METHODS AND SYSTEMS FOR OPERATING SOLAR TOWER SYSTEMS

Applicant: BRIGHTSOURCE INDUSTRIES (ISRAEL) LTD., Jerusalem (IL)

Inventors: Gil KROYZER, Jerusalem (IL); Rotem HAYUT, Jerusalem (IL); Joseph SCHWARZBACH, Jerusalem (IL); Amos EITAN, Jerusalem (IL)

Assignee: BRIGHTSOURCE INDUSTRIES (ISRAEL) LTD., Jerusalem (IL)

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ABSTRACT

A solar energy system can be controlled and operated responsive to detected and/or predicted changes in insolation conditions. By placing an imaging aperture of an imaging device as part of an external surface of a solar receiver, an orientation of each heliostat in a heliostat field can be determined. The imaging device can be used to image at least a portion of the heliostat field based on light passing through the imaging aperture, which is proximate to, adjacent to, or at least partially within the capture area of the solar receiver so as to acquire at least one image indicating a change in a distribution of insolation levels falling on the portion of the field. Characteristics of heliostats within the portion of the field can be calculated based on the at least one image. Aiming directions of one or more can be changed based on the calculated characteristics.
3. Acquire one or more images indicative of one or more clouds with respect to heliostat field.

S105
Analyze the one or more images and determine a shading parameter for heliostat field.

S110
Establish, modify, or maintain at least one operating parameter of the solar energy system.

FIG. 8

FIG. 9
FIG. 13A

Time = t₀

FIG. 13B

Time = t₁

Direction of beam travel

Direction of beam travel
FIG. 13C

Time = t2

Direction of beam travel

FIG. 13D

Time = t3

Direction of beam travel
Direction of beam travel

*For clarity the receiver is not shown in this figure.
*for clarity the receiver is not shown in this figure

FIG. 15A

Direction of beam travel

FIG. 15B

*for clarity the receiver is not shown in this figure
For each heliostat, capture S309 image/s of the reflected sunlight.

Analyze S321 data obtained for each of the heliostats.

According to the results of the data analysis, select S365 a sub-plurality of heliostats to cause to be simultaneously aimed to the target.

Direct S301 the heliostat to the target (i.e., solar energy receiver) mounted on the tower.

Direct S205 the heliostat to an array of imaging devices whose imaging aperture is within an aiming point of the receiver. The projected reflection beam to traverse across the array.

Capture S309 an image/s of the reflected light as it traverses the array of imaging devices.

According to captured image/s, determine S315 one or more beam projection parameters of the heliostat,

FIG. 16B

FIG. 16A
METHODS AND SYSTEMS FOR OPERATING SOLAR TOWER SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims the benefit of U.S. Provisional Application No. 61/610,845, filed Mar. 14, 2012, which is hereby incorporated by reference herein in its entirety.

FIELD

[0002] The present disclosure relates generally to solar energy systems, and, more particularly, to methods and systems for operating and controlling a tower-based solar energy system.

SUMMARY

[0003] Some embodiments, relate to methods of facilitating the conversion of solar radiation to thermal and electric energy.

[0004] In some embodiments, a method of controlling a solar energy system includes reflecting insolation from each of a plurality of heliostats in a field of heliostats to a receiver configured to receive reflected flux. During operation of the solar energy system, each of the heliostats may be controlled to traverse an array of imaging devices whose imaging apertures are located within the capture area of the receiver.

[0005] Embodiments of the present disclosure relate to techniques and apparatus for operating a solar steam system responsive to detected and/or predicted changes in insolation conditions. Techniques disclosed herein may be applied to detection or prediction of a reduction in insolation due to any factor, or combination of factors. Factors that may cause a permanent or temporary reduction in insolation include, but are not limited to, cloud coverage, an increased presence of dust, a dysfunctional heliostat and solar eclipses.

[0006] By placing an imaging device or more specifically the imaging aperture of the imaging device within a capture area of the receiver, the orientation of each of the heliostats can quickly be determined. Determining the orientation of each of the heliostats can ensure that heliostats are adjusted and/or oriented quickly. Adjusting heliostats quickly allows the receiver to have a higher concentration of insolation for a greater fraction of the time.

[0007] In some embodiments, a receiver is configured to receive insolation reflected from heliostats located within a field of heliostats. An imaging device may be positioned such that the imaging device’s imaging aperture is located within a capture area of the receiver. For example, the imaging device may be a pinhole camera or a camera obscura. The imaging aperture may be optically connected to a camera. The imaging device may be configured to acquire an image containing multiple pixels. The brightness of each pixel may be dependent on the amount of light reflected from the heliostat to the receiver.

[0008] As the imaging device is located within a high insolation flux zone, the imaging device may be designed in order to withstand the high temperatures associated with high energy fluxes. The imaging device may include a cooling system configured to cool the camera.

[0009] Use of such an imaging device may aid in quickly determining if any heliostat in the field of heliostats is either not reflecting light onto the receiver or if the heliostat is not reflecting the expected amount of sunlight onto the receiver. This may be determined by the brightness of a specific portion of the image, wherein at least a subset of the heliostats within the field of heliostats in the image is at least a portion of the image. The method can further include sending a signal to change the aiming point of one or more heliostats based upon the acquired image.

[0010] By acquiring at least one image indicating a change in distribution of changing insolation levels on at least a subset of the heliostats within the field of heliostats, one may calculate which heliostats are shaded and which are unshaded. The change in distribution in insolation levels may result in a change in flux distribution across an aiming point of the receiver. The change in insolation levels may be a result of c dirt, breakage of heliostats, shading by structures, shading by clouds, and shading by flora or fauna.

[0011] As a result of the detecting of the shaded heliostats, the aiming direction of one or more of the unshaded heliostats may be changed in order to compensate for the change in the flux distribution on the receiver.

[0012] Embodiments of the present disclosure relate to methods of determining the amount of solar energy flux incident on the external surface of the receiver. During operation of the solar energy system, each of the heliostats may be controlled to track the apparent movement of the sun to reflect insolation to the external surface of the receiver. An array of imaging devices, whose imaging apertures is within a capture area of the receiver, are configured to capture an image of the light incident on the external surface of the receiver. Based on the acquired image or set of images, the total energy flux level on the receiver may be calculated. Based on the calculated total energy flux, each of the plurality of heliostats may be directed to reflect insolation onto aiming points on the external surface of the receiver. The aiming points may be the same or may be different than those prior to the determining of the total flux.

[0013] In some embodiments, a method of controlling a solar energy system includes acquiring at least one image of a shadow on a subset of heliostats within a field of heliostats. The at least one imaging device used to acquire the at least one image may have an imaging aperture located within a capture area of the receiver. Based on the acquired image, the operating parameters of the solar energy system may be modified or changed. Operating parameters may include but are not limited to changing a temperature of an external energy conversion device, changing a turbine operating parameter, and changing an aiming direction of one or more heliostats.

[0014] Some embodiments relate to a method of controlling a solar energy system. The system may include a tower-based receiver and a field of heliostats controlled to direct insolation toward a capture area of the receiver, a subset of the heliostats being controlled to direct insolation at respective aiming points within the capture area. The method may include (i) using at least one camera, imaging the field from light passing through an imaging aperture, located proximate, adjacent, or at least partially within the capture area of the receiver, to acquire at least one image indicating a change in a distribution of insolation levels falling on the field, (ii) using an image processor, responsive to said at least one image, calculating characteristics of heliostats within the field of heliostats, (iii) responsive to said characteristics, changing aiming directions of one or more heliostats in said field.
The step of calculating may include identifying shaded heliostats and unshaded heliostats. The step of calculating may include determining a magnitude of change in insolation levels falling on each heliostat in said at least one image. In some embodiments, the calculating may be effective to determine variations in insolation levels falling on heliostats as a result of dirt, breakage of heliostats, shading by structures, shading by clouds, and shading by flora or fauna.

The changing the aiming direction of the heliostat may result in a change in a flux distribution across the capture area of the first receiver. The changing the aiming direction of the heliostat may include calculating a characteristic of a change in a flux distribution responsive to said characteristics of heliostats. The calculating characteristics of heliostats may include calculating characteristics of shaded heliostats within the field of heliostats.

The imaging aperture may be located at least partially within a capture area of the receiver. Alternatively, the imaging aperture is within the capture area of the first receiver. The camera may be cooled using a heat exchanger connected to the at least one camera to transfer heat to a heat transfer fluid. The camera may have a heat exchanger and a pump or fan configured to move a heat transfer fluid across a heat transfer surface of the heat exchanger, the heat exchanger being configured to cool the camera thereby. In some embodiments, the camera may be actively cooled by conveying a heat transfer fluid across a heat transfer surface conducting heat from the camera. The camera may be actively cooled using a thermoelectric cooling system.

The changing the aiming directions of the heliostats may include calculating a characteristic and a consequence of maintaining a respective aiming direction of at least one heliostat. The aiming directions changed by said changing may intercept said capture area, or alternatively they may intercept a capture area of a second receiver. In a further embodiment, the changing includes aiming at least one of the one or more heliostats from respective multiple aiming points so that they no longer intercept the capture area of the receiver. Responsive to the calculated characteristics, a total energy flux on an external surface of the receiver may be calculated. Based on the calculated total energy flux, heliostats may be directed to reflect the solar radiation onto aiming points on the external surface of the first receiver based at least in part on the calculated total energy flux. During operation of the solar energy system, the total energy flux may be calculated continuously.

Some embodiments relate to a method of controlling a solar energy system. The method may include at some times reflecting sunlight from each of a plurality of heliostats to an energy conversion target mounted on a tower and at other times controlling each heliostat so that the light beam reflected by the heliostat traverses an array of imaging device positioned within an area defined by the target. The method may further include acquiring multiple images of each of the heliostats. At least one geometric parameter of each of the heliostats may be estimated based at least in part on the acquired images. The estimating may also be based on a nominal geometric parameter of each of the heliostats. Based at least in part on the estimated geometric parameter the heliostats may be oriented to reflect sunlight to a target on the receiver. The solar flux distribution of each heliostat on an external face of the receiver may be determined based at least in part on the light intensity of the light reflected by the heliostats as seen in the acquired images.

In some embodiments, the reflected beam shape may be determined based at least in part on the determined solar flux distribution of each of the heliostats. Based at least in part on the determining of the solar flux distribution a heliostat may be directed to reflect incoming solar radiation onto aiming points on the external surface of the receiver.

Some embodiments relate to a method of controlling a solar energy system, the system having a receiver mounted on a tower and a field of heliostats arranged to direct insolation toward a capture aperture of the receiver. The method includes (i) generating at least one image, containing the at least one subset of heliostats, from light received through an imaging aperture, located adjacent or fully or partly within the capture area, from insolation reflected from a region coinciding with locations of at least a subset of the heliostats within the field of heliostats, the at least one image indicating a change in a distribution of insolation levels, resulting in a change in a flux distribution across the capture aperture falling on the at least a subset of the heliostats, (ii) using at least one programmable controller connected to control positions of at least a subset of the heliostats within the field of heliostats, responsive to said image, calculating characteristics of heliostats within the field of heliostats and (iii) using the one programmable controller, responsive to at least a result of the calculating, changing aiming directions of one or more heliostats to effect a target flux distribution responsive to data stored in the at least one programmable controller.

In some embodiments, the changing the aiming directions of the heliostat may include calculating a characteristic of the change in a flux distribution and is additionally responsive to a result of said calculating. The calculating may include identifying shaded heliostats and unshaded heliostats. The calculating may be effective to determine variations in insolation levels falling on heliostats as a result of dirt, breakage of heliostats, shading by structures, shading by clouds, and shading by flora or fauna.

Some embodiments relate to a computer readable medium having recorded thereon instructions for performing the above mentioned methods. Some embodiments relate to a controller programmed to perform the above mentioned methods.

Some embodiments relate to a system having a tower-based first receiver and a field of heliostats controlled by a controller to direct insolation toward a capture area of the receiver, the controller may also be configured to implement the abovementioned methods.

Objects and advantages of embodiments of the present disclosure will become apparent from the following description when considered in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments will hereinafter be described with reference to the accompanying drawings, which have not necessarily been drawn to scale. Where applicable, some features may not be illustrated to assist in the illustration and description of underlying features. Throughout the figures, like reference numerals denote like elements.

FIG. 1 shows a solar energy tower system, according to one or more embodiments of the disclosed subject matter.
FIG. 2 shows a solar energy tower system illustrating individual heliostats, according to one or more embodiments of the disclosed subject matter.

FIG. 3 shows another solar energy tower system with secondary reflector, according to one or more embodiments of the disclosed subject matter.

FIG. 4 shows a solar energy tower system including multiple towers, according to one or more embodiments of the disclosed subject matter.

FIG. 5 shows a solar energy tower system including multiple receivers in a single tower, according to one or more embodiments of the disclosed subject matter.

FIG. 6 is a schematic diagram of a heliostat control system, according to one or more embodiments of the disclosed subject matter.

FIG. 7A shows a solar energy tower system including an imaging device, according to one or more embodiments of the disclosed subject matter.

FIG. 7B shows a solar energy tower system an imaging device for cloud compensation, according to one or more embodiments of the disclosed subject matter.

FIG. 8 is a schematic diagram of an imaging device, according to one or more embodiments of the disclosed subject matter.

FIG. 9 is a process flow diagram for operating a solar energy system to account for shading, according to one or more embodiments of the disclosed subject matter.

FIG. 10A is a simplified aerial view of a receiver and a portion of a heliostat field of a solar energy system, according to one or more embodiments of the disclosed subject matter.

FIGS. 10B-10C show the view of FIG. 10A with different portions of the heliostat field shaded by one or more clouds, according to one or more embodiments of the disclosed subject matter.

FIG. 11 shows shadows created by clouds of different thicknesses, according to one or more embodiments of the disclosed subject matter.

FIG. 12 illustrates heliostat offset, according to one or more embodiments of the disclosed subject matter.

FIGS. 13A-13E, 14A-14B, and 15A-15B are diagrammatic elevation views of various examples of arrays of imaging devices whose imaging aperture is within a capture area of the receiver, according to one or more embodiments of the disclosed subject matter. Note that in FIGS. 14B-15B, the receiver is not shown to allow more clear illustration of the imaging device features.

FIGS. 16A-16B are flowcharts of operational steps of heliostat operation in a solar energy system, according to one or more embodiments of the disclosed subject matter.

FIG. 17 is diagrammatic elevation view of an array of imaging devices whose imaging aperture is within a capture area of the receiver illustrating a method for calibrating multiple heliostats at substantially the same time, according to one or more embodiments of the disclosed subject matter.

DETAILED DESCRIPTION

Embodiments of the present disclosure relate generally to solar energy systems that include at least one solar field, e.g., one or more apparatus for redirecting insolation toward a solar target. Solar targets can be configured to convert insolation into another form of energy, e.g., electricity (for example, by using photovoltaic cells), thermal energy (for example, by using sun solar thermal systems), or biofuels. The one or more solar fields may have different geometries. For example, a plurality of heliostats can track the sun to reflect incident sunlight onto a solar target, for example, at or near the top of a solar tower.

Embodiments of solar tower systems are shown in FIGS. 1-5. In embodiments, incident solar radiation can be used by the solar tower systems to generate solar steam and/or for heating molten salt. In FIG. 1, a solar tower system can include a solar tower 50 that receives reflected focused insolation from a solar field 60 of heliostats (individual heliostats 70 are illustrated in FIG. 2). Mounted in or on the solar tower 50 is a solar energy receiver system 500, which can include one or more individual receivers. The solar receivers can be constructed to heat water and/or steam and/or supercritical steam and/or another type of heat transfer fluid using insolation received from the heliostats. For example, the solar tower 50 can have a height of at least 25 meters, at least 50 meters, at least 75 meters, at least 150 meters or even higher.

With reference to FIG. 2, two individual heliostats 70 are shown. The heliostats 70 can be aimed at solar energy receiver system 500, for example, a solar energy receiving surface of one or more receivers of system 500. Lines 700 represent optical paths for beams of sunlight reflected by heliostats 70 onto the solar energy receiver system. Heliostats 70 can adjust their orientation to track the sun as it moves across the sky, thereby continuing to reflect sunlight onto one or more aiming points associated with the solar energy receiver system 500. This tracking capability may be provided at least in part by a heliostat controller (not shown) for controlling one or more orientation parameters of heliostat 70.

The solar energy receiver system 500 can be arranged at or near the top of tower 50, as shown in FIGS. 1-2. In another embodiment, a secondary reflector 40 can be arranged at or near the top of a tower 50, as shown in FIG. 3. The secondary reflector 40 can receive insolation from the field of heliostats 60 and redirect the insolation (e.g., through reflection) toward a solar energy receiver system 500. The solar energy receiver system 500 can be arranged within the field of heliostats 60, outside of the field of heliostats 60, at or near ground level, at or near the top of another tower 50, above or below reflector 40, or elsewhere.

More than one solar tower 50 can be provided, each with a respective solar energy receiver system thereon, for example, a solar power steam system. The different solar energy receiving systems may have different functionalities. For example, one of the solar energy receiving systems may heat water using the reflected solar radiation to generate steam while another of the solar energy receiving systems may serve to superheat steam using the reflected solar radiation. The multiple solar towers 50 may share a common heliostat field 60 or have respective separate heliostat fields. Some of the heliostats may be constructed and arranged so as to alternatively direct insolation at solar energy receiving systems in different towers. In addition, the heliostats may be configured to direct insolation away from any of the towers, for example, during a dumping condition.

For example, in the embodiment of FIG. 4, two solar towers 50A, 50B are provided, each with a respective solar energy receiving system. A first tower 50A has a first solar energy receiving system 500A while a second tower 50B has a second solar energy receiving system 500B. The solar towers 50A, 50B can receive reflected solar radiation from a
common field of heliostats 60A. The solar towers 50A, 50B can also receive reflected solar radiation from separate fields of heliostats 60B. At any given time, a heliostat within the field of heliostats 60A may be directed to a solar receiver of any one of the solar towers 50A, 50B. Although only two solar towers with respective solar energy receiving systems are shown in Fig. 4, any number of solar towers and solar energy receiving systems can be used.

[0050] More than one solar receiver can be provided on a solar tower. The multiple solar receivers in combination may form a part of the solar energy receiving system. The different solar receivers may have different functionalities. For example, one of the solar receivers may heat water using the reflected solar radiation to generate steam while another of the solar receivers may serve to superheat steam using the reflected solar radiation. Alternatively, one or more receivers may heat molten salts or metals. The multiple solar receivers can be arranged at different heights on the same tower or at different locations (e.g., different faces, such as a north face, a west face, etc.) on the same tower. Some of the heliostats in field 60 may be constructed and arranged so as to alternatively direct insolation at the different solar energy receiving systems.

[0051] For example, in the embodiment of Fig. 5, two solar receivers are provided on a single tower 50. The solar energy receiving system 500 includes a first solar receiver 810 and a second solar receiver 820. At any given time, a heliostat 70 may be aimed at either of the two solar receivers, or at none of the receivers. A subset of heliostats may be aimed at one receiver while another subset is aimed at the other receiver. In some use scenarios, the aim of a heliostat 70 may be adjusted so as to move a centroid of the reflected beam projected at the tower 50 from one of the solar receivers (e.g., 810) to the other of the solar receivers (e.g., 820). Although only two solar receivers and a single tower are shown in Fig. 5, any number of solar towers and solar receivers can be used.

[0052] Heliostats 70 in a field 60 can be controlled through a central heliostat field control system 91, for example, as shown in Fig. 6. For example, a central heliostat field control system 91 can communicate hierarchically through a data communications network with controllers of individual heliostats. Fig. 6 illustrates a hierarchical control system 91 that includes three levels of control hierarchy, although in other implementations there can be more or fewer levels of hierarchy, and in still other implementations the entire data communications network can be without hierarchy, for example, in a distributed processing arrangement using a peer-to-peer communications protocol.

[0053] At a lowest level of control hierarchy (i.e., the level provided by heliostat controllers) in the illustration there are provided programmable heliostat control systems (HCS) 65, which control the two-axis (azimuth and elevation) movements of heliostats (not shown), for example, as they track the movement of the sun. At a higher level of control hierarchy, heliostat array control systems (HACS) 92, 93 are provided, each of which controls the operation of heliostats in heliostat fields 96, 97, by communicating with programmable heliostat control systems 65 associated with those heliostats through a multipoint data network 94 employing a network operating system such as CAN, DeviceNet, Ethernet, or the like. At a still higher level of control hierarchy a master control system (MCS) 95 is provided which indirectly controls the operation of heliostats in heliostat fields 96, 97 by communicating with heliostat array control systems 92, 93 through network 94.

[0054] In Fig. 6, the portion of network 94 provided in heliostat field 96 can be based on copper wire or fiber optics connections, and each of the programmable heliostat control systems 65 provided in the field 96 can be equipped with a wired communications adapter, as are master control system 95, heliostat array control system 92 and wired network control bus router 100, which is optionally deployed in network 94 to handle communications traffic to and among the programmable heliostat control systems 65 in the field 96 more efficiently. In addition, the programmable heliostat control systems 65 provided in heliostat field 97 communicate with heliostat array control system 93 through network 94 by means of wireless communications. To this end, each of the programmable heliostat control systems 65 in the field 97 is equipped with a wireless communications adapter 102, as is wireless network router 101, which is optionally deployed in network 94 to handle network traffic to and among the programmable heliostat control systems 65 in the field 97 more efficiently. In addition, master control system 95 is optionally equipped with a wireless communications adapter (not shown).

[0055] As shown in Fig. 7A, an imaging system may include one or more imaging devices 198 arranged behind receiver 500, such that its imaging aperture is located proximate to, adjacent to or at least partially within the capture area of receiver 500. A capture area may be defined as the area to which the heliostat reflects sunlight onto the receiver. The capture area may be defined by the operation needs of the solar energy system and therefore change on a minute, hourly, daily, or any other time basis. In some embodiments, the image device may be placed such that the imaging device’s imaging aperture is located between adjacent receiver panels. According to embodiments, the imaging device is a pinhole camera or a camera obscura.

[0056] As shown in Fig. 7A, heliostats 70 within the field can be aimed to reflect insolation toward a capture area of a receiver, i.e., solar energy receiving system 500, mounted on tower 50, to heat water, molten salt, or any other material.

[0057] As noted above, the capture area of the receiver may be defined as the area of the receiver upon which the heliostats reflects insolation. The capture area is not necessarily a finite point or area on the receiver and may change depending on the operational needs of the system. In some embodiments, the imaging aperture of the imaging device lies within the capture area of the receiver. In other embodiments, the imaging aperture is located at least partially within the capture area of the receiver.

[0058] The solar energy system may further include a controller or computer to receive image data from one or more cameras 198, which then may be used to calculate characteristics of the individual heliostats. The controller may also be configured to change the aiming directions of one or more of the heliostats.

[0059] In operation, sunlight beams 310, 320, 330 from the sun 300 can strike the reflective surface of heliostat mirrors 70. The heliostats can then reflect beams 311, 321, 331 towards the receiver 500. The reflected rays 311, 321, 331, in addition to beams reflected from other heliostats in the field, can heat the receiver 500 to temperatures of between 400° C. and 800° C.
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 images that are significantly different than original calibration images may be compared with the original calibration images so as to determine if there are any changes in the heliostat field. The system can automatically detect the orientations of all of the heliostats in the field and change the aiming points of the heliostats as necessary.

After the controller has assigned a portion of an image to each heliostat in a field, the aiming direction of each heliostat may be changed in order to maximize the amount of flux directed at receiver 500. To do so, the controller can try to maximize the sunlight seen by the camera 198 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 controller can determine that the heliostat is shaded in some way (for example, by cloud 192 in FIG. 7B) or not oriented/positioned accurately.

As the temperature on the outer surface of the receiver 500 is hot, i.e. between 400° C and 800° C, the imaging device 600 may need to be protected from the heat. As shown in FIG. 8, a first end of the imaging device 600 which includes the imaging aperture 610 (i.e., the hole module) may comprise high performance alloys, such as HASTELLOY®. As with the other drawings in this application, the embodiment of FIG. 8 has not necessarily been drawn to scale.

The size of the imaging aperture 610 can be small enough to allow only small amounts of light to pass through the imaging aperture 610, thereby providing a sharp image. However, if the size of the imaging aperture is too small, the resolution of the image worsens. This is caused by the diffraction pattern characterized by wavelength of the light entering the aperture (e.g., Airy disk). The size of the imaging aperture can thus be optimized to take into account the sharpness of the image as well as the diffraction of the image. In some examples, the imaging aperture has a diameter of 0.9 mm. The imaging device 600 can further include a semitransparent screen 620 such that the light passing through the imaging aperture 610 is projected as an image on the side of the screen opposite the aperture (i.e., the front side of semitransparent screen 620). According to some embodiments, the screen may be made of glasses, sheets, and/or thin ceramics that can withstand temperatures of approximately 80° C and 100° C. The distance from the imaging aperture to the semitransparent screen (i.e., the “f” of the imaging device) may be optimized in order to obtain a good spatial resolution for heliostats which are distant from the tower (i.e., 1 km away from the tower, 3 km away from the tower or further). In some examples, the distance between the imaging aperture and the screen is between 50 cm and 1 m.

Filters in front of the imaging device 600 can allow only light at particular wavelengths to enter the imaging device and to enhance the resolution of the acquired image. In some examples, the filter is configured so that light at a wavelength of 400 nm is allowed to enter the device. Of course other wavelengths ranges or wavebands can also be allowed according to one or more contemplated embodiments.

The imaging device 600 can optionally include an optical element which may be used to expand, contract, or condition the sunlight as necessary prior to entry of the beam into the camera.

The imaging device 600 may further include a camera 630, such as a digital camera that acquires the image projected on the semitransparent screen 620. According to some embodiments, the temperature of the area proximate to the camera may be less than approximately 50° C.

In one embodiment, a cooling system 650 can be used to cool and protect the imaging device. For example, the cooling system may include a heat exchanger connected to the imaging device in order to cool the imaging device by transferring heat to a heat transfer fluid. The cooling system may further include a pump or a fan configured to move the heat transfer fluid across the heat transfer surface of the heat exchanger. In a further embodiment, the imaging device may be cooled by actively cooling the imaging device by conveying a heat transfer fluid across the heat transfer surface conducting heat from the imaging device. In an embodiment, the cooling system may be a thermoelectric cooling system.

In operation, sunlight reflected from heliostats can travel through the imaging aperture 610. The sunlight can further travel through a filter and optionally any optics. Finally, the sunlight can then be projected onto the semitransparent screen 620 where it can be acquired by the digital camera 630. The acquired image may include pixels whose brightness may be dependent on the amount of light reflected from the heliostats.

When clouds pass between the sun and the heliostats, insolation may temporarily be interrupted. As a result, the radiation reflected onto a solar receiver may differ from an ideal or expected flux distribution. This can result in local variations in temperature or flux that could damage the receiver. Moreover, the variations in flux can result in less than ideal operating conditions, for example, a reduction in steam produced or superheating steam temperature.

The calculating of the heliostat characteristics may include identifying shaded and unshaded heliostats. Additionally or alternatively, the calculating may include determining the magnitude change in insolation levels falling on each heliostat.

In some embodiments, heliostats may not have the ability to reflect insolation to the receiver. The variation in insolation level may be as a result of one or more of dirt, breakage of heliostats, shading by structures, shading by clouds, and shading by flora or fauna, etc.

According to one or more embodiments of the disclosed subject matter, images representative of cloud shadows with respect to a field of heliostats can be used to adjust operation of a solar energy system. For example, images of a field of heliostats and shadows produced by the clouds can be obtained. The images can be analyzed to determine a shading parameter. Based on the shading parameter, an operating parameter of the solar energy system can be changed or maintained. For example, the operating parameter may include aiming directions for one or more of unshaded heliostats in the heliostat field. Cloud characteristics in addition to the location of the cloud shadow can be used in determining the shading parameter. Such characteristics can be used in determining if and/or how to change an operating parameter of the solar energy system. For certain cloud characteristics, it may be determined to maintain current operation of the solar energy system despite the shadow.
tion of a solar energy system with respect to cloud shading, the skilled artisan is directed, for example, to U.S. Publication No. 2011/0220091, published Sep. 15, 2011 and entitled “Method and Apparatus for Operating a Solar Energy System to Account for Cloud Shading,” which is hereby incorporated by reference herein in its entirety.

[0073] As shown in FIG. 7B, an imaging system 198 is arranged so as to acquire substantially local images indicative of cloud cover 192 over (or in the vicinity of) the field of heliostats 70. To obtain such images, the imaging device 198 can be arranged to image at least a portion of the field of heliostats, thereby obtaining images of shadows cast by clouds 192.

[0074] The acquired images can be used to determine a shading parameter of the heliostat field. In addition, the imaging device 198 can be configured to provide at least one image at different times, for example, to provide time-lapse imaging. For example, the images from the one or imaging devices 198 can be analyzed by a processor (not shown) to determine the shading parameter.

[0075] Turning to FIG. 9, a process flowchart illustrating an embodiment of an operating method for a solar energy system is shown. At S100, one or more imaging devices 198 whose imaging aperture is located within a capture area on the receiver are used to acquire one or more images indicative of cloud cover with respect to the heliostat field. For example, one or more of the imaging devices 198 can be aimed at portions of the heliostat field or portions of the ground surrounding the heliostat field in order to provide images of cloud shadows.

[0076] At S105, the acquired at least one image can be analyzed by, for example, a processor to determine a shading parameter for the heliostat field. Examples of the shading parameter include but are not limited to: (i) a subset of the heliostats in the field of heliostats that are substantially shaded by clouds or that are substantially free of cloud shade, (ii) the dimensions of one or more shadows that cover a fraction of the heliostat field, and (iii) relative shade strengths at one or more distinct locations within the field of heliostats. In addition, the shading parameter can determine a prediction of cloud shadow location in addition to or in place of a real-time cloud shadow location.

[0077] The acquired images can be analyzed to determine useful information for carrying out S110. For example, the current or predicted location of a cloud-induced shadow location can be computed. As shown in FIG. 11, cloud vertical thickness can be estimated from the acquired images. Imaging device calibration data and/or analysis of images from multiple imaging devices having different perspectives of the cloud can be used to estimate cloud thickness.

[0078] Referring again to FIG. 9, at S110, the solar energy system can be operated according to the shading parameter. Operating parameters that can be regulated based on the shading parameter include but are not limited to: (i) an operating parameter of a tower-based solar steam system, (ii) an operating parameter of a tower-based molten salt system, (iii) an operating parameter of a biofuel generation system, (iv) an operating parameter of the heliostat field (e.g., heliostat aiming targets), and (v) an operating parameter of another portion of the energy apparatus (e.g., a steam generation or molten salt apparatus).

[0079] In an embodiment, the regulation of S110 can include adjusting heliostat aiming based on the determined shading parameter. Referring to FIG. 10A, an aerial view of a portion of heliostat field and a receiver are shown. Only eight heliostats 70a-70h have been illustrated for convenience; however, a practical embodiment of a heliostat field can include many more heliostats arranged therein (for example, on the order of thousands or tens of thousands of heliostats). Heliostats 70a, 70b, 70c, and 70d are arranged in a western portion of the heliostat field and are configured to reflect solar radiation onto the western face of solar energy receiving system 500, in embodiment FIG. 10A. Heliostats 70e, 70f, 70g, and 70h are arranged in a northern portion of the heliostat field and are configured to reflect solar radiation onto the northern face of solar energy receiving system 500, in embodiment FIG. 10A. Insolation reflected onto the north face of solar energy receiving system 500 (or another of the faces) can be converted into another form of energy than insolation reflected onto the west face of solar energy receiving system 500 (or any of the other faces).

[0080] In FIG. 10A, none of the heliostats are shaded by passing clouds. Heliostats 70a-70d have “better views” of the west face of solar energy receiving system 500 than of the north face. That is, the angle between the beam of reflected light from the respective heliostats 70a-70d and the normal to the respective face of the target is smaller in the case of the west face than in the case of the north face. As such, heliostats 70a-70d are directed toward the west face and therefore reflect incident radiation thereon. Similarly, heliostats 70e-70h have “better views” of the north face of solar energy receiving system 500 than of the west face. As such, heliostats 70e-70h are directed toward the north face and therefore reflect incident radiation thereon.

[0081] FIG. 10A is an example of a time when no cloud shadows obstruct solar radiation incident on the field of heliostats, however, when a cloud shades a portion of the heliostat field, the aiming points of the heliostats in the field may be re-arranged to compensate for the shade. For example, in FIG. 10B, the processor may determine (or predict) from acquired images that heliostats 70f-70h in region 106 of the heliostat field are (or will be) shaded by clouds, while the other heliostats will enjoy relatively unshaded conditions. In such a situation, the total amount of flux incident on the north face of solar energy receiving system 500 may be reduced to a greater extent than the total amount of flux incident on the west face. Accordingly, it may be advantageous to re-aim the heliostats 70f-70h from the west face to the north face to compensate for the reduced insolation flux on the north face.

[0082] For example, in FIG. 10C, the processor may determine (or predict) from acquired photographs that heliostats 70a-70c in region 106 of the heliostat field are (or will be) shaded by clouds, while the other heliostats will enjoy relatively unshaded conditions. In such a situation, the total amount of flux incident on the west face of solar energy receiving system 500 may be reduced to a greater extent than the total amount of flux incident on the north face. Accordingly, it may be advantageous in response to the detected shading (i.e., current conditions or predicted conditions) to re-aim heliostats 70c-70f from the north face to the west face to compensate for the reduced insolation flux on the north face.

[0083] In one or more embodiments, the operating the solar energy system according to the shading parameter can include modifying one or more aiming points of one or more heliostats, for example, to compensate for reduced insolation...
on one or more portions of the solar energy receiving system or on one or more solar receivers. For example, the modifying aiming points can be to maintain a uniform temperature or flux profile on a surface of one or more solar receivers. The modifying of the aim of each heliostat can include mechanically moving the heliostat aiming point to cause the projected heliostat beam to move from one face of the solar energy receiving system \( 500 \) on to another face of the solar energy receiving system.

Additionally, the aiming point of each heliostat may be modified in order to compensate for the reduced insolation caused by heliostats which are unable to reflect sunlight to the receiver due to one or more of dirt, breakage of heliostats, shading by structures, shading by clouds, shading by flora or fauna, and any other reason.

In an embodiment, the re-aiming of one or more heliostats can be an inter-tower aiming transition where the projected heliostat beam is moved from a first tower to a second tower, for example, in the multi-tower system of FIG. 4. In another embodiment, the re-aiming of one or more heliostats can include re-aiming from a first receiver to a second receiver. For example, the re-aiming can be from an evaporator (or steam generator) to a superheater. The different receivers can be located in the same tower (such as receiver \( 810 \) serving as an evaporator and receiver \( 820 \) serving as a superheater, as in FIG. 5). Alternatively, the different receivers can be different faces of the solar energy receiving system in a single tower. For example, the evaporator may be a north face of the receiving system \( 500 \) while the superheater may be a west face of the receiving system \( 500 \).

In an embodiment, the re-aiming of one or more heliostats may cause the respective beam projected therefrom to move only by a small distance at or near the top of the tower, for example, by less than ten meters, or less than five meters, or less than two meters. In another example, the heliostat aiming transition may be a supercritical steam generator-evaporator aiming transition.

According to some embodiments, a cloud may be classified as generating a weak shadow. In this embodiment, the aiming points of the heliostats in the field may not be adjusted in order to compensate for the weak shadow. In other words, even if the same shadow locations are predicted and/or detected as in FIGS. 10B-10C, because the clouds are classified as weak, it may be preferable not to re-aim the heliostats. Thus, the re-aiming of heliostats or changing any of the other operating parameters of the solar energy system may be contingent upon the result of the cloud classification and/or contingent upon any input parameter to the classification model (e.g., cloud color, texture, and/or height) per the analysis in S105 of FIG. 9.

Although the above operating parameters related to heliostat field operating parameters, the available operating parameters are not limited thereto. In embodiments, the operating parameter of a portion of the solar energy system other than the heliostat field may be modified, established, and/or maintained according to the shading parameter. For example, the north surface of the tower can have an evaporator/boiler and the south surface of the tower can have a superheater. In the event that the acquired image indicates that the heliostats that typically reflect insolation to the south end are shaded or about to shaded, without substantial shade to the north side where the evaporator/boiler is, then it may be advantageous to lower a turbine operating pressure, for example, in advance of the shadow.

In embodiments, it is possible to acquire a time series of images to estimate a trajectory of one or more clouds. The time series images can help predict a future shadow status with respect to the heliostat field. Accordingly, in S105, the shading parameter can include a future shading parameter, and, in S110, the operating can be carried out preemptively. In embodiments, the pre-emptive operation can be related to fossil-fuel derived steam. For example, in the event that the cloud image analysis indicates that an evaporator region of the heliostat field (i.e., a region of the heliostat field where the heliostats are aimed at an evaporator section of the receiver) is about to be shaded within a designated period of time, then it may be advantageous to initiate a natural gas boiler to be on-call for when natural-gas-derived steam is injected into the steam separation drum associated with the evaporator/boiler.

In embodiments, a pre-emptive operation relates to re-aiming of heliostats. Because heliostats may need a certain amount of travel time to re-aim, then it may be advantageous in anticipation of predicted or future shade conditions to re-aim some of the heliostats in the field of heliostats before the heliostat becomes shaded.

In embodiments, a location of a shadow at or near ground level produced by a cloud in the sky and/or a shape or size of a shaded region at or near ground level produced by the cloud is determined. For example, movement of a shadow as it moves across a field of heliostats in a system with multiple towers and fields of heliostats can be tracked. Characterization of such movement can include determining a shape of the shadow, a translational velocity of the shadow, and/or a rotational velocity of the shadow so as to determine and/or predict movement of the cloud shadow with respect to the field of heliostats or other components of the solar energy system. The determined shadow can depend upon a number of factors, including but not limited to the position of the sun as determined in advance from astronomical data, such as day of the year, time of day, and geographic location.

In embodiments, a physical location of the cloud or a portion thereof can be estimated from imaging device calibration data (e.g., including extrinsic data) or according to any other method known in the art. The imaging device calibration data can relate each pixel location of the imaging device and/or any images produced by the imaging device with a real-world location in space. The location of the cloud-generated shadow can be estimated according to the location in the sky of the sun at a given moment and the real world location of the cloud as estimated from the image, for example, by using ray-tracing or any other known techniques known in the art.

In embodiments, a method of operating a solar energy system including a heliostat field can include: (a) using an array of one or more imaging devices whose imaging aperture is located proximate, adjacent or at least partially within the capture area of the receiver to acquire images of one or more clouds, (b) analyzing content of the images to determine a shading parameter for the heliostat field or a portion thereof, and (c) in response to the analysis, establishing, modifying, or maintaining at least one operating parameter of the solar energy system. The shading parameter can define at least one of: (i) a sub-plurality of a plurality of
heliostats that are substantially shaded by clouds or that are substantially free of cloud shade; (ii) the dimensions of one or more shadows that cover a fraction of the solar field; and (iii) relative shade strengths at a plurality of distinct locations within the solar field.

[0094] In embodiments, the shading parameter can be a current shading parameter or a forecast shading parameter. Thus, it is possible to derive from one or more image(s) of clouds either a current shadow situation (i.e., shadows caused by the clouds) or a predicted or forecast shadow situation. This may be carried out using any technique (for example, using any image processing technique) known in the art.

[0095] In some embodiments, the step of establishing, modifying or maintaining the at least one operating parameter includes modifying a heliostat aim, for example. In some embodiments, the heliostat aim is modified to effect at least one aiming transition selected from the group consisting of: (i) an inter-tower aiming transition, (ii) an evaporator-superheater aiming transition; and (iii) a supercritical steam generator-evaporator aiming transition. In some embodiments, the step of establishing, modifying or maintaining the at least one operating parameter includes modifying a sun-tracking aim target (i.e. a target at which the heliostat is aimed while tracking the sun so the centroid of the heliostat’s beam projection on the target remains at a substantially constant location) of a projected heliostat beam from a first location at or near the top of a solar tower to a second location at or near the top of the solar tower.

[0096] In one example, rather than radically modifying the aim angle of any given heliostat, it is sufficient to “nudge” (i.e., slightly modify) the heliostat from the first aiming location to the second aiming location (e.g., in a manner that modifies the target location) of the centroid of the heliostat beam of reflected insolation by a “small distance” (i.e., between at least 5 cm, 10 cm, 20 cm, 50 cm, or 1 m, and at most 10 m, 5 m, or 2 m).

[0097] In some embodiments, the step of establishing, modifying or maintaining the at least one operating parameter includes commencing or concluding an insolation damping operation for one or more sun-tracking heliostats. In some embodiments, the step of establishing, modifying or maintaining the at least one operating parameter includes modifying a number of heliostats aimed at a target at or near the top of a solar tower or modifying a total aggregate multi-heliostat flux of insolation directed at the target at or near the top of a solar tower. In some embodiments, the step of establishing, modifying or maintaining the at least one operating parameter includes increasing or decreasing a temperature of an external energy conversion device such as a heater, boiler, chiller or condenser. In some embodiments, the step of establishing, modifying or maintaining the at least one operating parameter includes modifying a turbine operating parameter.

[0098] One of the possible functions of a control system (including local heliostat controller(s) and/or one or more higher-level controllers, for example, a centralized heliostat field controller) is to direct heliostats to various aiming points on the surface of a target, or alternatively not on the surface of a target when operating conditions require it. This is done on the basis of periodically or continuously evaluating various inputs, which can include (but not exhaustively): predictive and/or measured meteorological data and measured and/or calculated operating conditions and parameters of heliostats and receivers. Among the operating conditions and parameters which can be used in applying control functions are instant and historical temperature data for the external surface of the receiver, and instant and historical light energy flux density data for the external surface of the receiver. For example, the distribution of temperature across the surface of a receiver at a given moment can be compared with a predetermined set of desired values or with the data for an earlier moment in time in order for the controller to decide whether current heliostat aiming instructions are adequate to meet system optimization goals or safety-based operational constraints, and especially when taking into account measured and predictive weather data. Similarly, the distribution of energy flux density across the surface of a target at a given moment can be compared with a predetermined set of desired values, or, alternatively, used to calibrate the calculation of predicted flux densities that are used by a control system which generates sets of aiming points and directs heliostats to those aiming points based on those predicted patterns of resultant energy flux density. With respect to control of heliostat aiming points, the skilled artisan is directed to, for example, International Publication No. WO 2009/103077, published Aug. 20, 2009 and entitled “Devices, Methods, and Systems for Control of Heliostats,” which is hereby incorporated by reference herein in its entirety.

[0099] In some embodiments, a solar energy system may include a control system which may be configured for the calibration of heliostats, or more specifically, the calibration of the reflection of solar radiation on a target with respect to a desired or predicted reflection, for example, in terms of the location of the reflection, and/or in terms of the shape of the reflection, and/or in terms of the intensity of light flux at a plurality of points in the reflection, and/or in terms of any combination of data that describes the beam projection (reflection) in a desired format. As noted above, this functionality may be provided by the heliostat controller of a single heliostat either autonomously or in response to electronic communications received, for example, from a heliostat field controller.

[0100] FIG. 12 illustrates the concept of heliostat offset. It is noted that in many cases, the heliostat controller attempts to aim the heliostat at the target so that the centroid of the reflection beam is located at target centroid location 660. In many real-world scenarios, over time certain factors may cause the heliostat to deviate from its preferred operating parameters. For example, wind or rain may move the mirror or one or more heliostat moving parts associated with the aiming the heliostat, changes in temperature may distort the mirror, seismic activity may influence heliostat aiming or any other factors may influence heliostat aiming. For the present disclosure, the terms “aiming” and “directing” are used interchangeably.

[0101] As illustrated in FIG. 12, the actual centroid location 664 of the reflected heliostat beam obtained when the heliostat controller attempts to aim at location 660 actually deviates from the target centroid location.

[0102] Embodiments of the present invention provide techniques and apparatus for measuring the actual centroid location 664 according to the light detected by an array of imaging devices positioned within an area defined by the target (e.g., the receiver). The term centroid location may be defined as the area with the highest level of flux intensity. If desired, this information may then be used to determine the deviation vector 668. By having the aperture of the imaging device located within the capture area of the receiver, there is no need
to take the heliostats offline for calibration, and they may continuously reflect insolation on the receiver.

[F0103] FIGS. 13A-13E are illustrations of a one dimensional array 100 of imaging devices 101 (e.g., 101A-101F) whose imaging aperture is within a capture area of the receiver 105. FIGS. 15A-15B and 17 are illustrations of a two dimensional array 100 of imaging devices 101 whose imaging aperture is within a capture area of the receiver 105.

[F0104] As shown in FIGS. 13A-13E, in some embodiments, at one or more times, instead of being assigned to a specific point on the target, the reflection beam 398 (i.e., a reflection of a beam of sunlight incident to the heliostat) produced by each heliostat may be directed at array 100 of imaging devices whose imaging aperture is located within a capture area of the receiver. Each imaging device may be used for detecting the intensity of light reflected by heliostats. In the figures, element 399 represents the cross section of reflection beam 398 as it is projected onto the array 101 of imaging devices. In various embodiments, a maximum dimension of the cross section of reflection beam 398 as projected onto the target and/or the array 101 of light intensity may be at least 30 cm, at least 70 cm, at least 1 m, at least 1.5, at least 2 m, or more.

[F0105] As will be discussed in greater detail below, the at least one image acquired by at least one imaging device may be used to characterize reflection beam 398 and/or a property of the cross section 399 thereof to determine a "projected beam property." In one non-limiting example, a measurement of the shape or cross-sectional area (or an indicative parameter thereof) may be derived from the acquired image(s). In another example, a beam intensity map measuring the flux intensity at different locations of the reflected beam cross section 399 may be derived from the acquired image(s). In yet another example, a so-called beam offset may be derived from the data obtained from the acquired image(s).

[F0106] The acquired image(s) may be useful for calibrating the heliostat to determine and/or modify one or more operating parameters of one or more of the heliostats 70. The heliostat calibration may be carried out in a closed-loop system, although alternatively, it can be used in an open-loop system. A closed-loop system is one in which the data obtained or derived by the image(s) acquired from the array of imaging devices is used to change heliostat aiming instructions, to change the characterization of a heliostat in a database, or to bring about heliostat maintenance by having a computer program analyze the data and issue electronic instructions on a periodic or real-time basis without significant operator intervention. An open-loop system is one in which the data is stored or analyzed, and used at a later time for changing heliostat aiming instructions or for bringing about heliostat maintenance, usually after intervention by a human operator.

[F0107] FIGS. 13A-13E indicate a plurality of snapshots in time as the projection 399 of the reflected beam 398 traverses the array of imaging devices. In the example of FIGS. 13A-13E, data from the reflected light obtained from each of the imaging devices 101A-101F may be recorded for a plurality of points in time t1-t4. The shape of the beam (or any other beam projection parameter) may be determined according to: (i) the time series of the measurements; (ii) the speed at which the projection beam traverses the array of imaging devices (this may be constant or may vary in team); and/or (iii) the distance between the various imaging devices 101 at which the measurements are taken. In some embodiments, the intensity of the reflected light may be measured in terms of grayscale level (i.e., the greater the grayscale value, the greater the intensity of light being detected by the camera).

[F0108] Thus, in one example related to FIGS. 13A-13E, the computed area of the reflection beam 399 may be a function of the distance between 101B and 101E (where a large distance would indicate a larger area). Furthermore, in the example of FIGS. 13A-13E, the computed area of the reflection beam 399 may be a function of the reflected beam's projection traversal speed. In this case, a faster speed may indicate a larger beam area for fixed points in time. A larger speed indicates that the projection of the reflection beam has traveled a greater distance.

[F0109] Thus, in some embodiments, the system is capable of measuring or approximating the shape of a heliostat beam projection from time series data obtained from the imaging devices whose imaging aperture is within an aiming point of the receiver, including data obtained from moving the heliostats. This may be accomplished by designing the size and shape of the array of imaging devices whose imaging aperture is within a capture area of the receiver so that it can do this in conjunction with the movement of a heliostat. For example, as illustrated in FIGS. 13A-13E, the array 100 comprises a single line (or, alternatively, an arc, (not shown)) of imaging devices 101, provided substantially transversely to the tracking path of the beam projection 399 of light reflected from a heliostat. The array 100 can be used to generate a set of time series that can be used by the system, together with external data on the tracking speed of a heliostat and optionally the distance of a heliostat from the array, to approximate the shape of a heliostat beam projection.

[F0110] In another example, illustrated in FIG. 14A, an array 100 includes at least one additional and optionally parallel line or arc of imaging devices 101 whose imaging aperture is within a capture area of the receiver 105, which can be added in order to facilitate measurement or approximation of the speed of the beam projection 399 (since the distance between any two imaging devices 101 in the path of the beam projection 399, for example 101b and 101a in FIG. 14A, could be made known to the system).

[F0111] In yet another example, illustrated in FIG. 14B, the array 100 includes a two-dimensional array, or matrix, of at least partly offset rows or columns of imaging devices 101 which serve to increase resolution, in one or two dimensions, of the data obtained from the reflected sunlight. The size of the matrix can be continually increased to improve the resolution of the data capture.

[F0112] In yet another example, illustrated in FIGS. 15A and 15B, an array 100 of imaging devices 101 whose imaging aperture is within a capture area of the receiver may be arranged with different and non-uniform densities of imaging devices 101 in different areas of the array 100, for example so as to provide higher resolution at the edges of the array 100 (FIG. 15A), or alternatively so as to provide higher resolution at the center of the array 100 (FIG. 15B). Such non-uniform placement of imaging devices 101 may be, for example, in order to obtain a projection perimeter with greater resolution (as is shown in 15A) or for the purpose of determining with greater precision the statistical distribution or even the calculated centroid of a heliostat beam projection 399 (as in FIG. 15B).

[F0113] FIGS. 16A-16B illustrate flow charts of routines for operating a heliostat of a solar energy system according to some embodiments.
In FIG. 16A, in step S301 a heliostat is directed at the target (e.g., the receiver) mounted on the tower. In step S305, the same heliostat is directed to the array 100 of imaging devices 101 whose imaging aperture is at least partially within a capture area of the receiver 105 such that the projected heliostat reflection beam traverses across the array 100 of imaging devices 101.

In an example, the heliostat is redirected from a first orientation when it is aiming at an assigned specific point on a target to a second orientation when it is aiming at the array 100 of imaging devices 101 (and traverse across the array). The array of imaging devices may be located within an area defined by the target or a specific area on the target (i.e., the receiver). Therefore, the reflected insolation is being reflected onto the receiver and may simultaneously provide energy to the solar energy system (for example, to the working fluid) as well as traverse the array of imaging devices. In step S309 a portion of the sunlight reflected from the heliostats is captured by the array 100 of imaging devices 101 whose imaging aperture is within a capture area of the receiver 105. In step S315, one or more beam projection parameters of the heliostat are determined.

In FIG. 16B, in step S309, for each heliostat, at least a portion of the sunlight reflected from each respective heliostat is acquired by the imaging devices 101. In step S321, the data of the reflected sunlight is analyzed. In one particular example, the respective shape or flux intensity map of each heliostat is determined, for example, to create a database of heliostat shapes or heliostat intensity maps. In step S365, according to the results of the data analysis, heliostat selection may be carried out (i.e., a sub-plurality of the plurality of heliostats may be selected for simultaneous aiming at a specific point on the target). In one example, it may be desired to provide a certain flux distribution at the target, and heliostat reflection beams (whose beam parameters are known from the acquired data) may be selected accordingly.

In some embodiments, the method of calibrating a heliostat may also include estimating at least one geometric parameter for each heliostat based at least in part on the acquired images. The estimating may further include taking into account the nominal geometric parameter of each of the plurality of heliostats. Based at least in part on the at least one geometric parameter, the heliostats may be oriented to reflect sunlight to a target on the receiver.

In some embodiments, the system includes software for providing instructions to heliostats to track to the array 100, including at least one set of tracking coordinates and tracking speed. The instructions can be propagated through a data network or communicated directly in accordance with the architecture of the solar field control system. The instructions, if transmitted in advance, may include a time when the heliostat controller should initiate execution of the instructions, and the heliostat controller may be equipped with data storage means for storing such instructions.

Alternatively, the instructions can be pre-programmed in a heliostat controller. For example, a heliostat controller may include a stored set of instructions to track to the calibration array with a given periodicity such as, for example, weekly or monthly. In some embodiments, the heliostat calibration system is capable of obtaining a time series of data points representing the light intensity reflected by a heliostat to each digital imaging device whose imaging aperture is within a capture area of the receiver, including while the heliostat is in motion. For example, if it takes 30 seconds for the light reflected from a heliostat in motion to traverse an imaging device while the heliostat is tracking across the imaging device, then the time series would include a plurality of data points, for example, digital images, captured during those 30 seconds and preferably at a resolution sufficiently high as to indicate with a desired level of precision the beginning and end of the incidence of light on the imaging device as well as the intensity level at each time point. In another example, an array of the imaging devices whose imaging aperture is within a capture area of the receiver may capture a time series of data points beginning when a first device in the array detects light reflected from a heliostat and ending only when no devices in the array detects reflected light from the heliostat. In yet another example, all of the devices in the array obtain, record or process the digital images all of the time when it is known that heliostats are to be calibrated, leaving the task of determining beginning and ending time points for each individual heliostat to image- or data-processing software elsewhere in the system. The time series data from each imaging device may be recorded for later processing, and/or transmitted, whether directly or through a data network, to a computer or data storage device elsewhere in the system for processing and analysis of the data.

In some embodiments, the system also includes computer hardware and software for analyzing the data obtained or recorded from the digital imaging devices. The analysis is performed for the purpose of calibrating the heliostat, where calibrating may include at least one of: (i) determining the deviation of the calculated centroid of the heliostat’s beam projection from the predicted; (ii) determining or approximating the beam projection shape and its deviation from the predicted; (iii) determining the intensity of light at a specific point or a plurality of points within the beam projection and any deviation from the projected distribution of light intensity; (iv) determining the speed of the traversal of the beam projection and any deviation from the predicted; (v) correcting a structural or assembly error, or shape aberration, or any other malfunction or deviation from design in a heliostat; (vi) storing or using any of these data elements for the purpose of updating or changing a database of heliostat-related data or of updating or changing the aiming and/or tracking instructions of a heliostat; or (vii) analysis of the data by a system designer or operator.

In some embodiments, an analysis software is capable of calculating a beam projection shape and/or calculating the statistical distribution and/or centroid of the beam projection distribution, using data obtained and/or recorded by the imaging devices, including time series data, and optionally using statistical techniques applying a Gaussian or other probabilistic distribution to the light intensity of a heliostat beam projection. Additionally, the software can be capable of producing a digital map of the light intensity or energy fluxes at a specific point or a plurality of points in the beam projection. Any of these calculated parameters can be used in the calibration of heliostats as described above. Heliostats (or a control system for heliostats and/or heliostat controllers) may be configured to modify aiming instructions such as target coordinates in response to data obtained during the calibration process or in response to the result of the analysis of the data.

The analysis software can also include software to eliminate or cancel out the effects of diffuse or ambient light measured by the imaging devices, for example by measuring.
such light before and/or after the traversal of a heliostat beam. The analysis software can also include software for transformation of a curvilinear projection in order to "translate" a beam projection shape and/or map of light intensity values to the surface geometry of a receiver, taking into account: (i) the different angle of incidence of reflected light on the receiver compared with that on the array; (ii) the different attitude of the receiver with respect to the heliostat field.

In some embodiments, the solar power tower system includes multiple arrays of imaging devices whose imaging aperture is within a capture area of the receiver, such that the arrays are accessible to all the heliostats in a solar field. In an example, a solar power tower system includes a receiver, and additionally includes a field of heliostats surrounding the receiver, i.e., 360° around the tower. In such a configuration, the system can include at least four arrays, one on each side of the tower.

In other embodiments, a method for operating a solar power tower system includes using an array of digital imaging devices whose imaging aperture is within a capture area of the receiver to capture and/or record the light reflected from a heliostat for the purposes of calibration, where calibration can include at least one of: (i) determining or approximating a statistical distribution and/or centroid of a heliostat’s beam project and/or its deviation from a desired or predicted set of values; (ii) determining the beam projection shape and/or its deviation from a desired or predicted set of values; (iii) determining the intensity of light at a plurality of points within the beam projection and/or any deviation from a desired or predicted set of values; (iv) determining the speed of the traversal of the beam projection and/or any deviation from a desired or predicted set of values; (v) correcting a structural or assembly error, or shape aberration, or any other malfunction or deviation from design in a heliostat; (vi) storing or using any of these data elements for the purpose of updating or changing a database of heliostat-related data or of updating or changing the aiming and/or tracking instructions of a heliostat; or, (vii) analysis of the data by a system designer or operator.

According to the method, the array is used for the calibration of heliostats in a solar power tower system by causing each heliostat, or alternatively groups of heliostats, to traverse the array periodically in accordance with a manufacturer’s specification, for example once every two weeks, once every month, or once every two months. Therefore, the method preferably includes sending instructions, directly or through a data communications network, to a heliostat to cause it to track to the array. Alternatively, it would be possible to make use of a preprogrammed heliostat controller which causes a heliostat to track to the array with a desired periodicity or under certain preset conditions. In any of the embodiments, light reflected by the heliostat onto an array of imaging devices whose imaging aperture is within the capture area of the receiver can come from the sun, the moon, or from a light projector.

The method includes analyzing data obtained and/or recorded from the array of digital imaging devices whose imaging aperture is within a capture area of the receiver in order to yield a characterization of the beam projection of a heliostat, where the characterization includes at least one of: (i) a map of the light intensity at a plurality of points in the beam projection; (ii) the shape of the beam projection either as a set of points describing a perimeter or a mathematical expression for the shape; (iii) a mathematical expression for distribution of light in the beam such as a statistical distribution; (iv) a beam centroid; or, (v) the deviation of any of these measured or characterized parameters from a design target or from a predicted set of values. According to the method, the characterization, optionally including any measurable or calculable deviation from a design goal or predicted set of values, is optimally used by a control system and/or system operator to calibrate the aiming of the heliostat or for any other aspect of heliostat calibration as described above.

In some embodiments, the method includes causing a plurality of heliostats to track simultaneously or nearly simultaneously to an array, and acquiring and/or recording data of the reflected light for the purposes of heliostat calibration. In an example illustrated in FIG. 17, four heliostats track simultaneously to a two-dimensional array (i.e., an array having at least two columns and two rows, where the columns and/or rows can be in the shape of lines, staggered lines or arcs) from different directions at the same time in such a way that each heliostat beam projection can be independently analyzed. This arrangement is optimally arranged so that at least part and preferably at least half of each beam projection 399 traverses at least one row 106 or column 107 of imaging devices 101 within the array 100 before intersecting or overlapping with another beam projection 399. Similarly, after intersecting with other beam projections 399, at least part and preferably at least half of each beam projection 399 traverses at least one row 106 or column 107 of imaging devices 101 within the array 100 after ceasing to intersect or overlap with other beam projections 399. In the example, software captures most or all of the desired beam shape time series data for each beam projection during the time that the beam projection does not intersect with other beam projections. In another example, the imaging devices are digital imaging devices and different pixels or groups of pixels in the imaging device may be used for recording the data of different heliostats.

One of the functions of a control system can include directing heliostats to various aiming points on the surface of a receiver, or alternatively away from the surface of a receiver when operating conditions require. Such direction can be done on the basis of periodically or continuously evaluating various inputs to the control system. Such inputs can include, but are not limited to predictive and/or measured meteorological data as well as measured and/or calculated operating conditions and parameters of the heliostats and the receiver.

The operating conditions and parameters which can be used in applying control functions may include instant and historical temperature data for the external surface of the receiver, and instant and historical light energy flux density data for the external surface of the receiver. For example, the distribution of temperature across the surface of the receiver at a given moment may be compared with a pre-determined set of desired values or with the data for an earlier moment in time, in order for the controller to decide whether current heliostat aiming instructions are adequate to meet both system optimization goals and/or safety-based operational constraints. Measured and predictive weather data can also be taken into account.

Additionally or alternatively, the distribution of solar energy flux density across the surface of a receiver at a given instant may be compared with a predetermined set of desired values and/or used to calibrate the predicted flux densities to be used by a control system. The control system can generate sets of aiming points and can direct heliostats to
those aiming points based on the difference between the measured and the predicted patterns of light energy flux density. For example, the distribution of incoming solar energy flux can be compared with a data map representing flux distribution across the surface of the receiver, which may be stored in a data storage device, such as a volatile or non-volatile memory device, or magnetic or optical storage media.

[0131] In embodiments, a control system can include an array of cameras, each camera having an imaging device defined by having an imaging aperture located within the receiver capture area, which captures a digital image and/or a video of at least a subset of the heliostats within a heliostat field.

[0132] As the amount of light passing through the imaging aperture is indicative of the amount of flux hitting the receiver in the capture area, each camera in the array of cameras may detect and calculate the amount of energy flux being absorbed by the receiver at the point of the receiver where the imaging aperture is located. In some embodiments, an array of cameras whose imaging apertures are located within the receiver capture area (i.e., on the surface of the receiver) may be able to calculate the amount of energy flux on each point of the receiver (i.e., an energy flux map). In other examples, the total energy flux hitting the outer surface of the receiver may be detected and calculated.

[0133] The method can also include calculating time differential fluxes (i.e., changes in fluxes over a selected period of time). For example, the heat transfer fluid in a solar power tower system can be water and/or steam. Data values obtained from the imaging devices can be used to monitor compliance with predetermined limits for the time differential fluxes with respect to a specified time interval. In the event that flux at a point or region on the surface of a receiver rises less than is required by the predetermined limits for the specified time interval, the control system can ensure that a periodic re-aiming of the heliostats causes more solar energy flux to be directed at the deficient point or region. Or alternatively, if the flux at a point or region on the surface of a receiver is greater than is allowed according to the predetermined limits for the specified time interval, the control system can ensure that a periodic re-aiming of the heliostats causes less solar energy flux to be directed at that specific point or region.

[0134] The method can also include comparing the energy flux values or time differential flux values with a predetermined set of values, where the comparing is performed by a data processing system. For example, the time differential flux values can be compared with a data map representing ideal or desired time differential flux values for the given time of day, given time of year, and/or given operating conditions. The result of the comparison can include an algorithmic decision to change heliostat aiming (i.e., to reallocate heliostats to different parts of a receiver or even to different receivers in a multi-receiver or multi-tower system). For example, if the comparison of measured time differential flux values with the data map reveals areas of the receiver that are less than the data map, heliostats can be reallocated to focus on the deficient region of the receiver. Or alternatively, if the comparison of measured time differential flux values with the data map reveals areas of the receiver that are greater than the data map, heliostats can be reallocated to defocus from this region of the receiver.

[0135] The result of the comparison can also include producing an alarm, for example when fluxes or flux differentials deviate from a predetermined set of values, such as a data map of optimal flux differential values. The predetermined set of values can be changed based on operating conditions or during different times of day. In addition, different allowable flux ranges can be provided on different portions of the receiver surface at different times of day. For example, the flux ranges can take into account the changes in efficiency of the heliostats on the eastern and western sides of the solar fields in morning and afternoon due to the relatively more or less advantageous incident angle of solar radiation. In addition, a different range of allowable fluxes can be provided during daily start-up, or during or after transient operating fluctuations, such as those caused by passing clouds.

[0136] In some embodiments, the method can also include providing instructions to heliostats to change aiming points (or to defocus) on the basis of an alarm or on the basis of the comparing of differential flux values with a set of predetermined values. For example, a control system can evaluate the result of the energy flux value comparison and subsequently use this evaluation as a consideration in its algorithmic designation of aiming points and assignment of heliostats to aiming points. This may include defocusing of some heliostats (aiming them away from the target area) and may include reallocating the energy from some heliostats by re-aiming them to different points on the surface of the receiver. Alternatively, it may include a complete ‘reshuffle’ of heliostats and aiming points, geared at achieving a flux distribution that is more compliant with operating guidelines while achieving system optimization goals within the limitations of known or programmed constraints.

[0137] The method may also include creating a storage archive of data and using that data for revising solar field control instructions, techniques or performance models or model parameters.

[0138] It is noted that any of the embodiments described above may further include receiving, sending or storing instructions and/or data that implement the operations described above in conjunction with the figures upon a computer readable medium. Generally speaking, a computer readable medium may include storage media or memory media such as magnetic or flash or optical media, e.g., disk or CD-ROM, volatile or non-volatile media, such as RAM, ROM, etc, as well as transmission media or signals such as electrical, electromagnetic or digital signals conveyed via a communication medium such as network and/or wireless links.

[0139] It will be appreciated that the methods, processes, and systems described above can be implemented in hardware, hardware programmed by software, software instruction stored on a non-transitory computer readable medium or a combination of the above. For example, the processors described herein can be configured to execute a sequence of programmed instructions stored on a non-transitory computer readable medium. The processors can include, but are not limited to, a personal computer or workstation or other such computing system that includes a processor, microprocessor, microcontroller device, or is comprised of control logic including integrated circuits such as, for example, an Application Specific Integrated Circuit (ASIC). The instructions can be compiled from source code instructions provided in accordance with a programming language such as Java, C++, C#.net or the like. The instructions can also comprise code and data objects provided in accordance with, for example, the Visual Basic™ language, or another structured or object-oriented programming language. The sequence of
programmed instructions and data associated therewith can be stored in a non-transitory computer-readable medium such as a computer memory or storage device which can be any suitable memory apparatus, such as, but not limited to read-only memory (ROM), programmable read-only memory (PROM), electrically erasable programmable read-only memory (EEPROM), random-access memory (RAM), flash memory, disk drive, etc.

Furthermore, the disclosed methods, processes, and/or systems can be implemented by a single processor or by a distributed processor. Further, it should be appreciated that the steps discussed herein can be performed on a single or distributed processor (single and/or multi-core). Also, the methods, processes, and/or systems described in the embodiments above can be distributed across multiple computers or systems or can be co-located in a single processor or system. Exemplary structural embodiment alternatives suitable for implementing the methods, processes, and/or systems described herein are provided below, but not limited thereto.

The methods, processes, and/or systems described herein can be implemented as a programmed general purpose computer, an electronic device programmed with microcode, a hard-wired analog logic circuit, software stored on a computer-readable medium or signal, an optical computing device, a networked system of electronic and/or optical devices, a special purpose computing device, an integrated circuit device, a semiconductor chip, and a software module or object stored on a computer-readable medium or signal, for example. Moreover, embodiments of the disclosed methods, processes, and/or systems (e.g., computer program product) can be implemented in software executed on a programmed general purpose computer, a special purpose computer, a microprocessor, or the like.

Embodiments of the disclosed methods, processes, and/or systems (or their sub-components or modules) can be implemented on a general-purpose computer, a special-purpose computer, a programmed microprocessor or microcontroller and peripheral integrated circuit element, an ASIC or other integrated circuit, a digital signal processor, a hardwired electronic or logic circuit such as a discrete element circuit, a programmed logic circuit such as a programmable logic device (PLD), programmable logic array (PLA), field-programmable gate array (FPGA), programmable array logic (PAL), device, etc. In general, any process capable of implementing the functions or steps described herein can be used to implement embodiments of the methods, processes, systems and/or computer program product (software program stored on a non-transitory computer readable medium).

Furthermore, embodiments of the disclosed methods, processes, and/or systems can be readily implemented, fully or partially, in software using, for example, object or object-oriented software development environments that provide portable source code that can be used on a variety of computer platforms. Alternatively, embodiments of the disclosed methods, processes, and/or systems can be implemented partially or fully in hardware using, for example, standard logic circuits or a very-large-scale integration (VLSI) design. Other hardware or software can be used to implement embodiments depending on the speed and/or efficiency requirements of the systems, the particular function, and/or particular software or hardware system, microprocessor or microcomputer being utilized. Embodiments of the disclosed methods, processes, and/or systems can be implemented in hardware and/or software using any known or later developed systems or structures, devices and/or software by those of ordinary skill in the applicable art from the function description provided herein and with a general basic knowledge of solar energy systems and/or computer programming arts.

Features of the disclosed embodiments may be combined, rearranged, omitted, etc., within the scope of the present disclosure to produce additional embodiments. Furthermore, certain features may sometimes be used to advantage without a corresponding use of other features.

It is, thus, apparent that there is provided, in accordance with the present disclosure methods and apparatus for operating and controlling a solar energy system. Many alternatives, modifications, and variations are enabled by the present disclosure. While specific embodiments have been shown and described in detail to illustrate the application of the principles of the invention, it will be understood that the invention may be embodied otherwise without departing from such principles. Accordingly, Applicant intends to embrace all such alternatives, modifications, equivalents, and variations that are within the spirit and scope of the present invention.

1. A method of controlling a solar energy system, the system having a tower-based first receiver and a field of heliostats controlled to direct insolation toward a capture area of the first receiver, a subset of the heliostats being controlled to direct insolation at respective aiming points within the capture area, the method comprising:

   using at least one camera, imaging said field from light passing through an imaging aperture, which is proximate to, adjacent to, or at least partially within the capture area of the first receiver, to acquire at least one image indicating a change in a distribution of insolation levels falling on said field;

   using an image processor, responsively to said at least one image, calculating characteristics of heliostats within the field of heliostats; and

   responsively to said characteristics, changing aiming direction of one or more heliostats in said field.

2. The method of claim 1, wherein the calculating includes identifying shaded heliostats and unshaded heliostats.

3. The method of claim 1, wherein the calculating includes determining a magnitude of change in insolation levels falling on each heliostat in said at least one image.

4. The method of claim 1, wherein the calculating is effective to determine variations in insolation levels falling on heliostats as a result of at least one of dirt, breakage of heliostats, shading by structures, shading by clouds, and shading by flora or fauna.

5. The method of claim 1, wherein the changing the aiming direction results in a change in a flux distribution across the capture area of the first receiver.

6. The method of claim 1, wherein the changing the aiming direction includes calculating a characteristic of a change in a flux distribution responsively to said characteristics of heliostats.

7. The method of claim 1, wherein the calculating characteristics of heliostats includes calculating characteristics of shaded heliostats within the field of heliostats.

8. The method of claim 1, wherein the imaging aperture is located at least partially within the capture area of the first receiver.

9. The method of claim 1, wherein the imaging aperture is completely within the capture area of the first receiver.
10. The method of claim 1, further comprising cooling the at least one camera using a heat exchanger connected thereto so as to transfer heat to a heat transfer fluid.

11. The method of claim 1, wherein the at least one camera has a heat exchanger and a pump or fan configured to move a heat transfer fluid across a heat transfer surface of the heat exchanger, the heat exchanger being configured to cool the camera thereby.

12. The method of claim 1, further comprising actively cooling the at least one camera including conveying a heat transfer fluid across a heat transfer surface conducting heat from the camera.

13. The method of claim 1, wherein the changing the aiming direction includes calculating another characteristic and a consequence of maintaining a respective aiming direction of at least one heliostat.

14. The method of claim 1, wherein the aiming direction changed by said changing intercepts said capture area.

15. The method of claim 1, wherein the aiming direction of the at least one heliostat changed by said changing intercepts a capture area of a second receiver.

16. The method of claim 1, wherein the changing includes aiming at least one of the one or more heliostats from respective multiple aiming points so they no longer intercept the first receiver.

17. The method of claim 1, further comprising, responsive to said characteristics, calculating a total energy flux on an external surface of the first receiver.

18. The method of claim 17, wherein the changing aiming direction includes, responsively to at least a result of said calculating the total energy flux, directing heliostats to reflect the solar radiation onto aiming points on the external surface of the first receiver based at least in part on the calculated total energy flux.

19. The method of claim 18, wherein the calculating the total energy flux and directing are repeated continuously during operation of the solar energy system.

20-22. (canceled)

23. A method of controlling a solar energy system, the method comprising:
reflecting sunlight from each of a plurality of heliostats to an energy conversion target mounted on a tower; and
controlling each heliostat of the plurality of heliostats so that a light beam reflected by each heliostat traverses imaging device array positioned within an area defined by the energy conversion target.

24. The method of claim 23, further comprising, acquiring multiple images of each of the plurality of heliostats using the imaging device array.

25. The method of claim 24, further comprising, estimating at least one geometric parameter of each of the plurality of heliostats based at least in part on the acquired images.

26. The method of claim 25, further comprising, orienting each of the plurality of heliostats to reflect sunlight to the energy conversion target, based at least in part on the at least one geometric parameter.

27. The method of claim 25, wherein the estimating is further based on the nominal geometric parameter of each of the plurality of heliostats.

28. The method of claim 25, further comprising, determining the solar flux distribution of each heliostat on an external face of the energy conversion target based at least in part on light intensity of the light beam reflected by each of the plurality of heliostats as seen in the acquired images.

29. The method of claim 28, further comprising, determining a shape of the reflected light beam based at least in part on the determined solar flux distribution of each of the plurality of heliostats.

30. The method of claim 28, further comprising, directing at least one heliostat of the plurality of heliostats to reflect incoming solar radiation onto aiming points on the external surface of the energy conversion target based at least in part on the determining the solar flux distribution.

31. A method of controlling a solar energy system, the system having a receiver mounted on a tower and a field of heliostats arranged to direct insolation toward a capture aperture of the receiver, the method comprising:
generating at least one image from light received through an imaging aperture from insolation reflected from a region coinciding with locations of at least a subset of the heliostats within the field of heliostats,
the at least one image indicating a change in a distribution of insolation levels falling on the at least a subset of the heliostats,
the imaging aperture being located adjacent to or fully or partially within the capture aperture,
the generating including imaging a scene, containing the at least a subset of the heliostats,
the change in a distribution of insolation levels resulting in a change in a flux distribution across the capture aperture;
using at least one programmable controller that is connected to control positions of the at least a subset of the heliostats within said field of heliostats, calculating characteristics of heliostats within the field of heliostats responsive to said at least one image; and
using said at least one programmable controller, responsively to at least a result of said calculating, changing aiming directions of one or more heliostats to effect a target flux distribution responsive to data stored in the at least one programmable controller.

32. The method of claim 31, wherein the changing the aiming directions includes calculating a characteristic of the change in a flux distribution and is additionally responsive to a result of said calculating.

33. The method of claim 31, wherein the calculating includes identifying shaded heliostats and unshaded heliostats.

34. The method of claim 31, wherein the calculating is effective to determine variations in insolation levels falling on heliostats as a result of at least one of dirt, breakage of heliostats, shading by structures, shading by clouds, and shading by flora or fauna.

35. The method of claim 31, further comprising actively cooling the camera using a thermoelectric cooling system.