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(54) HELIOSTAT CONTROL SCHEME USING CAMERAS

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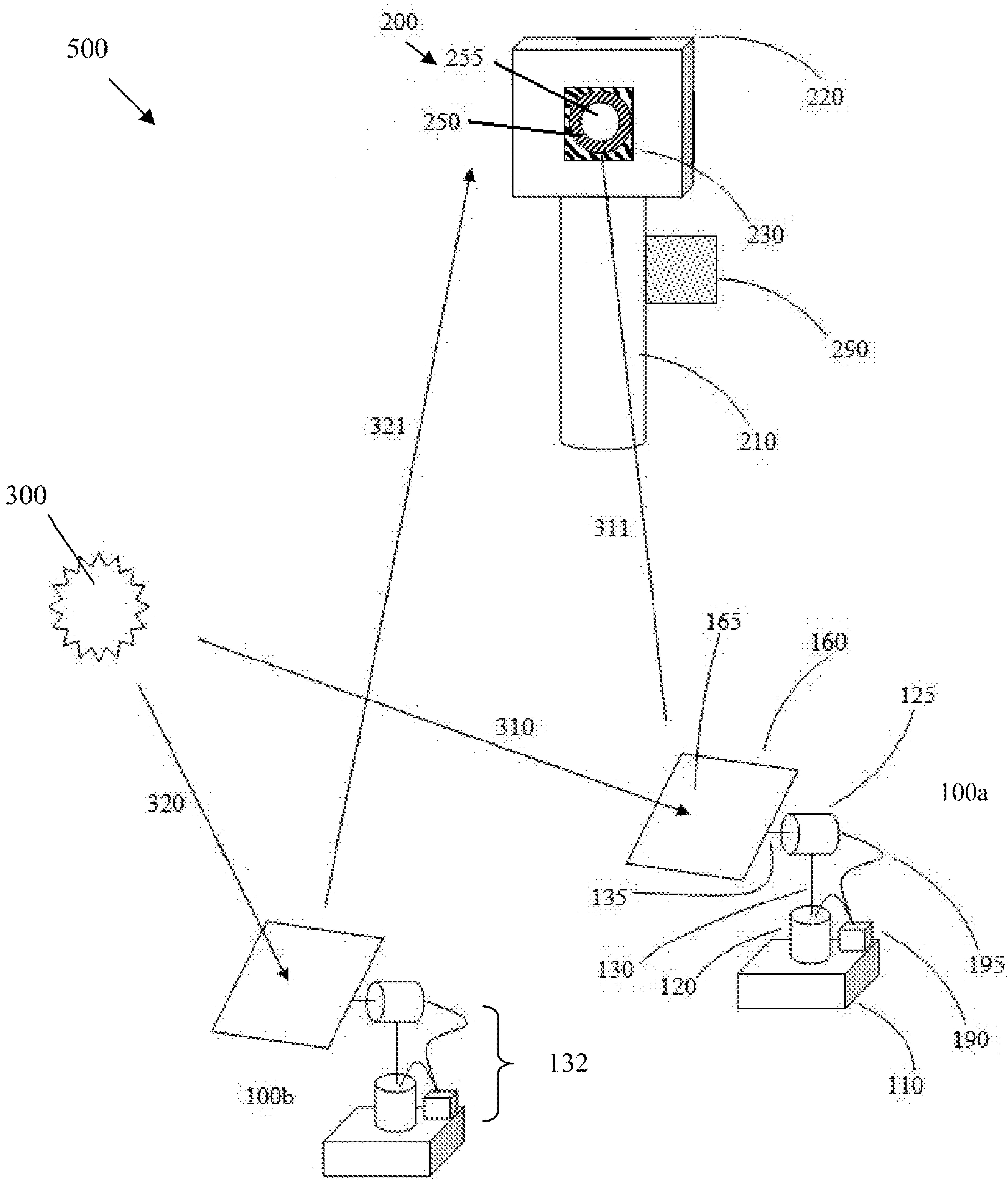
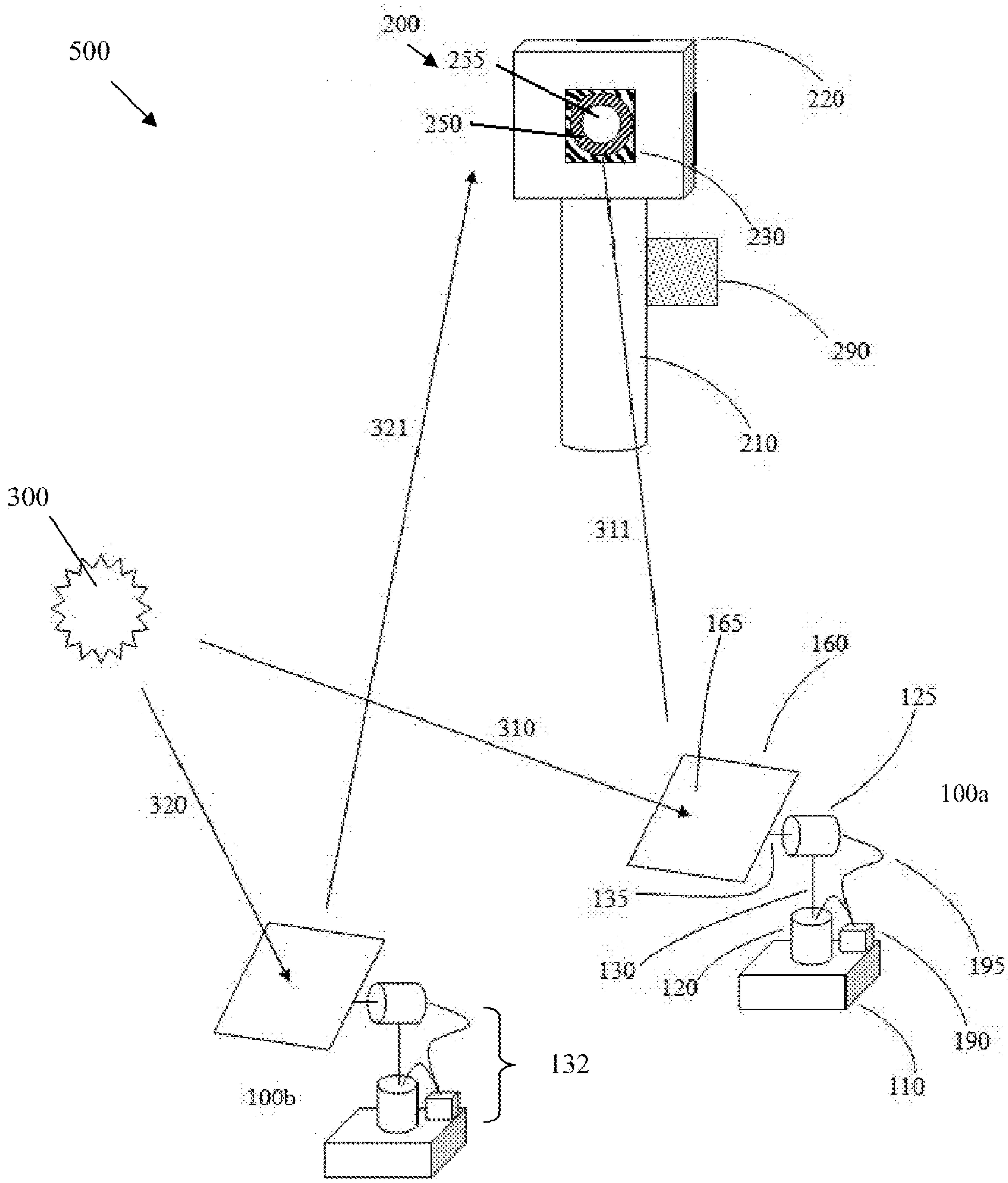
(57) ABSTRACT

A heliostat control system includes a receiver located within a receiver volume and a view port located proximate to the receiver volume. The receiver is configured to receive sunlight reflected from a mirror of a heliostat. The view port is optically connected to a camera, and the camera is configured to generate an image including pixels having a brightness dependent on an orientation of the mirror.




500
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290
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125
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100a
320
135
195
130
120
190
110
132
100b

FIG. 1

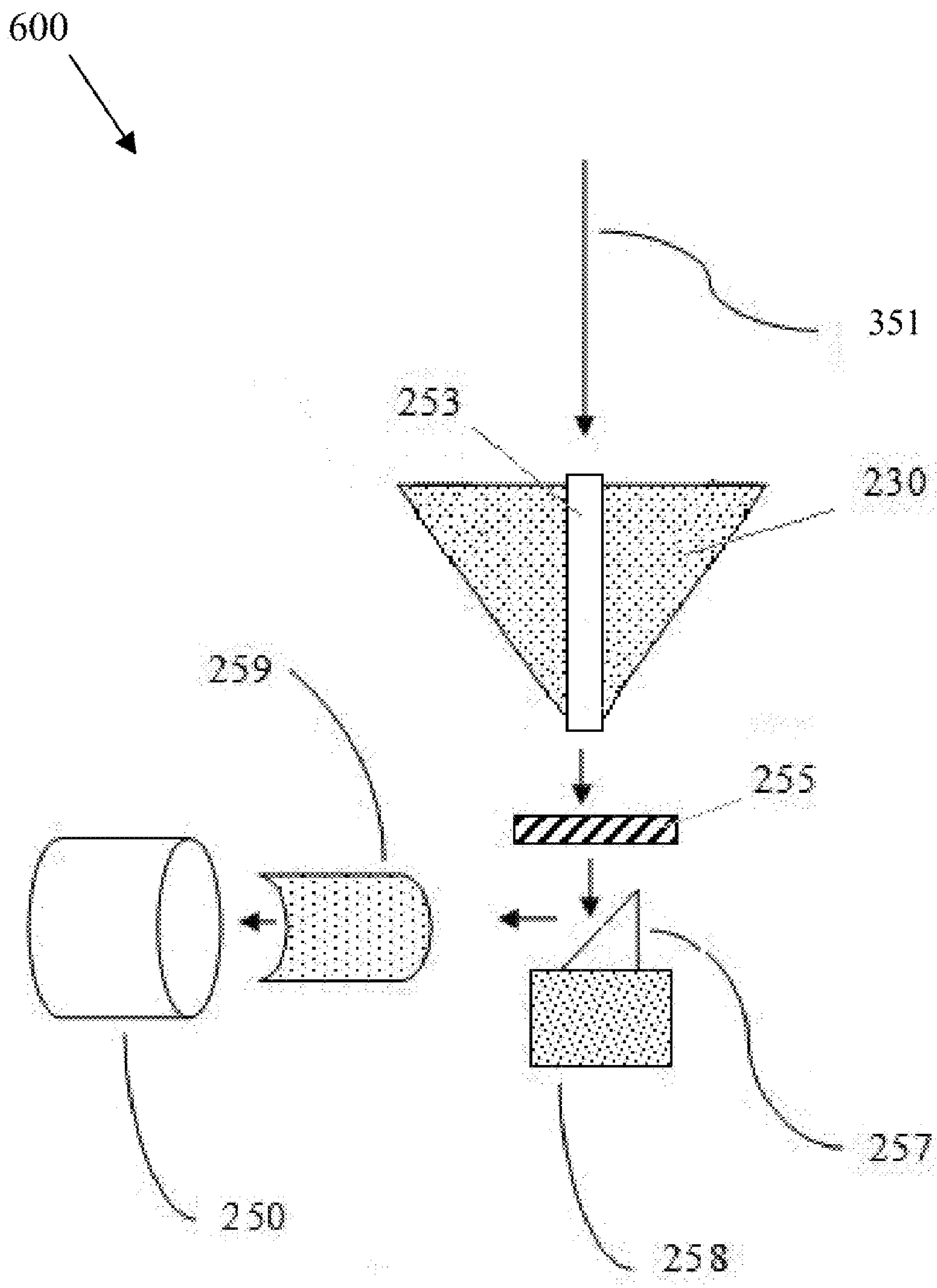
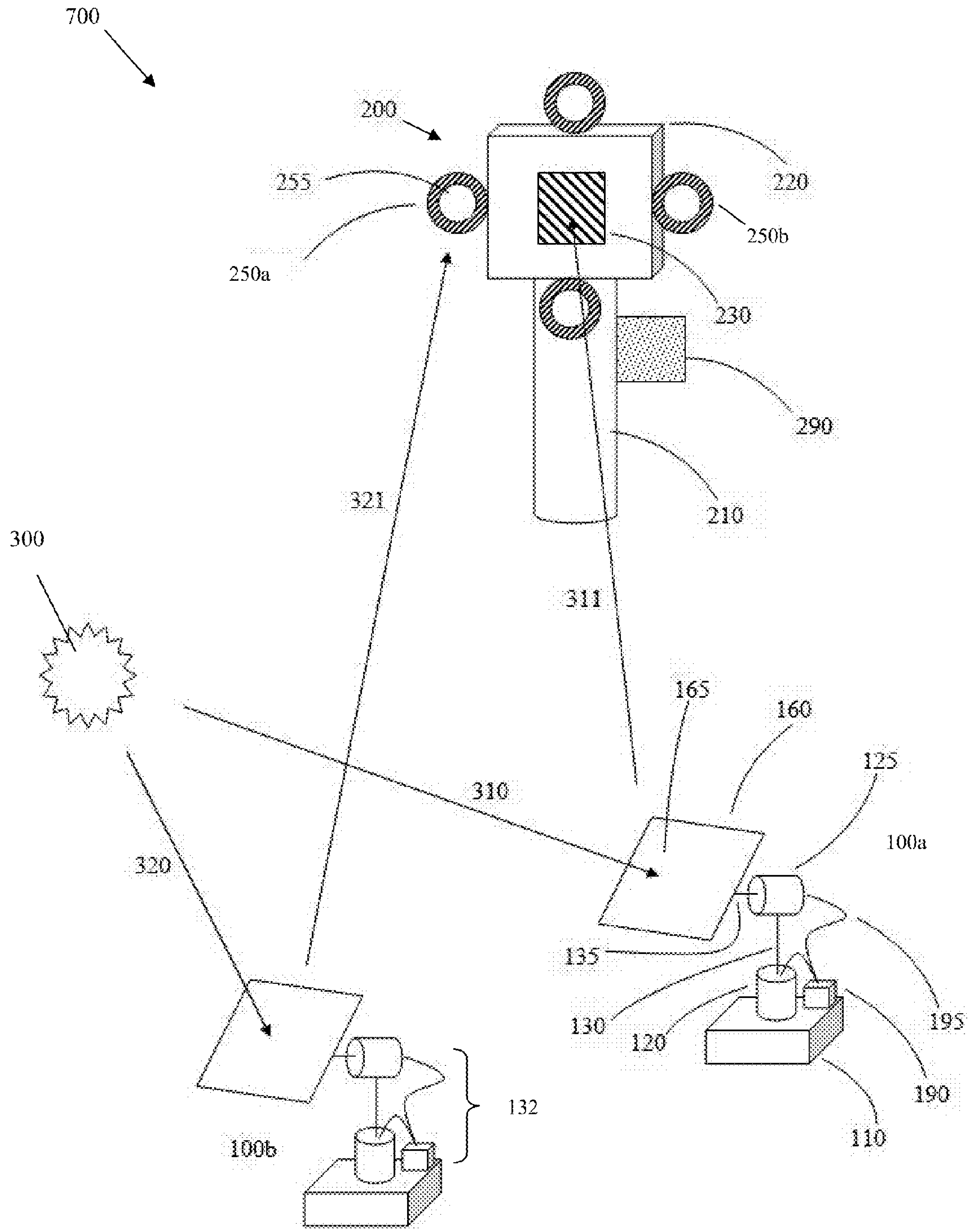


FIG. 2


700
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195
190
110
132
100b

FIG. 3

HELIOSTAT CONTROL SCHEME USING CAMERAS

TECHNICAL FIELD

[0001] The present disclosure relates generally to controlling heliostats using cameras.

BACKGROUND

[0002] A heliostat solar energy system generally includes a number of heliostats configured to reflect light into a receiver. The resulting heat can then be converted into power. Use of heliostats as a source of solar energy often requires receiver temperatures of nearly 1000° C., which in turn requires sunlight to be reflected from the heliostats into the receiver at high concentrations.

SUMMARY

[0003] In general, in one aspect, a heliostat control system includes a receiver located within a receiver volume and a view port located proximate to the receiver volume. The receiver is configured to receive sunlight reflected from a mirror of a heliostat. The view port is optically connected to a camera, and the camera is configured to generate an image including pixels having a brightness dependent on an orientation of the mirror.

[0004] This and other embodiments can optionally include one or more of the following features. The view port can be located within the receiver volume. There can be a plurality of heliostats, the receiver can be configured to receive sunlight reflected from a mirror of each of the plurality of heliostats, and the image can include pixels having a brightness dependent on an orientation of each of the mirrors.

[0005] The heliostat control system can further include a controller configured to receive the image from the camera and calculate an error in the orientation. The controller can be configured to send a signal to change the orientation of the mirror based upon the determined error. The controller can be configured to associate a portion of the image with the heliostat.

[0006] The heliostat control system can further include a cooling system configured to cool the camera. The camera can be located in the receiver volume. The camera can be located outside of the receiver volume. The heliostat control system can further include a reflecting mirror configured to reflect sunlight away from the receiver after it has entered the view port. The heliostat can further include an optical filter configured to reduce the intensity of the sunlight after it has entered the view port. The heliostat control system can further include a shading layer configured to protect the camera from sunlight. The heliostat control system can further include optics configured to alter the sunlight. There can be a plurality of view ports, and each view port can be optically connected to a corresponding camera. The view port can be configured to receive a portion of the sunlight that is received by the receiver.

[0007] In general, in one aspect, a method of heliostat control includes receiving sunlight in a receiver, generating an image from a camera, and determining an error in an orientation of the mirror based upon the image. The sunlight is reflected from a mirror of a heliostat. The camera is optically connected to a view port located within the receiver.

[0008] This and other embodiments can optionally include one or more of the following features. The sunlight can be reflected from a plurality of mirrors, each mirror can have a corresponding heliostat, and determining an error can include determining an error in an orientation of each of the mirrors. The error can be determined based upon a brightness of a portion of the image. The method can further include sending a signal to change the orientation of the mirror based upon the determined error. The method can further include assigning a portion of the image to the heliostat. The method can further include cooling the camera with a cooling system. Determining an error can include comparing images generated from a plurality of cameras. Determining an error can include comparing the image with an expected image.

[0009] In general, a method of heliostat control includes receiving sunlight in a receiver, generating a first image from a camera located proximate to the receiver, oscillating the heliostat at a known frequency, and assigning a portion of the image to the heliostat by identifying the oscillation in the first image. The sunlight is reflected from a mirror of a heliostat.

[0010] This and other embodiments can optionally include one or more of the following features. The method can further include generating a second image from the camera, locating in the second image the assigned portion, and determining an error in an orientation of the mirror based upon the assigned portion. The method can further include sending a signal to change the orientation of the mirror based upon the determined error.

[0011] Certain implementations may have one or more of the following advantages. Using cameras to detect the positioning of a heliostat can provide more precise positioning, be less expensive, require fewer components, and require less frequent maintenance and calibration than other tracking mechanisms, such as placing a sensor on each heliostat. Detecting the positioning of the heliostats allows the heliostats to be adjusted to provided higher concentration of the sunlight in the receiver. Higher concentration of sunlight in the receiver provides a higher quality or temperature of heat for the production of solar power.

[0012] By placing a camera, or view port of a camera, in the receiver, rather than outside of the receiver, misalignment of the heliostats can quickly be determined. Determining misalignment more quickly can ensure that heliostats are adjusted quickly. Adjusting heliostats quickly allows the receiver to have a higher concentration of sunlight for a greater fraction of the time.

[0013] Oscillating a heliostat at a known frequency allows a more accurate determination of which portions of an image of the heliostat field correspond to that particular heliostat. Accurate assignment of portions of the heliostat field image allows for a more accurate determination of which heliostat needs to be adjusted.

[0014] The details of one or more embodiments are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages will become apparent from the description, the drawings, and the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIG. **1** is a schematic diagram of a heliostat control system including cameras located inside the receiver.

[0016] FIG. **2** is a schematic diagram of a camera system having a view port located inside the receiver and a camera located outside of the receiver.

[0017] FIG. **3** is a schematic diagram of a heliostat control system including cameras located outside of the receiver.

[0018] Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0019] When heliostats are used as a source of heat (which can in turn be used as a source of power), the concentration of sunlight reflected into the heat-collecting receiver can be lower than the theoretical ideal due to misalignment of the heliostat mirrors caused by errors such as difficulties detecting the orientation of the mirrors or relative position of the receiver, deformation of the mirror, or movement of the heliostat or receiver by natural causes. Using a camera to generate an image including pixels having a brightness dependent on the orientation of the heliostat mirrors allows sunlight to be more accurately reflected into the receiver.

[0020] Referring to FIG. **1**, a heliostat control system **500**, e.g., for a solar power plant, includes a field of heliostats **100**, which can include up to hundreds or thousands of heliostats (only two heliostats **100***a*, **100***b* are shown in FIG. **1**). Each heliostat **100** includes a mirror **160** having a reflective surface **165** on the face of the mirror **160** closest to the sun **300**. The reflective surface **165** can be flat or curved for better optical performance. Moreover, the reflective surface **165** can be in the shape of a quadrilateral, e.g., a square, or it can have rounded edges, e.g., be circular. The mirror **160** can rest on a foundation **110**, which can be partially below ground.

[0021] An actuation system **132** is configured to move the heliostat mirror **160**. The actuation system **132** can include multiple motors, such as a motor **120** to move the heliostat **100** in the azimuth direction using a motor shaft **130**, and a motor **125** to adjust the altitude, i.e., angle of elevation, of the heliostat using a motor shaft **135**. The actuation system **132** further includes a transceiver **190** to receive commands directing the movement of the mirror **160**. Wires **195** can electrically connect the transceiver with the motors **120**, **125**. In other embodiments, the actuation system can include hydraulic, pneumatic, cable and pulley, ballasted, or ball and socket mechanisms to move the heliostat mirror in the azimuth direction and/or to adjust the altitude

[0022] The heliostat control system **500** further includes a tower system **200**. The tower system includes a receiver **230** to receive sunlight and a camera **250**, which can optionally include a filtering element **255** to reduce the intensity of the sunlight, and an optical element **259** (see FIG. **2**) to expand, contract, or condition the sunlight as necessary prior to entry of the beam into the camera. The receiver **230** can be shaped to receive concentrated sunlight, such as be circular in shape. The region in which the receiver is located can be called the "receiver volume" or the "hot region" of the tower system **200**. The receiver **230** can be located inside a housing **220** and can sit on top of a foundation structure **210**, which can be partially below ground.

[0023] The heliostat control system **500** further includes a controller or computer **290** to receive image data from the cameras **250**, to compute the movement of any heliostat mirrors **160** necessary to keep the heliostat oriented to reflect light to the receiver **230**, and to send commands to the transceivers **190** of the heliostats. The computer **290** can be part of the tower system **200**, as shown in FIG. **1**.

[0024] In operation, sunlight rays **320**, **310** from the sun **300** can strike the reflective surface **165** of the heliostat mirrors **160**. The reflective surface **165** can then reflect rays **321**, **311** towards the receiver **230**. The reflected rays **321**, **311**, in addition to rays reflected from other heliostats in the field, can heat the receiver **230** to temperatures of between 900° C. and 1200° C., such as between 950° C. and 1150° C. The heat can be used to drive various heat engines to produce power. For example, the heat can be used to warm cold air, which can then be expanded through a turbine engine which turns a generator shaft, which creates power. The more concentrated the sunlight is in the receiver **230**, the higher the temperature of the receiver **230**, and the more efficient the power generation of the system **500** can be.

[0025] In order to direct concentrated rays towards the receiver **230**, the normal vector of the reflective surface **165** must always bisect the angle between the rays **310**, **320** from the sun and the rays reflected towards the center of the receiver **230**. Thus, as the sun **300** moves across the sky, the orientation of the reflective surface **165** of the mirrors **160** must be adjusted to ensure that the reflected rays are hitting the receiver **230** without causing too much spillage, i.e., causing too many rays to be reflected outside of the receiver **230**.

[0026] The camera **255** mounted on the receiver **230** can be used to determine whether a particular mirror **160** is oriented to reflect substantially the maximum amount of light into the receiver, i.e., to orient the reflective surface **165** such that its normal vector substantially bisects the angle between the rays from the sun and the rays reflected towards the receiver. When rays from the heliostats **100** are reflected into the receiver **230**, and correspondingly to the camera **255**, the camera **255** observes and produces an image. The image produced by the camera **250** can include pixels having a brightness dependent on the orientation of the various heliostats. As a result, as discussed below, the image can be used to determine an error in the orientation of the mirrors.

[0027] A calibration step can be required prior to determining the actual error in orientation of a heliostat. During calibration, the assignment of a particular heliostat to a set of pixels in the camera's imaging array, can be determined. For example, during the calibration step, the camera **250** can observe and produce an image of the heliostat field. Portions of the image, or groups of pixels, can be assigned to a particular heliostat. In one embodiment, the heliostat can be oscillated at a known frequency. The computer **290** can then watch for that frequency of blinking in the image in order to identify that heliostat in the pixel array of the image. Proceeding through each of the heliostats, one at a time, each heliostat in an entire field of heliostats may be identified. Such a mechanism is important for unique identification of each heliostat. The computer **290** can maintain a database having the positions of all of the various heliostats in the field and the portions of the image corresponding to each of those heliostats.

[0028] Because there are generally multiple heliostats in a field, it may be advantageous to be able to detect when a heliostat is physically moved, or when a particular heliostat is added or removed from the field. Thus, in one embodiment, any new bright images that seem out of place may be compared with the original calibration images to look for changes. The system can automatically detect the positions of all of the heliostats in the field and recalibrate as necessary.

[0029] After the computer **290** has assigned a portion of an image to each heliostat in a field, the system **500** can be used to determine an error in an orientation of the mirrors (i.e. to determine whether the mirror is oriented to reflect a maximum amount of light into the receiver **230**) and subsequently to change the orientation of the mirrors **160** such that they reflect substantially the maximum amount of light into the receiver **230**. To do so, the computer **290** can try to maximize the sunlight seen by the camera **250** from each heliostat. If a portion of the image assigned to a particular heliostat does not include a bright spot, or includes a spot that is not as bright as expected, the computer **290** can determine that the mirror **160** for that heliostat is not oriented accurately. For example, in FIG. **1**, ray **321** is not hitting the center of the receiver **230**. As a result, the image produced by the camera **250** will not be as bright in the portion of the image corresponding to heliostat **100***b* as expected.

[0030] The computer **290** can send a command to motors on a particular heliostat, such as heliostat **100***b* in FIG. **1**, to direct the heliostat to move its mirror **160** accordingly. For example, the computer **290** can send a command, such as through a wireless or wired signal, through a transceiver **190** on the heliostat, which can in turn send a signal through wires **296** (or optionally can send a wireless signal) to the motors **120**, **125** on the heliostat. The motors can in turn adjust the mirrors **160** as directed.

[0031] For example, the motor **120** might first be commanded by the computer **290** to move a mirror **160** of a heliostat in a particular direction along the azimuth. If the brightness for the portion of the image assigned to that heliostat increases, then the computer **290** can command the motor **120** to continue to move the mirror **160** in that direction. In contrast, if the brightness decreases, then the computer **290** can command the motor **120** to move the mirror **160** in the opposite direction. These adjustment steps can then be repeated for elevating the mirror with motor **125**.

[0032] The system **500** can also use additional factors to optimize the movement of the heliostats. For example, the computer **290** can take into account celestial data and data of previous days' heliostat orientation paths. Further, the computer **290** can observe the image of the sun and use its distinct features, such as solar flares, to determine which direction to move.

[0033] As the receiver **220** is a hot, harsh environment, the camera **250** may need to be protected from the heat. In one embodiment, a cooling system can be used to protect the camera. For example, a jacket of coolant surrounding the camera can be connected to an external liquid coolant circulation system. Filters in front of the camera can allow only light at particular wavelengths to enter the camera while keeping the majority of the thermal energy away from the camera.

[0034] In another embodiment, shown in FIG. **2**, a camera system **600** can be used to protect the cameras **250** from the heat. The camera system **600** includes a view port **253** constructed of materials that withstand intense heat, such as ceramics, minerals, and metal alloys. In some embodiments, the materials are cooled in order to increase their resistance to heat. The view port **253** can extend through the receiver **230**, such as through the center of the receiver or just off the center of the receiver, or it can extend just outside of the receiver. The view port **253** can include an aperture that allows in only small amounts of light to pass, which can limit the amount of damaging thermal energy that enters the camera and can help sharpen the image. The camera system **600** can further include a filter **255**, optics **259**, and a camera **250**. A reflecting mirror **257** can be positioned on a base **258** between the view port **253** and the camera **250**. The reflecting mirror can be tilted as an angle between 0° and 90°, such as between 30° and 60°, for example 45.° Although not shown, a shading layer can extend outward from the receiver to keep spilled sunlight from hitting and damaging the camera **250** and related components. This shading structure could be made of reflective material, ceramic material, refractory material, or actively cooled material. Further, in some embodiments, the optical path can be routed from the viewport to cameras located behind the receiver itself.

[0035] In operation, sunlight **351** reflected from heliostats **100** (not shown in FIG. **2**) can travel through the view port **253**, such as through an aperture in the view port. The sunlight can further travel through the filter **255** to reduce the intensity of the sunlight to avoid damaging of the camera **250** and other components such as mirror **257** or optics **259**. Sunlight can then reflect off of the deflecting mirror **257** in order to move the sunlight from the region of the heat engine Finally, the sunlight can travel through optics **259** to expand, contract, or condition the sunlight as necessary to get the best accuracy, prior to entry of the sunlight into the camera. As in the embodiment described above, the camera can then produce an image including pixels having a brightness dependent on the orientation of the mirrors **160** of heliostats in the field. Such a configuration allows the rays to be sensed close to, or at the border of, the receiver **230** while keeping the electronic components of the camera **250** away from the hot environment of the receiver **230**.

[0036] In another embodiment, shown in FIG. **3**, a heliostat control system **700** includes multiple cameras **250** placed outside of the receiver **230**. Multiple cameras, e.g. four cameras, can be spaced around the receiver, e.g., above and below and to either side of the receiver **230**. The cameras **250** can be placed in proximity to the receiver where there is likely to be more spillage of sunlight, i.e., rays missing the receiver. For example, if the reflecting element **165** is rectangular in shape, and the receiver is circular in shape, the cameras can be placed around the corners of the receiver where there is likely to be more spillage.

[0037] In operation, each camera **250** can produce a separate image of the same portion of the heliostat field. As discussed above, the computer **290** can determine whether a particular heliostat is misaligned by analyzing the image data for that particular heliostat. In this embodiment, however, because the cameras **250** are not centered in the receiver **230**, the amount of sunlight seen by the camera from each heliostat **100** is not maximized. Rather, the image can be compared to the expected brightness, whether more or less bright, and the heliostats adjusted accordingly.

[0038] Additionally, when multiple images are produced from different cameras, the resulting images can be compared to one another. If the brightness is different from one camera to another in the portion of the image that corresponds to a particular heliostat, then the computer **290** can determine that the mirror of that particular heliostat is misaligned. For example, as shown in FIG. **3**, the ray **321** from heliostat **100***b* to the receiver **230** is not hitting the center of the receiver. As a result, the camera **250***a*, to which the ray **321** is closer, will see a brighter spot in the portion of the image corresponding to the heliostat **100***b* than will camera **250***b*.

[0039] The computer **290** can then command the motors of a misaligned heliostat to adjust the mirror **160**. As in the embodiment described above, the motors **120**, **125** can first be commanded to move a particular heliostat in a particular direction. In this embodiment, the mirror **160** can be moved by the motors until the mirrors see approximately equal brightnesses from the heliostat. For example, in FIG. **3**, mirror **160** of heliostat **100***b* can be moved such that the reflected ray **321** moves further away from camera **250***a* and closer to camera **250***b*. If the brightnesses of the portions of the images corresponding to heliostat **100***b* become equal for both cameras **250***a* and **250***b*, then the computer **290** can command the motors to stop moving the heliostat. In contrast, if camera **250***b* begins to see more light from **100***b* than camera **251**, the computer **290** can command the mirror **160** to move back in the opposite direction.

[0040] When cameras **250** are placed outside of the receiver **230**, as shown in FIG. **3**, the cameras need not receive spillage from the rays all of the time in order to be effective. Rather, the system can be configured to be triggered only when the reflected sunlight drifts out of the receiver and onto one of the cameras **250**.

[0041] In one embodiment, multiple cameras can be placed in the receiver. In another embodiment, multiple view ports can be placed in the receiver, each view port connected to a different camera. In another embodiment, multiple cameras can be mounted at a distance from the receiver, and optical paths can be used that project the image to the cameras.

[0042] In one embodiment the projected image from the field can be incident on the front side of a semitransparent screen. The cameras can observe the backside of this screen, where the intensity is drastically reduced. The screen could be made of glasses, sheets, thin ceramics.

[0043] By using a camera scheme to control the orientation of individual heliostat mirrors, a closed-loop heliostat control system can be provided that ensures that sunlight is reflected from each heliostat into the desired receiving location. Given the available speed of image processing, errors in the heliostat reflection can be controlled on a real-time, or near-real time basis. Such a system allows concentrated sunlight to enter the receivers for a large fraction of the day in order to provide sufficiently high temperatures for the creation of solar power.

[0044] Particular embodiments have been described. Other embodiments are within the scope of the following claims.

What is claimed is:

1. A heliostat control system, comprising:

a receiver located within a receiver volume, the receiver configured to receive sunlight reflected from a mirror of a heliostat; and

a view port located proximate to the receiver volume, the view port optically connected to a camera, the camera configured to generate an image including pixels having a brightness dependent on an orientation of the mirror.

2. The heliostat control system of claim **1**, wherein the view port is located within the receiver volume.

3. The heliostat control system of claim **1**, wherein there are a plurality of heliostats, the receiver is configured to receive sunlight reflected from a mirror of each of the plurality of heliostats, and the image includes pixels having a brightness dependent on an orientation of each of the mirrors.

4. The heliostat control system of claim **1**, further comprising a controller configured to receive the image from the camera and calculate an error in the orientation.

5. The heliostat control system of claim **4**, wherein the controller is further configured to send a signal to change the orientation of the mirror based upon the determined error.

6. The heliostat control system of claim **4**, wherein the controller is further configured to associate a portion of the image with the heliostat.

7. The heliostat control system of claim **1**, further comprising a cooling system configured to cool the camera.

8. The heliostat control system of claim **1**, wherein the camera is located in the receiver volume.

9. The heliostat control system of claim **1**, wherein the camera is located outside of the receiver volume.

10. The heliostat control system of claim **9**, further comprising a reflecting mirror configured to reflect sunlight away from the receiver after it has entered the view port.

11. The heliostat control system of claim **1**, further comprising an optical filter configured to reduce the intensity of the sunlight after it has entered the view port.

12. The heliostat control system of claim **1**, further comprising a shading layer configured to protect the camera from sunlight.

13. The heliostat control system of claim **1**, further comprising optics configured to alter the sunlight.

14. The heliostat control system of claim **1**, wherein there are a plurality of view ports, each view port optically connected to a corresponding camera.

15. The heliostat control system of claim **1**, wherein the view port is configured to receive a portion of the sunlight that is received by the receiver.

16. A method of heliostat control, comprising:

receiving sunlight in a receiver, the sunlight reflected from a mirror of a heliostat;

generating an image from a camera, the camera optically connected to a view port located within the receiver; and

determining an error in an orientation of the mirror based upon the image.

17. The method of claim **16**, wherein the sunlight is reflected from a plurality of mirrors, each mirror having a corresponding heliostat, and wherein determining comprises determining an error in an orientation of each of the mirrors.

18. The method of claim **16**, wherein the error is determined based upon a brightness of a portion of the image.

19. The method of claim **16**, further comprising sending a signal to change the orientation of the mirror based upon the determined error.

20. The method of claim **16**, further comprising assigning a portion of the image to the heliostat.

21. The method of claim **16**, further comprising cooling the camera with a cooling system.

22. The heliostat control system of claim **16**, wherein determining comprises comparing images generated from a plurality of cameras.

23. The heliostat control system of claim **16**, wherein determining comprises comparing the image with an expected image.

24. A method of heliostat control, comprising:

receiving sunlight in a receiver, the sunlight reflected from a mirror of a heliostat;

generating a first image from a camera located proximate to the receiver;

oscillating the heliostat at a known frequency; and

assigning a portion of the image to the heliostat by identifying the oscillation in the first image.

25. The method of claim **24**, further comprising:

generating a second image from the camera;

locating in the second image the assigned portion; and

determining an error in an orientation of the mirror based upon the assigned portion.

26. The method of claim **25**, further comprising sending a signal to change the orientation of the mirror based upon the determined error.

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