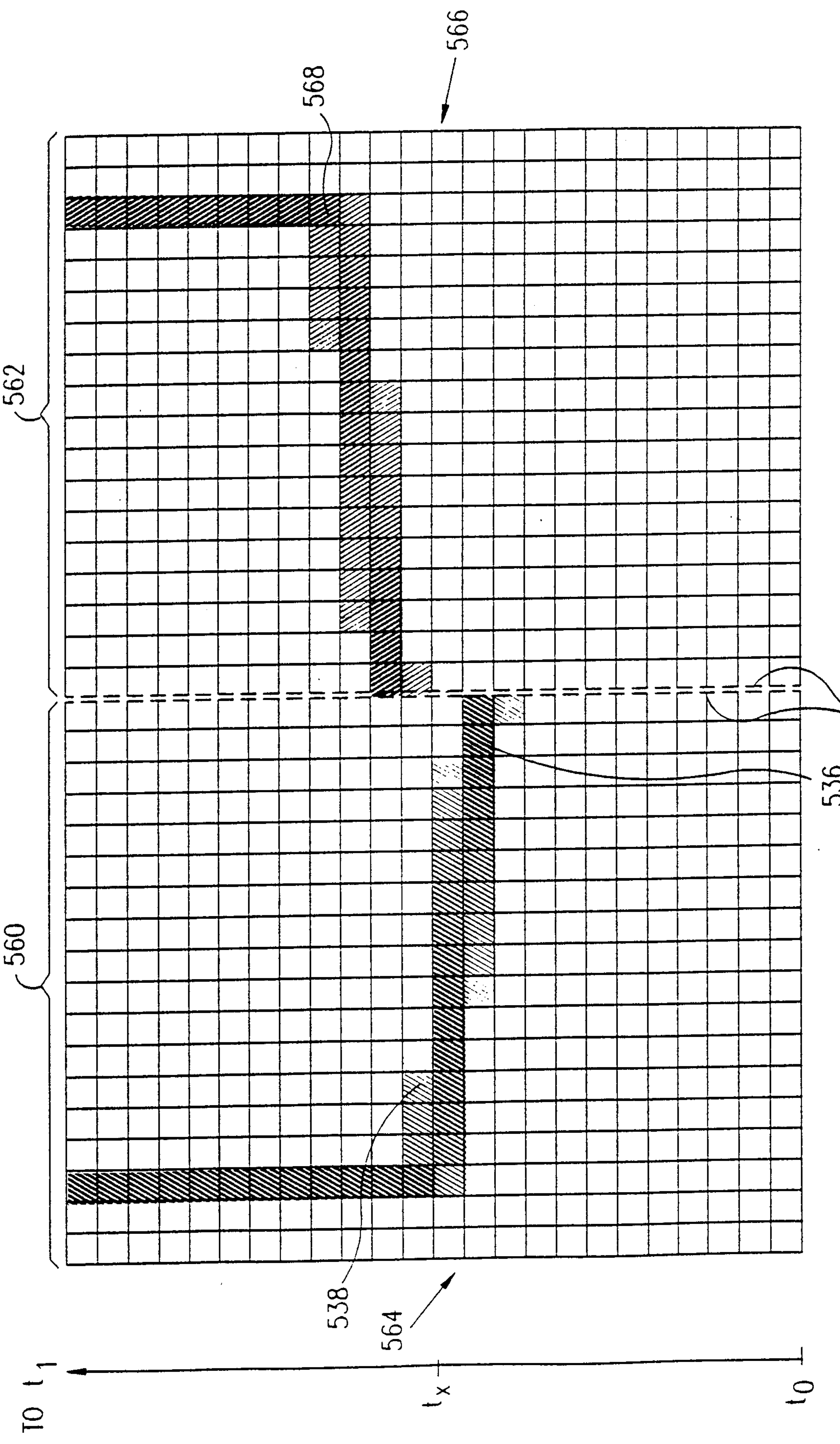
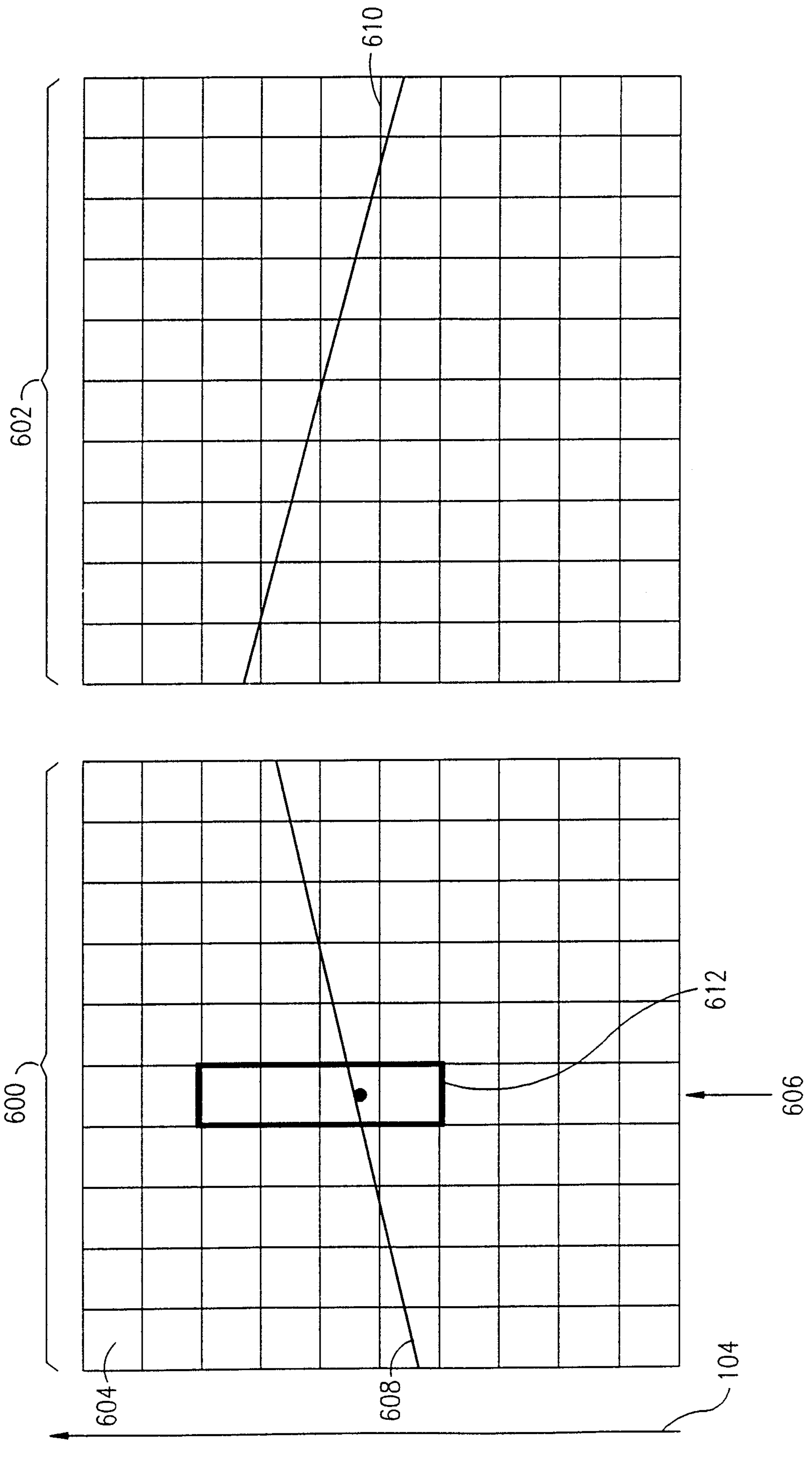


FIG. 11B

FIG. 12



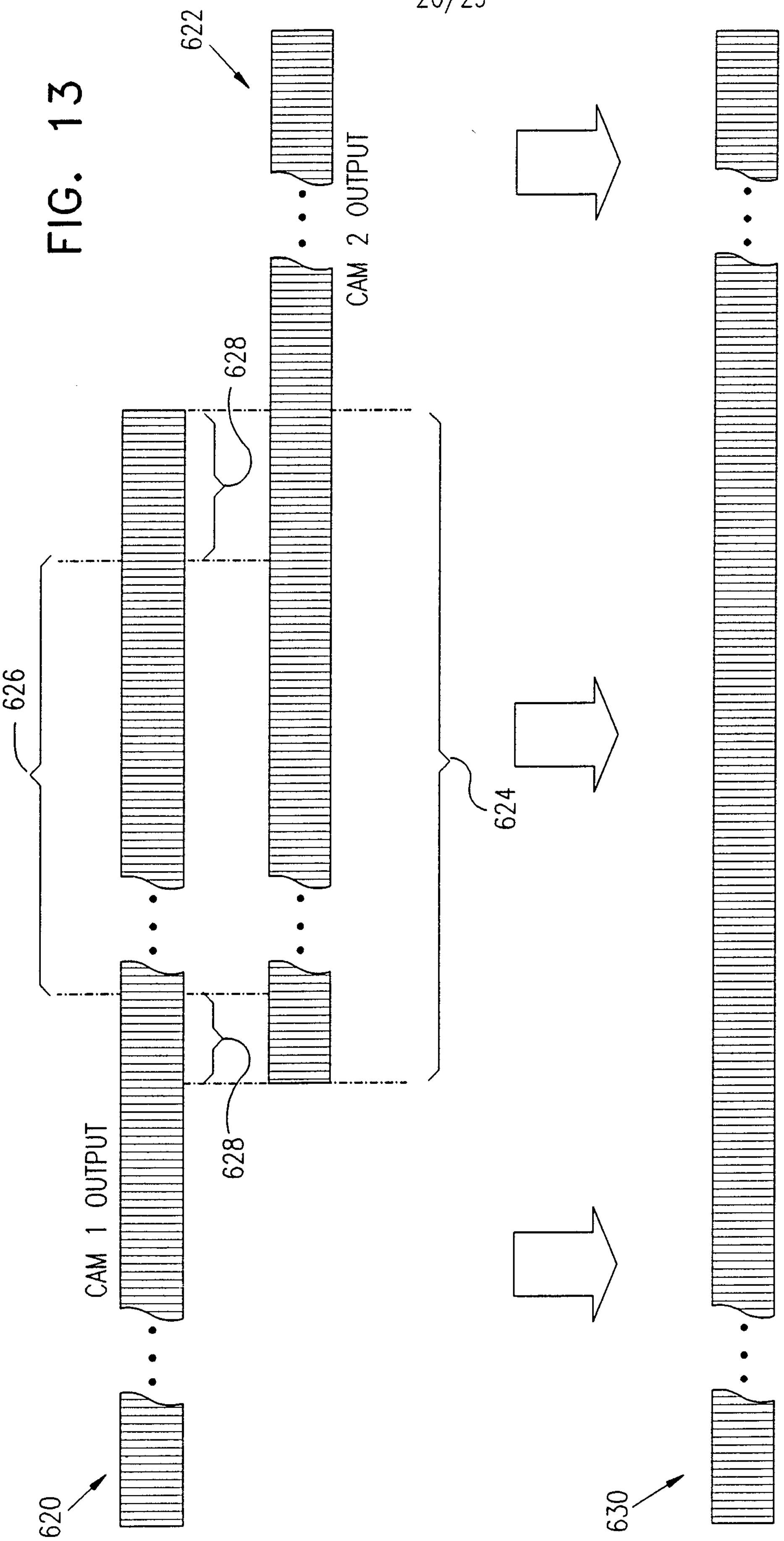


FIG. 13

FIG. 14

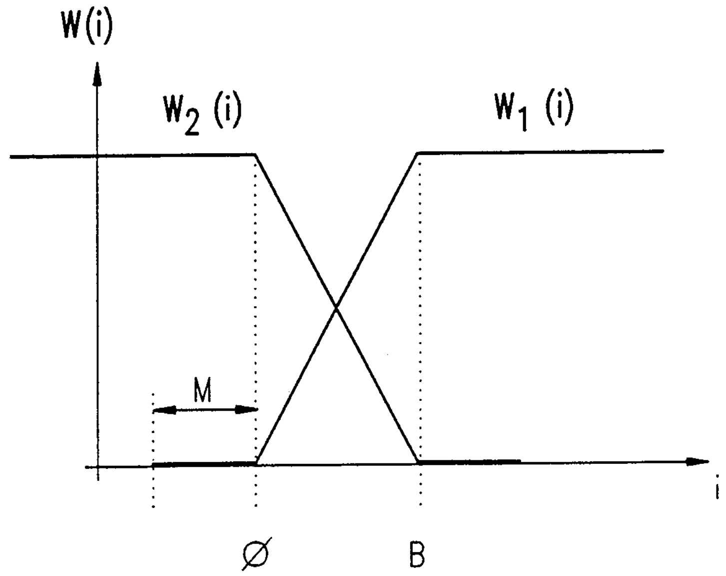


FIG. 15

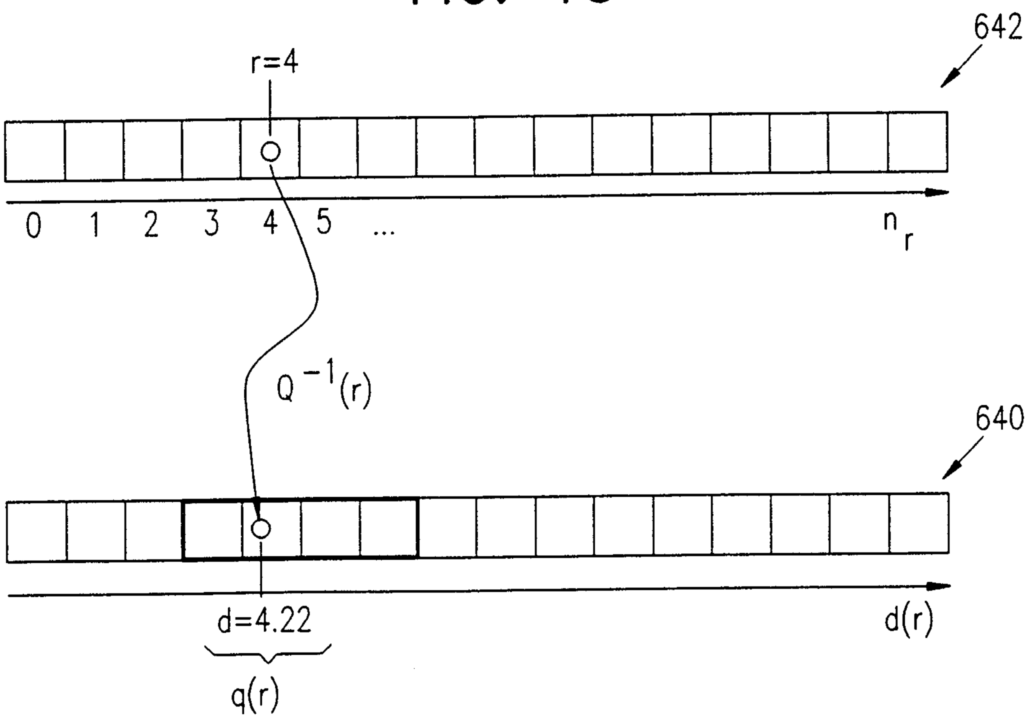
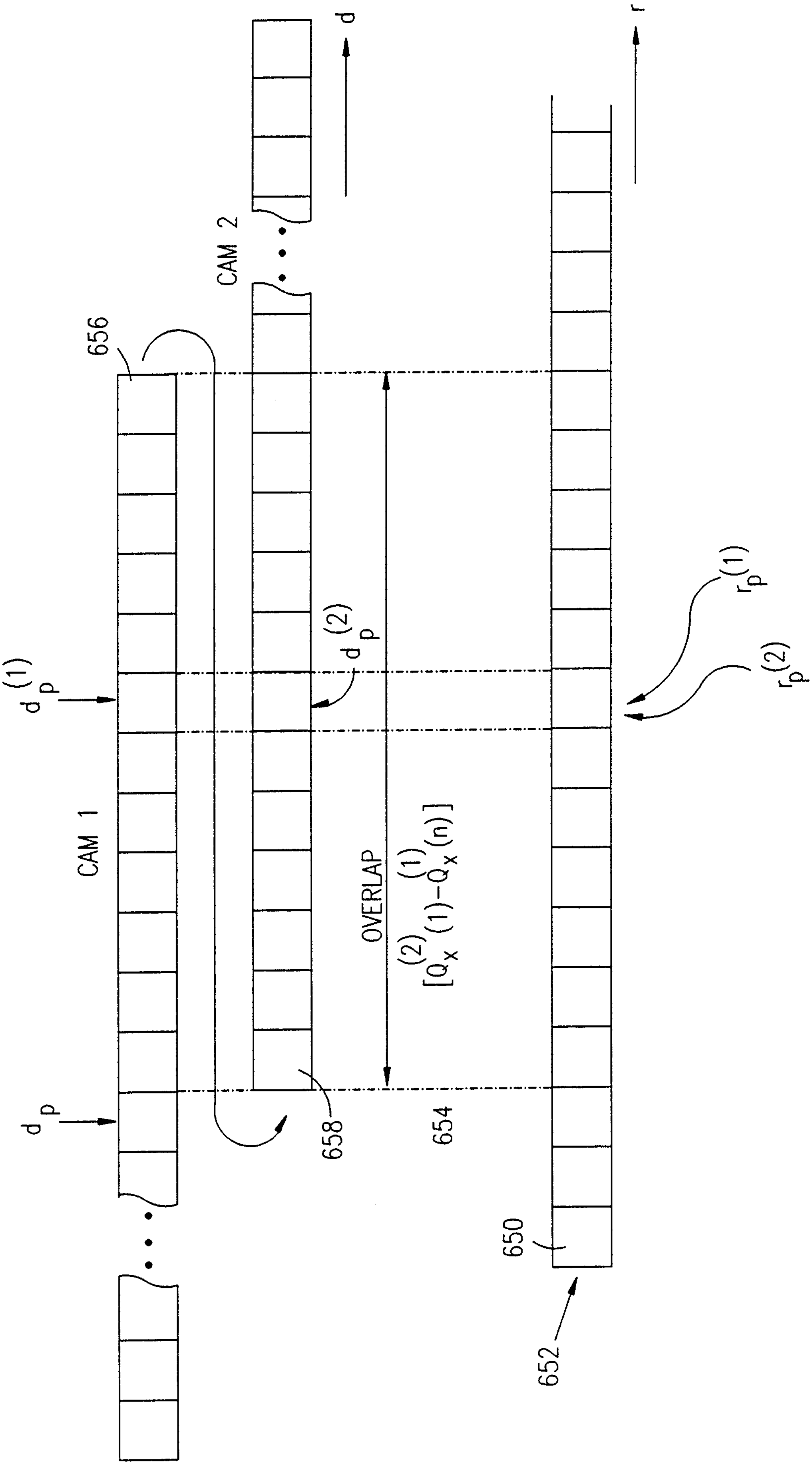


FIG. 16


CAM 1
CAM 2
656
658
654
650
652
d
r
d_p
$d_p^{(1)}$
$d_p^{(2)}$
$r_p^{(1)}$
$r_p^{(2)}$
OVERLAP
$[Q_x^{(2)}(1)-Q_x^{(1)}(n)]$

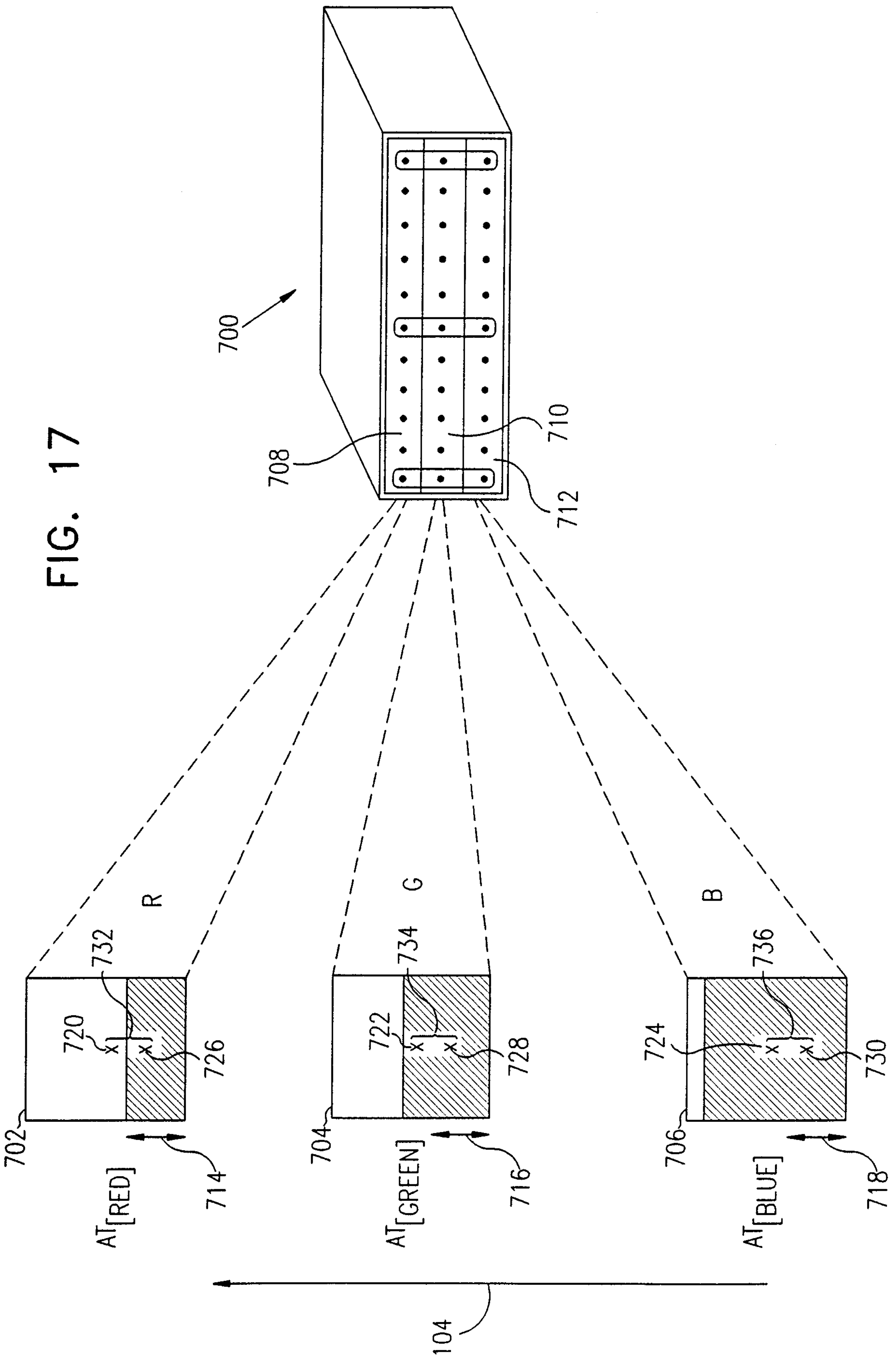

700
708
710
712
R
G
B
732
720
726
702
714
AT[RED]
734
722
728
704
716
AT[GREEN]
736
724
730
706
718
AT[BLUE]
104

FIG. 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL99/00450

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H04N 7/18, 9/47
US CL : 348/126, 129
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 348/126, 129, 133, 135

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

None

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

None

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,686,994 A (TOKURA) 11 November 1997, Figs 405, col. 6, line 48 - col. 7, line 44)	1-32
Y	US 5,298,989 A (TSUKAHARA et al) 29 March 1994, Figs. 1-2, col. 4, lines 1-48	5-10
Y	US 5,099,522 A (MORIMOTO) 24 March 1992, Fig. 5.	4-12

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
05 NOVEMBER 1999	14 DEC 1999

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