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(54) CAMERA-BASED HELIOSTAT TRACKING CONTROLLER

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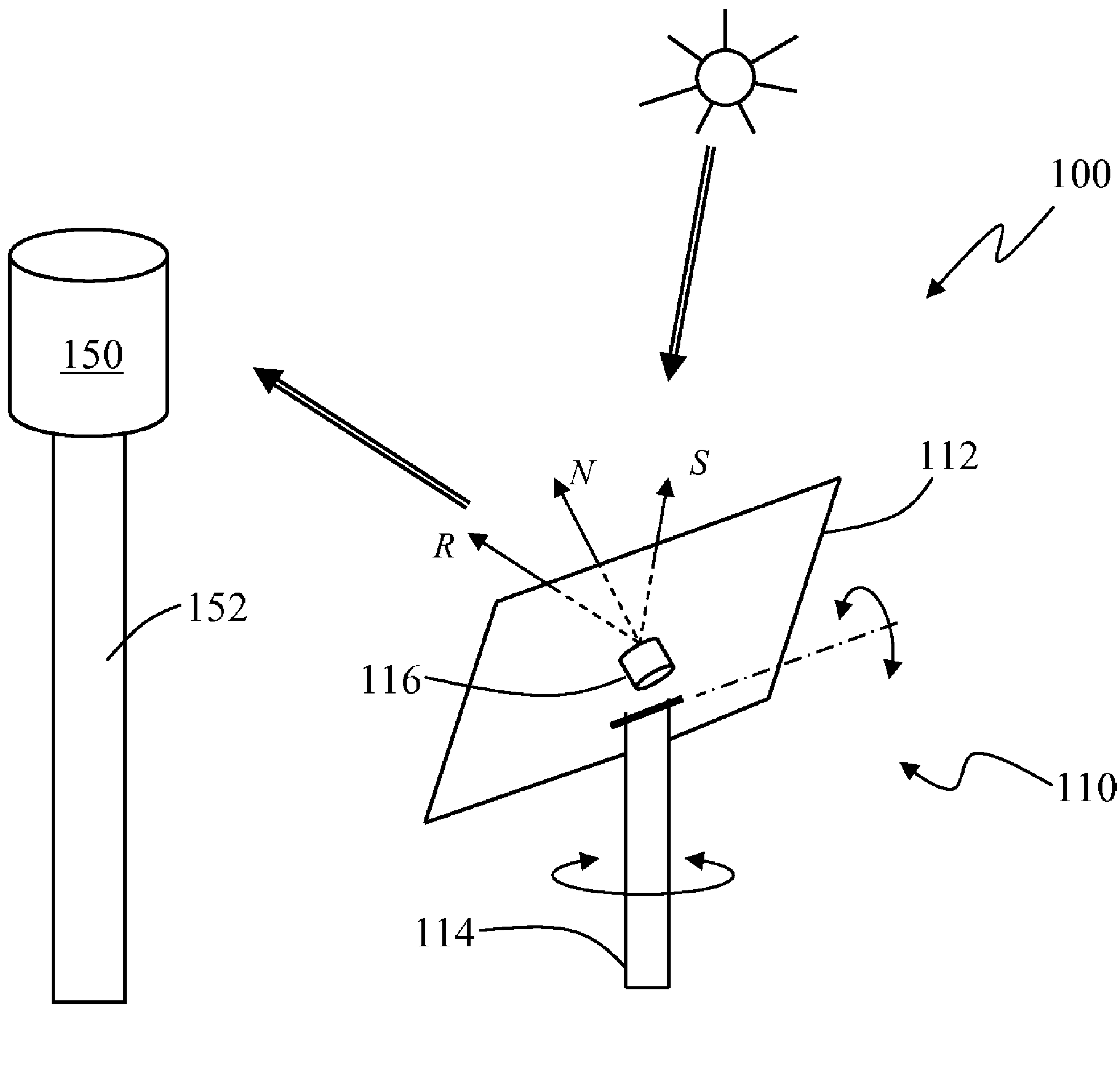
(57) ABSTRACT

Systems and methods for a heliostat directing incident sun light to a receiver based on an estimate or predicted receiver location and an imaged sun location



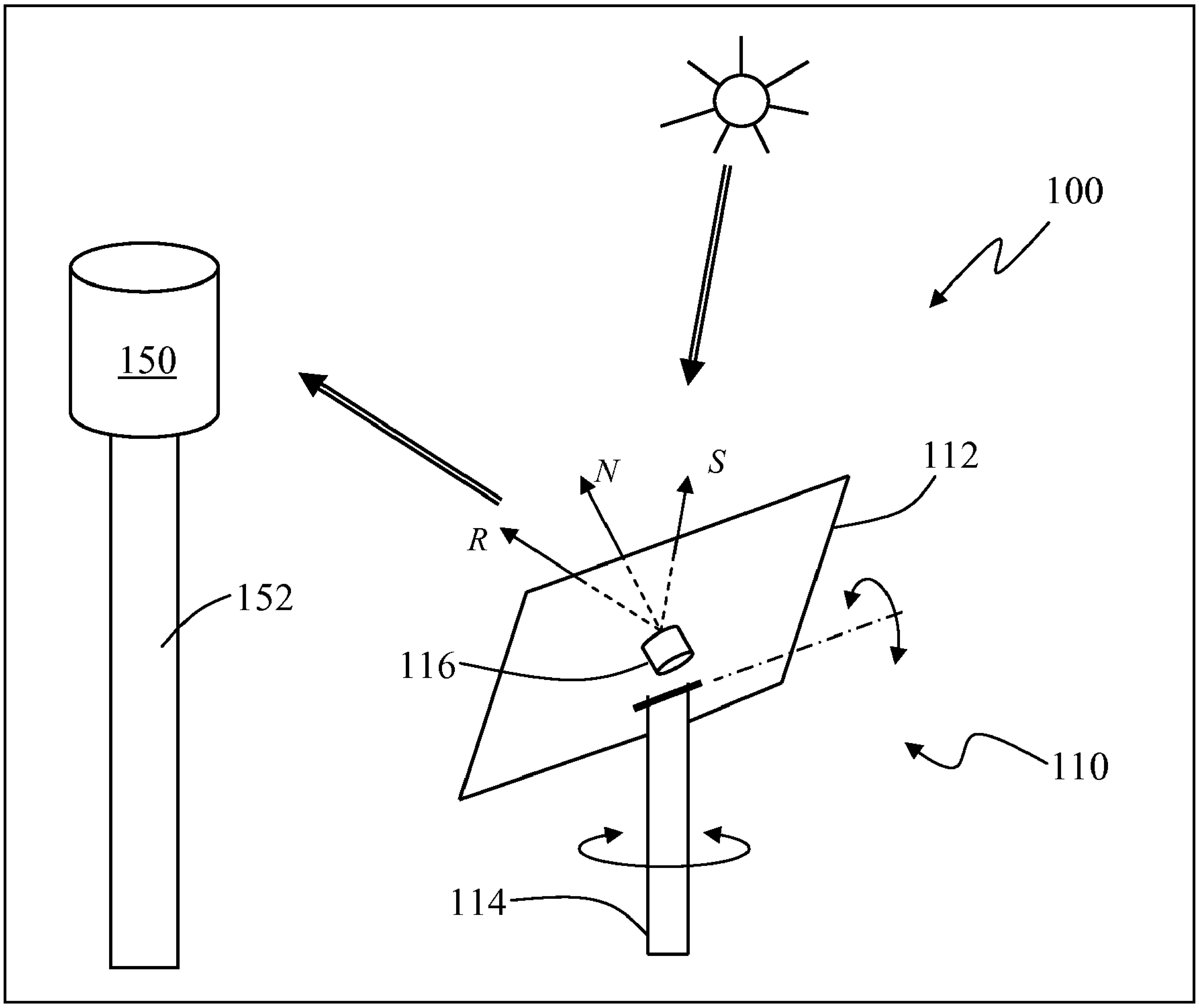


FIG. 1A

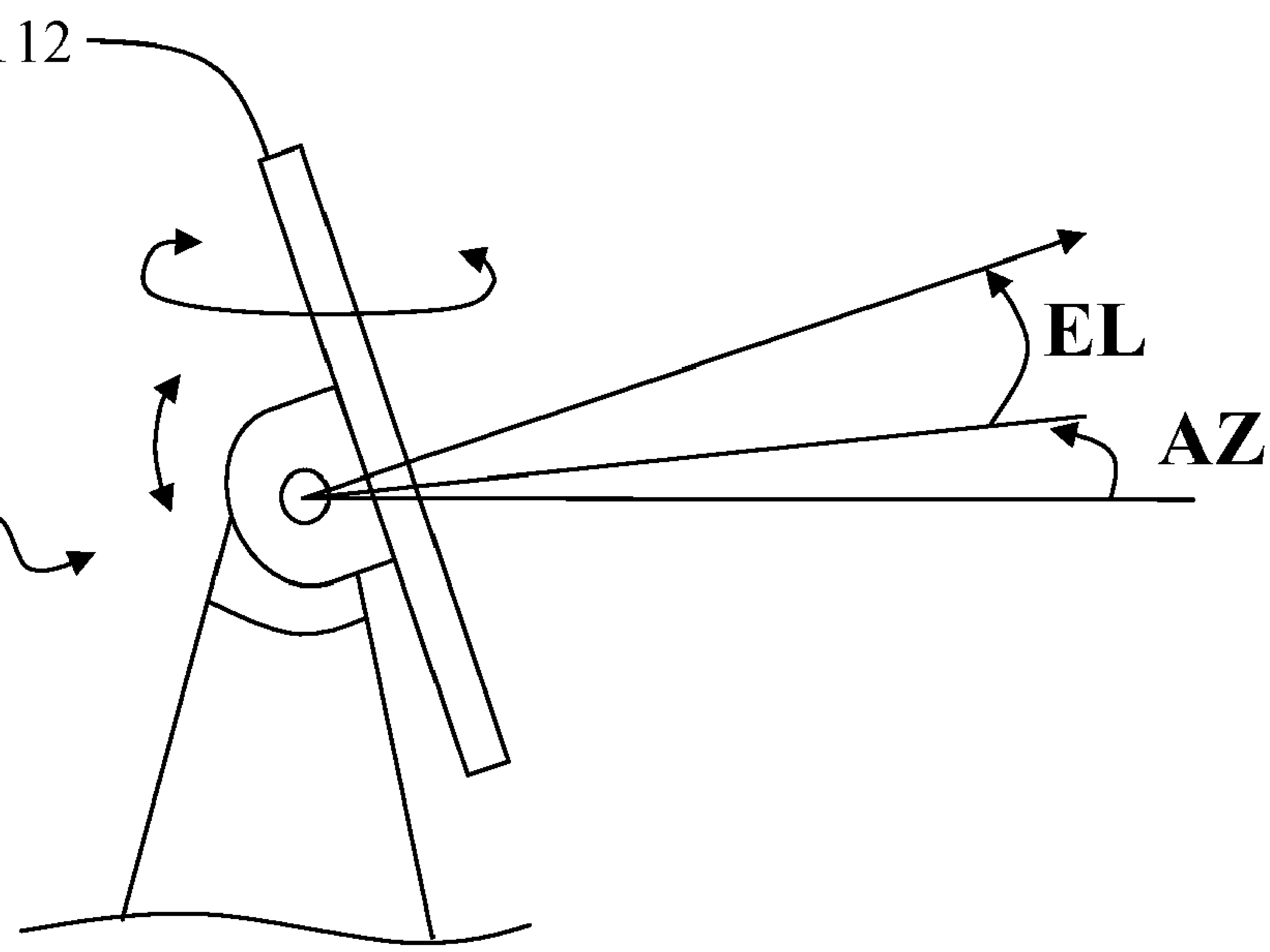


FIG. 1B

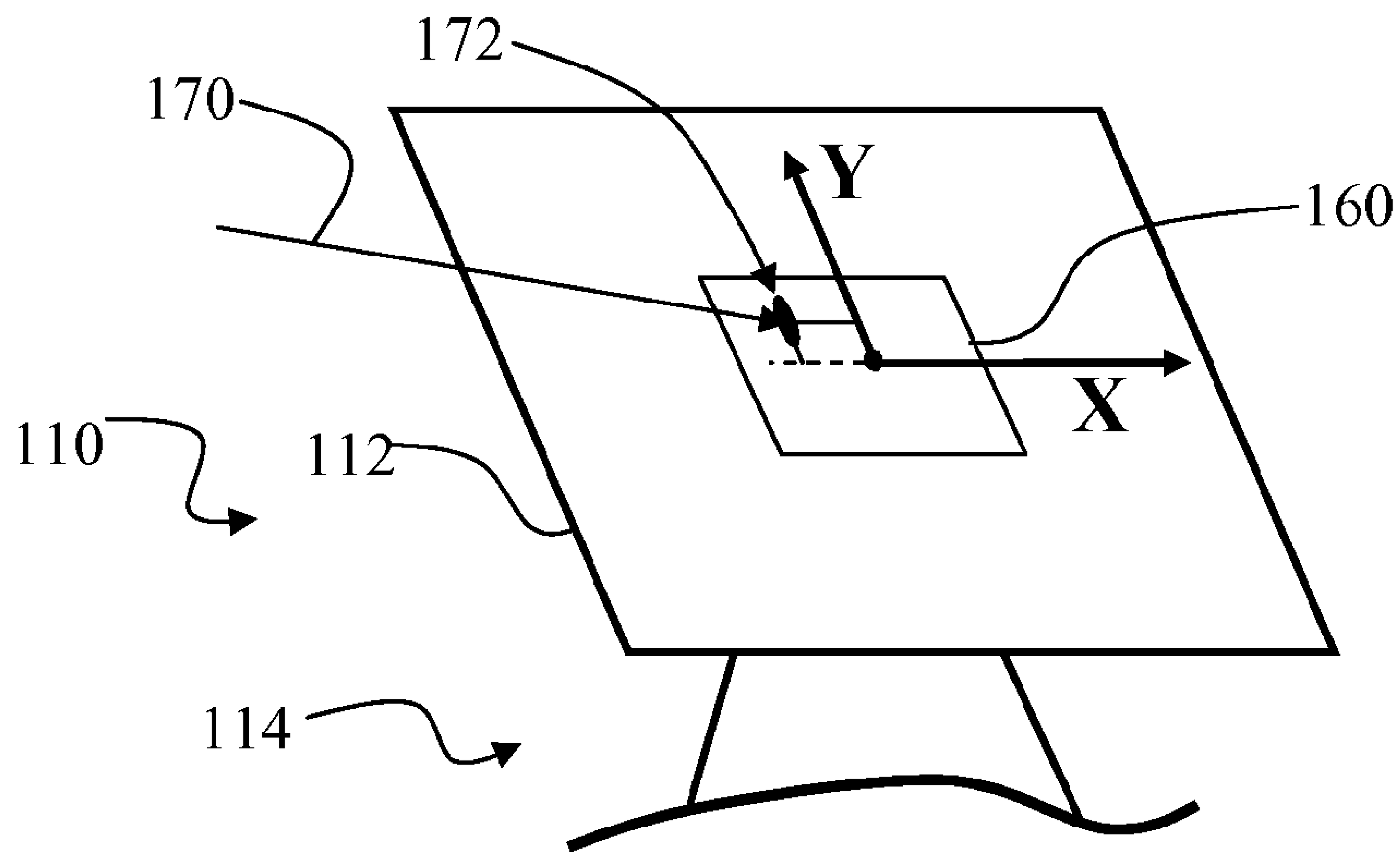


FIG. 1C

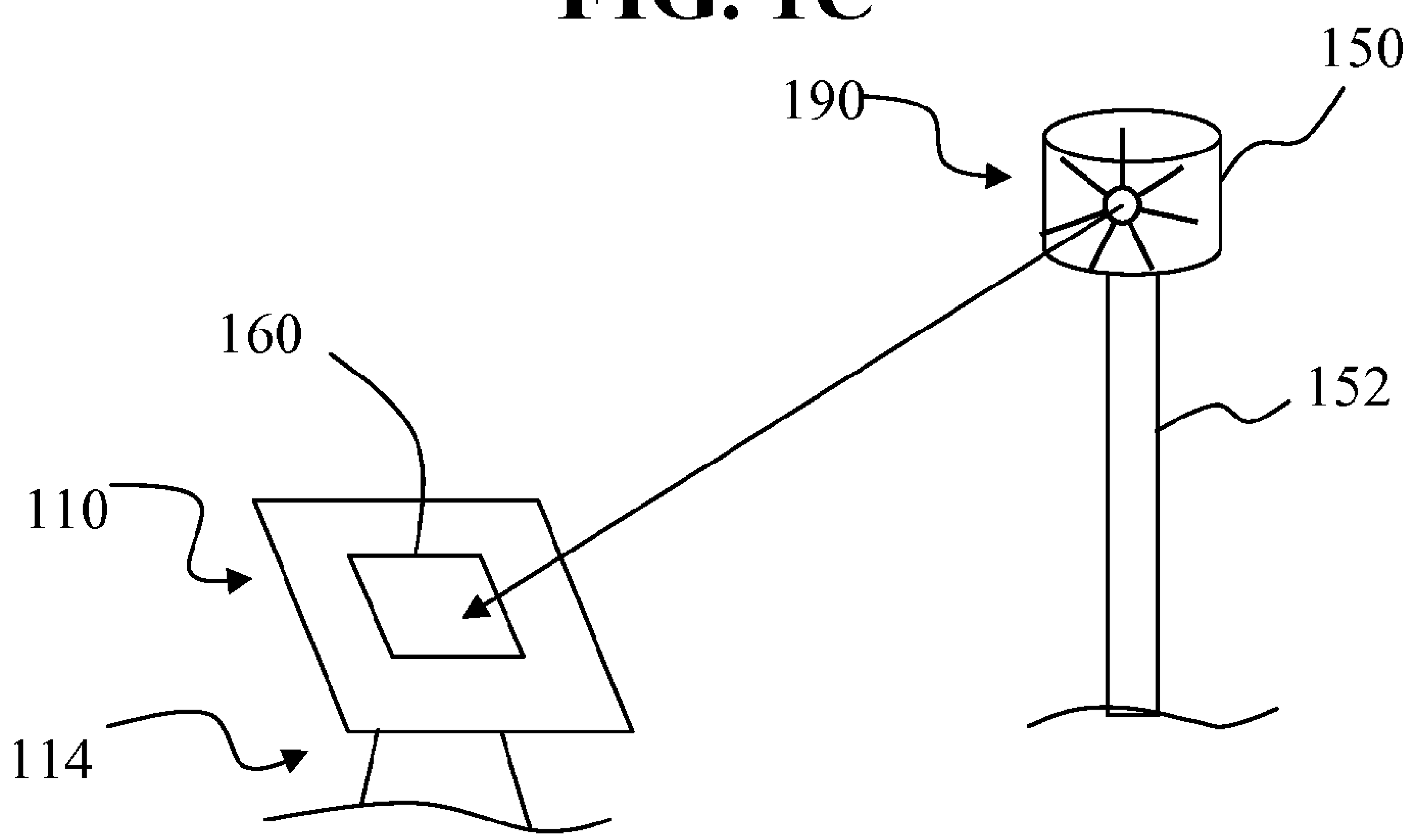


FIG. 1D

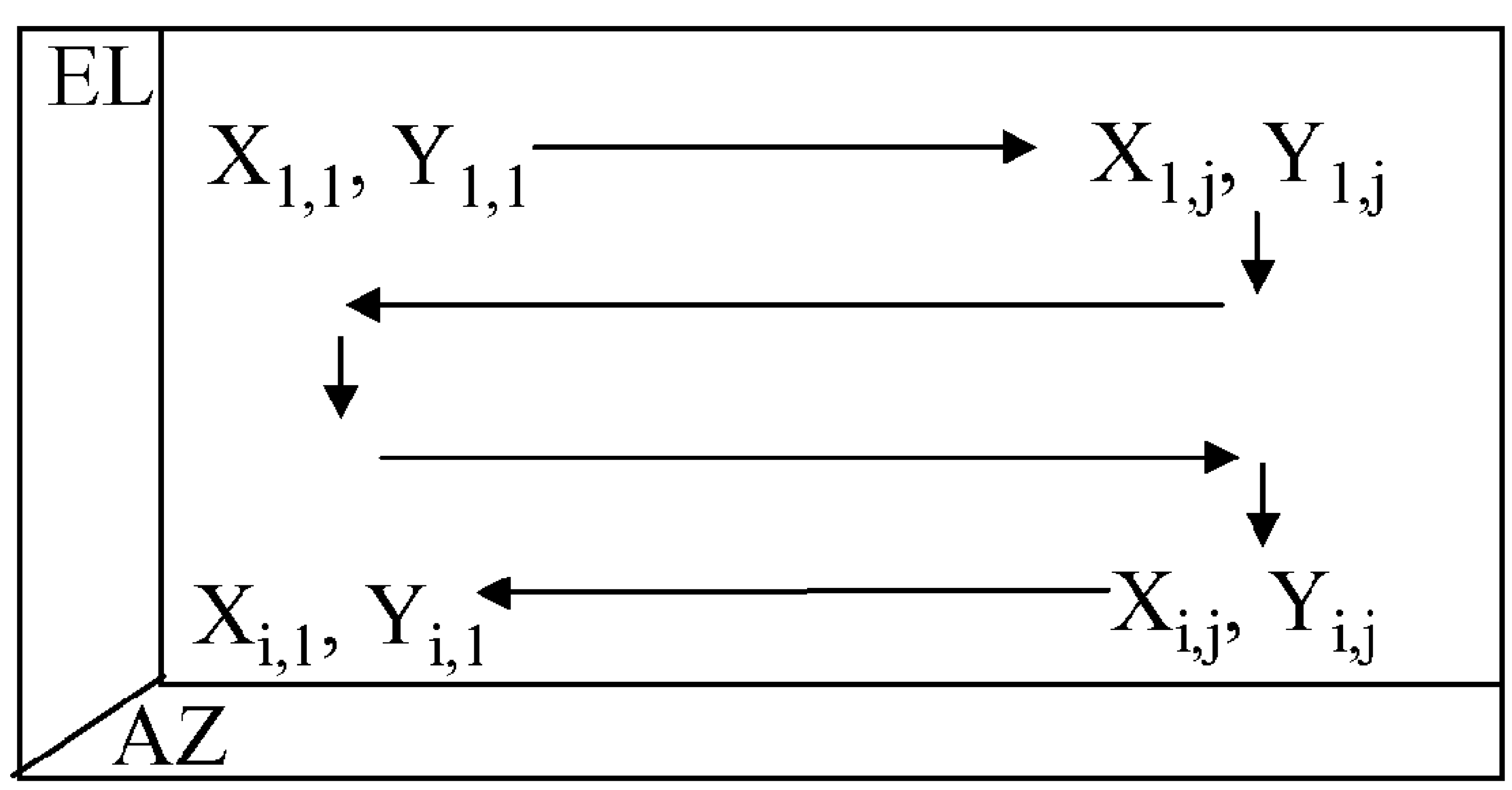


FIG. 1E

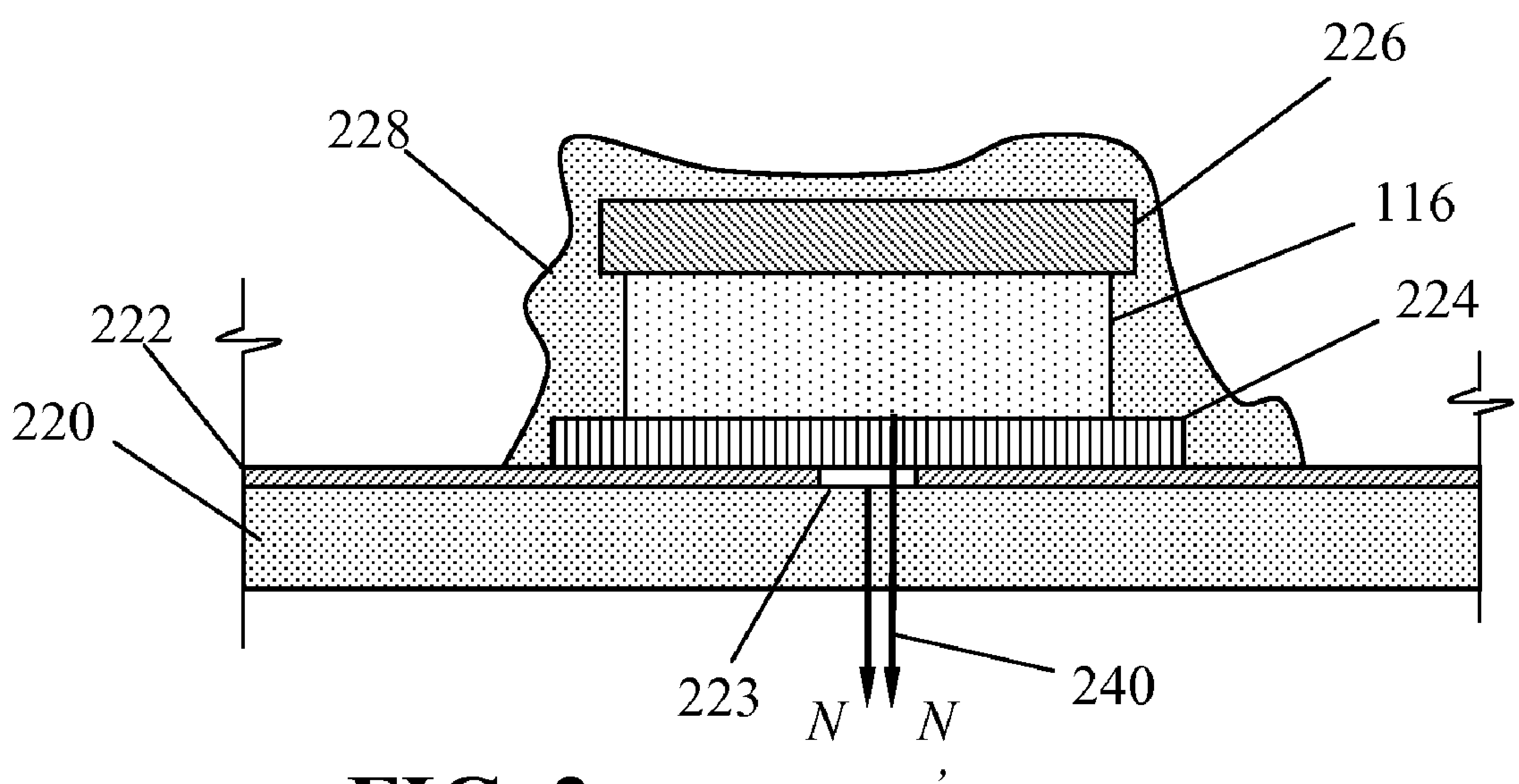


FIG. 2

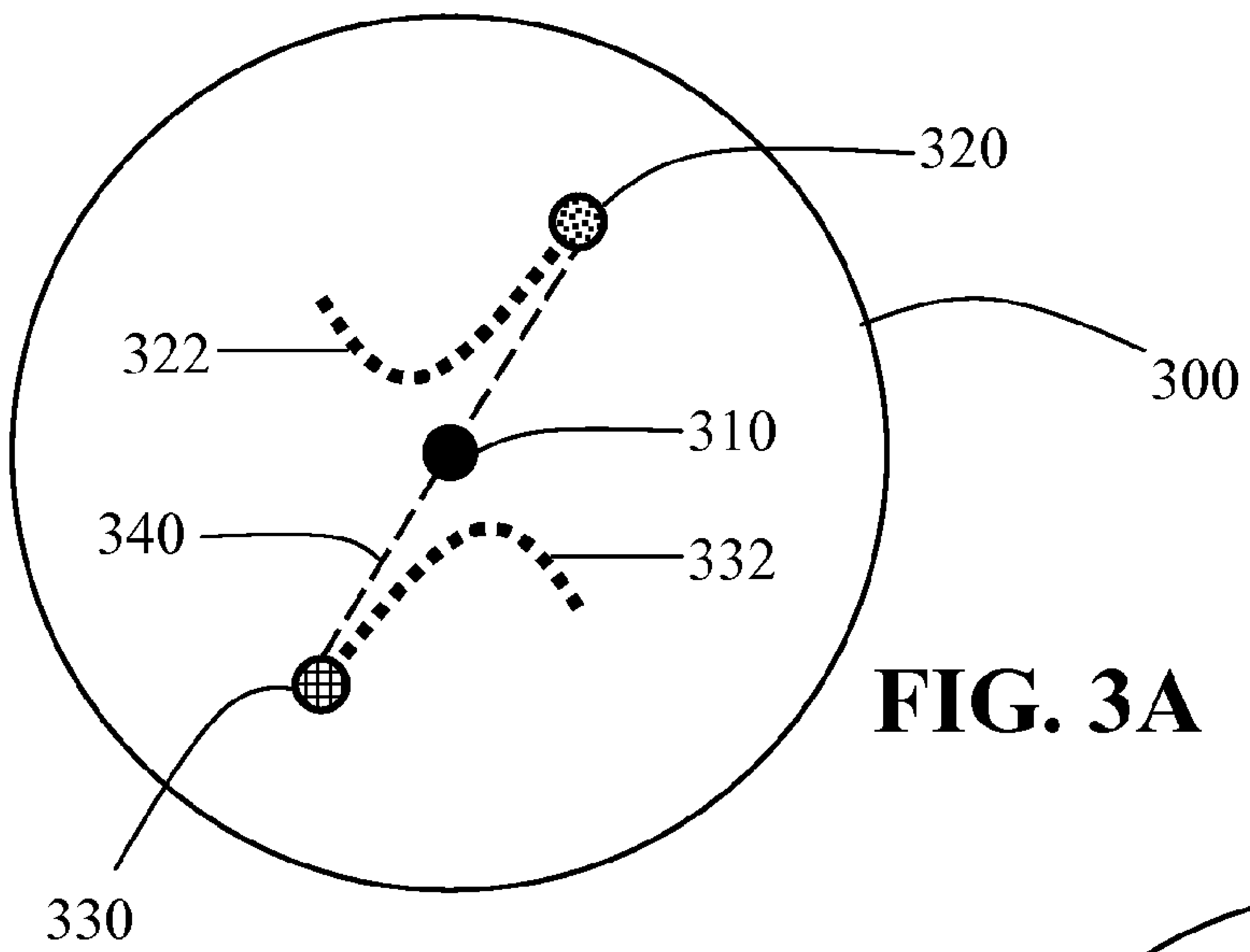


FIG. 3A

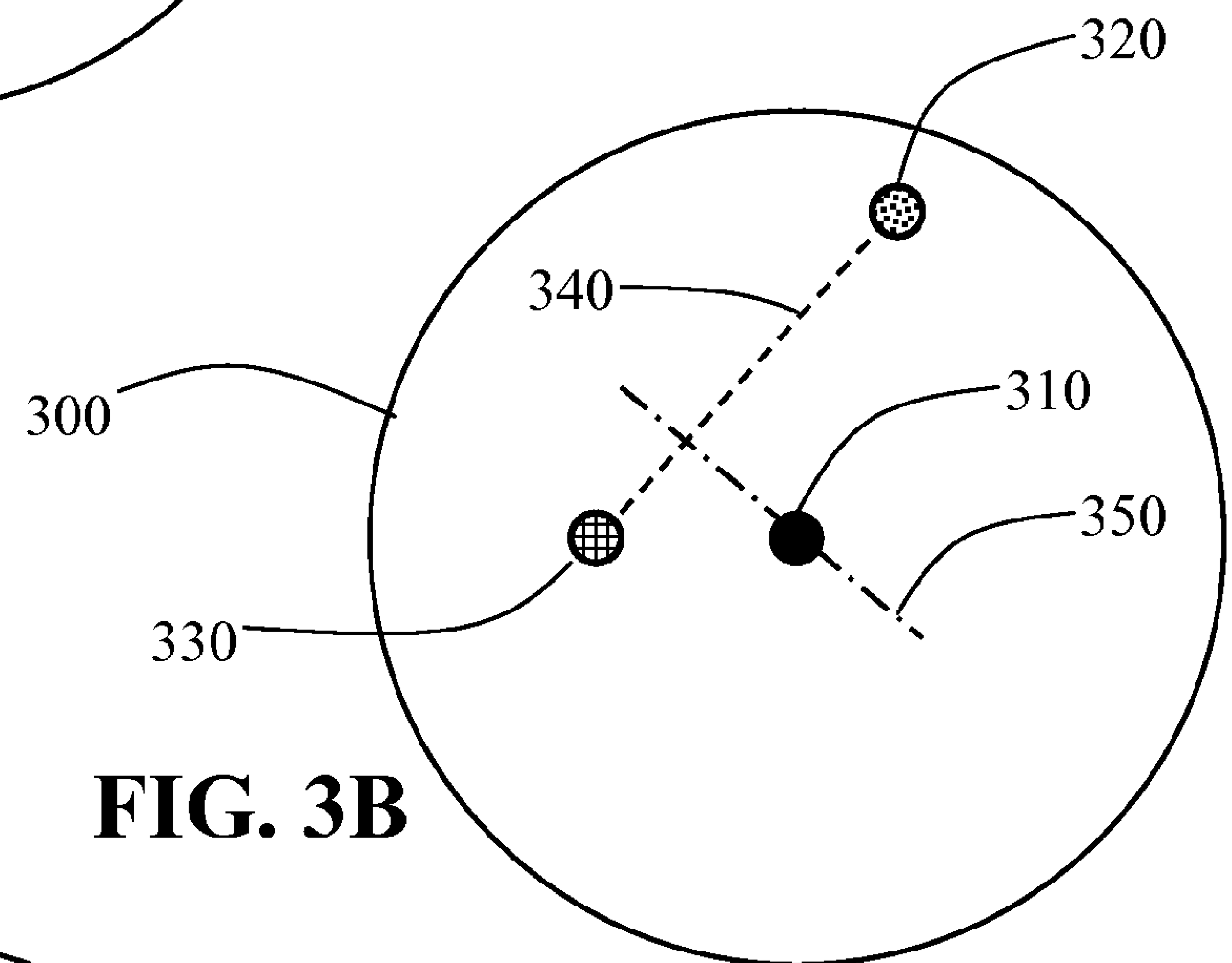


FIG. 3B

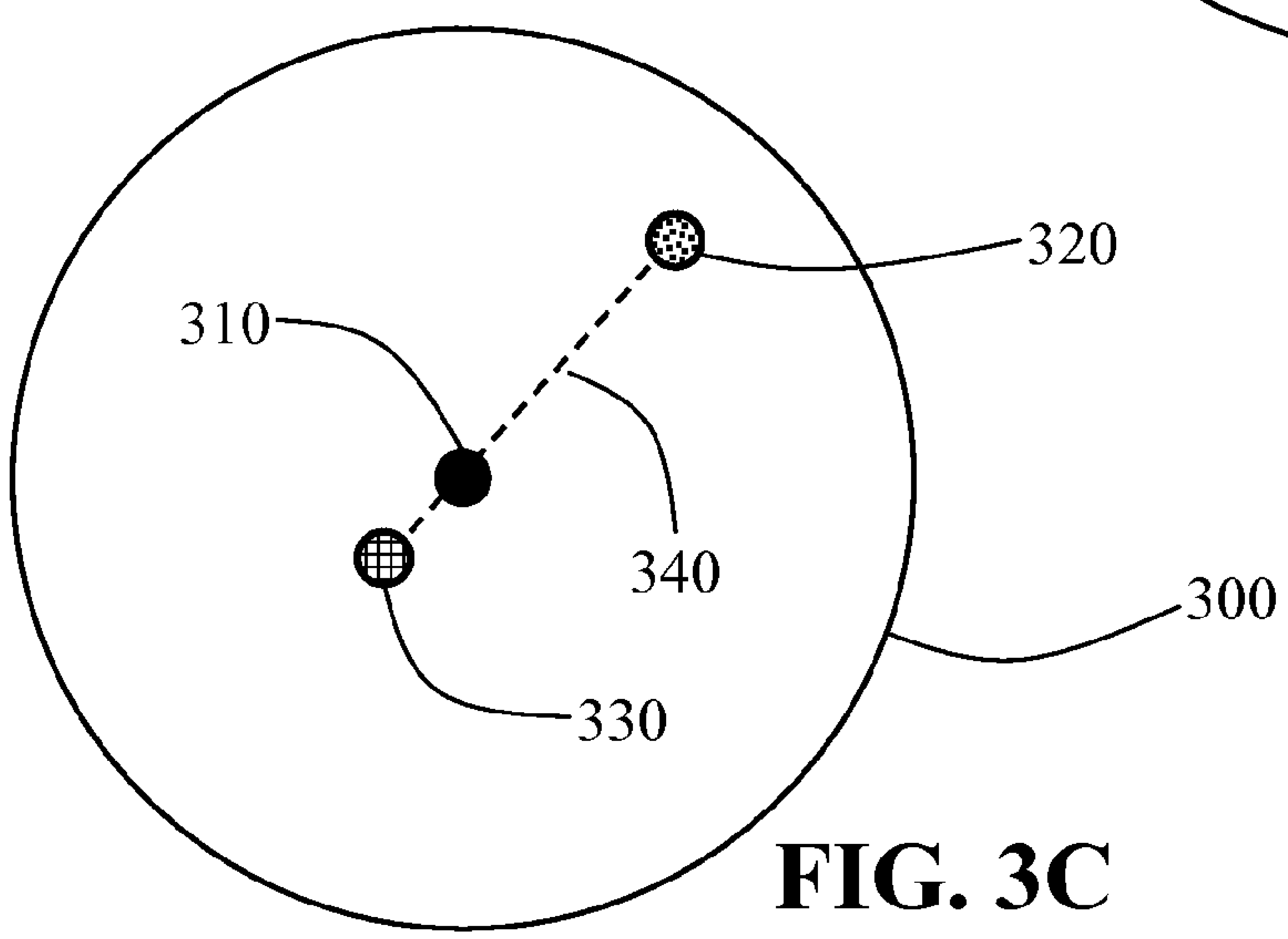


FIG. 3C

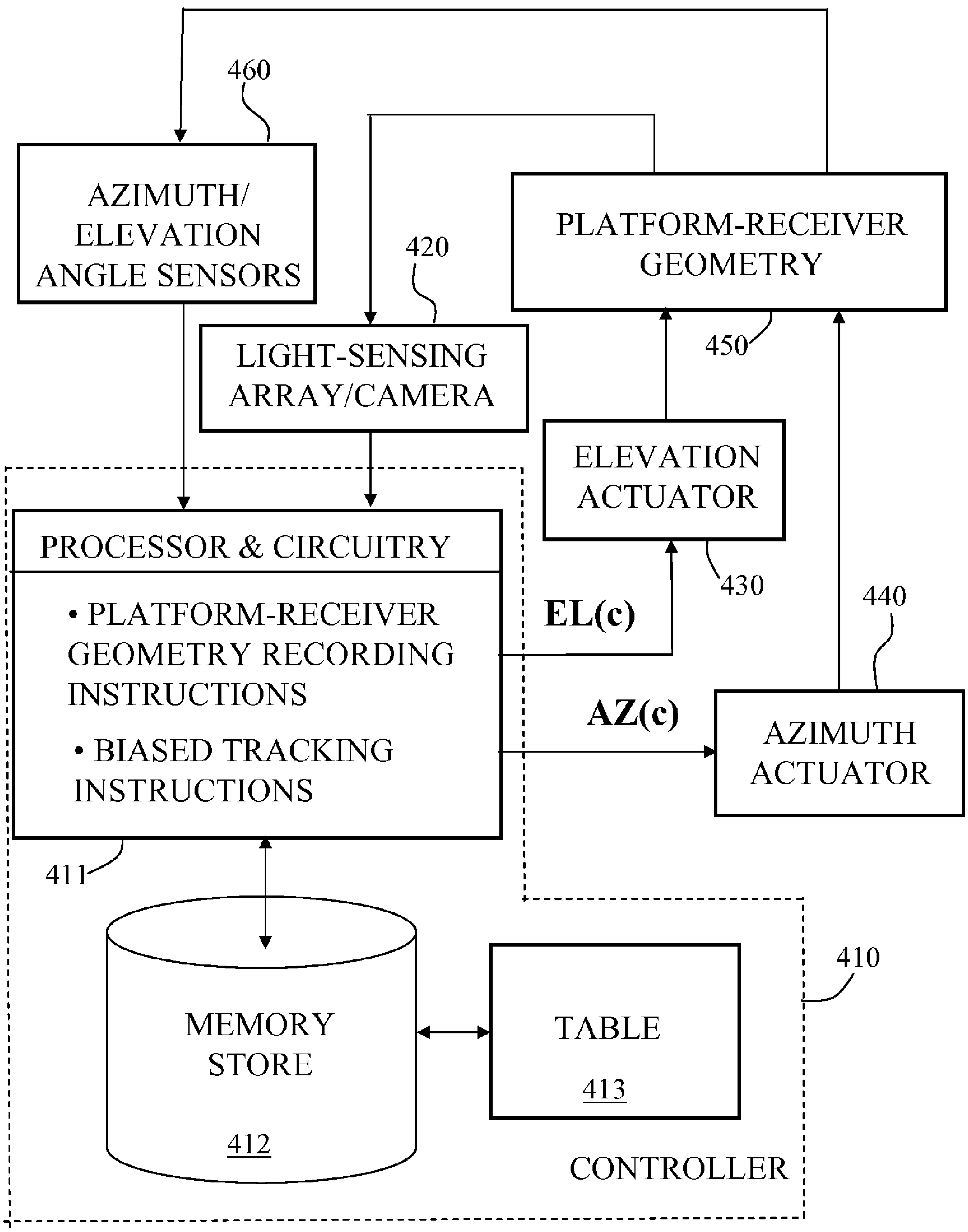

460
AZIMUTH/ ELEVATION ANGLE SENSORS
420
LIGHT-SENSING ARRAY/CAMERA
PLATFORM-RECEIVER GEOMETRY
450
ELEVATION ACTUATOR
430
PROCESSOR & CIRCUITRY
• PLATFORM-RECEIVER GEOMETRY RECORDING INSTRUCTIONS
• BIASED TRACKING INSTRUCTIONS
EL(c)
AZ(c)
440
AZIMUTH ACTUATOR
411
MEMORY STORE
412
TABLE
413
410
CONTROLLER

FIG. 4A

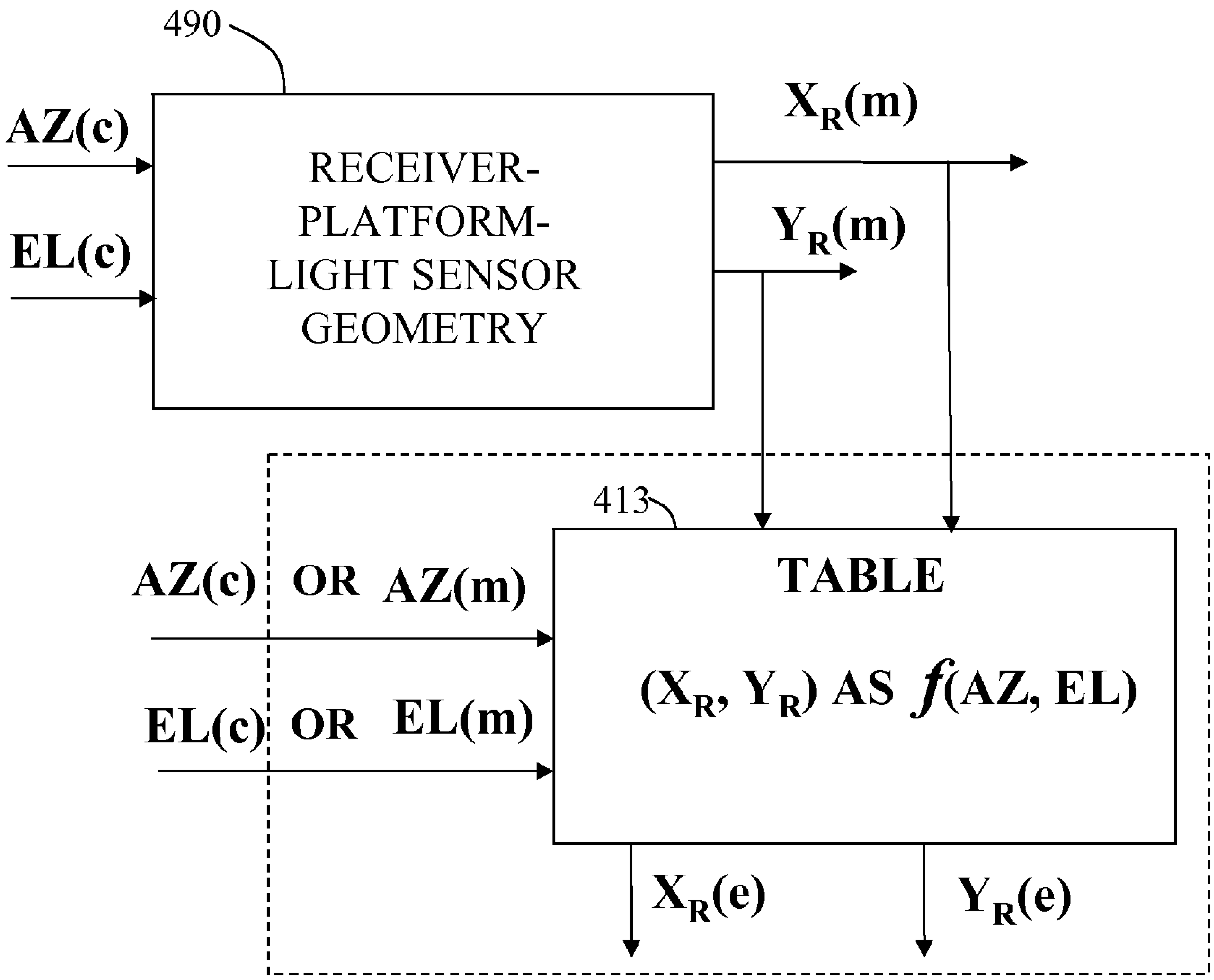

490
AZ(c)
EL(c)
RECEIVER-
PLATFORM-
LIGHT SENSOR
GEOMETRY
X_R(m)
Y_R(m)
413
TABLE
AZ(c) OR AZ(m)
EL(c) OR EL(m)
(X_R, Y_R) AS f(AZ, EL)
X_R(e)
Y_R(e)

FIG. 4B

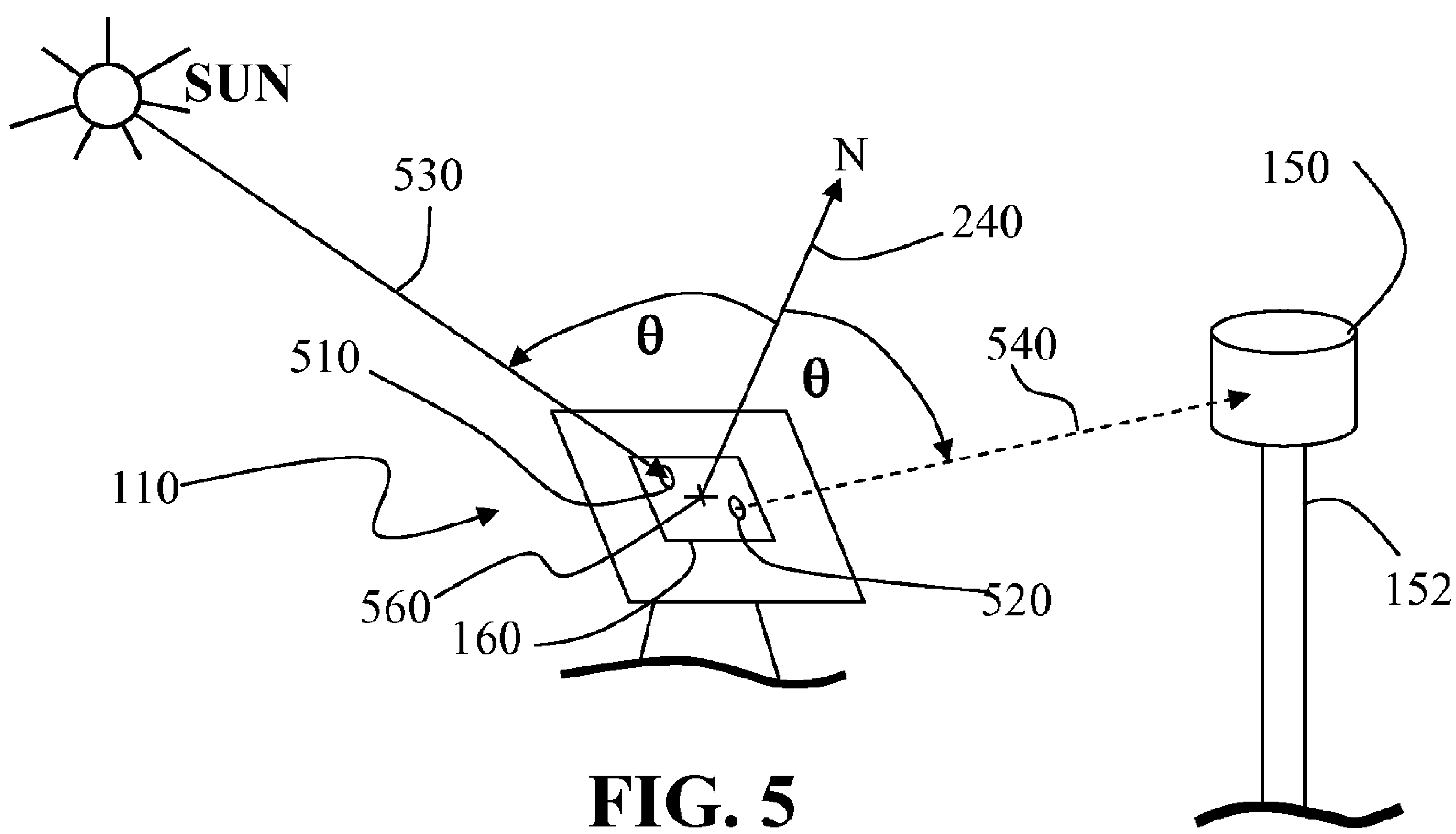

SUN
530
N
240
150
θ
θ
510
540
110
560
160
520
152

FIG. 5

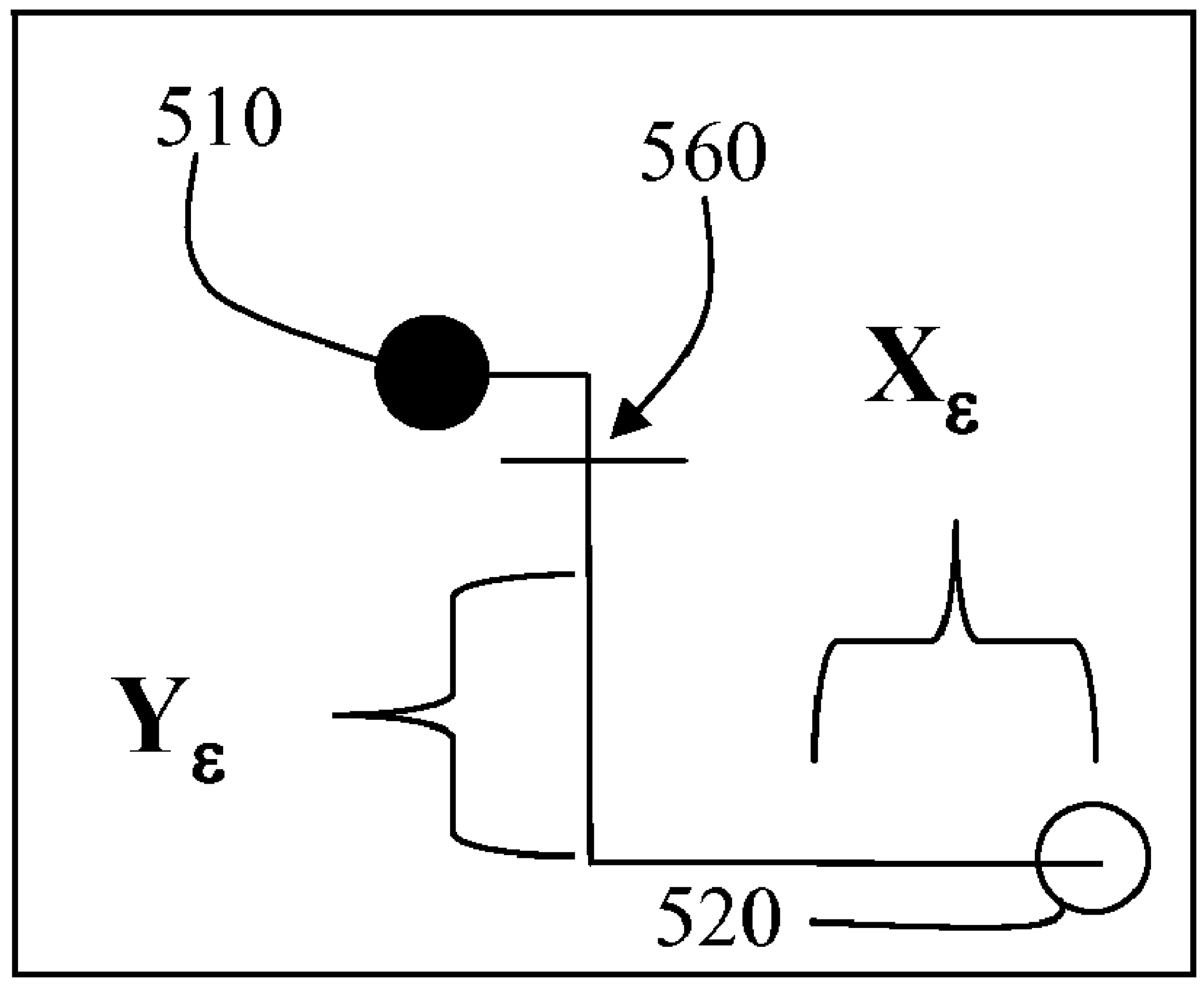


FIG. 6A

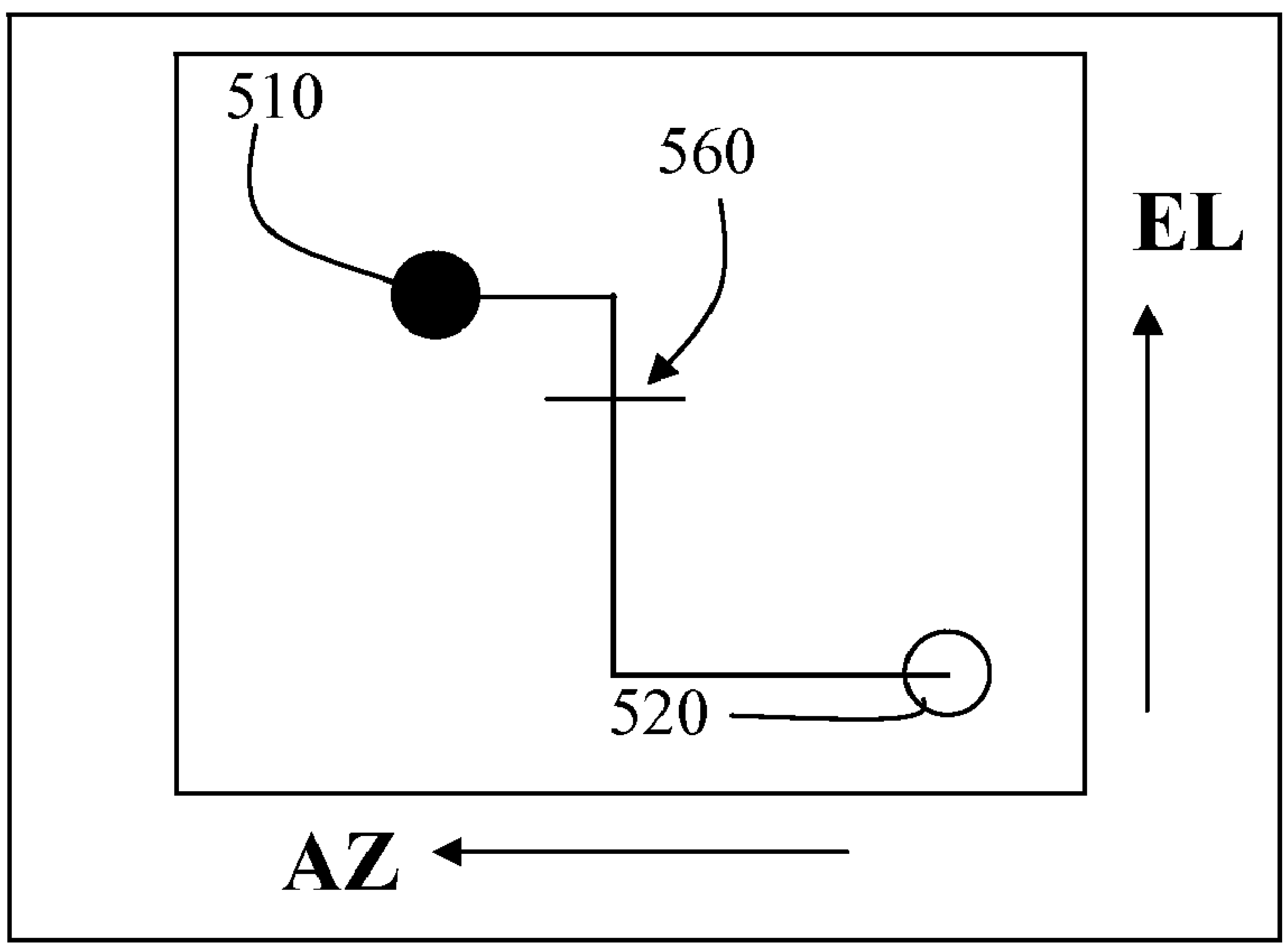


FIG. 6B

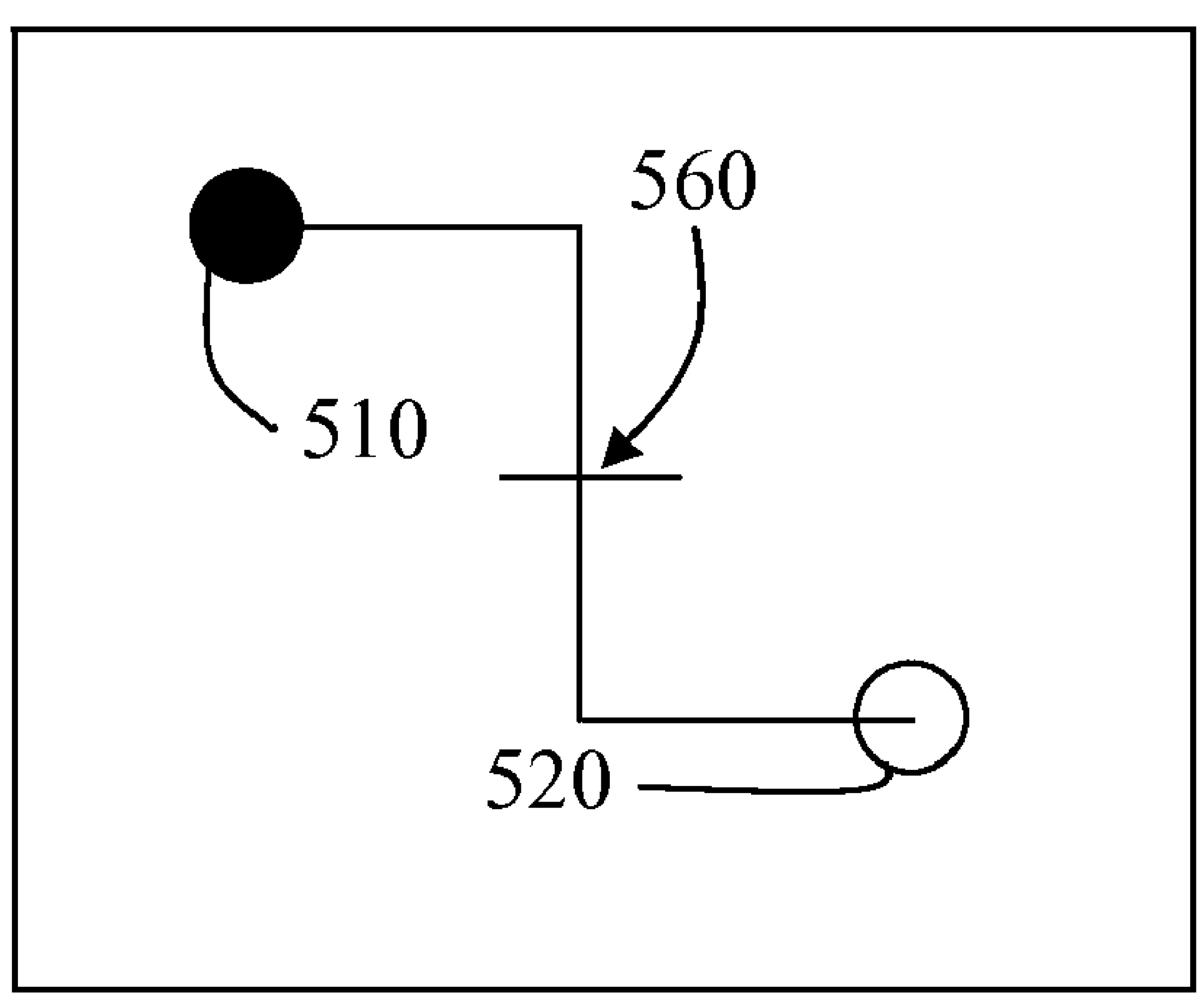


FIG. 6C

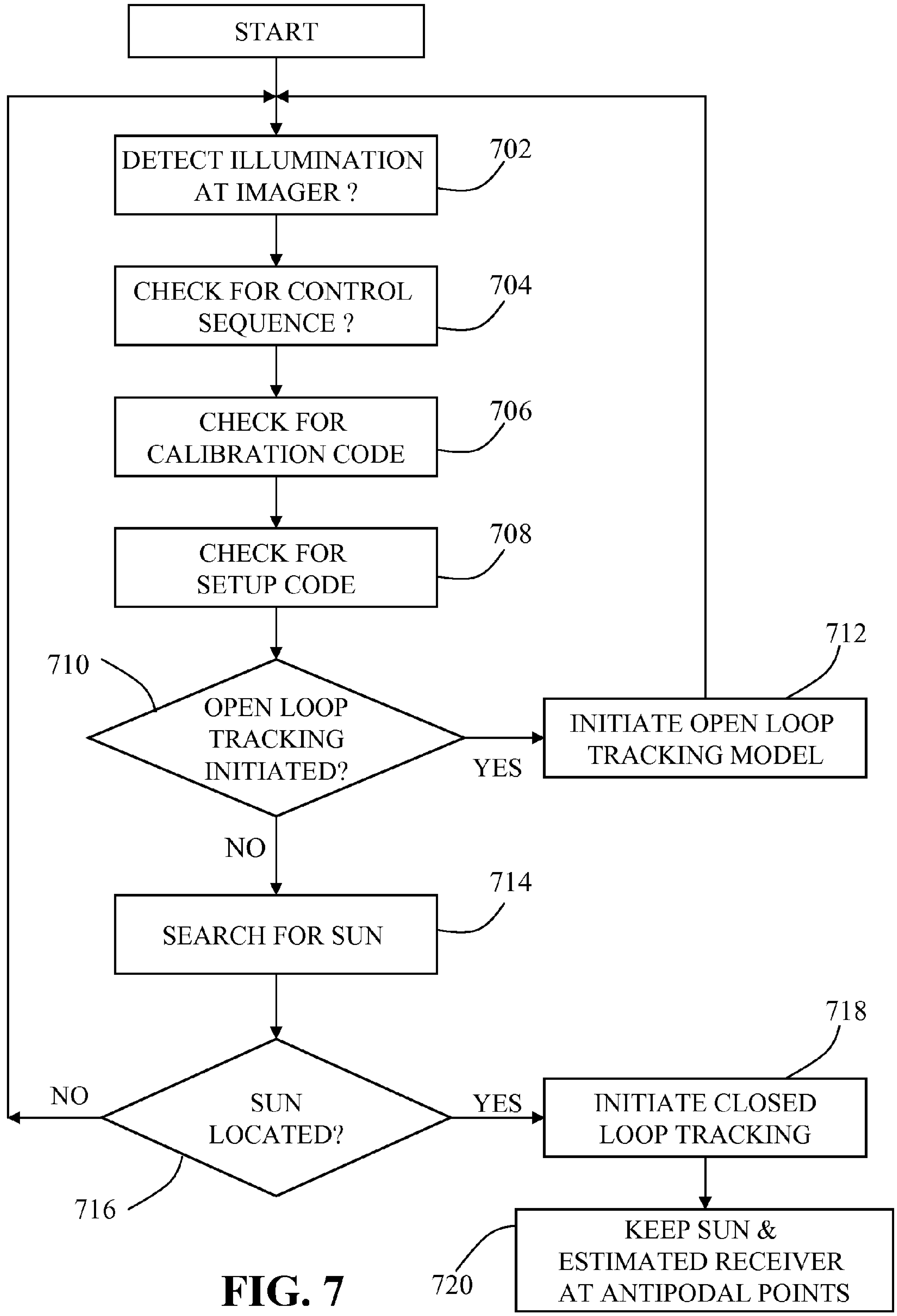

START
DETECT ILLUMINATION AT IMAGER ?
702
CHECK FOR CONTROL SEQUENCE ?
704
CHECK FOR CALIBRATION CODE
706
CHECK FOR SETUP CODE
708
710
OPEN LOOP TRACKING INITIATED?
YES
INITIATE OPEN LOOP TRACKING MODEL
712
NO
SEARCH FOR SUN
714
NO
SUN LOCATED?
YES
INITIATE CLOSED LOOP TRACKING
718
716
KEEP SUN & ESTIMATED RECEIVER AT ANTIPODAL POINTS
720

FIG. 7

CAMERA-BASED HELIOSTAT TRACKING CONTROLLER

TECHNICAL FIELD

[0001] The invention generally relates to a technique for configuring a heliostat to continuously reflect the sun onto a desired target, called "tracking." In particular, the invention relates to a system and method using a two dimensional imager disposed on the heliostat to aim a mirror or other optical element so as to continuously reflect the sun onto the aperture of a solar receiver.

BACKGROUND

[0002] In some solar thermal power plants, numerous heliostats may be employed to reflect light onto one or more receiver apertures. The mirrors of each of the heliostats must be continually repositioned in order to account for the relative motion of the sun. Mirror orientation errors must be exceedingly small to minimize spillage losses and achieve high concentration at the receiver aperture.

[0003] An array of heliostats with two degrees of freedom, e.g., azimuth-elevation, or tilt-tilt, may be applied in power-tower applications where the reflector or mirror of the heliostat may be characterized as having an average or center directional vector normal to the plane of a reflector. As part of a typical daylight operation, each heliostat may be commanded, e.g., by an external controller, to continuously reflect the sun onto a tower-mounted receiver aperture. This may be achieved when said mirror normal bisects the sun direction vector and receiver direction vector. However, this requires a knowledge of sun and receiver positions, e.g., in a fixed global coordinate system, and the forward kinematic map which converts motor positions to mirror normal, in the said coordinate system. The forward kinematic map will be a function of both rigid body and internal mechanical parameters of the heliostats, which in turn depend on the precise way a heliostat is installed and/or manufactured. For example, an azimuth axis of revolution may not be perfectly vertical, or the two axes of rotation of a heliostat may not be perfectly perpendicular.

[0004] An open-loop system, such as the system described in U.S. Pat. No. 4,564,275, to Stone, titled "Automatic Heliostat Track Alignment Method," may attempt to first estimate forward kinematic parameters of motor-to-normal mapping by a calibration phase, and then use those estimates and the known sun and receiver positions, e.g., via inverse kinematics, to achieve the bisection required for tracking. On the other hand, a closed-loop system may or may not include calibration to account for mounting and internal parameters of the heliostat while it attempts to establish, continually or continuously, a bisecting orientation via feedback. For example, a prior art closed-loop method has been described which estimates the output mirror orientation in real time, using an external camera and computer vision algorithms, via a photogrammetric method. See for example "Fast Determination of Heliostat Shape and Orientation by Edge Detection and Photogrammetry," by M. Röger et al., SolarPACES, 2008.

[0005] A closed-loop heliostat control system may include a camera that may be mounted rigidly to the heliostat mirror, with optical axis of the camera substantially aligned with the mirror normal. International Patent Application No. WO 2008/121335 A1 describes how such a setup may be used for closed-loop sun tracking control of the heliostat, namely, that from the camera's point of view, at the bisecting orientation, both sun and receiver (imaged as blobs) would appear symmetrically on the image sensor, and deviations thereof could be corrected in closed-loop to maintain the tracking orientation. In that system, the image sensor is required to image both sun and receiver simultaneously as compact blobs; due to the difference in brightness of said features, in one embodiment the prior art describes a special type of split-filter able to mask/attenuate a sub-region of the field of view, with a possible rotating degree of freedom to address the sun's changing location on the image sensor; another embodiment describes a Liquid Crystal Diode (LCD)-shutter device which emulates in function to that of the split-filter.

SUMMARY

[0006] The invention in one embodiment features a system for directing incident radiation from the sun to a target. The system includes a reflector for reflecting the sun's incident radiation; an imager connected to the reflector, the imager having an aperture (such as a pinhole or lens) and an imaging plane; a tracking controller coupled to the imager; and one or more actuators connected to the reflector and tracking controller. The tracking controller is configured to receive image data from the imager; determine a bisection error based on the image data; and orient the reflector till the bisection property is achieved, and in general, to preserve bisection continuously. The reflector may be a mirror that redirects sunlight to a receiver based on image data from a pinhole camera or other digital imager. In general, the optical axis of the camera is substantially aligned with the vector normal to the reflective surface so that the sun and the receiver appear at antipodal points with respect to the center of the camera's field of view. To increase tracking accuracy, however, the tracking controller in some embodiments orients the mirror based on a calibrated reference point that compensates for the deviation between the mirror normal vector and the optical axis of the camera, e.g., from a toleranced camera-to-mirror mounting process. In this configuration, the mirror normal substantially bisects the receiver and sun direction vectors with the receiver and sun imaged at substantially antipodal positions with respect to a center or reference origin (as determined by calibration) of the image sensor. By orienting the mirror to maintain the antipodal relationship of the sun and receiver, the heliostat may effectively track the sun in closed-loop and in spite of largely unknown or ignored global geometric information. Because each heliostat is able to generate its own bisection error signal (e.g., deviation from antipodality), they may independently execute tracking operations with their own embedded tracking controller.

[0007] Embodiments of the present invention include control systems and methods for continuously reflecting the sun onto a desired target, such as a solar receiver aperture. In some embodiments, a two-degree of freedom heliostat may include a camera rigidly mounted to the mirror, with optical axis substantially aligned with the heliostat normal. The camera may include a single light-attenuating filter, e.g., a single neutral density lens filter, and further include programmable gain and exposure controls. The heliostat may include an actuator having an absolute position that can be inferred from step counts with respect to a home position by the controller and/or a relative or absolute displacement encoder. The heliostat may include a controller configured to receive and process image from the camera and set gain and exposure controls of camera. The processor may be configured to execute instructions to correlate receiver points, spots or blobs captured by the camera with the two degrees of freedom of the heliostat and input the correlated data into a two-way table look-up. The processor may be further configured to generate actuator commands based on the sun points, spots, or blobs captured by the camera and based on the estimated receiver position based on the interpolated position estimated of a two-way table look-up.

[0008] An exemplary system of the present invention includes a heliostat supporting a flat or curved mirror that may be oriented along two angular degrees of freedom. The mirror's orientation may be controlled by commands issued by an individual (on-board microcontroller) or a remote central controller. Each degree of freedom may be actuated by a motor whose position relative to an origin or mechanical stop is known, e.g., counting the steps of a stepper motor with respect to a home or zero position, or using a relative or absolute encoder. Each heliostat of an array of heliostats may include onboard memory storage, which may be always powered, e.g., by on-board batteries, and/or a photovoltaic cell, or may be otherwise non-volatile. In some embodiments, a heliostat may be wired to a central controller and database, receiving power from said sources. In some embodiments of the heliostat system and method, an array of heliostats may be ground-mounted or otherwise stationary, and disposed about a power tower having a tower-mounted receiver and an aperture. The heliostat mirror is orientable along two degrees of freedom, and it comprises an image sensor (IS), e.g., a camera, which may be mounted rigidly to the heliostat mirror. The camera may be disposed over the mirror or behind it. If the camera is disposed behind the reflector, the reflector preferably includes a viewing hole or light-conducting aperture. The camera may be installed such that its optical axis is substantially aligned with the mirror normal. If the mirror is curved, the camera may be preferentially mounted at the mirror's center or a substantially fixed point relative to rotational motion, with optical axis along the normal at the mounting point. In addition, the heliostat may include a filter, such as a single neutral density filter, mounted over or integrated with the camera's objective lens.

[0009] In some embodiments, the invention comprises a method of tracking the sun with a heliostat, the heliostat including an imager mounted, or otherwise disposed proximate to a mirror. The method includes: (a) locating image features corresponding to the sun in a captured image; (b) estimating one or more image locations corresponding to a receiver based on a least one heliostat tilt angle; (c) actuating the mirror toward an orientation at which the vector normal to the mirror bisects the sun and the receiver direction, i.e., said image feature and image location appear substantially antipodal to the center of the image sensor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The present invention is illustrated by way of example and not limitation in the figures of the accompanying drawings, and in which:

[0011] FIG. **1**A is a diagrammatic illustration of one of a plurality of heliostats and a receiver for collecting and converting solar energy, in accordance with one exemplary embodiment;

[0012] FIG. **1**B is a diagrammatic illustration of exemplary rotation angles of a heliostat;

[0013] FIG. **1**C is a diagrammatic illustration of an exemplary image sensor reference frame of a heliostat;

[0014] FIG. **1**D is a diagrammatic illustration of a heliostat in relation to an illuminated tower-mounted receiver;

[0015] FIG. **1**E is a diagrammatic illustration of a table of illuminated receiver location values recorded according to a heliostat raster scan in the direction of the illuminated receiver;

[0016] FIG. **2** is a cross-sectional view of a heliostat mirror with integral imager, in accordance with one exemplary embodiment;

[0017] FIG. **3**A is diagrammatic illustration of an image of the sun and receiver acquired by the camera when properly aligned between the sun and receiver, in accordance with one exemplary embodiment;

[0018] FIGS. **3**B through **3**C are diagrammatic illustrations of an image of the sun and receiver at various stages of misalignment of the mirror normal vector with respect to the sun and receiver, in accordance with one exemplary embodiment;

[0019] FIG. **4**A is an exemplary functional block diagram of a system embodiment of the present invention;

[0020] FIG. **4**B is an exemplary block diagram of the building and use of a table lookup of illuminated receiver locations;

[0021] FIG. **5** illustrates in a diagram the antipodal regulation/solar tracking by a heliostat based on an estimated location of a receiver;

[0022] FIGS. **6**A, **6**B, and **6**C illustrate in a diagram antipodal regulation/solar tracking by a heliostat based on an estimated location of a receiver in the frame of the image sensor; and

[0023] FIG. **7** is a flowchart an exemplary method for tracking the sun using the imager and corresponding tracking controller, in accordance with one exemplary embodiment.

DETAILED DESCRIPTION

[0024] Illustrated in FIG. **1**A is a diagrammatic representation of one of a plurality of heliostats and a receiver for collecting and converting solar energy **100** in what may be referred to as a solar power plant that may be thermal or electric—depending on the type of receiver. The heliostat **110** may be configured to track the sun over the course of a day and reflect the incident light to the receiver **150** where it may be converted to heat or electricity. The heliostat includes a mirror **112**, actuator and support structure assembly **114** for changing the orientation of the mirror, and may include a tracking controller to determine the appropriate direction to aim the mirror and send commands to the appropriate actuator. Throughout the day, the orientation of each mirror is periodically adjusted about two degrees of freedom, e.g., two tilt angles or an ordered pair of angles: an azimuth angle and an elevation angle, to continually reflect light onto the receiver **150**. The heliostat is preferably one of a plurality of heliostats distributed in proximity to a tower **152** or other structure on which the receiver **150** is mounted. The receiver **150** may include a water-steam boiler, a molten salt system, a heat engine, one or more photovoltaic cells, a biomass cooker, a water purification system, or a combination thereof for generating electricity or otherwise collecting the sun's energy.

[0025] The heliostat **110** tracks the sun or other radiation source based on image data received from a two-dimensional imager **116**, e.g., a digital camera, rigidly attached or otherwise integrally incorporated into the mirror of the heliostat. The camera **116** captures an image of the sun which may then be communicated to a tracking controller. Under appropriate filtering and gain settings, the sun will be imaged as a compact set of pixels—a "blob" on the image sensor, and easily detectable by the tracking controller. Based on an interpolated database lookup, the tracking controller can estimate the location of the receiver, for example, in a planar camera reference frame (e.g., Cartesian or polar), based sensed, or commanded reflector orientation. On the prior art, e.g., International Patent Application No. WO 2008/121335 A1, the receiver is assumed imageable simultaneously with the sun, e.g., via a split filter. Here the sun is presumed much brighter than the receiver at all times so that under appropriate filtering, the latter may not be imageable at all. The tracking controller may then aim the mirror in the direction necessary to reflect incident light onto the receiver or other target. To accomplish this, the controller moves the mirror to an orientation where both sun and estimated receiver locations on the image sensor are substantially antipodal with respect to the center or an optionally calibrated reference point in the sensor. This reference point—which corresponds to the projection of the mirror normal vector onto the imager at the aperture—represents the deviation between the imager's optical axis and the mirror normal vector. As the sun moves across the sky, the camera detects the shift in sun position and drives the actuator system until the antipodal relationship with respect to the estimated receiver position is re-established, thereby providing a closed-loop tracking system. Because the sun will be typically imaged as a blob, or a compact set of pixels, the blob's centroid might be used to determine perfect antipodality. Although the sun and estimate of the receiver appear precisely antipodal if the normal to the imager plane coincides with the mirror normal, it may be necessary to correct for any angular offset between the normal to the imager plane N' and the mirror normal N, e.g., due to installation misalignment, which causes the calibrated reference point to shift away from the midpoint between the sun and receiver bright spots even when the mirror normal exactly bisects the angle between incident sunlight vector S and the estimated receiver vector R.

[0026] Illustrated in FIG. **1**B is a diagrammatic representation of a heliostat **110** showing a rotation in the plane of the local level as a rotation in azimuth (AZ) and a rotation perpendicular to the local level and ordered after the azimuth rotation as a rotation in elevation (EL). The two angular directions may be expressed in an unordered pair of rotation angles without loss of generalization for purposes of embodying the present invention.

[0027] Illustrated in FIG. **1**C is a diagrammatic representation a heliostat **110** showing an imaging array **160** (not to scale) having a Cartesian, e.g., X-Y, reference frame by which a sensed point **172** of incident light **170** may be registered. Knowledge of the rotation of said XY plane about the mirror normal is not relevant to the present invention, but "X" may be generally aligned with the horizontal, while "Y" is perpendicular to it along the mirror.

[0028] Illustrated in FIG. **1**D is a diagrammatic representation a heliostat **110** and a receiver **150** mounted on a tower **152** where a light source **190** is disposed on the receiver **150** and sensed by the image sensor **160** (not to scale) disposed proximate to the reflector of the heliostat **110**.

[0029] Illustrated in FIG. **1**E is a diagrammatic representation of a table of image sensor (X,Y) pairs that may be recorded as part of a raster scan by the heliostat **110** relative to the illuminated receiver **150** of FIG. **1**D.

[0030] A cross-sectional view of the exemplary camera-based tracking system is illustrated in FIG. **2**. The tracking system includes the imager **116**, e.g., a narrow aperture, camera, optically mounted to the back of the mirror **220** where it faces outward in a direction between the source and target. The camera-based tracking system may further include integrated control logic, i.e., a tracking controller **226**, for computing the tracking error and driving the actuator assembly that orients the mirror. The imager **116** preferably has a view of the source and target by means of a small aperture **223** in the mirror to admit light. The aperture **223** may be an actual opening or a section of glass where the reflective metallization **222** has been removed by laser etching or machining, for example. In some embodiments, a thin filter plate **224** is mounted between the mirror **220** and camera **116** to suppress the lateral spread of light and increase source/target image resolution. In other embodiments, the camera is mounted to an edge of the mirror, on the front face of the mirror, or cantilevered off to the side of the mirror, for example. Suitable imagers include a ⅙ inch format CIF (352×288) or VGA (640×480), or higher resolution, preferably small enough that it does not need a large filter plate. The resolution of the imager need only be high enough so that the center of the sun blob may be localized accurately enough to allow the control logic to determine a smooth path on which to actuate the mirror and achieve a light-reflection accuracy required by the application (as may be dictated by spillage and concentration requirements).

[0031] During assembly of the heliostat **110** before final assembly of the imager **116** on the mirror **220**, the imager may be positioned on the mirror by (a) aligning the optical axis of the camera—represented by normal vector **240**—to the mirror's normal vector perpendicular to the mirror plane, and (b) aligning the optical axis of the camera with the center of the pinhole aperture. The optical axis of the camera need not be precisely aligned with the mirror normal vector since the deviation there between may be determined and compensated using a calibration process. After proper placement of the imager **116**, the imager and tracking controller **226** may be encapsulated with epoxy **228**, potting compound, or other sealant to hermetically seal the electronics and camera behind the mirror, thereby protecting them from environmental damage. The aperture may be filled with an optical coupling agent to prevent an air gap from occurring between the mirror glass **220** and filter plate **224**. Before normal operation of the heliostat, the precise position and orientation of the imager with respect to the mirror may be determined and the calibrated reference point may be uploaded to non-volatile memory in the tracking controller.

[0032] During heliostat tracking operation, the camera **116** identifies the center of the sun's image on the sensor while the tracking controller **226** predicts or estimates the location of the receiver **150**, which is presumably not imaged in the sensor due to a much lower brightness. Given appropriate filtering, the sun is easily identified as the brightest (or only) blob in the image. For ease of processing, the image data may be thesholded into a binary one; alternatively, the sensor may be gray-level (allowing for sub-pixel center estimation) or black-and-white. Although the receiver **150** may become bright when fully illuminated by a field of heliostats, it will still be imaged faintly (if at all) on the image sensor under a suitable filter. In the present invention, the receiver location on the image sensor is estimated based on motor position counts and a table of correlated receiver positions. Once the tracking controller **226** identifies the locations on the image sensor representing the sun and receiver, it updates the mirror's elevation and/or azimuth angles so that the sun and receiver appear symmetrically on the sensor with respect to its center, thus placing the mirror in a bisecting orientation.

[0033] Illustrated in FIGS. **3**A through **3**C are diagrammatic illustrations of the locations **300** of sun and receiver (if it were visible) on the camera sensor at various stages of tracking or misalignment. When the mirror is properly aligned as shown in FIG. **3**A, the reference point or calibrated reference point **310** coincides with the mid-point on the line **340** between the image of the sun **320** and estimated receiver point **330**. The images of the sun **320** and estimated receiver center **330** are therefore shown substantially antipodal around the calibrated reference point **310** on the image sensor. During daylight, the image course of the sun and the estimate of the receiver spot trace out locii **322**, **332** that are instantaneously antipodal provided the mirror is continuously bisecting.

[0034] When the mirror is improperly aligned, the reference point or calibrated reference point **310** of the camera may be located off the line **340** between the sun **320** and estimated receiver spot **330** as shown in FIG. **3**B (see point **310** along orthogonal line **350**) or the reference point or calibrated reference point **310** of the camera may not be equidistant between the sun **320** and estimated receiver spot **330** as shown in FIG. **3**C. To restore proper bisection, the mirror may be actuated, for example, via closed-loop tracking, about its two degrees of freedom separately or concurrently.

[0035] During assembly of a heliostat **110**, a pick-and-place machine may be used to locate the imager **116** on the mirror **220**. Even a high precision manufacturing process may result in a small deviation between the imager and mirror. Although small, the difference between the orientation of the imager and mirror may hamper the ability of the heliostat to effectively redirect sunlight to a receiver with the required angular accuracy. A calibration procedure may be used to determine the precise difference between the imager's optical axis and the mirror's normal as well as the optical center of the imager and the optical center of the pinhole, lens system or aperture, thereby providing the correction needed to precisely locate the source and target from the image data acquired by the camera **116**.

[0036] FIG. **4**A is a top level functional block diagram of a system embodiment of the present invention where the controller **410** may comprise a processor and/or circuitry **411** configured to read and image data and locate features therein (e.g., blob detection and center estimation), and storing said features in a table **413** of a memory store **412**. In addition the processor and/or circuitry **411** may be configured to generate commands to actuate motors based on image features (e.g., the sun blob's center) and predicated locations of the receiver. The commanded changes to the motor positions, in this example are shown as an elevation command (EL(c)) and an azimuth command (AZ(c)), and may cause the respective elevation actuator **430** and azimuth actuator **440** to change the mirror orientation **450**. Alternatively, for a tilt-tilt kinematic, two similar tilt commands T**1**(*c*) and T**2**(*c*) would be available. A camera, image sensor **420** or a light-sensing array or scanning array of the platform provides a location (e.g., on the camera plane) of the receiver during the table building phase and a location of the sun during the daylight tracking phase. In some embodiments the commanded changes in motor position may be used to retrieve predicted receiver positions via a table lookup **413**. In some embodiments, motor positions available in azimuth and elevation from encoders **460** may be used to retrieve predicted receiver positions via table lookup **413**.

[0037] Accordingly, embodiments of the invention include control of a heliostat during two phases. A first phase comprises sweeping through various combinations of azimuth and elevation motor position pairs and recording, said motor position pair, the sensed position of a radiating and/or illuminated receiver where the background lighting is sufficiently dim to permit the heliostat light sensor or camera to sense the receiver as a point, spot, or blob. For example, during nighttime, with a bright or pulsating light positioned at the receiver aperture. A second phase comprises daylight tracking of the sun spot, or blob in a fashion that places the sun point complementarily equidistant from and collinear with an estimated receiver location on the image sensor, where the iteratively estimated receiver location may be retrieved via table lookup by using the current motor position(s) as indices. For example, the first phase may be embodied as a nighttime raster scan of the heliostat motor position space under some resolution, and the second phase may be embodied as the daytime sun-receiver bisecting closed-loop control system, where the sun is imaged as a non-saturating or blooming blob under a suitable filter and the receiver spot may be inferred from interpolations of the data obtained during the first phase and not be imaged at all. Because the sun and receiver need not be imaged simultaneously during the first or second phase, there is no need for a (moveable) split or shutterable filter.

[0038] An exemplary first phase may presume the heliostat is rigidly mounted to the ground or a stationary structure, with mounting parameters not known or only known to some tolerance. During nighttime, a relatively intense light source, e.g., bright incandescent or halogen, may be disposed at the center of the receiver aperture or target region. Preferably the size of the light source disk may be very small compared to the minimum heliostat distance and preferably smaller than, and centered at, the receiver aperture. The light source must be sufficiently bright to be suitably imaged by the image sensor (IS) under the filter used for daytime tracking by adjusting the sensor's sensitivity to high. Nighttime may be a preferred time for this exemplary first phase of operation because all other objects may be masked by the filter and by a decrease in brightness. Other bright objects in the sky such as stars and moon may be avoided if their position is approximately known, e.g., by a moon- or star-positioning algorithm. Alternatively, the bright light may emit only a narrow spectrum, attuned to a narrow band-pass filter on the camera. Still alternatively, the bright light may be flashed at a very short duty cycle, e.g. 0.1%, and at a very high brightness (1000× stronger than normal), so as to overwhelm any other light sources. In addition, the exact moment of flashing may trigger image acquisition by mirror-mounted cameras.

[0039] FIG. **4**B is a top level functional block diagram illustrating during the first phase that receiver-platform (heliostat reflector)-light sensor geometry **490** will yield measured illuminated received positions (XR(m), YR(m)) that are stored in a table **413** in records containing the measured (e.g., AZ(m), EL(m)) or commanded (e.g., AZ(c), EL(c)) positions in motor positions with relative or absolute AZ/EL angles, or tilt pair angles. Some embodiments may have step counts suitable for stepper motors representative of the effects of angle changes. Some embodiments may represent the two-way table as a two dimensional function of angles. Accordingly a representation of the motor positions may be applied in the second phase (the sun tracking phase) to generate estimates of the receiver location in the camera of image sensor space, i.e., (XR(e), YR(e)).

[0040] The exemplary pseudo-code of the first phase, when executed by the controller or other processor, may instruct the heliostat image sensor (IS) gain and exposure settings to be set high enough to allow for the receiver-related light source to be imaged preferably as a compact, non-saturating blob (compact pixel group). The IS or the image it produces, may be at a gray level of grayscale and/or may be subject to thresholding to produce a binary representation. The relationship between the heliostat motor positions and the receiver may be expressed as a two dimensional interpolant, a neural network, or as a table lookup and an interpolation which estimates the receiver location on the IS frame based on commanded or measured heliostat motor positions. An exemplary embodiment of the first phase to generate values for a table look-up has the heliostat initially commanded to go to a zero position, e.g., against a mechanical stop or limit or contact switch. Next, a raster scan in the two dimensional space of motor positions (reference is made to the pseudo-code below: th1, th2) of the heliostat is initiated, with both motors stepped at some resolution (reference is made to the pseudo-code below: th1step, th2step). In some embodiments, the resolution may be given as a number of steps where the relationship between step count and mirror angular displacement need not be known. Referring to the pseudo-code below, for each motor position pair (th1, th2) visited, an image processing method IS.GetBlob( ) is invoked to return the centroid of the receiver blob as imaged in the IS space that may be a rectangular pixel array. Subpixel estimation of the blob centroid may be used where the IS frame pair, i.e., the (x,y) pair, may be registered in fixed-point or floating-point. Following this step, the four-tuple (th1, th2, x, y) may be stored on an onboard memory (OBM) as the procedure OBM.Store(. . .). The specific organization of the data store may be a linear or two-dimensional array, a linked list, a hash table, a database, or a continuous function. In addition, the motor positions (th1, th2) may be embodied as integral step counts. As shown below, this data store may be indexed by the pair (th1, th2), so the data store organization may facilitate quick retrieval of the pair (x,y) based on (th1,th2) as indices or keys, e.g., as with a hash table, a dictionary or database.

[0041] Once the raster scan of the motor position space is completed, the first phase may terminate. Accordingly, if the first phase was not based on a post-daylight radiating receiver, the light source of an illuminated receiver may be turned off and removed from the receiver aperture. In a variant of a raster scan pattern of equally-spaced raster lines comprising equally spaced sample points, the (th1,th2) space may not be visited in uniform fashion, but rather visited where parts of the (th1, th2) space are sampled more finely than others. Such exemplary refined sampling may better accommodate troughs in the Jacobian determinant of the forward kinematic map. Alternatively, the (th1, th2) space may be traversed along a spiral or any other continuous path which provides coverage of the angular space under some resolution.

[0042] Exemplary pseudo-code representative of computer-readable instructions for executing the first phase; in this example, the table is constructed for the interpolated conversion of heliostat motor positions to a receiver imaged position on the sensor:

Algm1:

```
Position light source at receiver aperture;
IS.SetGain (HIGH);
For (th1 = 0; th1 <= th1max; th1 += th1step)
      For (th2 = 0; th2 <= th2max; th2 += th2step) {
            (x,y) = IS.GetBlob( );
            OBM.Store (th1, th2, x, y);
}
Remove light source from receiver aperture;
```

[0043] In this example, the first phase may be executed at least once and preferably in relative darkness with the exception of a bright light source positioned at the receiver aperture, e.g., at its center. The data store, in the case of heliostat-fixed memory, the onboard memory (OBM) is preferably non-volatile so that power to the memory store may be turned off for a period such as the duration of nighttime, e.g., overnight, Accordingly, the memory store may be referenced during the second phase, i.e., the solar tracking phase, to support the estimation of a receiver location point in the frame of reference of the image sensor (IS). In some embodiments, the gain and exposure settings of the IS may be set to high levels during the first phase and to low levels during a second phase (below), so that the sun may be imaged as a non-saturating or blooming blob through the same contiguous, i.e., non-split, filter used during the first phase.

[0044] Illustrated in FIG. **5** is a diagrammatic representation of a heliostat **110** and a receiver **150** mounted on a tower **152** where a point, spot, or blob **510** may be registered as the location of the sun is tracked relative to a predicted location of the receiver **520** in order that the platform normal **240**, N, in the plane of the sun, predicted receiver location, and imaging sensor center point **560**, bisects the angle between the direction vector of the incident sunlight **530** and the predicted location/direction vector **540** of the receiver. For example, FIG. **6**A shows a location in XY space, i.e., camera 2D space, of a sun blob **510**, the reference center point **560** and the predicted location of the receiver **520**. In this illustration, antipodal symmetry is not met as indication by the error values X_ϵ and Y_ϵ. The error values are determined by the controller executing instructions of the present invention and may cause the platform to move responsive to platform commands from the controller as shown in FIG. **6**B. Accordingly, while the error values X_ϵ and Y_ϵ are maintained within a threshold acceptable for the given receiver-to-platform geometry, i.e., a threshold consistent with a determined aiming accuracy, the antipodal symmetry is approximately met as shown in FIG. **6**C.

[0045] Alternatively, if during tracking the sun blob centroid and the estimated receiver position are not found to be symmetric or antipodal with respect to the center, a local search procedure, such as a "manhattan" method may be executed to improve the symmetry. For example, at a given motor position (az,el), the four (or eight) neighboring "manhattan" motions can be executed, (az+d,el),(az−d,el),(az,el+d),(az,el−d), and one may selected which best improves antipodal symmetry.

[0046] The second phase, i.e., the tracking phase, may be initiated with the heliostat being commanded to go to a zero position. Then a loop ensues which varies the heliostat mirror orientation until the IS registers a bright spot in its field of view (FOV) comparable to an expected sun blob that may be determined by the predicate IS.HasBlob( ). While the sun is in its daylight course, the following set of exemplary operations may be performed by the heliostat controller:

[0047] (i) The location of the sun blob (xsun, ysun) is retrieved by IS.GetBlob( ). Sub-pixel detection may be used. By applying a modulo operator to accommodate any lost steps, this exemplary subprocess may predictably track the current (th1,th2) configuration due to the heliostat motion starting from a known zero position.

[0048] (ii) With the sun blob (xsun, ysun) retrieved, the memory store can be queried for the position of the receiver based on data stored during the first phase scan of and indexed by the current motor positions (th1, th2). Optionally, the controller may measure the motor positions, e.g., via encoders. Because the scan in darkness may be accomplished at some finite resolution, an exactly matching retrieval (x,y) pair associated with the specific (th1, th2) may be rare. So, the function OBM.Query(th1, th2) finds, via interpolation or regularization (e.g., using closest neighbors to the query), the sub-pixel receiver location (xrcv, yrcv) most likely associated with the current (th1,th2) pair. Because the receiver (brightly lit or not lit) will be faint or completely masked below the black level of the camera when the latter gains are set to image a non-saturating sun under the filter, OBM.Query(. . .) this effectively allows the control system to predict the receiver location based on the data stored during the scan of the first phase.

[0049] (iii) The next step in the second phase includes generating commands to adjust the (th1, th2) of the heliostat to achieve symmetry of the visible sun blob and the estimated receiver blob. A closed-loop tracking is illustrated by example by the pseudocode below where the while loop which may invoke a Symmetric( ) predicate—may be a simple check for a Euclidian distance from (xsun,ysun) to (-xrcv,-yrcv), and a pseudo-coded adjustment body. This adjustment may select one of the Manhattan motions (sets of motions in straight lines at right angles to each other—akin to a stair-stepping pattern) in the (th1,th2) space expected to produce most improvement in symmetry. There may be, for example, four or eight such motions tried. That particular selection, and indeed, the entire sun tracking motion on a given day, may be stored, e.g., at the OBM, so as to guide and speedup the choices on the following day(s).

[0050] (iv) The process of the second phase may include a rest or sleep step for a period of time, e.g., few seconds to several tens of seconds (this depends on the maximum spillage allowable, a typical value is 15 seconds), until the process iterates to generate commands to reposition the heliostat mirror at a position that restores the antipodal symmetry between the visible sun and the predicted or estimated receiver as interpolated from tuples registered and stored during the first phase.

[0051] Exemplary pseudo-code representative of computer-readable instructions for executing the second phase; in this example, antipodal symmetry is maintained by the closed-loop tracking of the sun and the generation of estimated positions of the receiver based on data of a two-way table lookup:

Algm2:

```
IS.SetGain (LOW);
Heliostat.GoHome ( );
While ( !IS.HasBlob( ) )
  Vary heliostat angles to bring sun to view;
While ( SunIsUp( ) )
        (xsun, ysun) = IS.GetBlob( );
        (xrcv, rcv) = OBM.Query(th1,th2); // Interpolation
       While ( !Symmetric(xsun, ysun, xrcv, yrcv) )
            Vary heliostat angles to improve symmetry;
       Sleep (timeStep);
 }
```

[0052] Illustrated in FIG. **7** is an exemplary method for tracking the sun using the imager and corresponding tracking controller. In the morning, the tracking controller becomes active when the imager detects (step **702**) illumination above some predetermined threshold. The tracking controller then begins listening for (1) a control sequence (step **704**) instructing the tracking controller as to the proper tracking mode, for example, (2) calibration code (step **706**) instructing the tracking controller to initiate a calibration sequence in which the relative position of the mirror and receiver is precisely determined, and (3) setup code (step **708**) instructing the tracking controller to execute one or more configuration operations before being activated. The control sequence, calibration code, setup code, or combination thereof may be transmitted to the particular tracking controller using a wired system or wireless system including radio control (RC), infrared, or optical transmission mode received via the imager or other optical device. Alternatively, all the information may originate from an on-board processor.

[0053] If the control sequence specifies an open-loop tracking procedure, the decision block (test **710**) is answered in the affirmative and the tracking controller begins orienting (step **712**) the mirror based on a mathematical model prescribing the azimuth and elevation angles of the sun over the course of a day. If a closed-loop tracking mode is specified, then the decision block (test **710**) is answered in the negative and the heliostat controller begins looking for the sun (step **714**) in autonomous or local fashion, e.g., by detecting the sun blob on the camera sensor. If and when the sun is located (test **716**), the heliostat initiates (step **718**) a closed-loop tracking operation using feedback based on the camera image, and based on estimates of the receiver location, to continually orient the mirror so as to maintain (step **720**) the sun and receiver at the antipodal points about the camera's center axis, as described above in detail.

[0054] One of ordinary skill in the art will also appreciate that the elements, modules, and functions described herein may be further subdivided, combined, and/or varied and yet still be in the spirit of the embodiments of the invention. In addition, while a number of variations of the invention have been shown and described in detail, other modifications, which are within the scope of this invention, will be readily apparent to those of ordinary skill in the art based upon this disclosure, e.g., the exemplary flowcharts or processes described herein may be modified and varied and yet still be in the spirit of the invention. It is also contemplated that various combinations or subcombinations of the specific features and aspects of the embodiments may be made and still fall within the scope of the invention. Accordingly, it should be understood that various features and aspects of the disclosed embodiments can be combined with or substituted for one another in order to form varying modes of the disclosed invention. Thus, it is intended that the scope of the present invention herein disclosed should not be limited by the particular disclosed embodiments described above. Accordingly, the invention has been disclosed by way of example and not limitation, and reference should be made to the following claims to determine the scope of the present invention.

What is claimed is:

1. A system for directing incident radiation from a source to a target, the system comprising:
- a reflector for reflecting the incident radiation, the reflector having an optical axis and at least one angle of rotation;
- an imager attached to the reflector;
- a tracking controller coupled to the imager; and
- one or more actuators connected to the reflector and in communication with a tracking controller;
- wherein the tracking controller comprises a processor configured to:
  - i) receive image data from the imager;
  - ii) detect a source projection onto the image sensor
  - iii) determine an estimated target location relative to the imager based on predetermined target locations and at least one actuator position; and
  - iv) generate one or more actuator commands based on the received image data and the estimated target location.

2. The system of claim **1**, wherein the processor is further configured to receive at least one of: a first actuator position and a second actuator position; and determine an estimated target location on the image sensor based on a set of predetermined target locations and at least one received actuator position.

3. The system of claim **1** wherein the imager comprises a camera having a single neutral density lens filter.

4. A heliostat for directing incident light to a receiver, the heliostat comprising:
- a mirror for reflecting the incident light, the mirror having an optical axis substantially perpendicular to the mirror and at least one angle of rotation;
- an imager mounted to the mirror; and
- a tracking controller in communication with the imager; and
- one or more actuators in communication with the tracking controller;
- wherein the tracking controller comprises a processor configured to:
  - i) locate one or more image points corresponding to the center of the sun's projection on the imager;
  - ii) estimate at least one point on the imager corresponding to the receiver based on at least one actuator position; and
  - iii) generate one or more actuator commands to at least one reflector angle actuator to dispose the optical axis of the mirror between the one or more image points corresponding to the sun based on the image data from the imager and the at least one point corresponding to the receiver based on at least one actuator position.

5. The system of claim **4** wherein the imager comprises a camera having a single neutral density lens filter.

6. The heliostat of claim **4** wherein the tracking controller is further configured to: receive at least one actuator motor position; and determine an estimated target location based on a set of predetermined target locations and the received at least one actuator position.

7. A method of tracking the sun with a heliostat comprising an imager mounted to a mirror, the method comprising:
- determining one or more image points corresponding to the sun in a captured image;
- estimating one or more image points corresponding to a receiver based on a least one actuator position;
- actuating the mirror in one or more angular directions to improve the antipodal arrangement of the determined one or more image points corresponding to the sun and the estimated one or more image points corresponding to the receiver.

8. The method of claim **7** wherein the step of actuating the mirror further comprises at least one command based in part on a search based on a manhattan method.

9. The method of claim **7** further comprising:
- generating a lookup table based on captured image points of a receiver and at least one actuator position.

10. The method of claim **7** wherein the step of estimating one or more image points corresponding to a receiver is based on a least one actuator position and the generated lookup table based on captured image points of a receiver and the at least one actuator position.

* * * * *