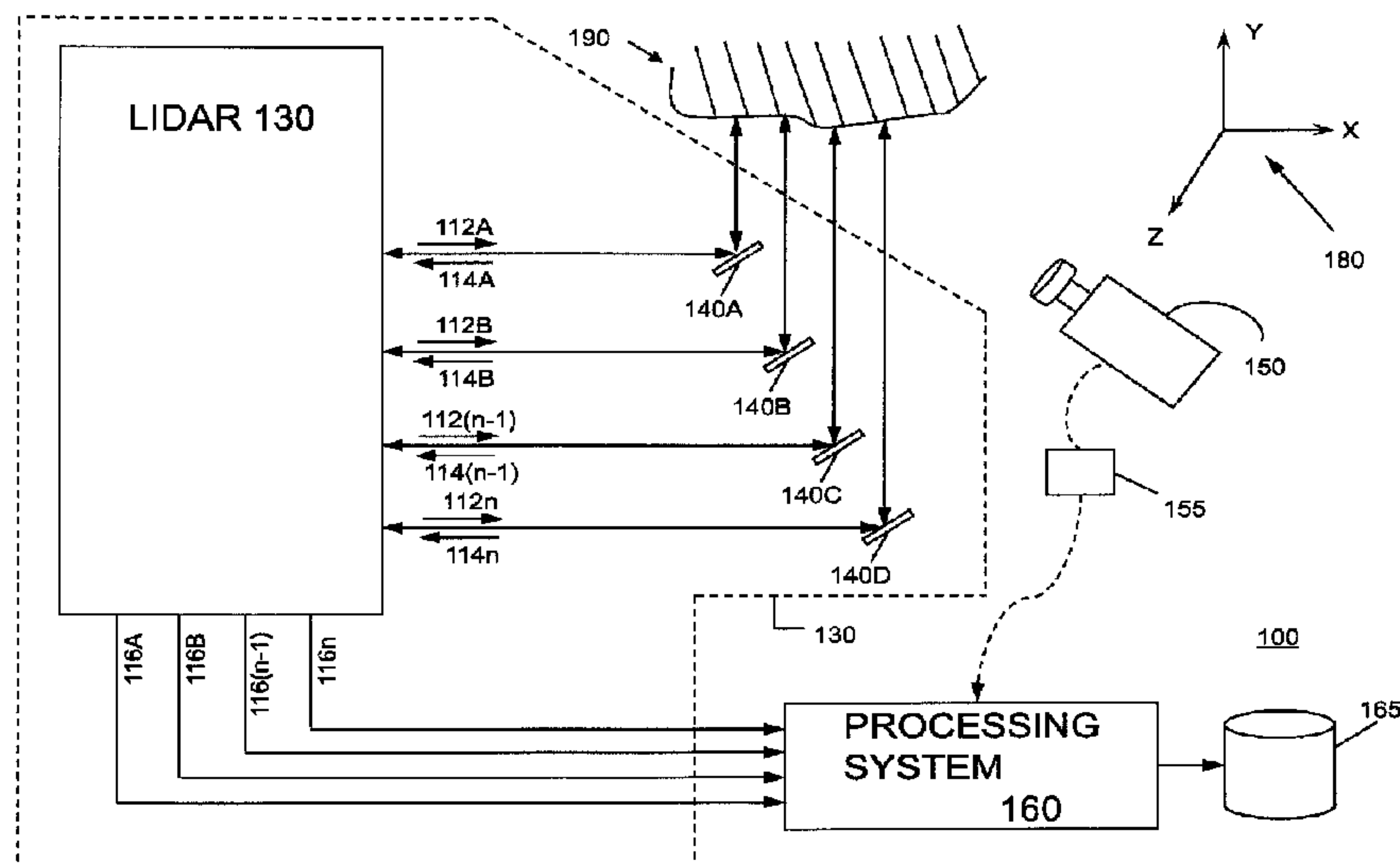




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(54) Title: SYSTEM AND METHOD FOR GENERATING THREE DIMENSIONAL IMAGES USING LIDAR AND VIDEO MEASUREMENTS



(57) Abrégé/Abstract:

A system uses range and Doppler velocity measurements from a lidar system and images from a video system to estimate a six degree-of-freedom trajectory of a target. The system estimates this trajectory in two stages: a first stage in which the range and Doppler measurements from the lidar system along with various feature measurements obtained from the images from the video system are used to estimate first stage motion aspects of the target (i.e., the trajectory of the target); and a second stage in which the images from the video system and the first stage motion aspects of the target are used to estimate second stage motion aspects of the target. Once the second stage motion aspects of the target are estimated, a three-dimensional image of the target may be generated.

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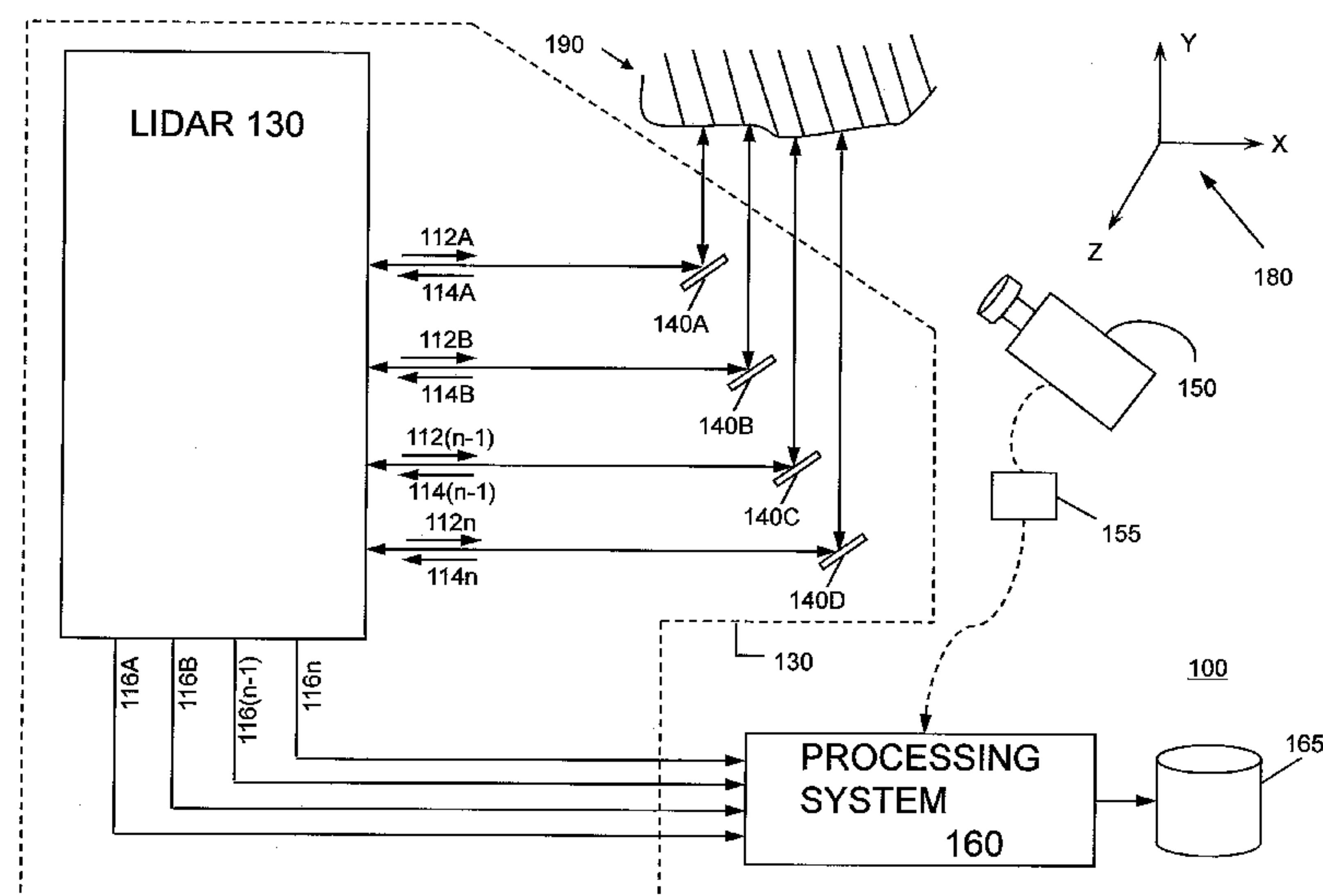


Fig. 1

(57) Abstract: A system uses range and Doppler velocity measurements from a lidar system and images from a video system to estimate a six degree-of-freedom trajectory of a target. The system estimates this trajectory in two stages: a first stage in which the range and Doppler measurements from the lidar system along with various feature measurements obtained from the images from the video system are used to estimate first stage motion aspects of the target (i.e., the trajectory of the target); and a second stage in which the images from the video system and the first stage motion aspects of the target are used to estimate second stage motion aspects of the target. Once the second stage motion aspects of the target are estimated, a three-dimensional image of the target may be generated.

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System and Method for Generating Three Dimensional Images Using Lidar and Video Measurements

Field of the Invention

(01) The invention is generally related to combining lidar (i.e., laser radar) measurements and video images to generate three dimensional images of targets, and more particularly, to resolving a six-degree-of-freedom trajectory associated with a moving target via the lidar measurements and the video images to obtain a motion stabilized three dimensional image of the target.

Background of the Invention

(02) Various conventional systems attempt to merge lidar measurements and video images to obtain three dimensional images of targets.

(03) Typically, these conventional systems require some pre-specified initial model of the target in order to combine lidar measurements with the video image to form a three dimensional image.

(04) Unfortunately, the pre-specified initial model places significant restraints on the ability of the systems to combine lidar measurements with the video image and as a result, the three dimensional image is seldom sufficient for purposes of identifying the target.

(05) Furthermore, these conventional systems typically are unable to adequately account for motion of the target and hence often require that the target remain substantially motionless during an image capture period.

(06) What is needed is an improved system and method for capturing three dimensional images using lidar and video measurements.

Summary of the Invention

(07) Various implementations (illustrative embodiments) of the invention combine measurements generated by a lidar system with images generated by a video system to resolve a six degrees of freedom trajectory that describes motion of a target. Once this trajectory is resolved, an accurate three-dimensional image of the target may be generated. In some implementations of the invention, the trajectory describing the motion of the target comprises a three-dimensional translational velocity and a three-dimensional rotational velocity for the target.

(08) In some implementations of the invention, the lidar system and the video system are coupled to a processor that resolves the trajectory of the target. In some implementations of the invention, the lidar system includes two or more beams that scan the target. In some implementations of the invention, the lidar system includes four or more beams that scan the target. Each of the beams generates a range and a Doppler velocity for each of a plurality of points on the target. In some implementations of the invention, the points are expressed in terms of an azimuth and elevation angle relative to the lidar system. In some implementations of the invention, the video system includes a camera that provides a plurality of frames (i.e., two-dimensional images) of the target.

(09) In some implementations of the invention, the processor uses the range and Doppler velocity measurements from the lidar system and the images from the video system to resolve the trajectory of the target. In some implementations of the invention, the processor accomplishes this in two stages: a first stage in which the range and Doppler measurements along with various feature measurements obtained from the images are used to estimate first stage motion aspects of the target (i.e., the trajectory of the target); and a second stage in which the images are used to estimate second stage motion aspects of the target. Once the trajectory of the target is determined (i.e., from the second stage motion aspects of the target), a three-dimensional image of the target may be generated.

(09a) In another illustrative embodiment, a system for generating a three-dimensional image of a target from lidar measurements and video images includes a lidar subsystem that directs at least two beams toward the target and that generates a range measurement and a Doppler velocity measurement for each of a plurality of points on the target for each of the at least two beams. The system further includes a video subsystem that provides a plurality of two-dimensional images of the target, and a processor. The processor receives, from the lidar subsystem, the range measurement and the Doppler velocity measurement for each of the plurality of points on the target, and also receives, from the video subsystem, the plurality of images of the target. The processor estimates a translational velocity component v_z^{trans} and angular velocity components ω_x and ω_y for each of the plurality of points on the target from the range measurements and the Doppler velocity measurements from the lidar subsystem. The processor further estimates translational velocity components v_x^{trans} and v_y^{trans} and the angular velocity component ω_z for each of the plurality of points on the target from two-dimensional position and velocity measurements of at least one feature of the target obtained from the plurality of images of the target and from the estimated velocity component v_z^{trans} and the estimated angular velocity components ω_x and ω_y . The processor generates the three-dimensional image of the target using the estimated translational velocity components v_x^{trans} , v_y^{trans} , and v_z^{trans} and the estimated angular velocity components ω_x , ω_y and ω_z .

(09b) In another illustrative embodiment, a method for generating a three-dimensional image of a target from lidar measurements from a lidar subsystem and video images from a video subsystem includes receiving, from the lidar subsystem, a range measurement and a Doppler velocity measurement for each of a plurality of points on the target for each of at least two beams of the lidar subsystem. The method further includes receiving, from the video subsystem, a plurality of two-dimensional images of the target, and estimating a translational velocity component v_z^{trans} and angular velocity components ω_x and ω_y for each of the plurality of points on the target from the range measurements and the Doppler velocity measurements from the lidar subsystem. The method further includes estimating translational velocity components v_x^{trans} and v_y^{trans} and the angular velocity component ω_z for each of the plurality of points on the target from two-dimensional position and velocity measurements of at least

one feature of the target obtained from the plurality of images of the target and from the estimated velocity component v_z^{trans} and the estimated angular velocity components ω_x and ω_y . The method further includes generating the three-dimensional image of the target using the estimated translational velocity components v_x^{trans} , v_y^{trans} , and v_z^{trans} and the estimated angular velocity components ω_x , ω_y and ω_z .

(10) These implementations (illustrative embodiments), their features and other aspects of the invention are described in further detail below.

Brief Description of the Drawings

- (11) Figure 1 illustrates a combined lidar and video camera system according to various implementations of the invention.
- (12) Figure 2 illustrates a lidar (i.e., laser radar) according to various implementations of the invention.
- (13) Figure 3 illustrates a scan pattern for a lidar subsystem that employs two lidar beams according to various implementations of the invention.
- (14) Figure 4 illustrates a scan pattern for a lidar subsystem that employs four lidar beams according to various implementations of the invention.
- (15) Figure 5 illustrates a relationship between points acquired from the lidar subsystem from separate beams at substantially the same instance of time that may be used to estimate an x-component of angular velocity of a target according to various implementations of the invention.
- (16) Figure 6 illustrates a relationship between points acquired from the lidar subsystem from separate beams at substantially the same instance of time that may be used to estimate a y-component of angular velocity of a target according to various implementations of the invention.
- (17) Figure 7 illustrates a relationship between points acquired from the video subsystem that may be used to estimate a two-dimensional (e.g. x and y components) translational velocity and a z-component of angular velocity of a target according to various implementations of the invention.
- (18) Figure 8 illustrates a scan pattern of a lidar beam according to various implementations of the invention.
- (19) Figure 9 illustrates a timing diagram which may be useful for describing various timing aspects associated with measurements from the lidar subsystem according to various implementations of the invention.

(20) Figure 10 illustrates a timing diagram which may be useful for describing various timing aspects associated with measurements from the lidar subsystem in relation to measurements from the video subsystem according to various implementations of the invention.

(21) Figure 11 illustrates a block diagram useful for processing lidar measurements and video images according to various implementations of the invention.

(22) Figure 12 illustrates a block diagram useful for processing lidar measurements and video images according to various implementations of the invention.

(23) Figure 13 illustrates a block diagram useful for processing lidar measurements and video images according to various implementations of the invention.

(24) Figure 14 illustrates a block diagram useful for processing lidar measurements and video images according to various implementations of the invention.

(25) Figure 15 illustrates a block diagram useful for processing lidar measurements and video images according to various implementations of the invention.

Detailed Description

(26) Figure 1 illustrates a combined lidar and video camera system 100 according to various implementations of the invention. Various implementations of the invention utilize synergies between lidar measurements and video images to resolve six degrees of freedom for motion of a target to a degree not otherwise possible with either a lidar or video camera alone.

(27) Combined system 100 includes a lidar subsystem 130, a video subsystem 150, and a processing system 160. As illustrated, lidar subsystem 130 includes two or more lidar beam outputs 112 (illustrated as a beam 112A, a beam 112B, a beam 112(n-1), and a beam 112n); two or more reflected beam inputs 114 each corresponding to one of beams 112 (illustrated as a reflected beam 114A, a reflected beam 114B, a reflected beam 114(n-1), and a reflected beam 114n); two or more lidar outputs 116 each associated with a pair of beam 112/reflected beam 114 (illustrated as a lidar output 116A

associated with beam 112A/reflected beam 114A, a lidar output 116B associated with beam 112B/reflected beam 114B, a lidar output 116(n-1) associated with beam 112(n-1)/reflected beam 114(n-1), and a lidar output 116n associated with beam 112n/reflected beam 114n).

(28) In some implementations of the invention, beam steering mechanism 140 may be employed to steer one or more beams 112 toward target 190. In some implementations of the invention, beam steering mechanism 140 may include individual steering mechanisms, such as a steering mechanism 140A, a steering mechanism 140B, a steering mechanism 140C, and a steering mechanism 140D, each of which independently steers a beam 112 toward target 190. In some implementations of the invention, one beam steering mechanism 140 may independently steer pairs or groups of beams 112 toward target 190.

(29) In some implementations of the invention, beam steering mechanism 140 may include one or more mirrors, each of which may or may not be separately controlled, each mirror steering one or more beams 112 toward target 190. In some implementations of the invention, beam steering mechanism 140 may directly steer an optical fiber of beam 112 without use of a mirror. In some implementations of the invention, beam steering mechanism 140 may be controlled to steer beams 112 in azimuth and/or elevation. Various techniques may be used by beam steering mechanism 140 to steer beam(s) 112 toward target 190 as would be appreciated.

(30) In some implementations of the invention, beam steering mechanism 140 may be used to control both an azimuth angle and an elevation angle of two beams 112 toward the target. By controlling both the azimuth angle and the elevation angle, the two beams 112 may be used to scan a volume for potential targets or track particular targets such as target 190. Other scanning mechanisms may be employed as would be apparent. In some implementations of the invention, the two beams 112 may be offset from one another. In some implementations of the invention, the two beams 112 may be offset vertically (e.g., in elevation) or horizontally (e.g., in azimuth) from one another by a

predetermined offset and/or a predetermined angle, either of which may be adjustable or controlled.

(31) In some implementations of the invention, beam steering mechanism 140 may be used to control both an azimuth angle and an elevation angle of four beams 112 toward the target. In some implementations, the four beams 112 may be arranged with horizontal and vertical separations. In some implementations, the four beams may be arranged so as to form at least two orthogonal separations. In some implementations, the four beams may be arranged in a rectangular pattern, with pairs of beams 112 offset from one another vertically and horizontally. In some implementations, the four beams may be arranged in other patterns, with pairs of beams 112 offset from one another. The separations of the four beams 112 may be predetermined offsets and/or predetermined angles, which may be fixed, adjustable and/or controlled.

(32) A certain portion of each beam 112 may be reflected back from target 190 to lidar subsystem 130 as reflected beam 114. In some implementations of the invention and as illustrated in Figure 1, reflected beam 114 follows the same optical path (though in reverse) as beam 112. In some implementations of the invention, a separate optical path may be provided in lidar subsystem 130 or in combined system 100 to accommodate reflected beam 114.

(33) In some implementations of the invention, lidar subsystem 130 receives a reflected beam 114 corresponding to each beam 112, processes reflected beam 114, and outputs lidar output 116 to processing system 160.

(34) Combined system 100 also includes video subsystem 150. Video subsystem 150 may include a video camera for capturing two dimensional images 155 of target 190. Various video cameras may be used as would be apparent. In some implementations of the invention, the video camera may output images 155 as pixels at a particular resolution and at a particular image or frame rate. Video images 155 captured by video subsystem 150 are forwarded to processing system 160. In some implementations of the invention, lidar subsystem 130 and video subsystem 150 are offset from one another in terms of position and orientation. In particular, lidar measurements typically correspond to three

dimensions (e.g., x, y, and z) whereas video images typically correspond to two dimensions (e.g., x and y). Various implementations of invention calibrate lidar subsystem 130 with video subsystem 150 to ensure that data provided by each system refers to the same location in a given coordinate system as would be apparent.

(35) Combined system 110 may include one or more optional video subsystems (not otherwise illustrated) for capturing additional two-dimensional images 155 of target 190 from different positions, perspectives or angles as would be apparent.

(36) In some implementations of the invention, processing system 160 receives lidar outputs 116 from lidar subsystem 130 and images 155 from video subsystem 150 and stores them in a memory or other storage device 165 for subsequent processing. Processing system 160 processes lidar outputs 116 and images 155 to generate a three-dimensional image of target 190. In some implementations of the invention, processing system 160 determines a trajectory of target 190 from a combination of lidar outputs 116 and images 155 and uses the trajectory to generate a motion stabilized three-dimensional image of target 190.

(37) In some implementations of the invention, lidar subsystem 130 may include, for each of beams 112, a dual frequency, chirped coherent laser radar system capable of unambiguously and simultaneously measuring both range and Doppler velocity of a point on target 190. Such a laser radar system is described in co-pending U.S. Patent No. 7,511,824, entitled "Chirped Coherent Laser Radar System and Method," (the "Chirped Lidar Specification"). For purposes of clarity, a "beam" referenced in the Chirped Lidar Specification is not the same as a "beam" referred to in this description. More particularly, in the Chirped Lidar Specification, two beams are described as output from the laser radar system, namely a first beam having a first frequency (chirped or otherwise) and a second beam having a second frequency (chirped or otherwise) that are simultaneously coincident on a point on a target to provide simultaneous measurements of both range and Doppler velocity of the point on the target. For purposes of simplicity and clarity, a singular "beam" as discussed herein may refer to the combined first and second beams output from the laser radar

system described in the Chirped Lidar Specification. The individual beams discussed in the Chirped Lidar Specification are referred to herein henceforth as "signals."

Nonetheless, various implementations of the invention may employ beams other than those described in the Chirped Lidar Specification provided these beams provide simultaneous range and Doppler velocity measurements at points on the target.

(38) Figure 2 illustrates a lidar 210 that may be used to generate and process beam 112 and reflected beam 114 to provide lidar output 116 according to various implementations of the invention. Each lidar 210 unambiguously determines a range and Doppler velocity of a point on target 190 relative to lidar 210. Lidar 210 includes a first frequency lidar subsection 274 and a second frequency lidar subsection 276. First frequency lidar subsection 274 emits a first frequency target signal 212 toward target 190 and second frequency lidar subsection 276 emits a second frequency target signal 214 toward target 190. The frequencies of first target signal 212 and second target signal 214 may be chirped to create a dual chirp system.

(39) First frequency lidar subsection 274 may include a laser source controller 236, a first laser source 218, a first optical coupler 222, a first signal delay 244, a first local oscillator optical coupler 230, and/or other components. Second frequency lidar subsection 276 may include a laser source controller 238, a second laser source 220, a second optical coupler 224, a second signal delay 250, a second local oscillator optical coupler 232 and/or other components.

(40) First frequency lidar subsection 274 generates first target signal 212 and a first reference signal 242. First target signal 212 and first reference signal 242 may be generated by first laser source 218 at a first frequency that may be modulated at a first chirp rate. First target signal 212 may be directed toward a measurement point on target 190 either independently or combined with second target signal 214. First frequency lidar subsection 274 may combine target signal 256 that was reflected from target 190 with first reference signal 242, which is directed over a path with a known or otherwise fixed path length, to result in a combined first target signal 262.

(41) Second frequency lidar subsection 276 may be collocated and fixed with respect to first frequency lidar subsection 274 (i.e., within lidar 210). More particularly, the relevant optical components for transmitting and receiving the respective laser signals may be collocated and fixed. Second frequency lidar subsection 276 may generate second target signal 214 and a second reference signal 248. Second target signal 214 and second reference signal 248 may be generated by second laser source 220 at a second frequency that may be modulated at a second chirp rate. In some implementations of the invention, the second chirp rate is different from the first chirp rate.

(42) Second target signal 214 may be directed toward the same measurement point on target 190 as first target beam 212. Second frequency lidar subsection 276 may combine one portion of target signal 256 that was reflected from target 190 with second reference signal 248, which is directed over a path with a known or otherwise fixed path length, to result in a combined second target signal 264.

(43) Processor 234 receives combined first target signal 262 and combined second target signal 264 and measures a beat frequency caused by a difference in path length between each of the reflected target signals and its corresponding reference signal, and by any Doppler frequency created by target motion relative to lidar 210. The beat frequencies may then be combined linearly to generate unambiguous determinations of range and Doppler velocity of target 190 as set forth in the Chirped Lidar Specification. In some implementations, processor 234 provides the range and Doppler velocity measurements to processing system 160. In some implementations, processor 234 is combined with processing system 160; in such implementations, processing system 160 receives combined first target signal 262 and combined second target signal 264 and uses them to determine range and Doppler velocity.

(44) As described, each beam 112 provides simultaneous measurements of range and Doppler velocity of a point on target 190 relative to lidar 210. According to various implementations of the invention, various numbers of beams 112 may be used to provide these measurements of target 190. In some implementations of the invention, two or more beams 112 may be used. In some implementations of the invention, three or more

beams 112 may be used. In some implementations of the invention four or more beams 112 may be used. In some implementations of the invention, five or more beams 112 may be used.

(45) In various implementations of the invention, beams 112 may be used to gather measurements for different purposes. For example, in some implementations of the invention, a particular beam 112 may be used for purposes of scanning a volume including target 190. In some implementations of the invention, multiple beams 112 may be used to accomplish such scanning. In some implementations of the invention, a particular beam 112 may be used to monitor a particular feature or position on target 190. In some implementations of the invention, multiple beams 112 may be used to independently monitor one or more features and/or positions on target 190. In some implementations of the invention, one or more beams 112 may be used to scan target 190 while one or more other beams 112 may be used to monitor one or more features and/or positions on target 190.

(46) In some implementations of the invention, one or more beams 112 may scan target 190 to obtain a three dimensional image of target 190 while one or more other beams 112 may be monitoring one or more features and/or positions on target 190. In some implementations of the invention, after a three dimensional image of target 190 is obtained, one or more beams 112 may continue scanning target 190 to monitor and/or update the motion aspects of target 190 while one or more other beams 112 may monitor one or more features and/or positions on target 110.

(47) In some implementations of the invention, measurements obtained via one or more beams 112 used to monitor and/or update the motion aspects of target 190 may be used to compensate measurements obtained via the one or more other beams 112 used to monitor one or more features and/or positions on target 190. In these implementations of the invention, the gross motion of target 190 may be removed from the measurements associated with various features and/or positions on target 190 to obtain fine motion of particular points or regions on target 190. In various implementations of the invention, fine motion of target 190 may include various vibrations, oscillations, or motion of certain

positions on the surface of target 190 relative to, for example, a center of mass, a center of rotation, another position on the surface of target 190 or other position. In various implementations of the invention, fine motion of target 190 may include, for example, relative motion of various features such as eyes, eyelids, lips, mouth corners, facial muscles or nerves, nostrils, neck surfaces, etc. or other features of target 190.

(48) In some implementations of the invention, based on the gross motion and/or the fine motion of target 190, one or more physiological functions and/or physical activities of target 190 may be monitored. For example, co-pending U.S. Patent No. 7,507,203, entitled "System and Method for Remotely Monitoring Physiological Functions" describes various systems and methods for monitoring physiological functions and/or physical activities of an individual.

(49) In some implementations of the invention, one or more beams 112 may be used to monitor one or more locations on an eyeball of target 190 and measure various position and motion aspects of the eyeball at the each of these locations. Co-pending U.S. Patent No. 7,699,469, entitled "System and Method for Tracking Eyeball Motion" describes various systems and methods for tracking the movement of an eyeball.

(50) In some implementations of the invention, one or more beams 112 may be used to focus on various features or locations on a face of target 190 and measure various aspects of the face with respect to the features or locations on the face of target 190. For example, certain facial features or facial expressions may be monitored over a period of time to infer a mental state of target 190, to infer an intent of target 190, to infer a deception level of target 190 or to predict an event associated with target 190 (e.g., certain facial muscles may twitch just prior to a change in expression or prior to speech).

(51) In some implementations of the invention, one or more beams 112 may be used to monitor one or more locations on a neck of target 190. The measured motion aspects of the neck of target 190 may be used to determine throat movement patterns, vocal cord vibrations, pulse rate, and/or respiration rate. In some implementations of the invention,

one or more beams 112 may be used to monitor one or more locations on an upper lip of target 190 to detect and measure vibrations associated with speech of target 190. These vibrations may be used to substantially reproduce the speech of target 190.

(52) In some implementations of the invention, one or more beams 112 may serve one purpose during a first period or mode of operation of combined system 100 and may switch to serve a different purpose during a second period or mode of operation of combined system 100. For example, in some implementations of the invention, multiple beams 112 may be used to measure various motion aspects of target 190 so that processing system 160 may determine or acquire a trajectory of target 190. Once the trajectory of target 190 is acquired, some of the multiple beams 112 may switch to monitoring certain other aspects or features of target 190 while other ones of the multiple beams 112 measure motion aspects of target 190 so that its trajectory can be maintained.

(53) In some implementations of the invention, five beams 112 scan target 190 to obtain a three dimensional image of target 190. In these implementations, four of these beams 112 each scan a portion of target 190 (using various scanning patterns as described in further detail below) while a fifth beam 112 performs an "overscan" of target 190. The overscan may be a circular, oval, elliptical or similar round scan pattern or a rectangular, square, diamond or similar scan pattern or other scan pattern useful for capturing multiple measurements of various points on target 190 (or at least points within close proximity to one another) within relatively short time intervals. These multiple measurements may correspond to other measurements made by the fifth beam 112 (i.e., multiple visits to the same point by the fifth beam 112) or to measurements made by one or more of the other four beams 112 (i.e., visits to the same point by the fifth beam and one or more of the other four beams 112). In some implementations, the pattern of the overscan may be selected to provide additional vertical and/or horizontal spread between measurements of target 190. Both the multiple measurements and additional spread may be used to improve estimates of the motion of target 190. Use of the fifth beam 112 to overscan target 190 may occur during each of the different modes of operation referred to above.

(54) In some implementations of the invention, once the trajectory of target 190 is satisfactorily acquired, one or more beams 112 may provide measurements useful for maintaining the trajectory of target 190 as well as monitor other aspects of features of target 190. In such implementations, other beams 112 may be used to scan for other targets in the scanning volume.

(55) As illustrated in Figure 1, a target coordinate frame 180 may be used to express various measurements associated with target 190. Various coordinate frames may be used as would be appreciated. In some implementations of the invention, various ones of the subsystems 130, 150 may express aspects of target 190 in coordinate frames other than target coordinate frame 180 as would be appreciated. For example, in some implementations of the invention, a spherical coordinate frame (e.g., azimuth, elevation, range) may be used to express measurements obtained via lidar subsystem 130. Also for example, in some implementations of the invention, a two dimensional pixel-based coordinate frame may be used to express images 155 obtained via video subsystem 150. Various implementations of the invention may use one or more of these coordinate frames, or other coordinate frames, at various stages of processing as will be appreciated.

(56) As would be appreciated, in some implementations of the invention, various coordinate transformations may be required to transform measurements from lidar subsystem 130, which may be expressed in a spherical coordinates with reference to lidar subsystem 130 (sometimes referred to as a lidar measurement space), to the motion aspects of target 190, which may be expressed in Cartesian coordinates with reference to target 190 (sometimes referred to as target space). Likewise, various coordinate transformations may be required to transform measurements from video subsystem 150, which may be expressed in Cartesian or pixel coordinates with reference to video subsystem 150 (sometimes referred to as video measurement space), to the motion aspects of target 190. In addition, measurements from combined system 100 may be transformed into coordinate frames associated with external measurement systems such as auxiliary video, infrared, hyperspectral, multispectral or other auxiliary imaging systems. Coordinate transformations are generally well known.

(57) As would be appreciated, in some implementations of the invention, various coordinate transformations may be required to transform measurements from lidar subsystem 130 and/or video subsystem 150 to account for differences in position and/or orientation of each such subsystem 130, 150 as would be apparent.

(58) Figure 3 illustrates a scan pattern 300 which may be used to scan a volume for targets 190 according to various implementations of the invention. Scan pattern 300 includes a first scan pattern section 310 and a second scan pattern section 320. First scan pattern section 310 may correspond to a scan pattern of a first beam 112 (e.g., beam 112A) that may be used to scan the volume (or portion thereof). Second scan pattern section 320 may correspond to a scan pattern of a second beam 112 (e.g., beam 112B) that may be used to scan the volume (or portion thereof).

(59) As illustrated in Figure 3, the first beam 112 scans an upper region of scan pattern 300 whereas the second beam 112 scans a lower region of scan pattern 300. In some implementations of the invention, the scan pattern sections 310, 320 may include an overlap region 330. Overlap region 330 may be used to align or "stitch together" first scan pattern section 310 with second scan pattern section 320. In some implementations of the invention, scan patterns 310, 320 do not overlap to form overlap region 330 (not otherwise illustrated).

(60) In implementations of the invention where lidar subsystem 130 employs a vertically displaced scan pattern 300 (such as that illustrated in Figure 3), first beam 112 is displaced vertically (i.e., by some vertical distance, angle of elevation, or other vertical displacement) from a second beam 112. In this way, the pair of beams 112 may be scanned with a known or otherwise determinable vertical displacement.

(61) While scan pattern 300 is illustrated as having vertically displaced scan pattern sections 310, 320 in Figure 3, in some implementations of the invention, scan pattern may have horizontally displaced scan sections. In implementations of the invention where lidar subsystem 130 employs a horizontally displaced scan pattern (not otherwise illustrated), first beam 112 is displaced horizontally (i.e., by some horizontal distance, angle of azimuth, or other horizontal displacement) from second beam 112. In this way,

the pair of beams 112 may be scanned with a known or otherwise determinable horizontal displacement.

(62) While Figure 3 illustrates a scan pattern 300 with two vertically displaced scan pattern sections 310, 320, various numbers of beams may be stacked to create a corresponding number of scan pattern sections as would be appreciated. For example, three beams may be configured with either vertical displacements or horizontal displacements to provide three scan pattern sections. Other numbers of beams may be used either horizontally or vertically as would be appreciated.

(63) Figure 4 illustrates a scan pattern 400 for lidar subsystem 130 that employs four beams 112 according to various implementations of the invention. As illustrated in Figure 4, lidar subsystem 130 includes four beams 112 arranged to scan a scan pattern 400. Scan pattern 400 may be achieved by having a first pair of beams 112 displaced horizontally from one another and a second pair of beams 112 displaced horizontally from one another and vertically from the first pair of beam 112, thereby forming a rectangular scanning arrangement. Other scanning geometries may be used as would be apparent. Scan pattern 400 may be achieved by controlling the beams independently from one another, as pairs (either horizontally or vertically), or collectively, via beam scanning mechanism(s) 140.

(64) Scan pattern 400 includes a first scan pattern section 410, a second scan pattern section 420, a third scan pattern section 430, and a fourth scan pattern section 440. In some implementations of the invention, each of the respective scan pattern sections 410, 420, 430, 440 may overlap an adjacent scan pattern portion by some amount (illustrated collectively in Figure 4 as overlap regions 450). For example, in some implementations of the invention, scan pattern 400 includes an overlap region 450 between first scan pattern section 410 and third scan pattern section 430. Likewise, an overlap region 450 exists between a first scan pattern section 410 and a second scan section 420. In some implementations of the invention, various ones of these overlap regions 450 may not occur or otherwise be utilized. In some implementations of the invention, for example, only vertical overlap regions 450 may occur or be utilized. In some implementations of

the invention, only horizontal overlap regions 450 may occur or be utilized. In some implementations of the invention, no overlap regions 450 may occur or be utilized. In some implementations of the invention, other combinations of overlap regions 450 may be used.

(65) As illustrated in Figure 3 and Figure 4, the use by lidar subsystem 130 of multiple beams 112 may increase a rate at which a particular volume (or specific targets within the volume) may be scanned. For example, a given volume may be scanned twice as fast using two beams 112 as opposed to scanning the same volume with one beam 112. Similarly, a given volume may be scanned twice as fast using four beams 112 as opposed to scanning the same volume with two beams 112, and four times as fast as scanning the same volume with one beam 112. In addition, multiple beams 112 may be used to measure or estimate various parameters associated with the motion of target 190 as will be discussed in more detail below.

(66) According to various implementations of the invention, particular scan patterns (and their corresponding beam configurations) may be used to provide measurements and/or estimates of motion aspects of target 190. As described above, each beam 112 may be used to simultaneously provide a range measurement and a Doppler velocity measurement at each point scanned.

(67) In some implementations of the invention, for each beam 112, a point scanned by that beam 112 may be described by an azimuth angle, an elevation angle, and a time. Each beam 112 provides a range measurement and a Doppler velocity measurement at that point and time. In some implementations of the invention, each point scanned by beam 112 may be expressed as an azimuth angle, an elevation angle, a range measurement, a Doppler velocity measurement, and a time. In some implementations of the invention, each point scanned by beam 112 may be expressed in Cartesian coordinates as a position (x, y, z), a Doppler velocity and a time.

(68) According to various implementations of the invention, measurements from lidar subsystem 130 (i.e., lidar outputs 116) and measurements from video subsystem 150 (frames 155) may be used to measure and/or estimate various orientation and/or motion

aspects of target 190. These orientation and/or motion aspects of target 190 may include position, velocity, acceleration, angular position, angular velocity, angular acceleration, etc. As these orientation and/or motion aspects are measured and/or estimated, a trajectory of target 190 may be determined or otherwise approximated. In some implementations of the invention, target 190 may be considered a rigid body over a given time interval and its motion may be expressed as translational velocity components expressed in three dimensions as v_x^{trans} , v_y^{trans} , and v_z^{trans} , and angular velocity components expressed in three dimensions as ω_x , ω_y , and ω_z over the given time interval. Collectively, these translational velocities and angular velocities correspond to six degrees of freedom of motion for target 190 over the particular time interval. In some implementations of the invention, measurements and/or estimates of these six components may be used to express a trajectory for target 190. In some implementations of the invention, measurements and/or estimates of these six components may be used to merge the three-dimensional image of target 190 obtained from lidar subsystem 130 with the two-dimensional images of target 190 obtained from video subsystem 150 to generate three-dimensional video images of target 190.

(69) In some implementations of the invention, the instantaneous velocity component $v_z(t)$ of a point on target 190 may be calculated based on the range measurement, the Doppler velocity measurement, the azimuth angle and the elevation angle from lidar subsystem 130 as would be apparent.

(70) Lidar subsystem 130 may be used to measure and/or estimate translational velocity v_z^{trans} and two angular velocities of target 190, namely ω_x and ω_y . For example, Figure 5 illustrates an exemplary relationship between points with corresponding measurements from two beams 112 that may be used to estimate x and y components of angular velocity of target 190 according to various implementations of the invention. More particularly, and generally speaking, as illustrated in Figure 5, in implementations where beams 112 are displaced from one another along the y-axis, a local velocity along the z-axis of point P_A determined via a first beam 112, a velocity of point P_B determined via a second beam 112, and a distance between P_A and P_B may be used to estimate an angular velocity of these points about the x-axis (referred to herein as ω_x) as would be

appreciated. In some implementations of the invention, these measurements may be used to provide an initial estimate of ω_x .

(71) Figure 6 illustrates another exemplary relationship between points with corresponding measurements from two beams 112 that may be used to estimate an angular velocity according to various implementations of the invention. More particularly, as illustrated in Figure 6, in implementations where beams 112 are displaced from one another on target 190 along the x-axis, a velocity of point P_A determined via a first beam 112, a velocity of point P_B determined by a second beam 112, and a distance between P_A and P_B on target 190 along the x-axis may be used to estimate an angular velocity of these points about the y-axis (referred to herein as ω_y). In some implementations of the invention, these measurements may be used to provide an initial estimate of ω_y .

(72) Figure 5 and Figure 6 illustrate implementations of the invention where two beams 112 are disposed from one another along a vertical axis or a horizontal axis, respectively, and the corresponding range (which may be expressed in three-dimensional coordinates x, y, and z) and Doppler velocity at each point are measured at substantially the same time. In implementations of the invention that employ beams 112 along a single axis (not otherwise illustrated), an angular velocity may be estimated based on Doppler velocities measured at different points at different times along the single axis. As would be appreciated, better estimates of angular velocity may be obtained using: 1) measurements at points at the extents of target 190 (i.e., at larger distances from one another), and 2) measurements taken within the smallest time interval (so as to minimize any effects due to acceleration).

(73) Figure 5 and Figure 6 illustrate conceptual estimation of the angular velocities about different axes, namely the x-axis and the y-axis. In general terms, where a first beam 112 is displaced on target 190 along a first axis from a second beam 112, an angular velocity about a second axis orthogonal to the first axis may be determined from the velocities along a third axis orthogonal to both the first and second axes at each of the respective points.

(74) In some implementations of the invention, where two beams are displaced along the y-axis from one another (i.e., displaced vertically) and scanned horizontally with vertical separation between scans, estimates of both ω_x and ω_y may be made. While simultaneous measurements along the x-axis are not available, they should be sufficiently close in time in various implementations to neglect acceleration effects. In some implementations of the invention where two beams 112 are displaced along the x-axis from one another and at least a third beam 112 is displaced along the y-axis from the pair of beams 112, estimates of ω_x , ω_y and v_z^{trans} may be made. In some implementations of the invention, estimates of both ω_x , ω_y and v_z^{trans} may be made using four beams 112 arranged in a rectangular fashion. In such implementations, the measurements obtained from the four beams 112 include more information than necessary to estimate ω_x , ω_y and v_z^{trans} . This so-called “overdetermined system” may be used to improve the estimates of ω_x , ω_y and v_z^{trans} as would be appreciated.

(75) As has been described, range and Doppler velocity measurements taken at various azimuth and elevation angles and at various points in time by lidar subsystem 130 may be used to estimate translational velocity v_z^{trans} and estimate two angular velocities, namely, ω_x and ω_y , for the rigid body undergoing ballistic motion.

(76) In some implementations of the invention, ω_x , ω_y and v_z^{trans} may be determined at each measurement time from the measurements obtained at various points as would be appreciated. In some implementations of the invention, ω_x , ω_y and v_z^{trans} may be assumed to be constant over an particular interval of time. In some implementations of the invention, ω_x , ω_y and v_z^{trans} may be determined at various measurement times and subsequently averaged over a particular interval of time to provide estimates of ω_x , ω_y and v_z^{trans} for that particular interval of time as would be appreciated. In some implementations of the invention, the particular time interval may be fixed or variable depending, for example, on the motion aspects of target 190. In some implementations of the invention, a least squares estimator may be used to provide estimates of ω_x , ω_y and v_z^{trans} over a particular interval of time as would be appreciated. Estimates of ω_x , ω_y and v_z^{trans} may be obtained in other manners as would be appreciated.

(77) In some implementations of the invention, images from video subsystem 150 may be used to estimate three other motion aspects of target 190, namely translational velocity components v_x^{trans} and v_y^{trans} and angular velocity component ω_z over a given interval of time. In some implementations of the invention, frames 155 captured by video subsystem 150 may be used to estimate x and y components of velocity for points on target 190 as it moves between frames 155. Figure 7 illustrates a change in position of a particular point or feature I_A between a frame 155 at time T and a frame 155 at subsequent time $T+\Delta t$.

(78) In some implementations of the invention, this change of position is determined for each of at least two particular points or features in frame 155 (not otherwise illustrated). In some implementations of the invention, the change of position is determined for each of many points or features. In some implementations of the invention, translational velocity components v_x^{trans} and v_y^{trans} , and angular velocity component ω_z of target 190 may be estimated based on a difference in position of a feature $I_A(T)$ and $I_A(T+\Delta t)$ and a difference in time, Δt , between the frames 155. These differences in position and time may be used to determine certain velocities of the feature, namely, v_x^{feat} and v_y^{feat} that may in turn be used to estimate the translational velocity components v_x^{trans} and v_y^{trans} , and angular velocity component ω_z of target 190. Such estimations of velocity and angular velocity of features between image frames are generally understood as would be appreciated.

(79) In some implementations of the invention, many features of target 190 are extracted from consecutive frames 155. The velocities v_x^{feat} and v_y^{feat} of these features over the time interval between consecutive frames 155 may be determined based on changes in position of each respective feature between the consecutive frames 155. A least squares estimator may be used to estimate the translational velocities v_x^{trans} and v_y^{trans} , and the angular velocity ω_z from the position changes of each the extracted features.

(80) In some implementations of the invention, a least squares estimator may use measurements from lidar subsystem 130 and the changes in position of the features in

frames 155 from video subsystem 150 to estimate the translational velocities v_x^{trans} , v_y^{trans} and v_z^{trans} and the angular velocities ω_x , ω_y , and ω_z of target 190.

(81) As has been described above, lidar subsystem 130 and video subsystem 150 may be used to estimate six components that may be used describe the motion of target 190. These components of motion may be collected over time to calculate a trajectory of target 190. This trajectory may then be used to compensate for motion of target 190 to obtain a motion stabilized three dimensional image of target 190. In various implementations of the invention, the trajectory of target 190 may be assumed to represent ballistic motion over various intervals of time. The more accurately trajectories of target 190 may be determined, the more accurately combined system 100 may adjust the measurements of target 190 to, for example, represent three dimensional images, or other aspects, of target 190.

(82) In various implementations of the invention, a rate at which measurements are taken by lidar subsystem 130 is different from a rate at which frames 155 are captured by video subsystem 150. In some implementations of the invention, a rate at which measurements are taken by lidar subsystem 130 is substantially higher than a rate at which frames 155 are captured by video subsystem 150. In addition, because beams 112 are scanned through a scan volume by lidar subsystem 130, measurements at different points in the scan volume may be taken at different times from one another; whereas pixels in a given frame 155 are captured substantially simultaneously (within the context of video imaging). In some implementations of the invention, these time differences are resolved in order to provide a more accurate trajectory of target 190.

(83) As illustrated in Figure 8, in some implementations of the invention, a scan pattern 840 may be used to scan a volume for targets. For purposes of explanation, scan pattern 840 represents a pattern of measurements taken by a single beam. In some implementations multiple beams may be used, each with their corresponding scan pattern as would be apparent. As illustrated, scan pattern 840 includes individual points 810 measured left to right in azimuth at a first elevation 831, right to left in azimuth at a second elevation 832, left to right in azimuth at a third elevation 833, etc., until a particular

scan volume is scanned. In some implementations, scan pattern 840 may be divided into intervals corresponding to various timing aspects associated with combined system 100. For example, in some implementations of the invention, scan pattern 840 may be divided into time intervals associated with a frame rate of video subsystem 150. In some implementations of the invention, scan pattern 840 may be divided into time intervals associated with scanning a particular elevation (i.e., an entire left-to-right or right-to-left scan). In some implementations of the invention, scan pattern 840 may be divided into time intervals associated with a roundtrip scan 820 (illustrated in Figure 8 as a roundtrip scan 820A, a roundtrip scan 820B, and a roundtrip scan 820C) at one or more elevations (i.e., a left-to-right and a return right-to-left scan at either the same or different elevations). Similar timing aspects may be used in implementations that scan vertically in elevation (as opposed to horizontally in azimuth). Other timing aspects may be used as well.

(84) As illustrated in Figure 8 and again for purposes of explanation, each interval may include N points 810 which may in turn correspond to the number of points 810 in a single scan (e.g., 831, 832, 833, etc.) or in a roundtrip scan 820. A collection of points 810 for a particular interval is referred to herein as a sub-point cloud and a collection of points 810 for a complete scan pattern 840 is referred to herein as a point cloud. In some implementations of the invention, each point 810 corresponds to the lidar measurements of range and Doppler velocity at a particular azimuth, elevation, and a time at which the measurement was taken. In some implementations of the invention, each point 810 corresponds to the lidar measurements of range (expressed x, y, z coordinates) and Doppler velocity and a time at which the measurement was taken.

(85) Figure 9 illustrates a timing diagram 900 useful for describing various timing aspects associated with measurements from lidar subsystem 130 according to various implementations of the invention. Timing diagram 900 includes points 810 scanned by beam 112, sub-point clouds 920 formed from a plurality of points 810 collected over an interval corresponding to a respective sub-point cloud 920, and a point cloud 930 formed from a plurality of sub-point clouds 920 collected over the scan pattern. Timing diagram 900 may be extended to encompass points 810 scanned by multiple beams 112 as would be appreciated.

(86) Each point 810 is scanned by a beam 112 and measurements associated with each point 810 are determined by lidar subsystem 130. In some implementations of the invention, points 810 are scanned via a scan pattern (or scan pattern section). The interval during which lidar subsystem 130 collects measurements for a particular sub-point cloud 920 may have a time duration referred to as T_{SPC} . In some implementations of the invention, the differences in timing of the measurements associated with individual points 810 in sub-point cloud 920 may be accommodated by using the motion aspects (e.g., translational velocities and angular velocities) for each point to adjust that point to a particular reference time for sub-point cloud 920 (e.g., t_{RSPC}). This process may be referred to as stabilizing the individual points 810 for the motion aspects of target 190.

(87) In some implementations of the invention, the velocities may be assumed to be constant over the time interval (i.e., during the time duration T_{SPC}). In some implementations of the invention, the velocities may not be assumed to be constant during the period of the scan pattern and acceleration effects may need to be considered to adjust the measurements of points 810 to the reference time as would be appreciated. In some implementations of the invention, adjustments due to subdivision of the time interval may also need to be accommodated. As illustrated in Figure 9, the reference time for each sub-point cloud 920 may be selected at the midpoint of the interval, although other reference times may be used.

(88) In some implementations of the invention, similar adjustments may be made when combining sub-point clouds 920 into point clouds 930. More particularly, in some implementations of the invention, the differences in timing of the measurements associated with sub-point clouds 920 in point cloud 930 may be accommodated by using the motion aspects associated with the measurements.

(89) In some implementations of the invention, the measurements associated with each sub-point cloud 920 that is merged into point cloud 930 are individually adjusted to a reference time associated with point cloud 930. In some implementations of the invention, the reference time corresponds to a frame time (e.g., time associated with a frame 155).

In other implementations of the invention, the reference time correspond to an earliest of the measurement times of points 1110 in point cloud 930, a latest of the measurement times of points 1110 in point cloud 930, an average or midpoint of the measurement times of points 1110 in point cloud 930, or other reference time associated with point cloud 930.

(90) Although not otherwise illustrated, in some implementations of the invention, similar adjustments may be made to combine point clouds 930 from individual beams 112 into aggregate point clouds at a particular reference time. In some implementations of the invention, this may be accomplished at the individual point level, the sub-point cloud level or the point cloud level as would be appreciated. For purposes of the remainder of this description, sub-point clouds 920 and point clouds 930 refer to the collection of points 810 at their respective reference times from each of beams 112 employed by lidar subsystem 130 to scan target 190.

(91) In some implementations of the invention, motion aspects of target 190 may be assumed to be constant over various time intervals. For example, motion aspects of target 190 may be assumed to be constant over T_{SPC} or other time duration. In some implementations of the invention, motion aspects of target 190 may be assumed to be constant over a given T_{SPC} , but not necessarily constant over T_{PC} . In some implementations of the invention, motion aspects of target 190 may be assumed to be constant over incremental portions of T_{SPC} , but not necessarily over the entire T_{SPC} . As a result, in some implementations of the invention, a trajectory of target 190 may be expressed as a piece-wise function of time, with each "piece" corresponding to the motion aspects of target 190 over each individual time interval.

(92) In some implementations, timing adjustments to compensate for motion may be expressed as a transformation that accounts for the motion of a point from a first time to a second time. This transformation, when applied to measurements from, for example, lidar subsystem 130, may perform the timing adjustment from the measurement time associated with a particular point (or sub-point cloud or point cloud, etc.) to the desired reference time. Furthermore, when the measurements are expressed as vectors, this

transformation may be expressed as a transformation matrix. Such transformation matrices and their properties are generally well known.

(93) As would be appreciated, the transformation matrices may be readily used to place a position and orientation vector for a point at any time to a corresponding position and orientation vector for that point at any other time, either forwards or backwards in time, based on the motion of target 190. The transformation matrices may be applied to sub-point clouds, multiple sub-point clouds and point clouds as well. In some implementations, a transformation matrix may be determined for each interval (or subinterval) such that it may be used to adjust a point cloud expressed in one interval to a point cloud expressed in the next sequential interval. In these implementations, each interval has a transformation matrix associated therewith for adjusting the point clouds for the trajectory of target 190 to the next interval. In some implementations, a transformation matrix may be determined for each interval (or subinterval) such that it may be used to adjust a point cloud expressed in one interval to a point cloud expressed in the prior sequential interval. Using the transformation matrices for various intervals, a point cloud can be referenced to any time, either forward or backward.

(94) Figure 10 illustrates a timing diagram 1000 useful for describing various timing aspects associated with measurements from lidar subsystem 130 in relation to measurements from video subsystem 150 according to various implementations of the invention. In some implementations of the invention, point cloud 930 may be referenced to the midpoint of a time interval between frames 155 or other time between frames 155. In some implementations of the invention, point cloud 930 may be referenced to a frame time corresponding to a particular frame 155. Point cloud 930 may be referenced in other manners relative to a particular frame 155 as would be appreciated.

(95) As illustrated in Figure 10, PC_{m-1} is the expression of point cloud 930 referenced at the frame time of frame I_{n-1} ; PC_m is the expression of point cloud 930 referenced at the frame time of frame I_n ; and PC_{m+1} is the expression of point cloud 930 referenced at the frame time of frame I_{n+1} ; and PC_{m+2} is the expression of point cloud 930 referenced at the

frame time of frame I_{n+2} . In some implementations, point cloud 930 may be referenced at other times in relation to the frames and frames times as would be apparent.

(96) As described above, a transformation matrix $T_{i,i+1}$ may be determined to transform an expression of point cloud 930 at the i^{th} frame time to an expression of point cloud 930 at the $(i+1)^{\text{th}}$ frame time. In reference to Figure 10, a transformation matrix $T_{m-1,m}$ may be used to transform PC_{m-1} to PC_m ; a transformation matrix $T_{m,m+1}$ may be used to transform PC_m to PC_{m+1} ; and a transformation matrix $T_{m+1,m+2}$ may be used to transform PC_{m+1} to PC_{m+2} . In this way, transformation matrices may be used to express point clouds 930 at different times corresponding to frames 155.

(97) According to various implementations of the invention, the transformation matrices which are applied to point cloud 930 to express point cloud 930 from a first time to a second time are determined in different processing stages. Generally speaking, transformation matrices are directly related with six degree of motion parameters $\omega_x, \omega_y, \omega_z, v_x^{\text{trans}}, v_y^{\text{trans}},$ and v_z^{trans} that may be calculated in two steps: first $\omega_x, \omega_y,$ and v_z^{trans} from lidar subsystem and second $v_x^{\text{trans}}, v_y^{\text{trans}},$ and ω_z from video subsystem.

(98) Figure 11 illustrates a block diagram of a configuration of processing system 160 that may be used during a first phase of the first processing stage to estimate a trajectory of target 190 according to various implementations of the invention. In some implementations of the invention, during the first phase of the first stage, a series of initial transformation matrices (referred to herein as $T_{i,i+1}^{(0)}$) are determined from various estimates of the motion aspects of target 190. As illustrated, lidar subsystem 130 provides range, Doppler velocity, azimuth, elevation and time for at each point as input to a least squares estimator 1110 that is configured to estimate angular velocities ω_x and ω_y and translational velocity v_z^{trans} over each of a series of time intervals. In some implementations of the invention, angular velocities ω_x and ω_y and translational velocity v_z^{trans} are iteratively estimated by varying the size of the time intervals (or breaking the time intervals into subintervals) as discussed above until any residual errors from least squares estimator 1110 for each particular time interval reach acceptable levels as would

be apparent. This process may be repeated for each successive time interval during the time measurements of target 190 are taken by lidar subsystem 130.

(99) Assuming that target 190 can be represented over a given time interval as a rigid body (i.e., points on the surface of target 190 remain fixed with respect to one another) undergoing ballistic motion (i.e., constant velocity with no acceleration), an instantaneous velocity of any given point 810 on target 190 can be expressed as:

$$\mathbf{v} = \mathbf{v}^{\text{trans}} + [\boldsymbol{\omega} \times (\mathbf{R} - \mathbf{R}_c - \mathbf{v}^{\text{trans}} * \Delta t)] \quad \text{Eq. (1)}$$

where

$\mathbf{v}$ is the instantaneous velocity vector of the given point;
 $\mathbf{v}^{\text{trans}}$ is the translational velocity vector of the rigid body;
 $\boldsymbol{\omega}$ is the rotational velocity vector of the rigid body;
 $\mathbf{R}$ is the position of the given point on the target;
 $\mathbf{R}_c$ is the center of rotation for the target; and
 Δt is the time difference of each measurement time from a given reference time.

(100) Given the measurements available from lidar subsystem 130, the z-component of the instantaneous velocity may be expressed as:

$$v_z = v_z^{\text{trans}} + [\boldsymbol{\omega} \times (\mathbf{R} - \mathbf{R}_c - \mathbf{v}^{\text{trans}} * \Delta t)]_z \quad \text{Eq. (2)}$$

where

v_z is the z-component of the instantaneous velocity vector;
 v_z^{trans} is the z-component of the translational velocity vector; and
 $[\boldsymbol{\omega} \times (\mathbf{R} - \mathbf{R}_c - \mathbf{v}^{\text{trans}} * \Delta t)]_z$ is the z-component of the cross product.

(101) In some implementations of the invention, frame-to-frame measurements corresponding to various features from images 155 may be made. These measurements may correspond to a position (e.g., x^{feat} , y^{feat}) and a velocity (e.g., v_x^{feat} , v_y^{feat}) for each of the features and for each frame-to-frame time interval. In implementations where a z-coordinate of position is not available from video subsystem 150, an initial estimate of z may be made using, for example, an average z component from the points from lidar

subsystem 130. Least squares estimator 1120 estimates angular velocities ω_x , ω_y , and ω_z and translational velocities v_x^{trans} , v_y^{trans} , and v_z^{trans} which may be expressed as a transformation matrix $T_{i,i+1}^{(0)}$ for each of the relevant time intervals. In some implementations of the invention, a cumulative transformation matrix corresponding to the arbitrary frame to frame time interval may be determined.

(102) Figure 12 illustrates a block diagram of a configuration of processing system 160 that may be used during a second phase of the first processing stage to estimate a trajectory of target 190 according to various implementations of the invention. In some implementations of the invention, during the second phase of the first stage, new transformation matrices (referred to herein as $T_{i,i+1}^{(1)}$) are determined from various estimates of the motion aspects of target 190. As illustrated, measurements from lidar subsystem 130 of range, Doppler velocity, azimuth, elevation and time for at each of the N points are input to a least squares estimator 1110 of processing system 160 along with the transformation matrices $T_{i,i+1}^{(0)}$ to estimate angular velocities ω_x and ω_y and translational velocity v_z^{trans} over each of a series of time intervals in a manner similar to that described above during the first phase.

(103) The primary difference between the second phase and the first phase is that least squares estimator 1120 uses the calculated z position of the features based on $T_{i,i+1}^{(0)}$ as opposed to merely an average of z position. Least squares estimator 1120 estimates new angular velocities ω_x , ω_y , and ω_z and new translational velocities v_x^{trans} , v_y^{trans} , and v_z^{trans} which may be expressed as a transformation matrix $T_{i,i+1}^{(1)}$ for each of the relevant time intervals. Again, in some implementations of the invention, a cumulative transformation matrix corresponding to the frame to frame time interval may be determined.

(104) Figure 13 illustrates a block diagram of a configuration of processing system 160 that may be used during a third phase of the first processing stage to estimate a trajectory of target 190 according to various implementations of the invention. In some implementations of the invention, during the third phase of the first stage, new transformation matrices (referred to herein as $T_{i,i+1}^{(2)}$) are determined from various

estimates of the motion aspects of target 190. As illustrated, lidar subsystem 130 provides range, Doppler velocity, azimuth, elevation and time for at each of the points as input to a least squares estimator 1110 to estimate angular velocities ω_x and ω_y and translational velocity v_z^{trans} over each of a series of time intervals in a manner similar to that described above during the first phase. In this phase, calculated values of v_x and v_y for each point based on $T_{i,i+1}^{(1)}$ as determined during the prior phase are input into least squares estimator 1120 as opposed to the feature measurements used above.

(105) The primary difference between the third phase and the second phase is that least squares estimator 1120 uses $T_{i,i+1}^{(1)}$ to describe motion between the relevant frames 155. Least squares estimators 1110, 1120 estimate new angular velocities ω_x , ω_y , and ω_z and new translational velocities v_x^{trans} , v_y^{trans} , and v_z^{trans} which may be expressed as a transformation matrix $T_{i,i+1}^{(2)}$ for each of the relevant time intervals. Again, in some implementations of the invention, a cumulative transformation matrix corresponding to the frame to frame time interval may be determined.

(106) In various implementations of the invention, any of the phases of the first processing stage may be iterated any number of times as additional information is gained regarding motion of target 190. For example, as the transformation matrices are improved, each point 810 may be better expressed at a given reference time in relation to its measurement time.

(107) During the first processing stage, the translational velocities of each point (not otherwise available from the lidar measurements) may be estimated using features from the frames 155. Once all velocity components are known or estimated for each point, transformation matrices may be determined without using the feature measurements as illustrated in Figure 13.

(108) Figure 14 illustrates a block diagram of a configuration of processing system 160 that may be used during a first phase of the second processing stage to refine a trajectory of target 190 according to various implementations of the invention. The first processing stage provides transformation matrices sufficient to enable images 155 to be mapped onto point clouds 830 at each of the respective frame times. Once so mapped,

differences in pixels themselves (as opposed to features in images 155) from consecutive images 155 may be used to further refine the trajectory of target 190. In some implementations of the invention, during the first phase of the second processing stage, a series of new transformation matrices (referred to herein as $T_{i,j+1}^{(3)}$) are refinements of $T_{i,j+1}^{(2)}$ on the basis of the offsets between image I_i and an image I_j namely, Δx_{ij} , Δy_{ij} , $\Delta \theta z_{ij}$. As illustrated, an estimator 1410 determines a difference between an image I_i and an image using the appropriate transformation matrix $T_{i,j}^{(2)}$ to express the images at the same frame time.

(109) Figure 15 illustrates a block diagram of a configuration of processing system 160 that may be used during a second phase of the second processing stage to further refine a trajectory of target 190 according to various implementations of the invention. To the extent that additional accuracy is necessary, the transformation matrices from the first phase of the second processing stage (e.g., $T_{i,j+1}^{(3)}$) may be used in connection with the measurements from lidar subsystem 130 to further refine the transformation matrices (referred to herein as $T_{i,j+1}^{(4)}$). In some implementations of the invention, during this phase, measurements from lidar subsystem 130 that occur within any overlap regions 360, 450 are used. These measurements correspond to multiple measurements taken for the same point (or substantially the same point) at different times. This phase is based on the premise that coordinate measurements of the same point on target 190 taken different times should transform precisely to one another with a perfect transformation matrix. In other words, the coordinates of the underlying points should directly map to one another at the different points in time. The differences (i.e., corrections) between the measurements may be expressed as Δz_{ij} , $\Delta \theta x_{ij}$, and $\Delta \theta y_{ij}$, input into least squares estimator 1510, refining the transform matrices $T_{i,j+1}^{(3)}$ to $T_{i,j+1}^{(4)}$. In some implementations of the invention, multiple measurements corresponding to use of an overscan beam may be used in a similar manner.

(110) While illustrative embodiments of the invention have been described and illustrated herein in terms of various implementations, the invention is not so limited and is limited only by the scope of the following claims, as would be apparent to one skilled in the art. These and other implementations of the invention will become apparent upon consideration of the disclosure provided above and the

accompanying figures. In addition, various components and features described with respect to one implementation of the invention may be used in other implementations as well.

THE SUBJECT-MATTER OF THE INVENTION FOR WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED IS DEFINED AS FOLLOWS:

1. A system for generating a three-dimensional image of a target from lidar measurements and video images, the system comprising:
 - a lidar subsystem that directs at least two beams toward the target and that generates a range measurement and a Doppler velocity measurement for each of a plurality of points on the target for each of the at least two beams;
 - a video subsystem that provides a plurality of two-dimensional images of the target;
 - and
 - a processor that:
 - receives, from the lidar subsystem, the range measurement and the Doppler velocity measurement for each of the plurality of points on the target,
 - receives, from the video subsystem, the plurality of images of the target,
 - estimates a translational velocity component v_z^{trans} and angular velocity components ω_x and ω_y for each of the plurality of points on the target from the range measurements and the Doppler velocity measurements from the lidar subsystem,
 - estimates translational velocity components v_x^{trans} and v_y^{trans} and the angular velocity component ω_z for each of the plurality of points on the target from two-dimensional position and velocity measurements of at least one feature of the target obtained from the plurality of images of the target and from the estimated velocity component v_z^{trans} and the estimated angular velocity components ω_x and ω_y , and
 - generates the three-dimensional image of the target using the estimated translational velocity components v_x^{trans} , v_y^{trans} , and v_z^{trans} and the estimated angular velocity components ω_x , ω_y and ω_z .
2. The system of claim 1, wherein the processor estimates the translational velocity component v_z^{trans} and the angular velocity components ω_x and ω_y using a least squares estimator.

3. The system of claim 1, wherein the lidar subsystem directs at least four beams toward a target and generates a range measurement and a Doppler velocity measurement for each of a plurality of points on the target for each of the at least four beams.
4. The system of claim 1, wherein the at least two beams are displaced from one another by a known distance or angle.
5. The system of claim 3, wherein at least two of the at least four beams are displaced from one another by a known distance or angle along a first axis and wherein at least two of the at least four beams are displaced from one another by a known distance or angle along a second axis.
6. The system of claim 5, wherein the first axis and the second axis are orthogonal to one another.
7. A method for generating a three-dimensional image of a target from lidar measurements from a lidar subsystem and video images from a video subsystem, the system comprising:
 - receiving, from the lidar subsystem, a range measurement and a Doppler velocity measurement for each of a plurality of points on the target for each of at least two beams of the lidar subsystem;
 - receiving, from the video subsystem, a plurality of two-dimensional images of the target;
 - estimating a translational velocity component v_z^{trans} and angular velocity components ω_x and ω_y for each of the plurality of points on the target from the range measurements and the Doppler velocity measurements from the lidar subsystem;
 - estimating translational velocity components v_x^{trans} and v_y^{trans} and the angular velocity component ω_z for each of the plurality of points on the target from two-dimensional position and velocity measurements of at least one feature of the target obtained from the plurality of images of the target and from the estimated velocity component v_z^{trans} and the estimated angular velocity components ω_x and ω_y ; and
 - generating the three-dimensional image of the target using the estimated translational

velocity components v_x^{trans} , v_y^{trans} , and v_z^{trans} and the estimated angular velocity components ω_x , ω_y and ω_z .

8. The method of claim 7, wherein receiving, from the lidar subsystem, a range measurement and a Doppler velocity measurement for each of a plurality of points on the target for each of at least two beams of the lidar subsystem comprises receiving, from the lidar subsystem, a range measurement and a Doppler velocity measurement for each of a plurality of points on the target for each of at least four beams of the lidar subsystem.

9. The method of claim 7, further comprising:
directing the at least two beams toward the target; and
generating a range measurement and a Doppler velocity measurement for each of a plurality of points on the target for each of the at least two beams.

10. The method of claim 9, wherein directing the at least two beams toward the target comprises directing at least four beams toward the target,
wherein generating a range measurement and a Doppler velocity measurement for each of a plurality of points on the target for each of the at least two beams comprises generating a range measurement and a Doppler velocity measurement for each of a plurality of points on the target for each of the at least four beams.

11. The method of claim 7, wherein the at least two beams are displaced from one another by a known distance or angle.

12. The method of claim 10, wherein at least two of the at least four beams are displaced from one another by a known distance or angle along a first axis and wherein at least two of the at least four beams are displaced from one another by a known distance or angle along a second axis.

13. The method of claim 12, wherein the first axis and the second axis are orthogonal to one another.

Replacement Sheet

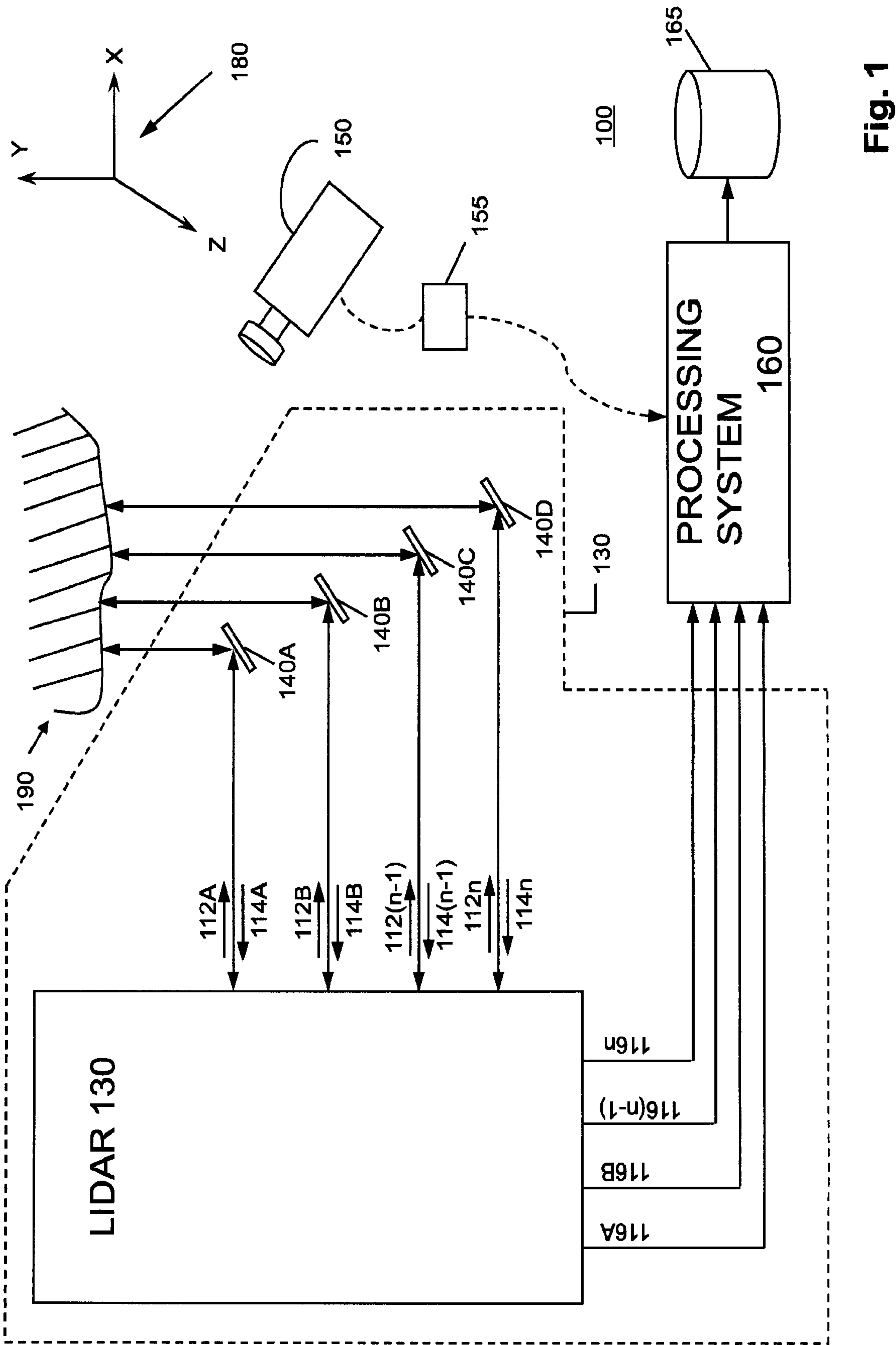


Fig. 1

Replacement Sheet

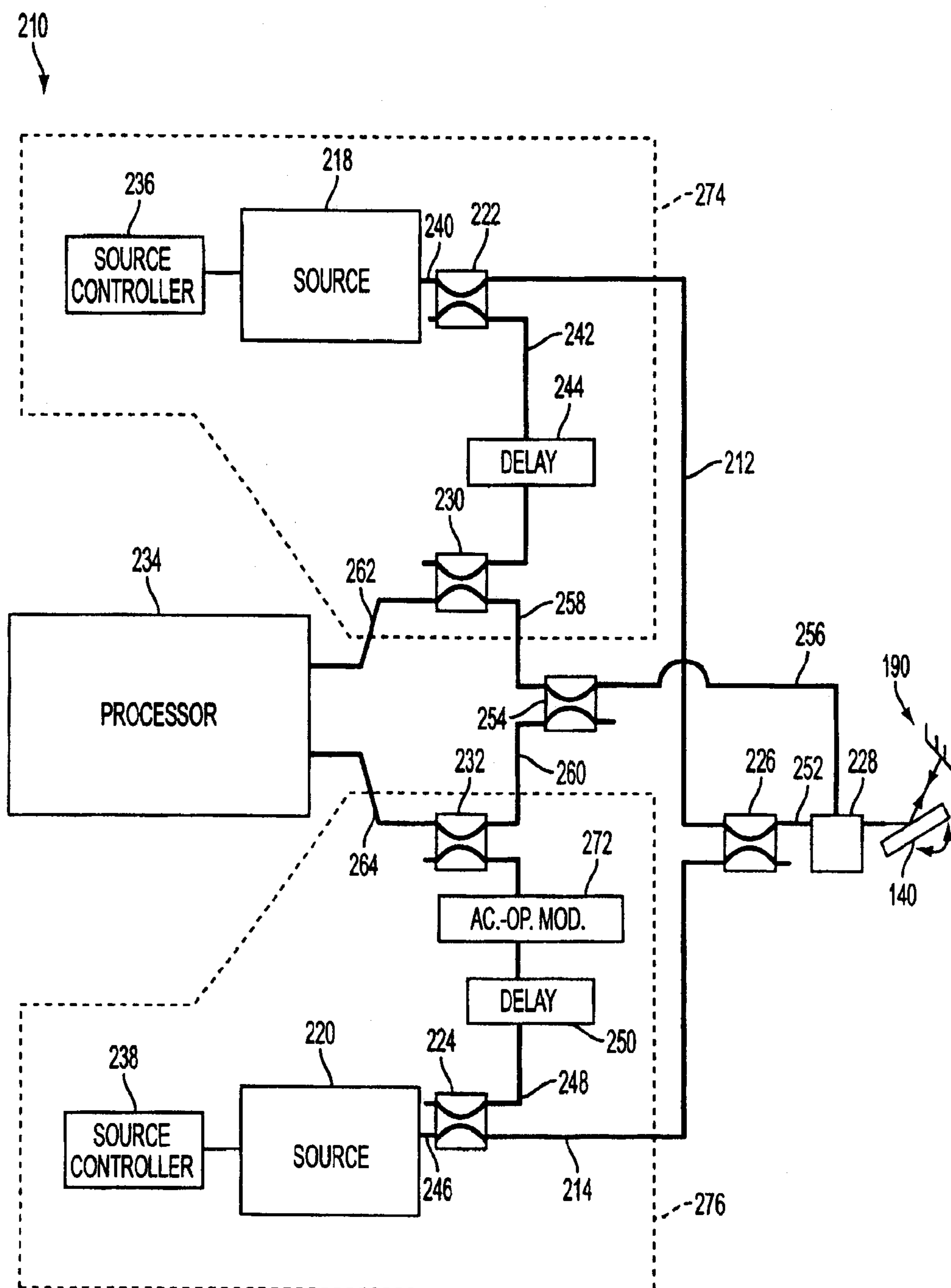


FIG. 2

Replacement Sheet

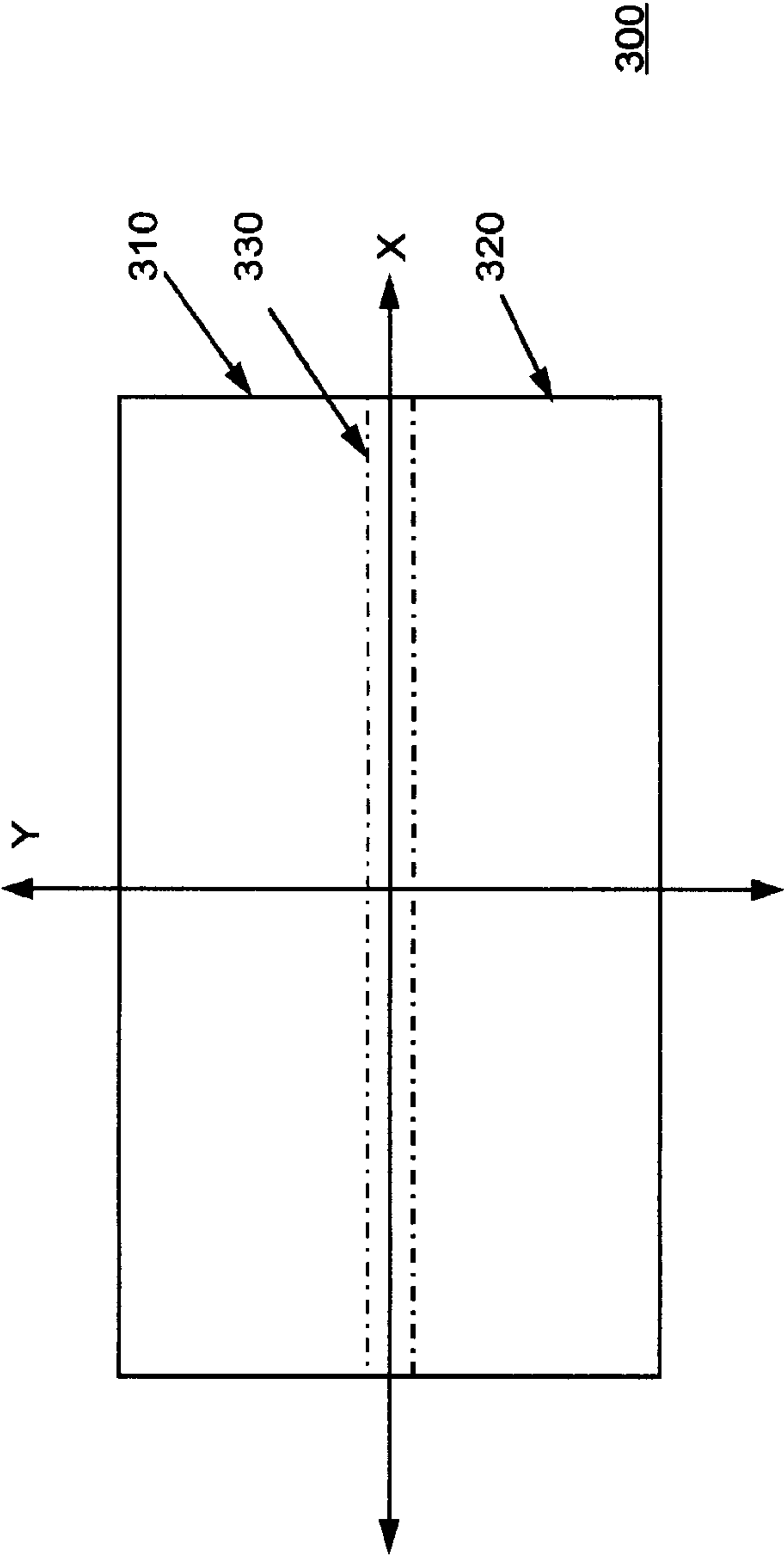


Fig. 3

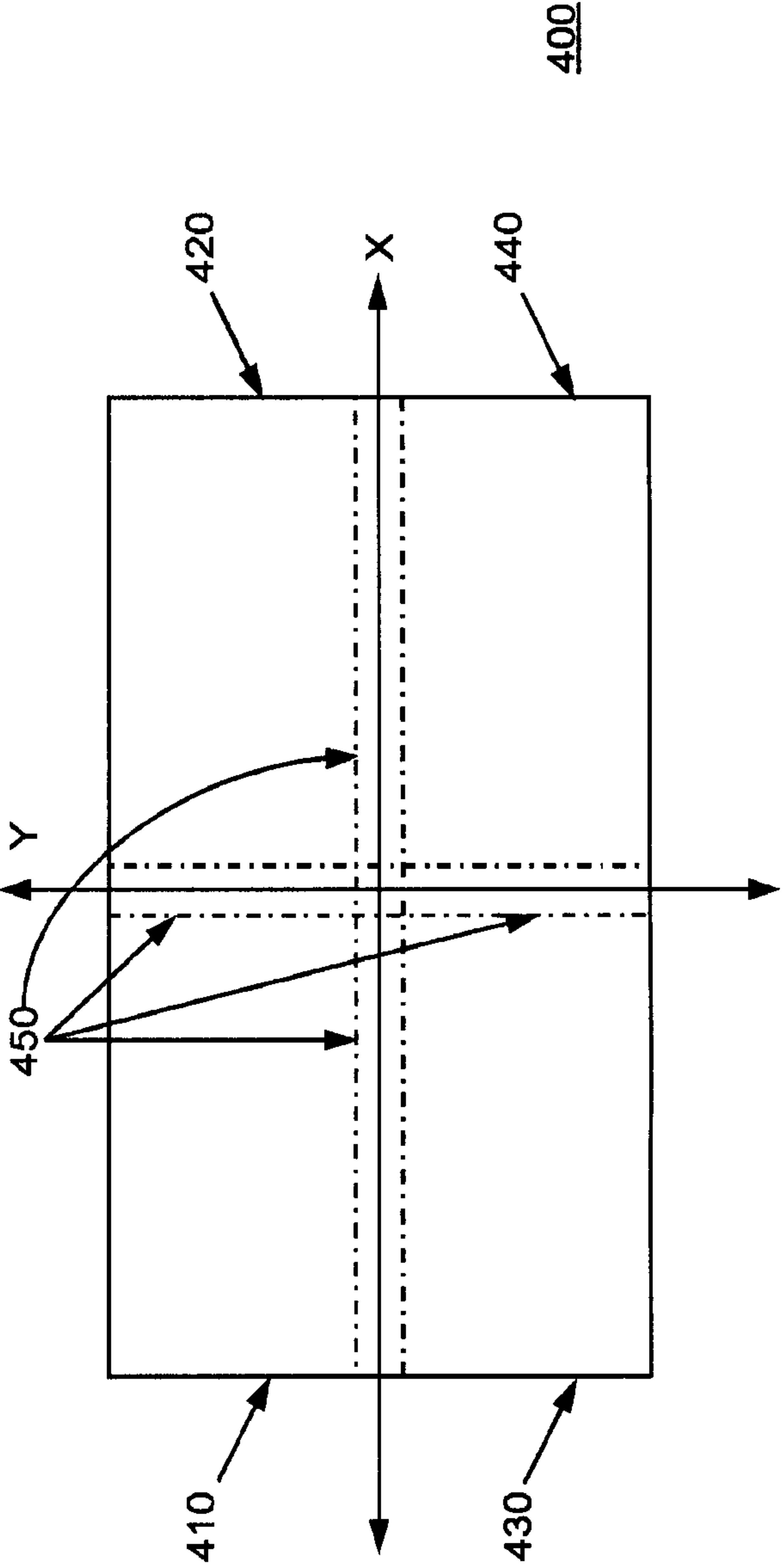
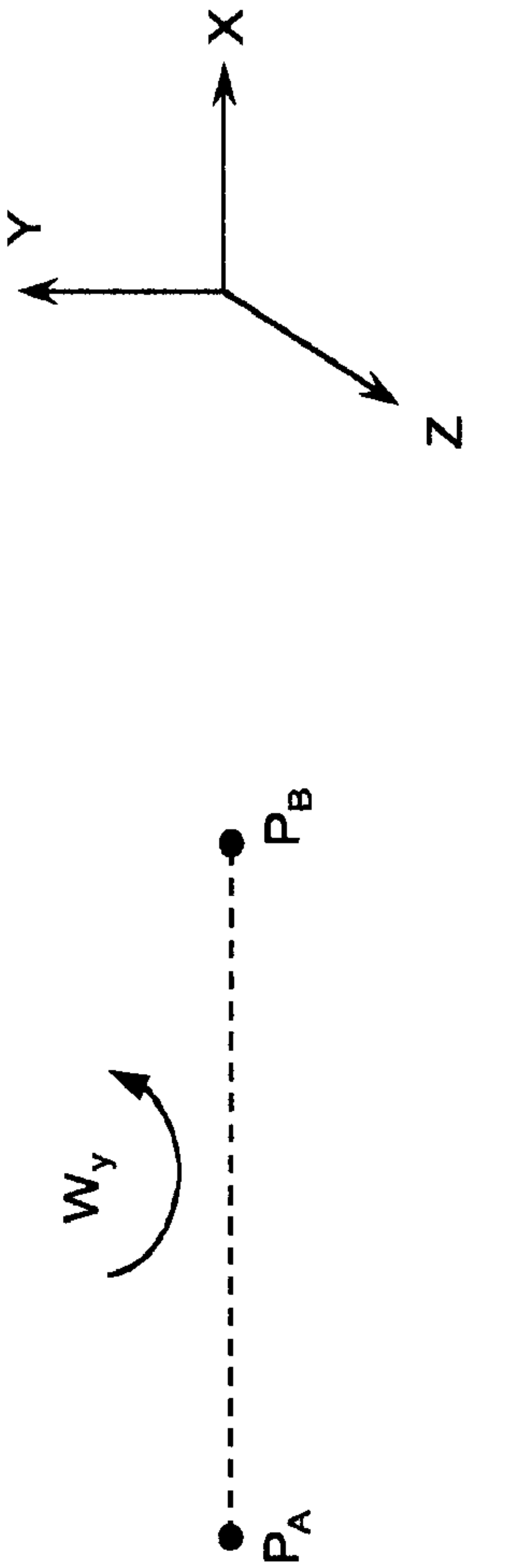
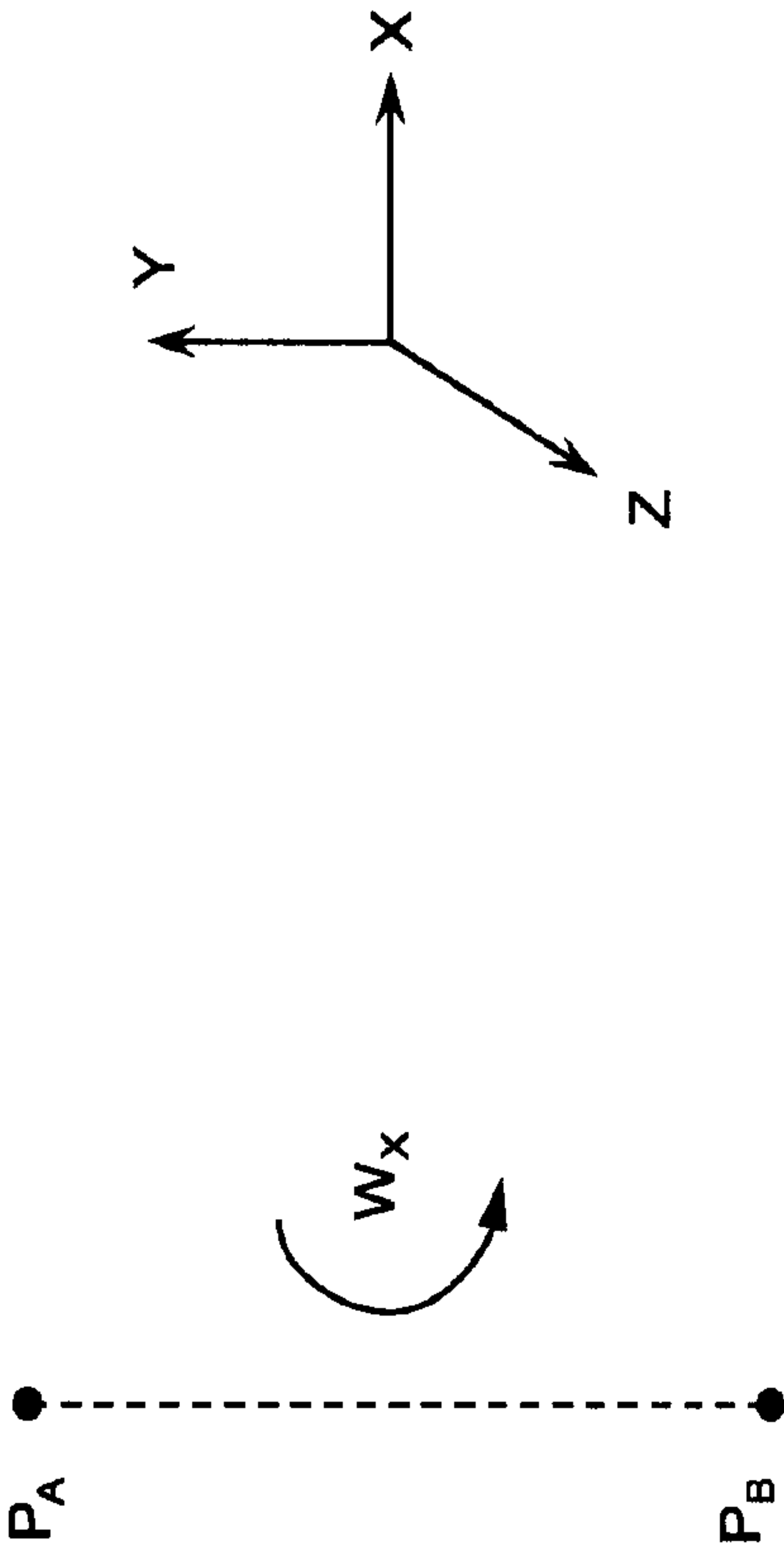


Fig. 4

Replacement Sheet



Replacement Sheet

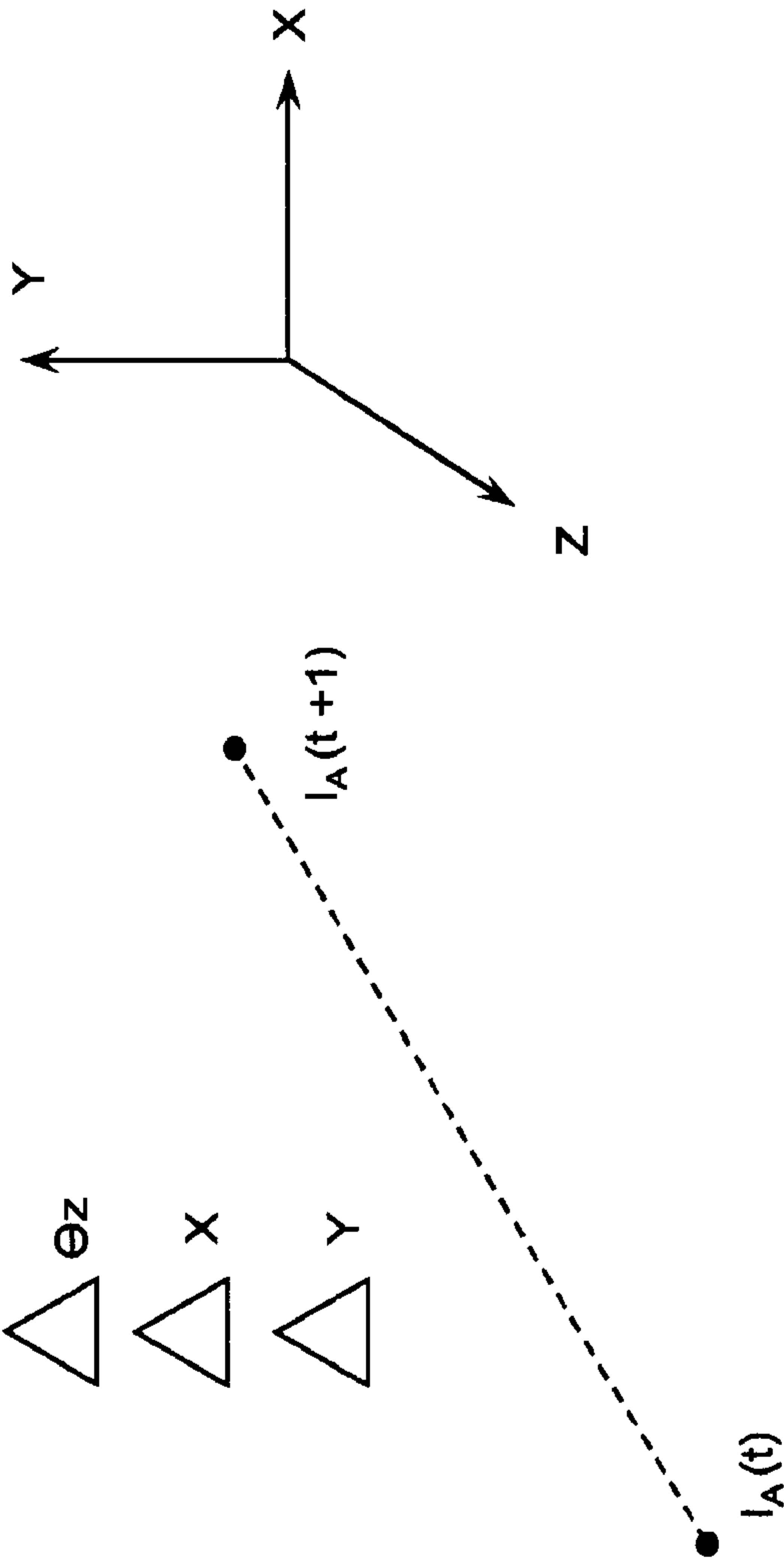


Fig. 7

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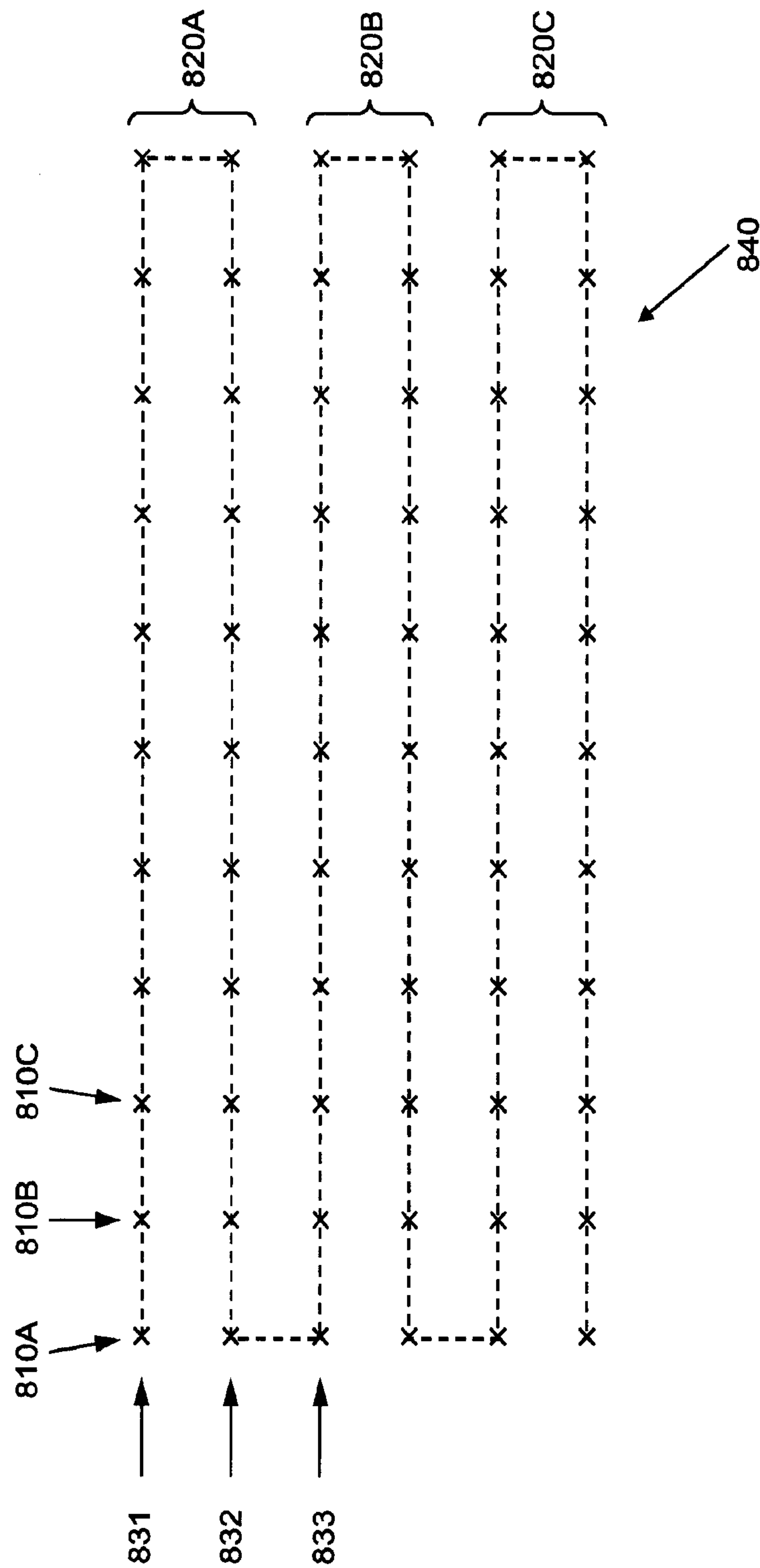


Fig. 8

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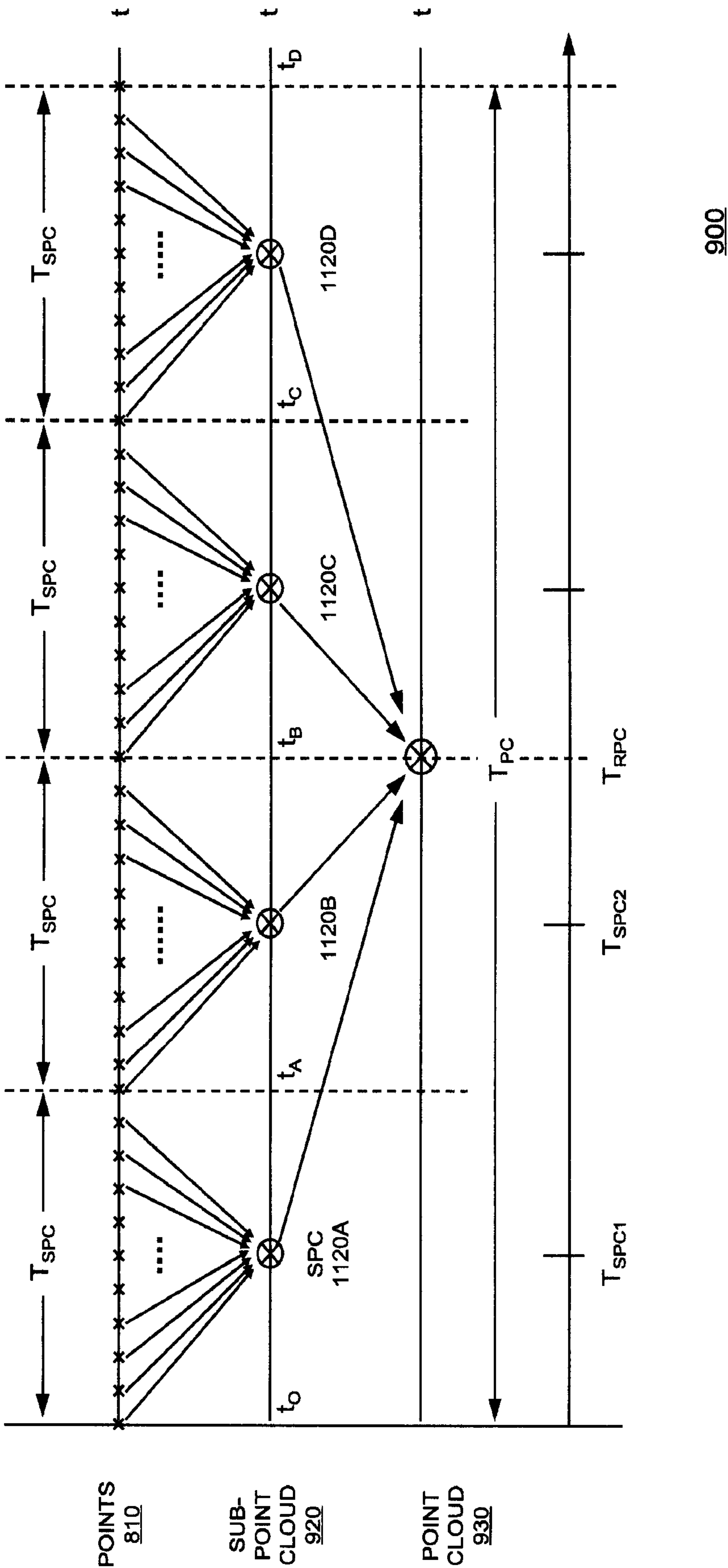
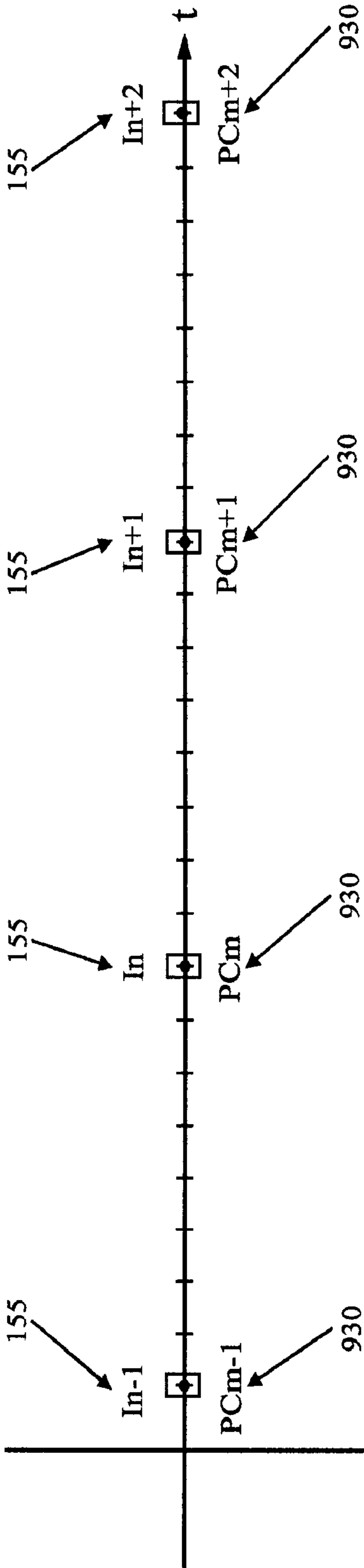


Fig. 9

Replacement Sheet



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Fig. 10

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STAGE 1 – PHASE 1

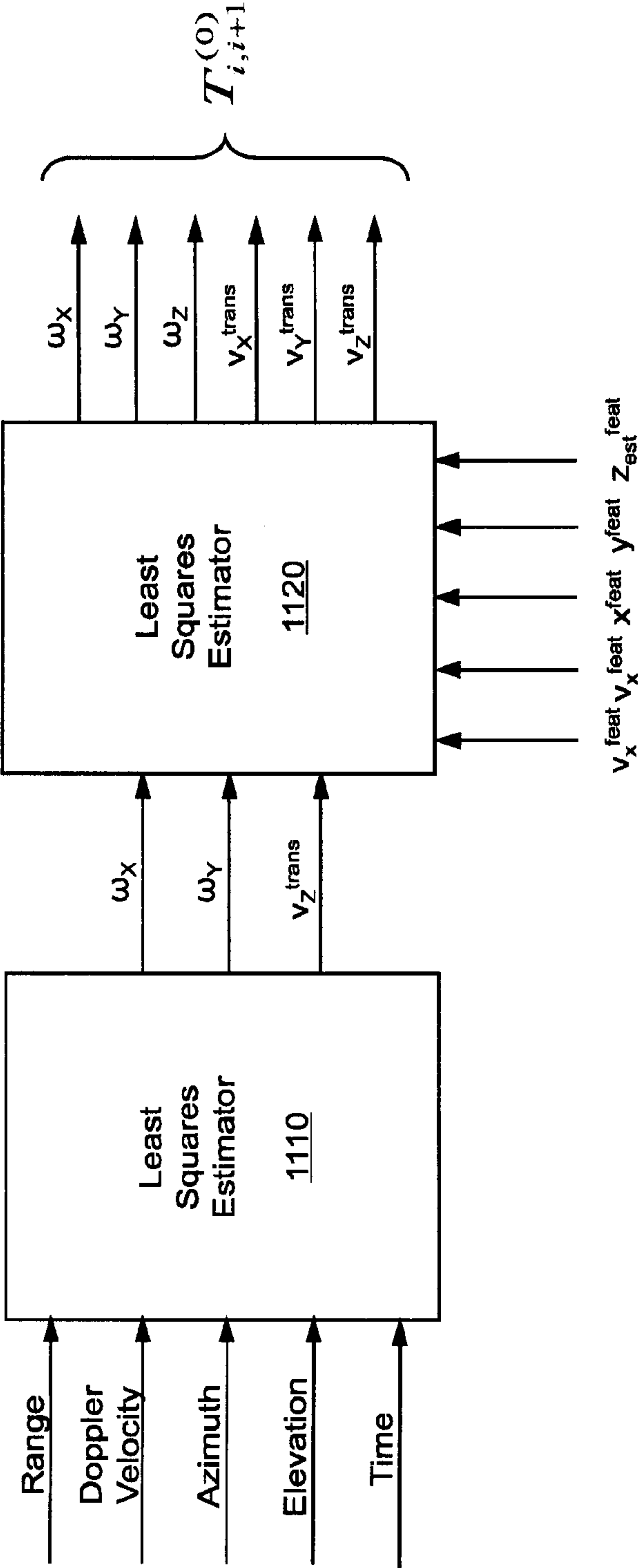


Fig. 11

Replacement Sheet

STAGE 1 – PHASE 2

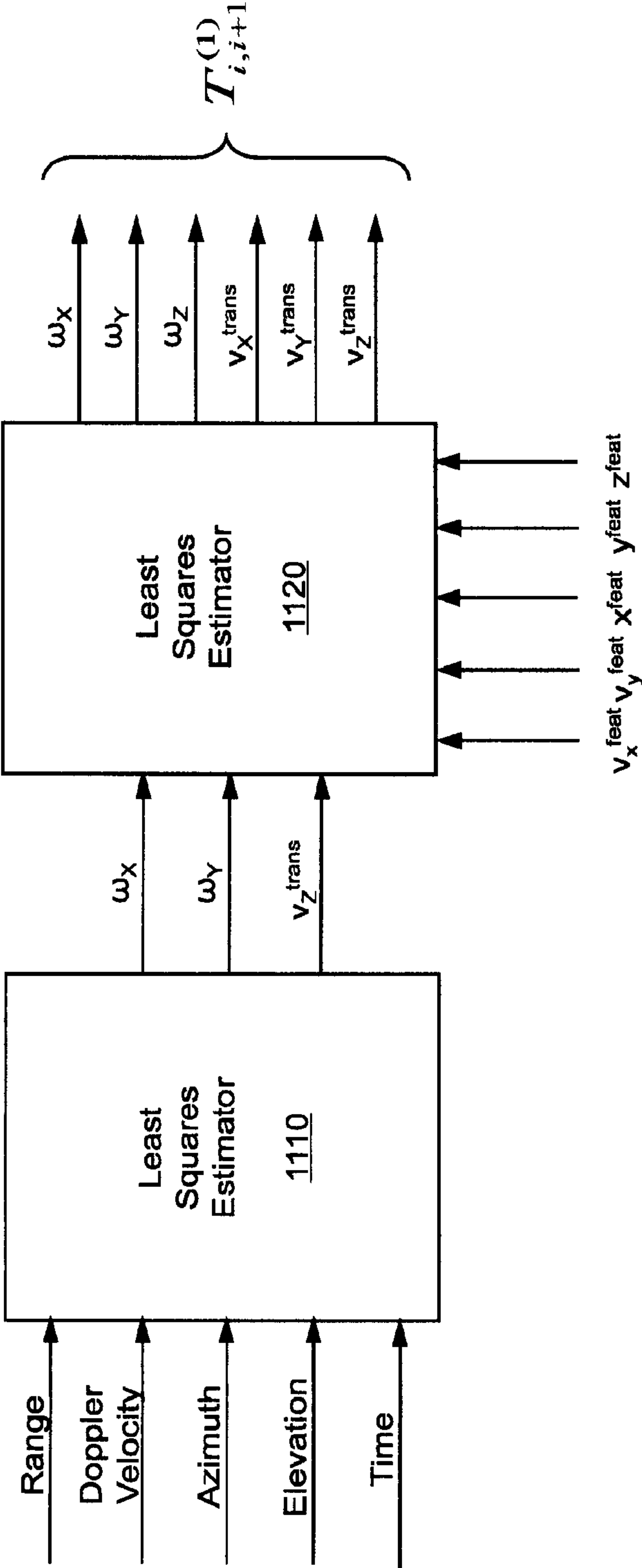


Fig. 12

Replacement Sheet

STAGE 1 – PHASE 3

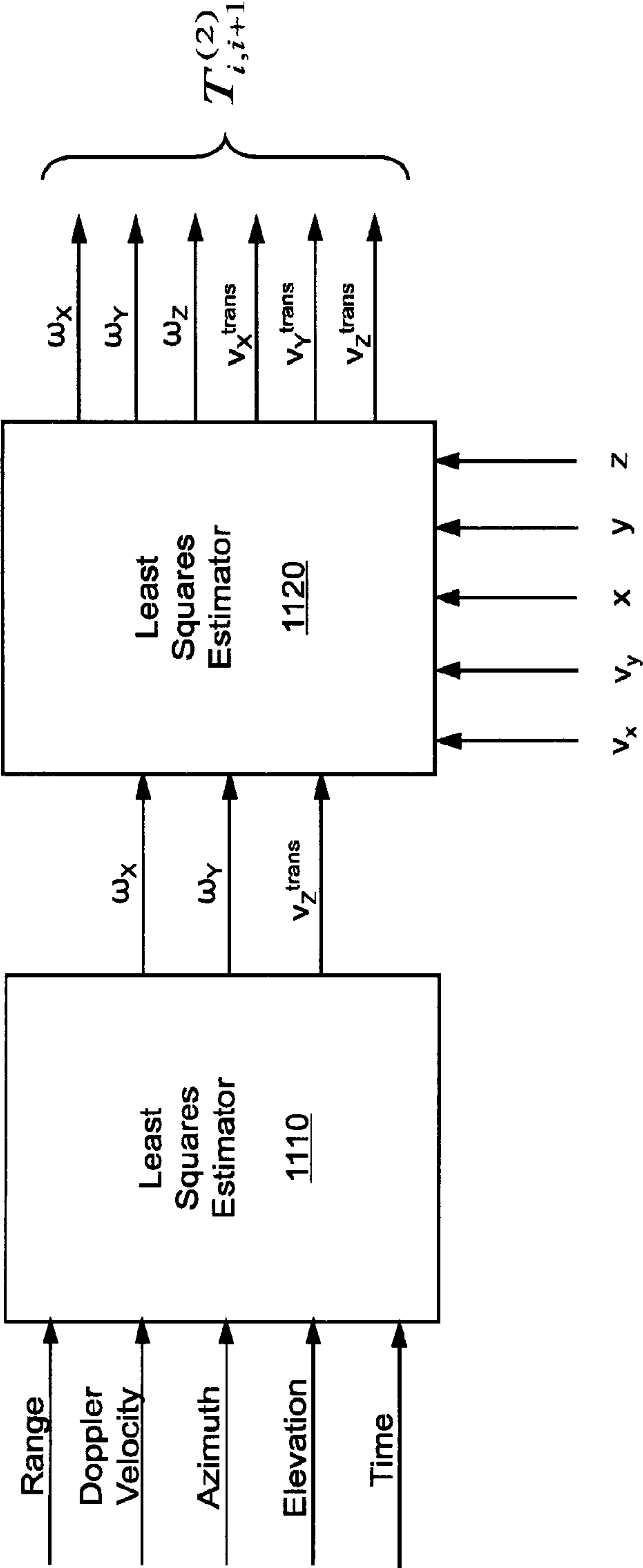


Fig. 13

Replacement Sheet

STAGE 2 – PHASE 1

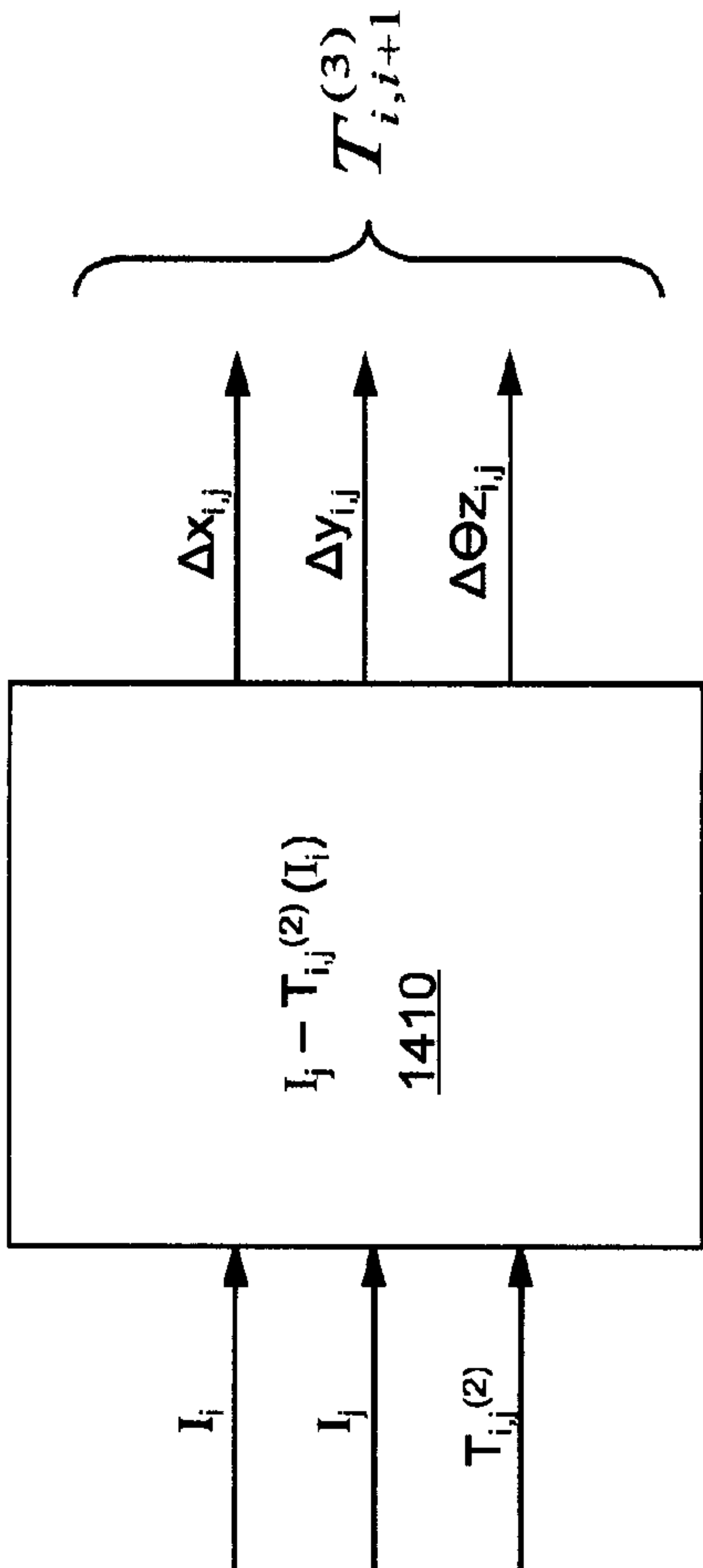


Fig. 14

Replacement Sheet

STAGE 2 – PHASE 2

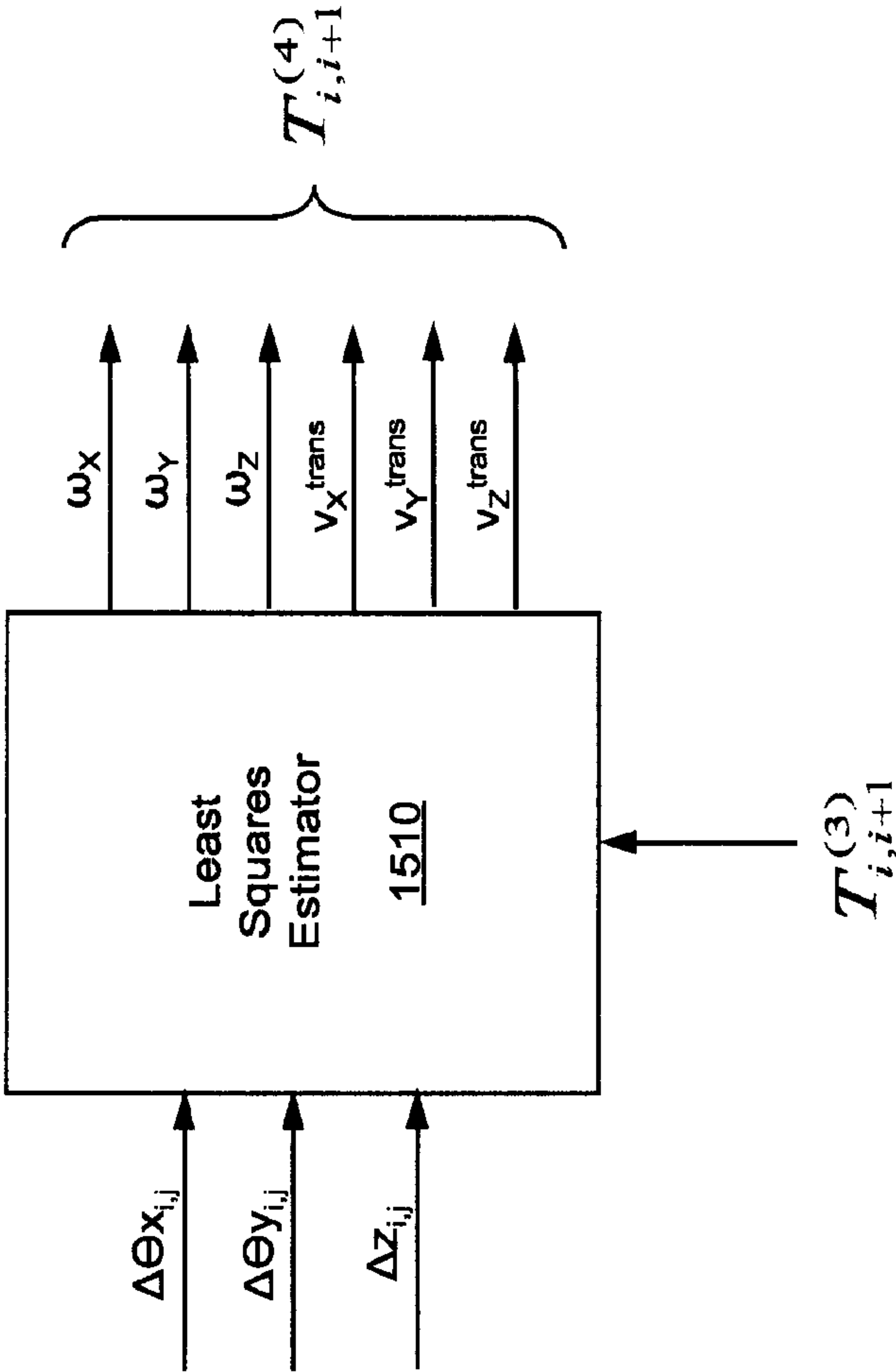


Fig. 15

