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(54) **SYSTEM FOR POSITIONING SOLAR PANELS IN AN ARRAY OF SOLAR PANELS TO EFFICIENTLY CAPTURE SUNLIGHT**

SYSTEM ZUR POSITIONIERUNG VON SOLARPANEELEN IN EINER ANORDNUNG VON SOLARPANEELEN ZUR EFFIZIENTEN ERFASSUNG VON SONNENLICHT

SYSTÈME DE POSITIONNEMENT DE PANNEAUX SOLAIRES DANS UN RÉSEAU DE PANNEAUX SOLAIRES POUR CAPTURER EFFICACEMENT LA LUMIÈRE SOLAIRE

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Description

TECHNICAL FIELD

[0001] This invention is related to energy conversion systems. More particularly, this invention is related to controlling solar tracking systems to efficiently capture solar radiation for conversion to electrical energy.

BACKGROUND

[0002] With the increasing recognition of the environmental affects and associated costs of burning fossil fuels, solar energy has become an attractive alternative. Solar tracking systems track the trajectory of the sun to more efficiently capture radiation, which is then converted to electrical energy. Solar tracking systems are less efficient when weather conditions change or when they do not account for local topographies that reduce the amount of light captured.

[0003] Document US 2012/004780 A1 discloses an apparatus for an integrated remotely controlled photovoltaic system, comprising a central backend server management system configured to facilitate management of two or more solar arrays at a remote site from a client device connected over a public wide area network.

[0004] Document US 2016/179994 A1 discloses a system for modeling resource availability, including a data collection system configured to collect information pertaining to resource availability in a geographic region, and a modeling system configured to process the collected information to generate data that identifies development sites specific to the geographic region.

[0005] Document US 2015/331972 A1 discloses methods for designing a solar photovoltaic array, including system designs, production drawings, permitting and construction drawings, and layouts for the mechanical and electrical systems.

[0006] Document US 2013/269754 A1 discloses a method including collecting site specific data, collecting field data at a site of an array of photovoltaic members, determining a current tracked irradiance of the array, calculating predicted irradiance for multiple orientations based on the site specific data and the sensed field data, and comparing a maximum predicted irradiance with the current tracked irradiance.

[0007] Document FR 3 038 397 A discloses a method for controlling the orientation of a single-axis solar tracker, repetitively performing the steps of observing the cloud cover over the solar tracker, comparing the observed cloud cover with cloud cover models archived in a database, approximating of observed cloud cover with a model of cloud cover, altering the orientation of the solar tracker based on the retained model of cloud cover.

SUMMARY

[0008] In accordance with the principles of the invention, a solar tracking system according to claim 1 is disclosed, the solar tracking system comprising: multiple rows of solar panel modules forming a grid of solar panel modules, wherein the multiple rows of solar panel modules are orientatable to a solar source independently of each other; and a control system configured to orient each of the multiple rows of solar panel modules to the solar source independently of each other based on a performance model to optimize an energy output from the grid of solar panel modules, characterized in that the performance model predicts an energy output from the grid of solar panel modules based on an orientation of each of the multiple rows of solar panel modules to the solar source and first data comprising weather conditions local to each of the multiple rows of solar panel modules and a predicted amount of irradiance upon each of the multiple rows of solar panel modules, wherein the amount of irradiance is a function of a diffuse horizontal irradiance, DHI, to global horizontal irradiance, GHI, ratio.

[0009] As one example, each row of solar panel modules can be oriented at a different incident angle to the solar source than each of the other rows of solar panel modules is oriented to the solar source. The performance model optimizes the total output of the grid, which, due to interactions (couplings) between adjacent rows, does not necessarily correspond to optimizing the output from each individual row.

[0010] In one embodiment, the performance model is characterized by a polynomial, which determines orientations for each individual row of solar panel modules to optimize (e.g., maximize) the total energy output from the grid of solar panel modules. Preferably, the parameters of the performance model are determined based on the topography. The parameters are periodically updated based on weather conditions, such as forecast and historical weather data. In this way, the performance model is a learning model that continuously optimizes the solar tracking system to account for changing weather conditions.

[0011] In another embodiment, the performance model comprises a diffuse table, which correlates energy outputs for the solar tracking system to weather conditions.

[0012] In accordance with an embodiment of the invention, topography is determined using laser site survey, learned survey using energy readings on photovoltaics coupled to the solar panel modules, energy readings on the solar panel modules, airplane and drone imaging that correlates the position of the sun and resulting shading to topographic position, to name only a few examples. Weather conditions are determined using satellite weather forecasts informed by local data ("ground truth"), cameras looking at the sky, power measurements on the solar panel modules and voltage measurement on the photovoltaics.

[0013] The solar tracking system in accordance with the embodiments uses a mesh network that provides fail safe functionality.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The following figures are used to illustrate embodiments of the invention. In all the figures, the same label refers to the identical or a similar element.

Figure 1 shows a portion of a solar tracking system including multiple rows of solar panel modules.

Figure 2 shows a solar tracking system in accordance with one embodiment of the invention.

Figure 3 is a block diagram of a diffuse control architecture NX Supervisory Control and Data Acquisition (SCADA) in accordance with one embodiment of the invention.

Figure 4 shows the steps of a process, an enhanced tracking algorithm, for determining parameters of a global optimal performance model for a solar grid in accordance with one embodiment of the invention.

Figure 5 is a diffuse table generated from yearly data, according to one embodiment of the invention.

Figure 6 is a graph of diffuse ratio table tracking, plotting tracker angle ratio coefficients versus DHI/GHI ratios, according to one embodiment of the invention.

Figure 7 is a graph of diffuse ratio table backtracking, plotting tracker angle ratio coefficients versus DHI/GHI ratios, according to one embodiment of the invention.

Figure 8 shows the components of a SCADA in accordance with one embodiment of the invention.

Figure 9 shows a configuration comprising a row of solar panel modules and a "skinny solar panel" used to determine relative heights of multiple SPMs using shading, in accordance with one embodiment of the invention.

Figures 10-23 show algorithms and results of using the algorithm to determine relative heights in accordance with one embodiment of the invention.

DETAILED DESCRIPTION

[0015] A solar tracking system in accordance with the principles of the invention more efficiently captures radiance for conversion to electrical energy. It will be appreciated that for large energy-generating systems, such as those generating hundreds of megawatts, a small percentage gain in efficiency translates to large gains in energy output.

[0016] In accordance with the invention, a solar tracking system comprising individual rows of solar panel modules adjusts each row independently of the others to provide more finely tuned tracking and also efficiently captures diffuse radiation to increase the total energy output by the system. The solar tracking system is based on a performance model that is preferably periodically tuned based on learning algorithms that compare predicted values (e.g., radiance incident on the solar panels or output generated at the solar panels) to the actual values and updates the performance model accordingly. In one embodiment, the performance model is generated by plotting weather conditions (e.g., ratios of diffuse fraction index to optimal diffuse gain or ratios of diffuse radiance to direct radiance) and fitting a curve (the performance model) to the data using regression. In another embodiment, this data is stored in a diffuse table.

[0017] Figure 1 shows a portion of a solar tracking system 100 including multiple solar panels 110A-D forming a grid of solar panel modules, used to explain the principles of the invention. Each of the solar panel modules 110A-D has a light-collecting surface for receiving solar radiation, which is later converted into electricity for storage in a battery and for distribution to a load. Embodiments of the invention determine a performance model, predicting the output of the grid, used to orient each of the rows of solar panel modules to the sun or other radiation source to optimize the total energy output from the grid. The performance model is determined from local weather conditions local to each of the rows of solar panel modules, and preferably is determined from a topography of the area containing the grid. As one example, the performance model accounts for dependencies (coupling) between the rows (adjacent and otherwise) of solar panels. For example, if the row of solar panel modules 110A shades or partially shades the row of solar panel modules 110B, the two are said to be coupled. In other words, due to shading at a particular time of day or other relationships between the rows 110A and 110B, maximizing the global energy output by the entire grid does not necessarily correspond to maximizing the energy output by the row 110A and 110B. Instead, the global energy output might be maximized by coordinating the outputs, such as by orienting the row 110A to generate 80% of its maximum and the row 110B to generate 10% of its maximum. The performance model determines these coefficient or gains (and thus the orientation angles to the sun) for each of the all the rows in the system 100, including the rows 110A and 110B.

[0018] As used herein, in one embodiment, "orient" means to change an angle between the normal to a solar panel module and the line to the sun (the "incident angle"), to change any combination of x-y-z coordinates of a solar panel module with respect a fixed location (e.g., GPS location), to rotate the solar panel module along any of the x-y-z coordinate axes, or any combination of these. After reading this disclosure, those skilled in the art will recognize other ways to orient a row of solar panel modules to change an amount of radiation impinging on it and converted to electrical energy.

[0019] Figure 2 shows a solar tracking system 200 in accordance with one embodiment of the invention. The solar tracking system 200 is a distributed peer-to-peer network. The solar tracking system 200 includes multiple rows of solar panel modules (SPMs) SPM_1 ... SPM_8, together forming a grid of solar panel modules. Each SPM_i (here i = 1 to 8, though other values are contemplated) is coupled to a corresponding self-powered controller

(SPC_i) and drive assembly (DA_i, not shown). Each SPC_i has logic for orienting its corresponding drive assembly (DA_i) and thus SPM_i based on orientation commands. As one example, an SPC_i receives an orientation command from a network control unit (described below) to orient an incident angle θi between the SPC_i and the sun. The corresponding drive assembly DA_i positions the SPM_i to the angle θi. Each of the rows SPM_i 205i is able to be oriented independently of the other rows.

[0020] Each of the rows of solar panel modules SPM_i receives light, converts the light into electricity, and stores the electricity in a corresponding data storage medium, SM_i, for i = 1 to 8. The storage media SM_1 ... SM_8 are ganged together and electrically coupled through a distribution panel 215 to customer loads 220. Network control units (NCU) NCU_1 and NCU_2 are each wirelessly coupled to one or more of the SPMs. As shown in Figure 2, NCU_1 is wirelessly coupled to SPCs SPC_1 to SPC_4 and NCU_2 is wirelessly coupled to SPCs SPC_5 to SPC_8. NCU_1 and NCU_2 are both coupled over an Ethernet cable to an NXFP switch 250. The switch 250 couples NCU_1 and NCU_2 to a NX Supervisory Control and Data Acquisition (SCADA) 260, which in turn is couple to a switch 270 coupled to a remote host 296 over a network such as a cloud network. In some embodiments, the remote host 296 performs processing such as generating performance models, retrieving weather data, to name only a few such tasks. For ease of reference, the combination of NCU_1, NCU_2, NX SCADA 260 and NXFP switch 250 is referred to as an "SCU" system controller 265. Together, the components enclosed by the dotted line 280 are collectively referred to as "grid" or "zone" 280.

[0021] Preferably, each NCU in the zone 280 is coupled to each of the remaining NCUs in the zone 280, thereby forming a mesh architecture. Thus, if for any reason NCU_1 loses communication to the NX SCADA 260, NCU_1 can communicate with the NX SCADA 260 through NCU_2. In other words, each NCU in the zone 280 acts as a gateway to the NX SCADA 260 for any other NCU in the zone 280. This added redundancy provides a failsafe network. In one embodiment, the NCUs in the zone 280 are wirelessly coupled to each other.

[0022] Each NCU in the zone 280 has added functionality. As some examples, the NCUs in the zone 280 together ensure that the performance model is globally optimized and the components in the zone 280 are operating properly. If, for example, SPC_1 instructs NCU_1 that it is shaded but, according to the performance model SPC_1 should not be shaded, the NCU_1 determines that an error has occurred. Each SPC also informs its associated NCU when it has changed its orientation. Using this information, the NCUs can thus keep track of the orientations of the solar panel modules SPM_i.

[0023] In accordance with one embodiment, if a row of solar panel modules suffers catastrophic failure and cannot communicate with its associated SCADA, the solar panel module enters a default mode. As one example, in default mode, an SPM_i optimizes its energy conversion independently of the energy conversion for the entire grid.

[0024] It will be appreciated that Figure 2 has been simplified for ease of illustration. In other embodiments, the zone 280 contains fewer, but preferably more, than 8 SPMs and 2 NCUs. In one embodiment, the ratio of SPCs to NCUs is at least between 50:1 to 100:1. Thus, as one example, during normal operation, NCU_1 communicates with SPC_1 through SPC_{50}, NCU_2 communicates with SPC_{51} to SPC_{100}, etc.

[0025] According to the invention, a performance model is generated, which predicts an energy output from the grid of solar panel modules based on an orientation of each of the multiple rows of solar panel modules to the solar source and first data comprising weather conditions local to each of the multiple rows of solar panel modules and a predicted amount of irradiance upon each of the multiple rows of solar panel modules, wherein the amount of irradiance is a function of a diffuse horizontal irradiance, DHI, to global horizontal irradiance, GHI, ratio. According to an embodiment, the amount of irradiance is further a function of direct normal irradiance, DNI, or ground reflected radiation. By fitting the weather conditions to output, a base performance model is determined using regression or other curve-fitting techniques. It will be appreciated that each SPM has its own performance model, based, among other things, on its topography and local weather conditions. As explained below, each base performance model is then updated based on diffuse fraction sky.

[0026] As one example, the parameters of the base performance model are pushed to an SPC associated with a solar panel module SPM_i. These parameters reflect an orientation for a solar panel module if no adjustments based on "diffuse fraction" sky were needed. To account for diffuse radiation, parameters based on the diffuse angle adjustment are also sent to the particular SPC_i. As one example, the parameters for a base performance model indicate that, for global optimization of the performance model, a solar panel module should be oriented at an incidence angle of 10 degrees. Diffuse angle adjustor data indicate that 10 degrees is not optimal for this SPM, but instead 70% (a factor of 0.7) of this angle should be used. Thus, the diffuse angle adjustor (gain factor) of 0.7 is pushed to the particular solar panel. When the particular SPC receives both parameters, it orients its associated solar panel to an incidence angle of (0.7)∗(10 degrees) = 7 degrees. Preferably, the diffuse angle adjustment is performed periodically, such as once every hour, though other periods are able to be used.

[0027] Some embodiments of the invention avoid shading in the morning, by using backtracking. The performance model thus generates some gains (e.g., target angles for orienting an SPM) for early morning tracking (to avoid shading) and another gain for other times. The system in accordance with these embodiments are said to operate in two modes: regular tracking and backtracking. That is, the system uses a backtracking algorithm

(performance model) at designated times in the early morning and a regular tracking algorithm at all other-times.

[0028] The performance model differentiates between forecasted weather and instantaneous weather. For example, an instantaneous change in weather (e.g., a momentary drop in radiance) may be attributable to a passing cloud rather than an actual change in weather. Thus, preferably the performance model gives more weight to forecasted weather.

[0029] Figure 3 is a block diagram of a diffuse control architecture NX SCADA 300 in accordance with one embodiment of the invention. The NX SCADA 300 receives as input weather forecast (e.g., DFI), NCU and SPC data (unmodified tracking angle), site configuration parameters (e.g., SPC Yield state and Diffuse table) and outputs tracking and backtracking optimal ratios for each SPC. A diffuse table in accordance with one embodiment of the invention plots optimal diffuse gain versus diffuse fraction indexes for determining a performance model.

[0030] Figure 4 shows the steps 400 of a process for determining parameters for performance models in accordance with one embodiment of the invention. Though the process is performed for each row of solar panels in a grid, the following explanation describes the process for a single row of solar panel modules in a grid. It will be appreciated that the process will be performed for the remaining rows of solar panel modules. First, in the step 405, the sun position angle (SPA) is calculated from the latitude and longitude for the particular row of solar panel modules and the time of day. Next, in the step 410, it is determined whether the BitO in the yield state is ON. Here, BitO and Bit1 are a two-bit sequence (Bit0Bit1) used to describe which of a possible 4 modes the solar tracker is in: BitO = 0/1 corresponds to row-to-row (R2R) tracking being OFF/ON, and Bit1= 0/1 corresponds to diffuse tracking being OFF/ON. Thus, for example, Bit0Bit1 = 01 corresponds to R2R tracking OFF and diffuse tracking ON, Bit0Bit1 = 10 corresponds to R2R tracking ON and diffuse tracking OFF, etc. In other embodiments, BitO = 1/0 corresponds to R2R tracking being OFF/ON and Bit1 = 1/0 corresponds to diffuse tracking is OFF/ON. The designations are arbitrary.

[0031] If BitO is not ON, the process proceeds to the step 415 in which SPA_Tracker is set to the SPA_Site, and continues to the step 425. If, in the step 410, it is determined that the BitO in the yield state is ON, then the process continues to the step 420, where the SPA for the tracker is translated, from which the process continues to the step 425. In the step 425, "backtracking" is calculated. From the step 425, the algorithm proceeds to the step 430, in which it is determined whether Bit1 in the yield state is ON. If Bit1 is ON, the process continues to the step 435; otherwise, if Bit1 in the yield state is OFF, the process continues to the step 455.

[0032] In the step 435, the process determines whether a diffused ratio has been received in the last 70 minutes. If a diffused ratio has been received in the last 70 minutes, the process continues to the step 440; otherwise, the process continues to the step 455. In the step 440, the process determines whether the particular SPC is in the backtracking mode. If it determined that the SPC is not in the backtracking mode, the process continues to the step 445; otherwise, the process continues to the step 450. In the step 445, the tracker target angle is set to (tracker target angle) ∗ diffused ratio. From the step 445, the process continues to the step 455. In the step 450, the target tracker angle is set to (target tracker angle) ∗ diffused_backtrack_ratio. From the step 455, the process continues to the step 455. In the step 455, the tracker is moved to the target tracker angle.

[0033] As shown in Figure 4, the steps 415, 420, and 425 form the R2R algorithm; the step 435 forms a "time relinquishment" algorithm; and the steps 440, 445, 450, 455 form the diffuse algorithm. In Figure 4, for the time relinquishment, if no diffuse ratio is received within the last 70 minutes, the ratios are set to 1.

[0034] Those skilled in the art will recognize that the steps 400 are merely illustrative of one embodiment of the invention. In other embodiments, some steps can be added, other steps can be deleted, the steps can be performed in different orders, and time periods (e.g., 70 minutes between diffuse adjustments) can be changed.

[0035] Figure 5 is a diffuse table generated from yearly data, according to one example, plotting optimal diffuse gain versus diffuse fraction index.

[0036] Figure 6 is a graph of a final diffuse ratio table for tracking, plotting tracker angle ratio coefficient versus DHI/GHI ratios, according to one embodiment of the invention. Figure 7 is a graph of a final diffuse ratio table for backtracking, plotting tracker angle ratio coefficient versus DHI/GHI ratios, according to one embodiment of the invention.

[0037] Figure 8 shows a SCADA 700 in accordance with one embodiment of the invention. The SCADA 800 comprises a row-to-row (R2R) tracking module 801, storage 805, a diffuse angle adjustor 810, first and second transmission modules 815 and 820, a DHI-GHI module 825, a weather lookup module 835, and a report engine 830. The R2R tracking module 801 is coupled to the storage 805, the diffuse angle adjustor 810, and the first transmission module 815. The R2R tracking module 801 tracks the slopes of solar panel modules at their locations, stores the slopes in the storage 805, sends target tracking angles (for given dates and times) to the diffuse angle adjustor 810, and transmits the slopes to the first transmission module 815 for pushing to the SPCs. The weather lookup module 835 collects weather data for the DHI-GHI module 825, which provides the weather data to the diffuse angle adjustor 810. The diffuse angle adjustor transmits the diffuse angles to the second transmission module 820, which pushes the data to its associated SPC, and also to the report engine 830. The local sensor data (LSD) module 840 receives local sensed weather data (e.g., weather, wind, or other local sensed data) from the NCUs and pushes the data to the weather lookup

module 835.

[0038] A topography module 802 is configured to store maps and communicate topographical information to the R2R tracking module 801. The information may be used to compute the row-to-row table. It is contemplated that the R2R tracking module 801 may include a topography module 802. The information stored in the topography module 802 may updated on a periodic basis. The topographical information can be determined, for example, using laser site surveys, learned surveys using photovoltaics on SPCs, closed-loop readings on the solar panel modules, or airplane or drone imaging.

[0039] As explained above, preferably the SCADA 800 pushes not the "optimal" angle for each individual SPA, but the angle that optimizes the total global energy output. The diffuse angle adjustor 810 pushes not an angle but a ratio (e.g., 70%, a "gain factor"). In a preferred embodiment, SCADA 800 is configured to transmit two gains: a gain for regular tracking and a gain for "backtracking," that is, a gain to avoid shading during early morning hours. Thus, in accordance with one embodiment, the SCADA 800 determines the time of day and thus whether to generate a regular tracking gain or a backtracking gain, which is pushed to the SPCs.

[0040] As explained above, in one embodiment a topology for each SPM is determined from shading between SPMs (adjacent and otherwise) using small solar panels ("skinny solar panels") each coupled to or integrated with a self-powered controller (SPC) on an SPM as described above or otherwise coupled to the SPM. As used herein, a skinny solar panel, like individual solar panels in an SPM, is able to read an amount of radiation (e.g., solar radiation) striking its surface. Like an SPM, this amount of radiation is able to be related to an orientation (e.g., incidence angle) of the surface to a solar source. Figure 9 shows a torque tube supporting both a skinny solar panel 910 and a row of solar panel modules 901, the SPM 901 comprising individual solar panels 901A-J. The torque tube is coupled to a drive assembly (not shown) for orienting (here, rotating) radiation-collecting surfaces of the SPM 901 and the skinny solar panel 910 to the solar source.

[0041] In one embodiment, the skinny solar panel 910 determines shading between SPMs and thus their relating heights. In this way, "height profiles" can be estimated. Below, β-events refer to a panel no longer being shaded. For example, when a first of the SPMs moves, a β-event can be triggered to show that other panels are no longer shaded. These shading events can determine relative heights and the order (sequence) of SPMs. Figures 10-23 are used to explain this determination in accordance with one embodiment of the invention.

[0042] Figure 11-17 show, among other things, how simple trigonometry can be sued to determine relative heights (dh). Figure 18 shows a simple recursive algorithm for determining relative heights. Figures 19-23 show the results of using this algorithm in accordance with one embodiment of the invention.

[0043] In different embodiments, a skinny solar panel is the same as or forms part of a photovoltaic that powers an SPC or is a component separate from the photovoltaic that powers an SPC. Thus, photovoltaics different from skinny solar panels can be used in accordance with Figures 9-23 to determine relative heights and ordering between SPMs are described herein.

[0044] In a preferred embodiment, the logic of a solar tracking system in accordance with the present invention is distributed. For example, referring to Figure 2, a base performance model is generated at SCADA 260 or at a central location coupled to the SCADA 260 over a cloud network. Diffuse adjustments (e.g., gains) are determined at the SCADA 260. Actual target angles for each SPC are determined at the associated SPCs based on the gains.

[0045] Using the cloud network, the SCADA 260 is able to receive weather forecasts, share information from the cloud to the NCUs and SPCs in the zone 280, offload computational functionality to remote processing systems, or any combination of these or any othertasks.

[0046] In operation of one embodiment, a global optimal performance model is generated for a solar tracking system in two stages. In the first stage, a detailed site geometry (topography) of the area containing the solar tracking system is determined. This can be determined using laser site surveys, learned surveys using photovoltaics on SPCs, closed-loop readings on the solar panel modules, or airplane or drone imaging.

[0047] As some examples, topography for the area containing an SPC is determined by orienting a photovoltaic on the SPC to the known location of the sun. The energy readings compared to the known location of the sun can be used to determine a position of the associated solar panel, including any one or more of its x-y-z coordinates relative to a fixed point (i.e., its GPS coordinates) or its grade/slope relative to normal or another fixed angle, to name only a few such coordinates. The solar panels can be oriented in similar ways and their local topographies similarly determined. In yet another embodiment, a separate sensing panel is installed on each row of solar panel modules. By adjusting the orientation of a sensing panel with respect to the sun, based on the time of day (i.e., angle of the sun) and outputs generated on the sensing panel, the relative positions of adjacent rows of solar panel modules can be determined. In still another embodiment, x-y-z coordinates of the edges of the rows of solar panel modules are physically measured.

[0048] In a second stage, periodic adjustments are made to the parameters of the performance model, such as by using weather conditions (e.g., forecast and historical conditions), using, for example, satellite weather forecasts, cameras trained to the sky, power measurements on the solar panel modules, and voltage measurement from the SPCs.

[0049] It will be appreciated that each of the SPCs, NCUs, and SCADA described herein comprises memory containing computer-executable instructions and a proc-

essor for performing those instructions, such as disclosed herein.

[0050] It will be appreciated that solar grids are able to span large areas, such that different portions of the solar grid experience different weather conditions. In accordance with embodiments of the invention, performance models are generated for each solar panel module and updated based on weather conditions local to each.

[0051] Those skilled in the art will recognize that various modifications can be made to the disclosed embodiments without departing from the scope of the invention. As one example, while the embodiments disclose multiple rows of solar panel modules, each row can be replaced by a single elongated solar panel module. Further, while the examples describe the radiation source as the sun, other radiation sources are contemplated by the principles of the invention, such as thermal radiation sources.

[0052] Systems for and methods of generating performance models are disclosed in U.S. Patent application serial no. 14/577,644, filed December 19, 2014, and titled "Systems for and Methods of Modeling, Step-Testing, and Adaptively Controlling In-Situ Building Components," which claims priority to U.S. provisional patent application serial number 61/919,547, filed December 20, 2013, and titled "System, Method and Platform for Characterizing In-Situ Building and System Component and Sub-component Performance by Using Generic Performance Data, Utility-Meter Data, and Automatic Step Testing," and U.S. provisional patent application serial number 62/022,126, filed July 8, 2014, and titled "System, Method and Platform for Automated Commissioning in Commercial Buildings".

[0053] Systems for and methods of self-powering solar trackers are disclosed in U.S. Patent application serial no. 14/972,036, filed December 16, 2015, titled "Self-Powered Solar tracker Apparatus".

[0054] Systems for and methods of row-to-row tracking are disclosed in U.S. Patent application serial no. 62/492,870, filed May 1, 2017, and titled "Row to Row Sun Tracking Method and System".

[0055] Tracking systems are described in U.S. Patent application serial no. 14/745,301, filed June 19, 2015, and titled "Clamp Assembly for Solar Tracker," which is a continuation of U.S. Patent application serial no. 14/489,416, filed September 17, 2014, and titled "Clamp Assembly for Solar Tracker," which is a continuation in part of U.S. Patent application serial no. 14/101,273, filed December 9, 2013, and titled, "Horizontal Balanced Solar Tracker," which claims priority to U.S. Patent application serial no. 61/735,537, filed December 10, 2012, and titled "Fully Adjustable Tracker Apparatus".

Claims

1. A solar tracking system (100; 200) comprising:

multiple rows of solar panel modules (110A-110D) forming a grid of solar panel modules, wherein the multiple rows of solar panel modules (110A-110D) are orientatable to a solar source independently of each other; and

a control system configured to orient each of the multiple rows of solar panel modules (110A-110D) to the solar source independently of each other based on a performance model to optimize an energy output from the grid of solar panel modules,

characterized in that

the performance model predicts an energy output from the grid of solar panel modules based on an orientation of each of the multiple rows of solar panel modules (110A-110D) to the solar source and first data comprising weather conditions local to each of the multiple rows of solar panel modules (110A-110D) and a predicted amount of irradiance upon each of the multiple rows of solar panel modules (110A-110D), wherein the amount of irradiance is a function of a diffuse horizontal irradiance, DHI, to global horizontal irradiance, GHI, ratio.

2. The solar tracking system (100; 200) of claim 1, wherein the amount of irradiance is further a function of direct normal irradiance, DNI, or ground reflected radiation.

3. The solar tracking system (100; 200) of claim 1, wherein the performance model is calibrated based on the outputs of the solar panel modules and on shading between the multiple rows of solar panel modules (110A-110D).

4. The solar tracking system (100; 200) of claim 3, wherein the shading is determined from second data comprising a topographical map indicating relative positions between adjacent ones of the multiple rows of solar panel modules (110A-110D).

5. The solar tracking system (100; 200) of claim 1, wherein each of the multiple rows of solar panel modules (SPM_i) comprises a corresponding self-powered controller (SPC_i), a drive assembly (DA_i), and a photovoltaic (PVi), for i = 1 to X.

6. The solar tracking system (100; 200) of claim 5, wherein the control system comprises multiple network control units (NCU_j) each coupled to a corresponding one or more of the self-powered controllers (SPC_i), for i = 1 to X, j = 1 to Y, Y < X, and each SPC_i is wirelessly coupled to a corresponding NCUj.

7. The solar tracking system (100; 200) of claim 6, wherein the multiple network control units (NCU_i) are coupled to a central controller (260; 300; 800).

8. The solar tracking system (100; 200) of claim 7, wherein the central controller (260; 300; 800) adjusts the performance model using machine learning algorithms based on energy sensed on the solar tracking system (100; 200).

9. The solar tracking system (100; 200) of claim 1, wherein the performance model comprises a polynomial having variables weighted by gains.

10. The solar tracking system (100; 200) of claim 9, wherein the gains comprise regular tracking gains and backtracking gains depending on a time of day.

11. The solar tracking system (100; 200) of claim 1, wherein the performance model comprises a diffuse table, or the weather conditions are determined from current weather conditions, forecasted weather conditions, or both.

12. The solar tracking system (100; 200) of claim 1, wherein an orientation of each of the multiple rows of solar panel modules (SPMi) is an incident angle θi between a normal to SM_i and a line from SM_i to the solar source, for i = 1 to X.

13. The solar tracking system (100; 200) of claim 7, wherein each SPC_i is configured to operate at a default operation when losing communication with a corresponding network control unit NCU_j.

14. The solar tracking system of claim 13, wherein the default operation comprises orientating an SM_i to a default angle to zenith.

15. The solar tracking system (100; 200) of claim 6, wherein the central controller (800) comprises:

a weather look-up module (835) for receiving weather data local to each of the rows of solar panel modules (SM_i);
a global-horizontal irradiance and diffuse horizontal irradiance (DHI-GHI) module (825);
a row-to-row tracking module (801) for determining a slope of each of the multiple rows of solar panel modules (SM_i) to a horizontal;
a diffuse-angle adjustor (810) for adjusting the performance model based on the slopes, a time of year, and a time of day;
a first transmission module (815) for pushing orientation commands to each of the self-powered controllers (SPC_i) based on the performance model; and
a second transmission module (820) for receiving data from each of the network control units

(NCU_j) for i = 1 to X, j = 1 to Y.

Patentansprüche

1. Ein Solarnachführsystem (100; 200), umfassend:

mehrere Reihen von Solarpanelmodulen (110A-110D), die ein Gitter aus Solarpanelmodulen bilden, wobei die mehreren Reihen von Solarpanelmodulen (110A-110D) unabhängig voneinander auf eine Solarquelle ausrichtbar sind; und
ein Steuersystem, das konfiguriert ist, basierend auf einem Leistungsmodell jede der mehreren Reihen von Solarpanelmodulen (110A-110D) unabhängig voneinander auf die Solarquelle auszurichten, um einen Energieertrag des Gitters aus Solarpanelmodulen zu optimieren,
dadurch gekennzeichnet, dass

das Leistungsmodell einen Energieertrag des Gitters aus Solarpanelmodulen basierend auf einer Ausrichtung jeder der mehreren Reihen von Solarpanelmodulen (110A-110D) zu der Solarquelle und ersten Daten, die lokale Wetterbedingungen für jede der mehreren Reihen von Solarpanelmodulen (1 10A-110D) und eine vorhergesagte Höhe einer Bestrahlungsstärke auf jeder der mehreren Reihen von Solarpanelmodulen (110A-110D) umfassen, vorhersagt, wobei die Höhe der Bestrahlungsstärke eine Funktion eines Verhältnisses von diffuser horizontaler Bestrahlungsstärke, DHI, zu globaler horizontaler Bestrahlungsstärke, GHI, ist.

2. Solarnachführsystem (100; 200) nach Anspruch 1, wobei die Bestrahlungsstärke ferner eine Funktion einer direkten Normalbestrahlungsstärke, DNI, oder einer vom Boden reflektierten Strahlung ist.

3. Solarnachführsystem (100; 200) nach Anspruch 1, wobei das Leistungsmodell basierend auf den Erträgen der Solarpanelmodule und einer Abschattung zwischen den mehreren Reihen von Solarpanelmodulen (110A-110D) kalibriert ist.

4. Solarnachführsystem (100; 200) nach Anspruch 3, wobei die Abschattung aus zweiten Daten, umfassend eine topographische Karte, die relative Positionen zwischen benachbarten Reihen der mehreren Reihen von Solarpanelmodulen (110A-110D) anzeigt, bestimmt ist.

5. Solarnachführsystem (100; 200) nach Anspruch 1, wobei jede der mehreren Reihen von Solarpanelmodulen (SPMi) ein entsprechendes selbstversorgtes Steuergerät (SPCi), eine Antriebsbaugruppe (DAi) und eine Photovoltaikanlage (PVi) für i = 1 bis X umfasst.

6. Solarnachführsystem (100; 200) nach Anspruch 5,

wobei das Steuersystem mehrere Netzwerksteuereinheiten (NCUj), die jeweils mit einem oder mehreren der entsprechenden selbstversorgten Steuergeräte (SPCi) gekoppelt sind, für i = 1 bis X, j = 1 bis Y, Y < X umfasst, und jedes SPCi drahtlos mit einer entsprechenden NCUj gekoppelt ist.

7. Solarnachführsystem (100; 200) nach Anspruch 6, wobei die mehreren Netzwerksteuereinheiten (NCUi) mit einem zentralen Steuergerät (260; 300; 800) verbunden sind.

8. Solarnachführsystem (100; 200) nach Anspruch 7, wobei das zentrale Steuergerät (260; 300; 800) das Leistungsmodell unter Verwendung von Algorithmen des maschinellen Lernens basierend auf einer an dem Solarnachführsystem (100; 200) erfassten Energie anpasst.

9. Das Solarnachführsystem (100; 200) nach Anspruch 1, wobei das Leistungsmodell ein Polynom mit nach Gewinnen gewichteten Variablen umfasst.

10. Das Solarnachführsystem (100; 200) nach Anspruch 9, wobei die Gewinne reguläre Nachführgewinne und Rückführgewinne in Abhängigkeit von der Tageszeit umfassen.

11. Solarnachführsystem (100; 200) nach Anspruch 1, wobei das Leistungsmodell eine diffuse Tabelle umfasst, oder die Wetterbedingungen aus aktuellen Wetterbedingungen, vorhergesagten Wetterbedingungen oder beidem bestimmt sind.

12. Solarnachführsystem (100; 200) nach Anspruch 1, wobei eine Ausrichtung jeder der mehreren Reihen von Solarpanelmodulen (SPMi) ein Einfallswinkel θi zwischen einer Normalen zu SMi und einer Linie von SMi zur Solarquelle für i = 1 bis X ist.

13. Solarnachführsystem (100; 200) nach Anspruch 7, wobei jede SPCi konfiguriert ist, in einem Standardbetrieb zu arbeiten, wenn sie die Kommunikation mit einer entsprechenden Netzwerksteuereinheit NCUj verliert.

14. Das Solarnachführsystem nach Anspruch 13, wobei der Standardbetrieb ein Ausrichten eines SMi auf einen Standardwinkel zum Zenit umfasst.

15. Solarnachführsystem (100; 200) nach Anspruch 6, wobei das zentrale Steuergerät (800) umfasst:

ein Wetter-Nachschlagemodul (835) zum Empfangen von lokalen Wetterdaten jeder der Reihen von Solarpanelmodulen (SMi);
ein Modul (825) für eine globale horizontale Bestrahlungsstärke und eine diffuse horizontale Bestrahlungsstärke (DHI-GHI);
ein Reihe-zu-Reihe-Nachführmodul (801) zum Bestimmen einer Neigung jeder der mehreren Reihen von Solarpanelmodulen (SMi) zu einer Horizontalen;
einen Ausrichter (810) eines diffusen Winkels zum Ausrichten des Leistungsmodells basierend auf den Neigungen, einer Jahreszeit und einer Tageszeit;
ein erstes Übertragungsmodul (815) zum Senden von Ausrichtungsbefehlen an jedes der selbstversorgten Steuergeräte (SPCi) basierend auf dem Leistungsmodell; und
ein zweites Übertragungsmodul (820) zum Empfangen von Daten von jeder der Netzwerksteuereinheiten (NCUj) für i = 1 bis X, j = 1 bis Y.

Revendications

1. Système de suivi solaire (100 ; 200) comprenant :

de multiples rangées de modules de panneau solaire (110A à 110D) formant une grille de modules de panneau solaire, dans lequel les multiples rangées de modules de panneau solaire (110A à 110D) sont orientables vers une source solaire indépendamment les unes des autres ; et
un système de commande configuré pour orienter chacune des multiples rangées de modules de panneau solaire (110A à 110D) vers la source solaire indépendamment les unes des autres d'après un modèle de performance pour optimiser un rendement énergétique issu de la grille de modules de panneau solaire,
caractérisé en ce que
le modèle de performance prédit un rendement énergétique à partir de la grille de modules de panneau solaire d'après une orientation de chacune des multiples rangées de modules de panneau solaire (110A à 110D) vis-à-vis de la source solaire et des premières données comprenant des conditions météorologiques locales à chacune des multiples rangées de modules de panneau solaire (110A à 110D) et une quantité prédite d'irradiance sur chacune des multiples rangées de modules de panneau solaire (110A à 110D), dans lequel la quantité d'irradiance est une fonction d'un rapport irradiance horizontale diffuse, DHI, sur irradiance horizontale globale, GHI.

2. Système de suivi solaire (100 ; 200) selon la revendication 1, dans lequel la quantité d'irradiance est en outre une fonction d'irradiance normale directe, DNI, ou de rayonnement réfléchi au sol.

3. Système de suivi solaire (100 ; 200) selon la revendication 1, dans lequel le modèle de performance est calibré d'après les sorties des modules de panneau solaire et l'ombrage entre les multiples rangées de modules de panneau solaire (110A à 110D).

4. Système de suivi solaire (100 ; 200) selon la revendication 3, dans lequel l'ombrage est déterminé à partir de deuxièmes données comprenant une carte topographique indiquant des positions relatives entre des rangées adjacentes parmi les multiples rangées de modules de panneau solaire (110A à 110D).

5. Système de suivi solaire (100 ; 200) selon la revendication 1, dans lequel chacune des multiples rangées de modules de panneau solaire (SPM_i) comprend un contrôleur auto-alimenté (SPC_i) correspondant, un ensemble entraînement (DA_i), et un photovoltaïque (PV_i), pour i = 1 à X.

6. Système de suivi solaire (100 ; 200) selon la revendication 5, dans lequel le système de commande comprend de multiples unités de commande réseau (NCU_j) couplées chacune à un ou plusieurs contrôleurs auto-alimentés correspondants parmi les contrôleurs auto-alimentés (SPC_i) , pour i = 1 à X, j = 1 à Y, Y < X, et chaque SPC_i est couplé sans fil à une NCU_j correspondante.

7. Système de suivi solaire (100 ; 200) selon la revendication 6, dans lequel les multiples unités de commande réseau (NCU_i) sont couplées à un contrôleur central (260 ; 300 ; 800).

8. Système de suivi solaire (100 ; 200) selon la revendication 7, dans lequel le contrôleur central (260 ; 300 ; 800) ajuste le modèle de performance à l'aide d'algorithmes d'apprentissage automatique d'après l'énergie captée sur le système de suivi solaire (100 ; 200) .

9. Système de suivi solaire (100 ; 200) selon la revendication 1, dans lequel le modèle de performance comprend un polynôme ayant des variables pondérées par des gains.

10. Système de suivi solaire (100 ; 200) selon la revendication 9, dans lequel les gains comprennent des gains de suivi réguliers et des gains de rétro-suivi dépendant de l'heure du jour.

11. Système de suivi solaire (100 ; 200) selon la revendication 1, dans lequel le modèle de performance comprend une table diffuse, ou les conditions météorologiques sont déterminées à partir de conditions météorologiques en cours, de conditions météorologiques prévues, ou des deux.

12. Système de suivi solaire (100 ; 200) selon la revendication 1, dans lequel une orientation de chacune des multiples rangées de modules de panneau solaire (SPMi) est un angle incident θi entre une normale à SM_i et une droite allant de SM_i à la source solaire, pour i = 1 à X.

13. Système de suivi solaire (100 ; 200) selon la revendication 7, dans lequel chaque SPC_i est configuré pour fonctionner selon un fonctionnement par défaut lors d'une perte de communication avec une unité de commande réseau NCU_j correspondante.

14. Système de suivi solaire selon la revendication 13, dans lequel le fonctionnement par défaut comprend l'orientation d'un SM_i à un angle par défaut par rapport au zénith.

15. Système de suivi solaire (100 ; 200) selon la revendication 6, dans lequel le contrôleur central (800) comprend :

un module de consultation météorologique (835) destiné à recevoir des données météorologiques locales de chacune des rangées de modules de panneau solaire (SM_i) ;
un module d'irradiance horizontale globale et d'irradiance horizontale diffuse (DHI-GHI) (825) ;
un module de suivi rangée par rangée (801) destiné à déterminer une pente de chacune des multiples rangées de modules de panneau solaire (SM_i) par rapport à une horizontale ;
un ajusteur d'angle diffus (810) destiné à ajuster le modèle de performance d'après les pentes, un moment de l'année, et une heure du jour ;
un premier module de transmission (815) destiné à pousser des commandes d'orientation à destination de chacun des contrôleurs auto-alimentés (SPC_i) d'après le modèle de performance ; et
un second module de transmission (820) destiné à recevoir des données provenant de chacune des unités de commande réseau (NCU_j) pour i = 1 à X, j = 1 à Y.

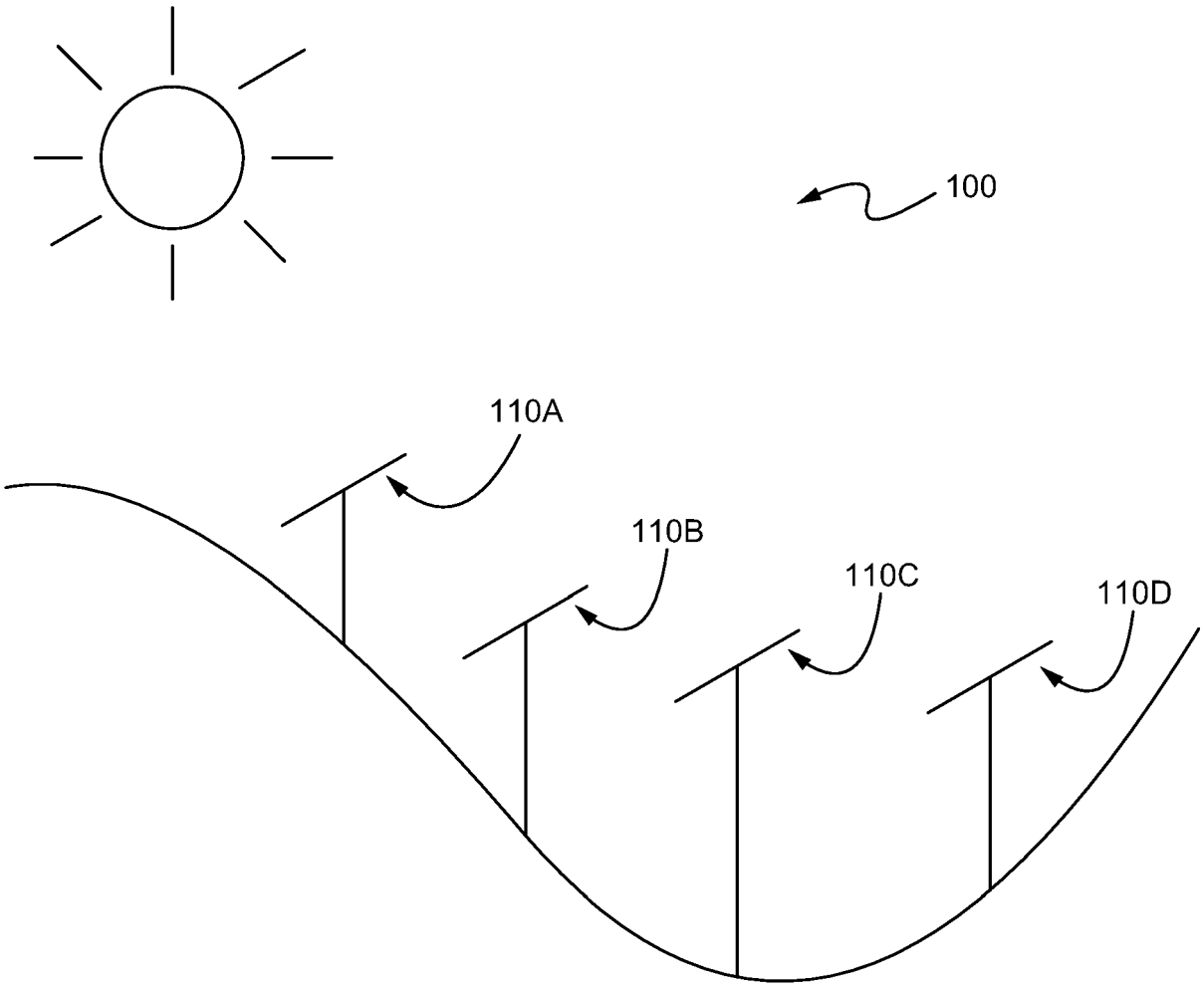


Fig. 1

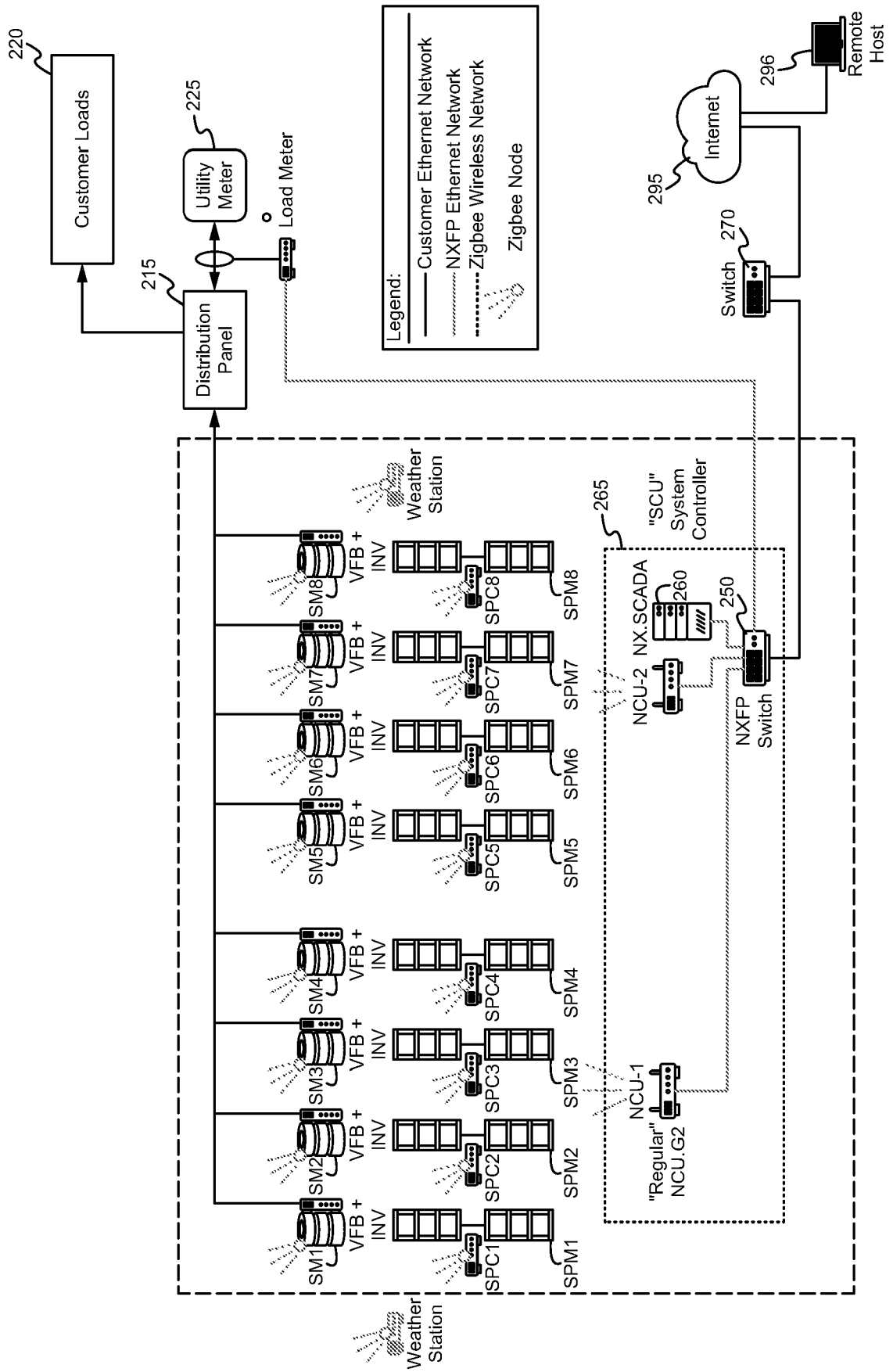

220
Customer Loads
225
Utility Meter
Load Meter
215
Distribution Panel
Legend:
Customer Ethernet Network
NXFP Ethernet Network
Zigbee Wireless Network
Zigbee Node
295
Internet
296
Remote Host
Switch
270
Weather Station
265
"SCU" System Controller
NX.SCADA
260
250
NCU-2
NXFP Switch
SM1
SM2
SM3
SM4
SM5
SM6
SM7
SM8
VFB +
INV
SPC1
SPC2
SPC3
SPC4
SPC5
SPC6
SPC7
SPC8
SPM1
SPM2
SPM3
SPM4
SPM5
SPM6
SPM7
SPM8
NCU-1
"Regular" NCU.G2
Weather Station

Fig. 2

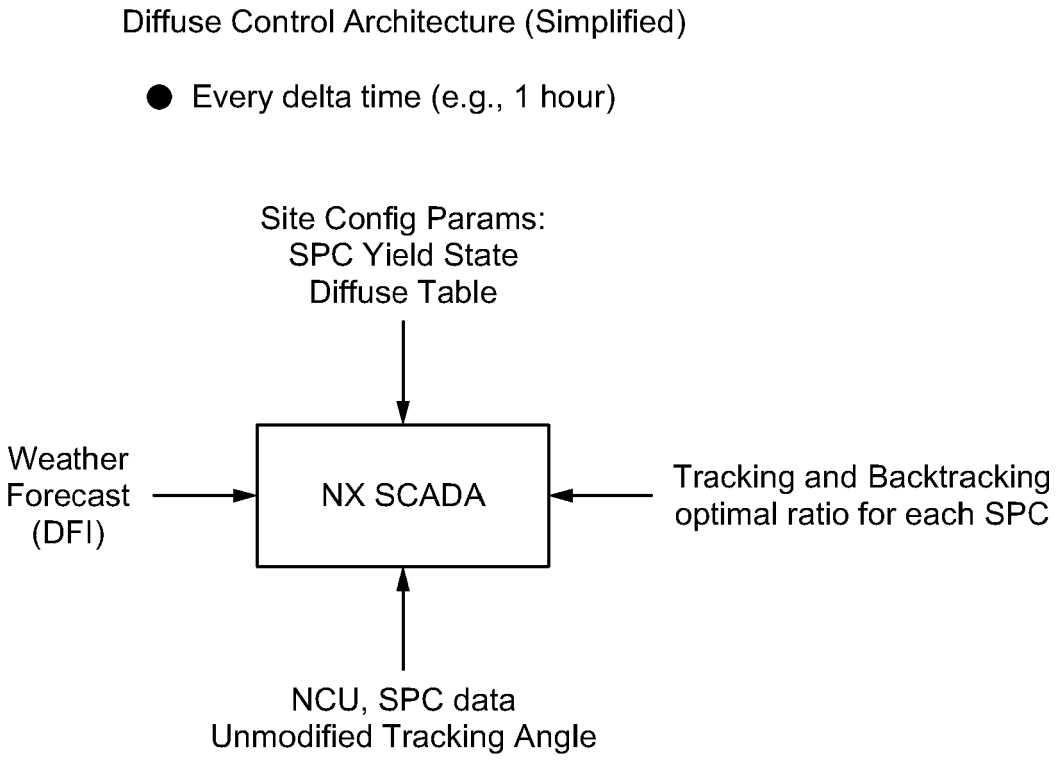

Diffuse Control Architecture (Simplified)
Every delta time (e.g., 1 hour)
Site Config Params:
SPC Yield State
Diffuse Table
Weather
Forecast
(DFI)
NX SCADA
Tracking and Backtracking
optimal ratio for each SPC
NCU, SPC data
Unmodified Tracking Angle

Fig. 3

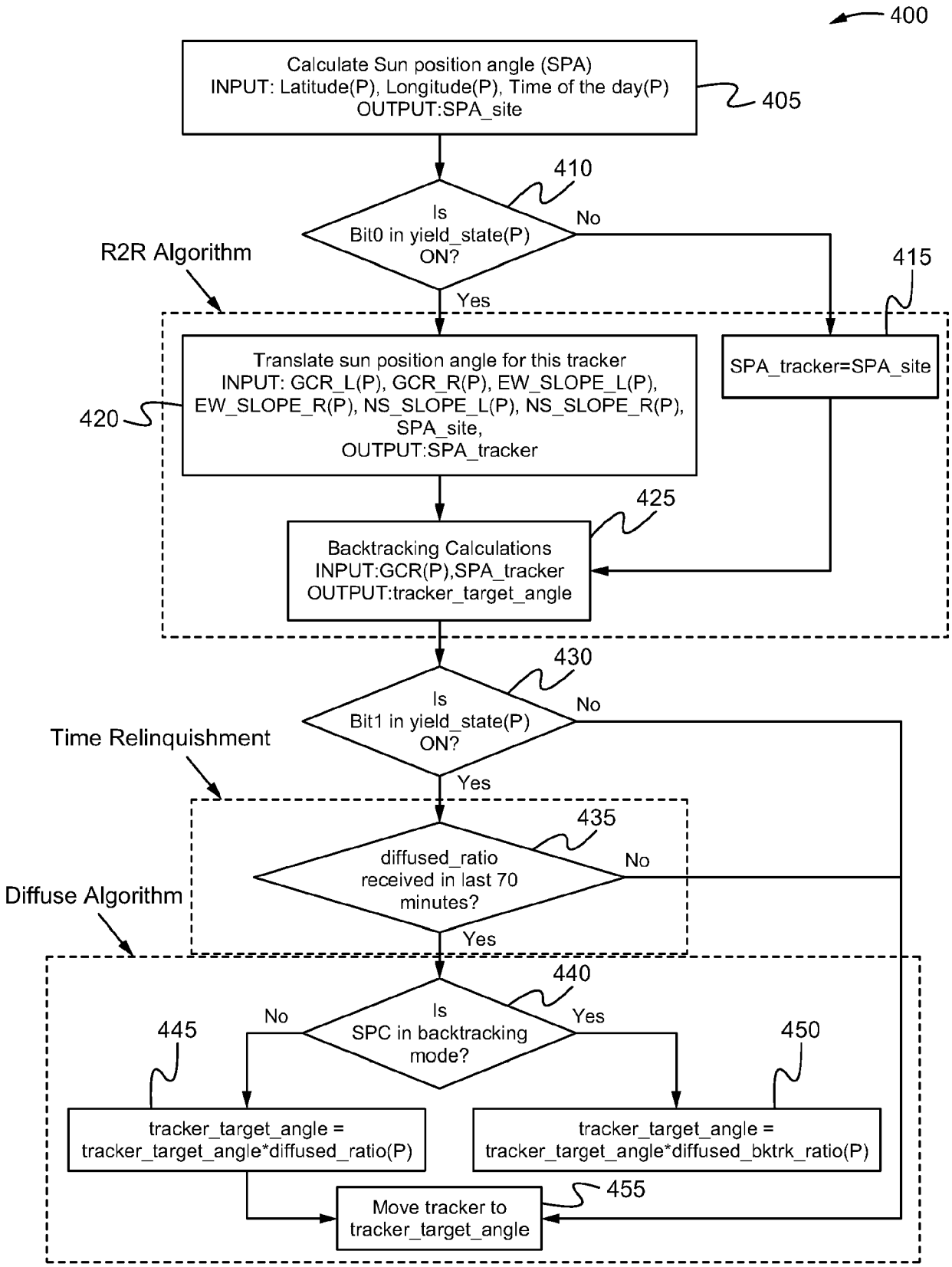

400
Calculate Sun position angle (SPA)
INPUT: Latitude(P), Longitude(P), Time of the day(P)
OUTPUT:SPA_site
405
410
Is
Bit0 in yield_state(P)
ON?
No
Yes
R2R Algorithm
415
Translate sun position angle for this tracker
INPUT: GCR_L(P), GCR_R(P), EW_SLOPE_L(P),
EW_SLOPE_R(P), NS_SLOPE_L(P), NS_SLOPE_R(P),
SPA_site,
OUTPUT:SPA_tracker
420
SPA_tracker=SPA_site
425
Backtracking Calculations
INPUT:GCR(P),SPA_tracker
OUTPUT:tracker_target_angle
430
Is
Bit1 in yield_state(P)
ON?
No
Time Relinquishment
Yes
435
diffused_ratio
received in last 70
minutes?
No
Diffuse Algorithm
Yes
440
Is
SPC in backtracking
mode?
No
Yes
445
450
tracker_target_angle =
tracker_target_angle*diffused_ratio(P)
tracker_target_angle =
tracker_target_angle*diffused_bktrk_ratio(P)
455
Move tracker to
tracker_target_angle

Fig. 4

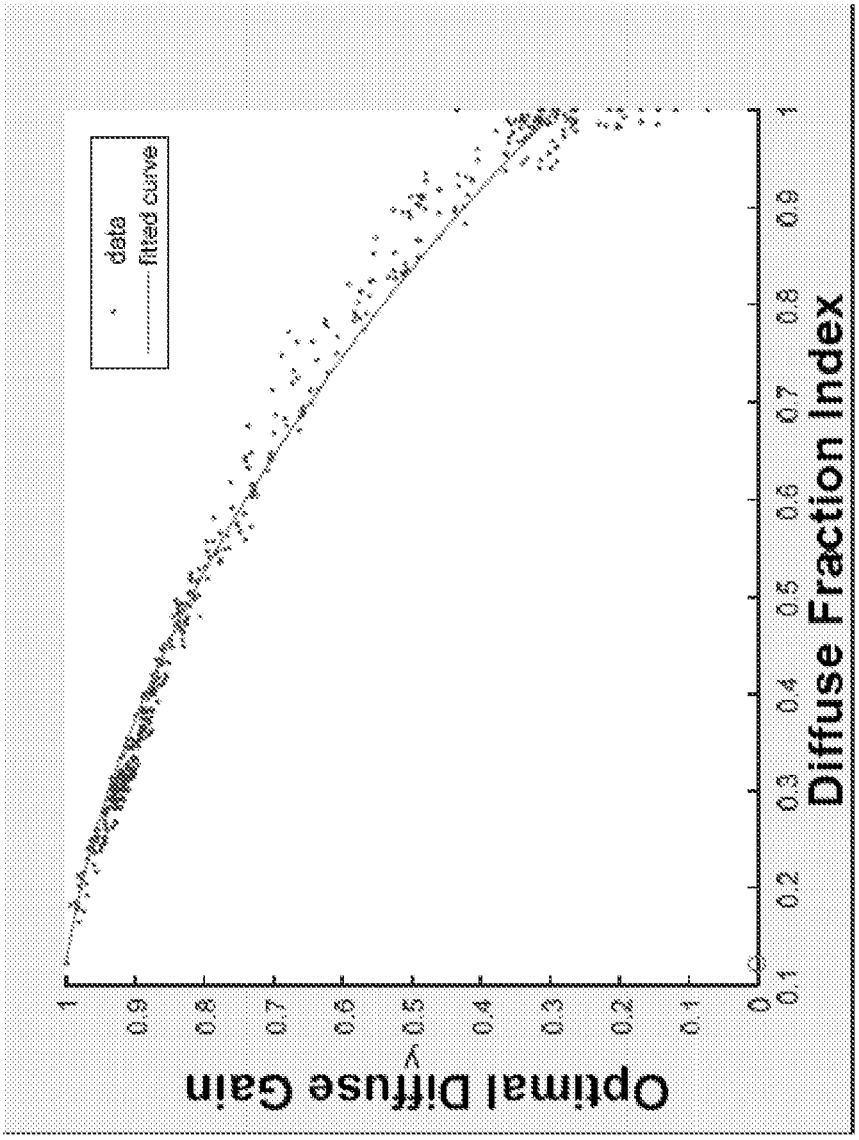

data
fitted curve
Optimal Diffuse Gain
Diffuse Fraction Index
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Fig. 5

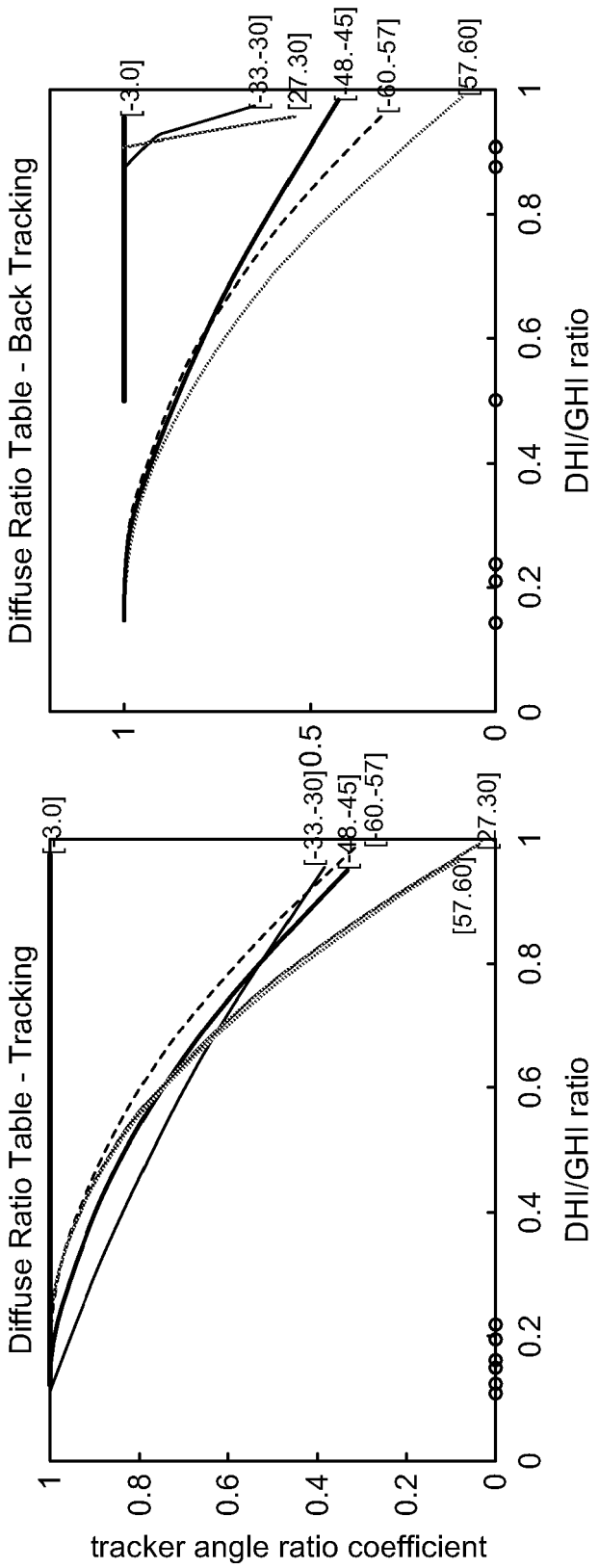

Diffuse Ratio Table - Back Tracking
[-3.0]
[-33.-30]
[27.30]
[-48.-45]
[-60.-57]
[57.60]
DHI/GHI ratio
Diffuse Ratio Table - Tracking
tracker angle ratio coefficient
DHI/GHI ratio

Fig. 6

Fig. 7

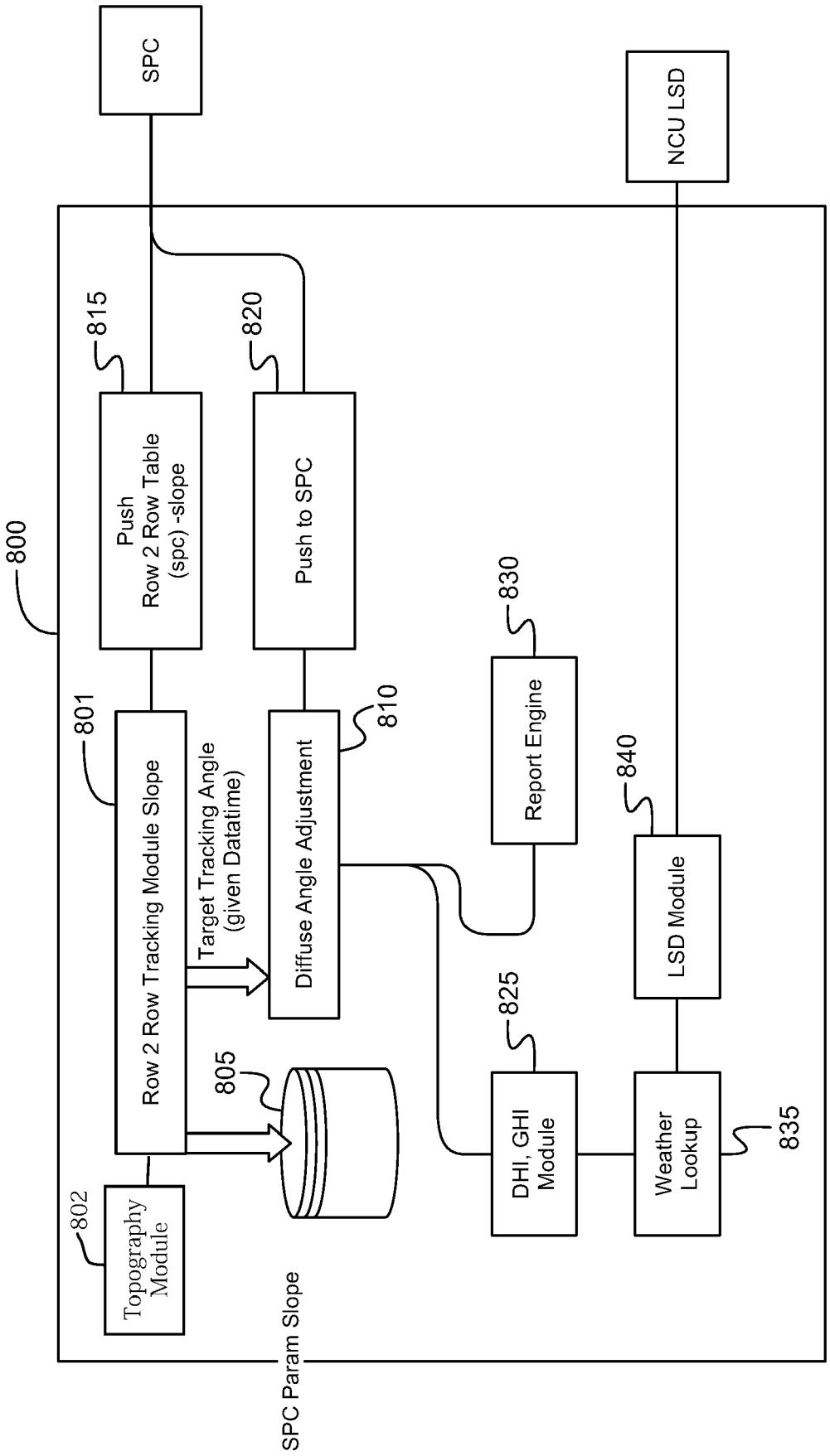

SPC
NCU LSD
800
815
820
Push
Row 2 Row Table
(spc) -slope
Push to SPC
801
Row 2 Row Tracking Module Slope
Target Tracking Angle
(given Datatime)
Diffuse Angle Adjustment
810
830
Report Engine
840
LSD Module
805
825
DHI, GHI
Module
Weather
Lookup
835
802
Topography
Module
SPC Param Slope

Fig. 8

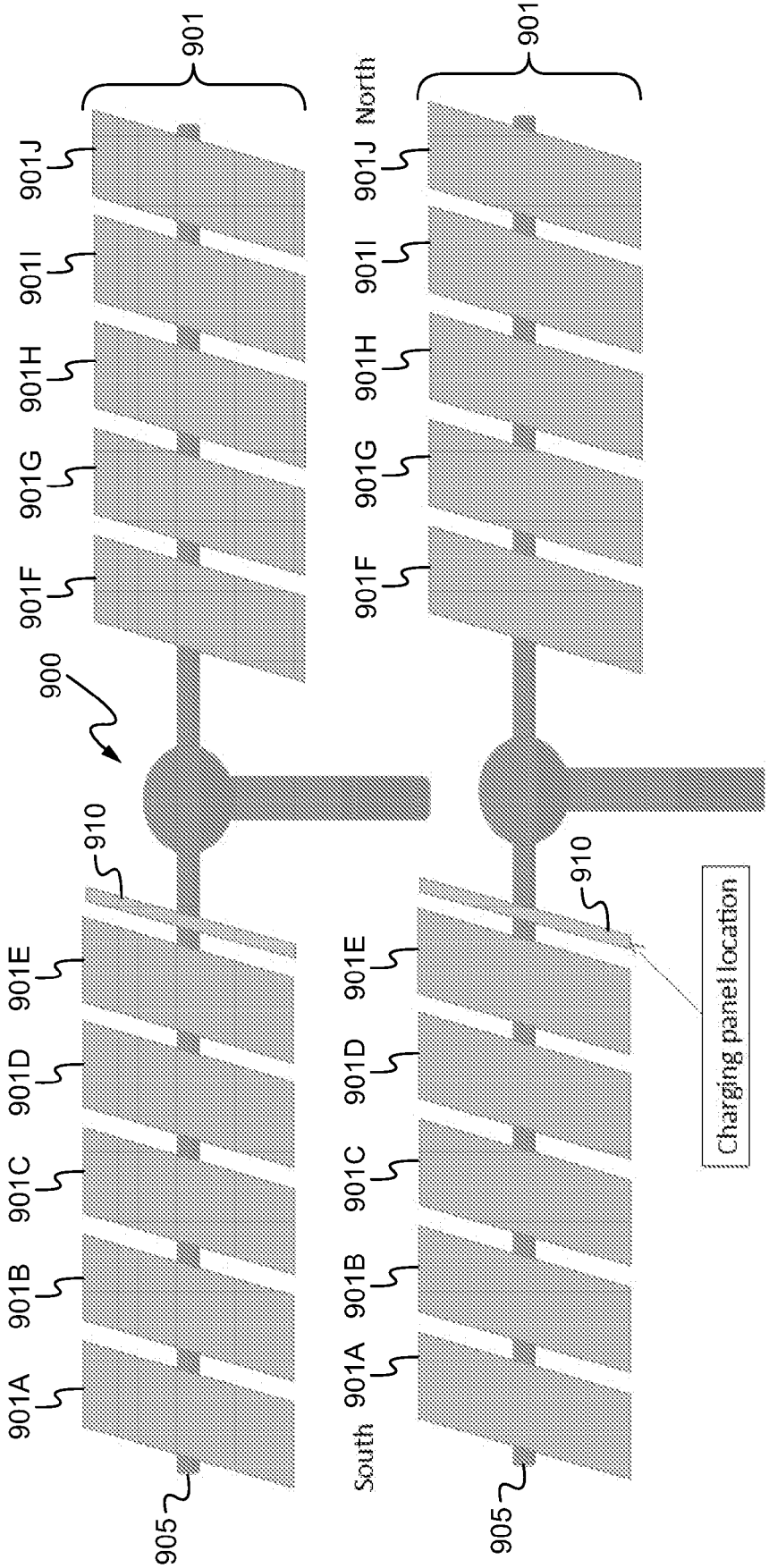
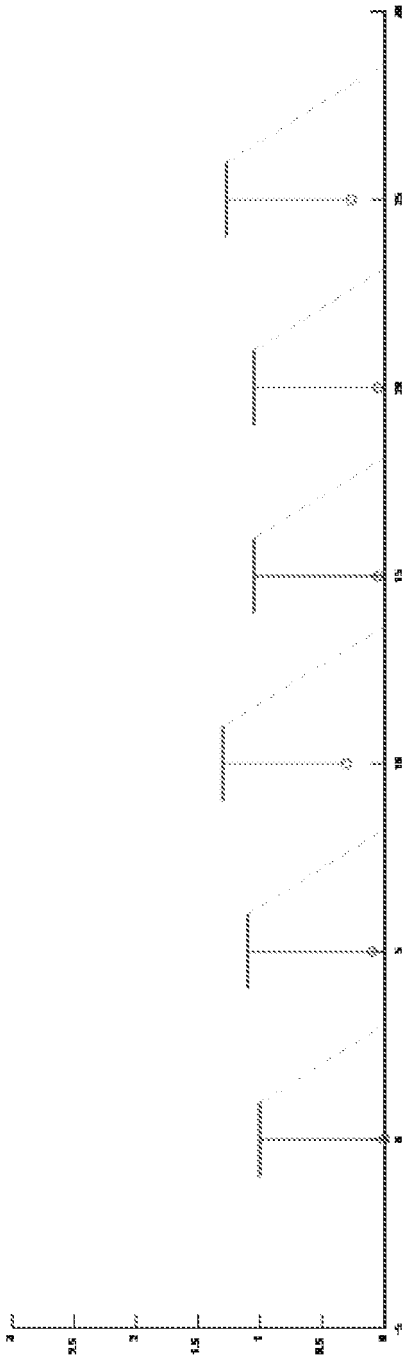

901
901J
901I
901H
901G
901F
900
910
901E
901D
901C
901B
901A
905
South
North
Charging panel location

Fig. 9



Vector of delta height: DH=[.1, 0.2, -0.25, 0, 0.22]

(Note: figure not to scale)

Fig. 10

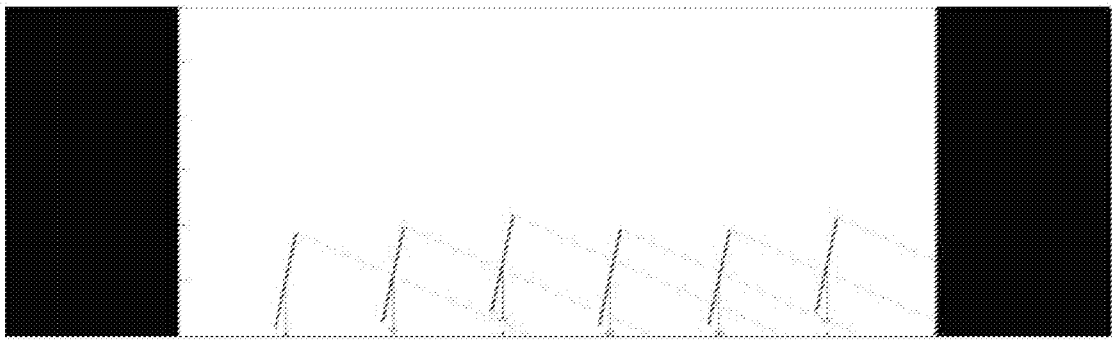
Using Simple Trigonometric

$$f(\theta_1, \theta_2, \beta, l, dh) = 0$$

Therefore if we measure β when the l=0 , by knowing the two panel positions we can solve for dh

Fig. 11

This is how the algorithm works (Simplified)



The final event list (in degrees)

β-event= [NaN 67.850 69.050 63.650 66.600 69.300]

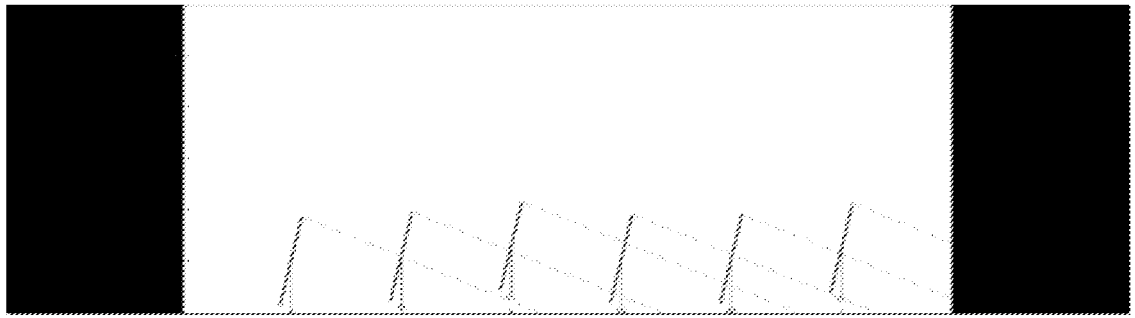
Which corresponds to estimated Delta height

DH_est= [0.0993 0.1973 -0.2524 -0.0011 0.2189]

Original DH=[.1, 0.2, -0.25, 0, 0.22]

Fig. 12

Using the other side: improve accuracy



The final event list (in degree)

β-event1 (morning): [NaN 67.85 69.05 63.65 66.60 69.30]

β-event2 (afternoon): [-65.40 -64.25 -69.70 -66.60 -64.00 NaN]

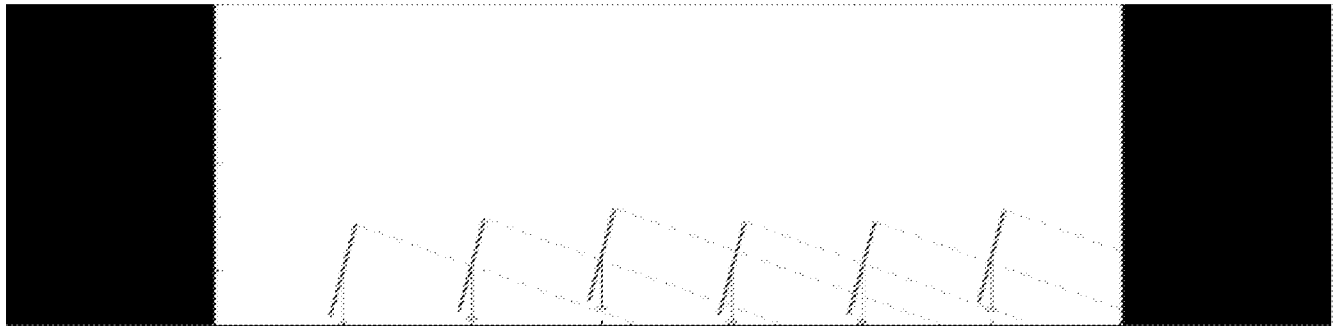
(DH_est1+DH_est1)/2=[0.1038 0.2006 -0.2492 0.0011 0.2206]

Original DH=[.1, 0.2, -0.25, 0, 0.22]

Fig. 13

EP 3 649 410 B9

Using the other side: reconstruct the order



Assuming the reading is as follows: spc_i in physical position

[6 3 4 1 2 5]

The final event list (in degree)

β-event1 (morning): : [63.65 66.60 67.85 69.05 69.30 NaN]

β-event2 (afternoon): [-66.60 -64.00 -64.25 -69.70 NaN -65.40]

Then we have:

DH_est1=[-0.2492 0.0011 0.1038 0.2006 0.2206 NaN]

DH-est_2=[0.0011 0.2189 0.1973 -0.2524 NaN 0.0993]

(Can reconstruct order by depth-first switch&match algorithm – implemented in Matlab)

Reconstructed order: [6 3 4 1 2 5]

Fig. 14

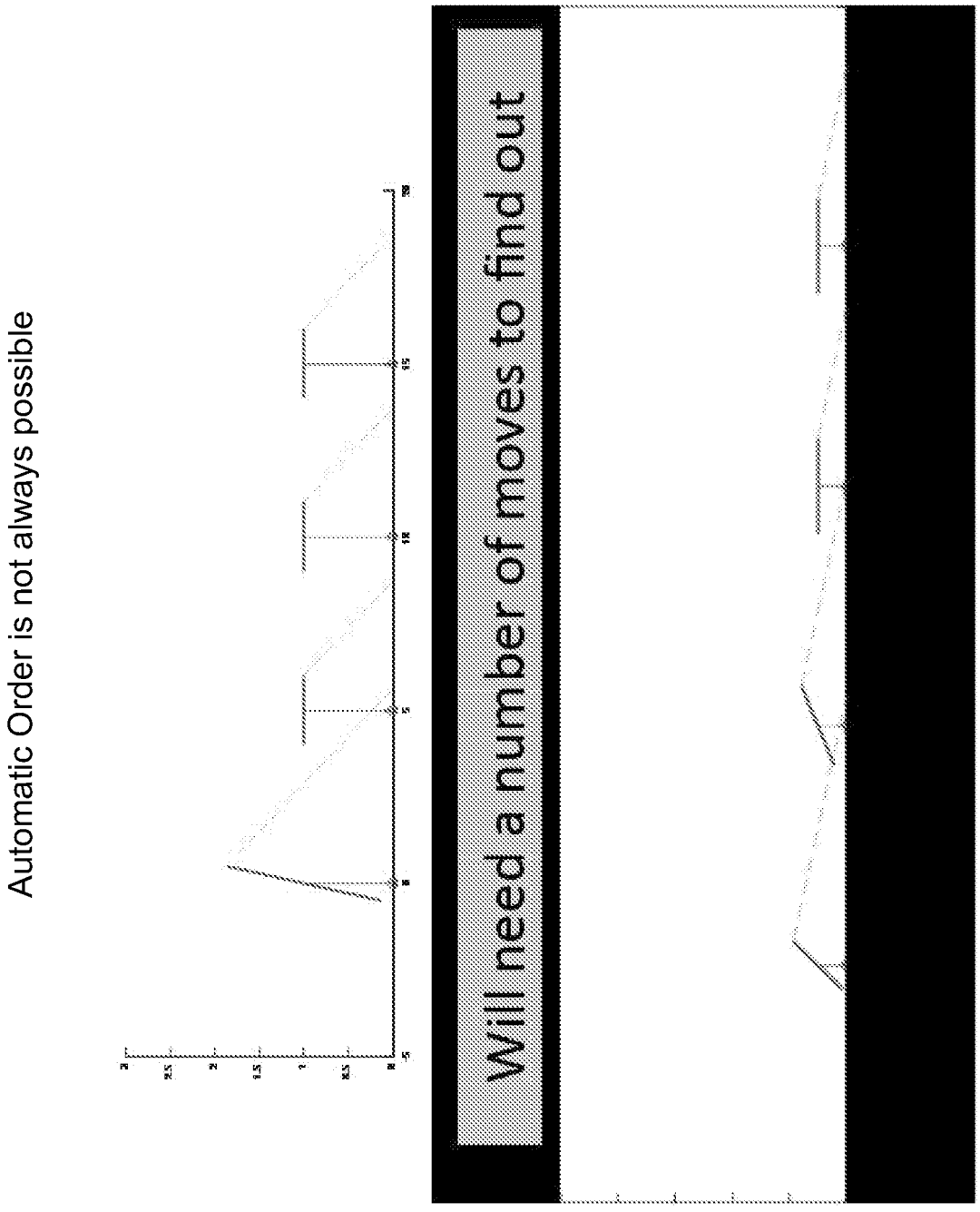

Automatic Order is not always possible
Will need a number of moves to find out

Fig. 15

Random (order and DH) examples:

Test #	Number of rows	Estimation Error (m)	Number of moves to estimate order (worst case)	Max DH
1	30	0.0018	3	0.3
1	30	0.0018	0	0.3
1	30	0.0012	0	0.3
1	30	0.0015	3	0.3
1	30	0.0016	0	0.3
1	30	0.0015	0	0.5
1	30	0.0016	0	0.5

Fig. 16

Random (order and DH) examples:

Test #	Number of rows	Estimation Error (m)	Number of moves to estimate order (worst case)	Max DH
1	30	0.0011	10	0.1
1	30	0.0009	21	0.1
1	30	0.0011	8	0.1
1	60	0.0017	5	0.3
1	60	0.0016	0	0.3
1	60	0.0018	4	0.3
1	60	0.0016	0	0.5

Fig. 17

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Simple Recursive Algorithm

```
estimated_order=zeros(1,plant.N)
[estimated_order,estimated_dh] = order_dh_estimation_v3(estimated_order,[],NaN,1);

function [out_list,dh_list] = order_dh_estimation(in_list,dh_list,marker,jglobal)
global deltaH_est1 deltaH_est2 plant

%% find elements with marker or close to marker
if jglobal==1,
   Nlist=1:plant.N;
   reconstructed_position_sensor=Nlist(isnan(deltaH_est1));
elseif isnan(marker),
   out_list=[];
   if sum(in_list)==sum(1:plant.N)
      out_list=[out_list;in_list];
   end
   return
else
   % find corresponding element
   [sorted,j_sorted]=sort(abs(deltaH_est1-marker));
   reconstructed_position_sensor=j_sorted(sorted<0.009);
end
nt=length(reconstructed_position_sensor);
if nt>=1,
out_list=[];
   for k=1:nt
      if ~ismember(reconstructed_position_sensor(k),in_list), %% remove elements already explored
         temp=in_list;
         temp(jglobal)=reconstructed_position_sensor(k);
         marker=deltaH_est2(reconstructed_position_sensor(k));
         [out_list_temp,dh_list] = order_dh_estimation_v2(temp,dh_list,marker,jglobal+1);
         out_list=[out_list;out_list_temp];
      end
   end
else
   out_list=[];
end
end
```

Fig. 18

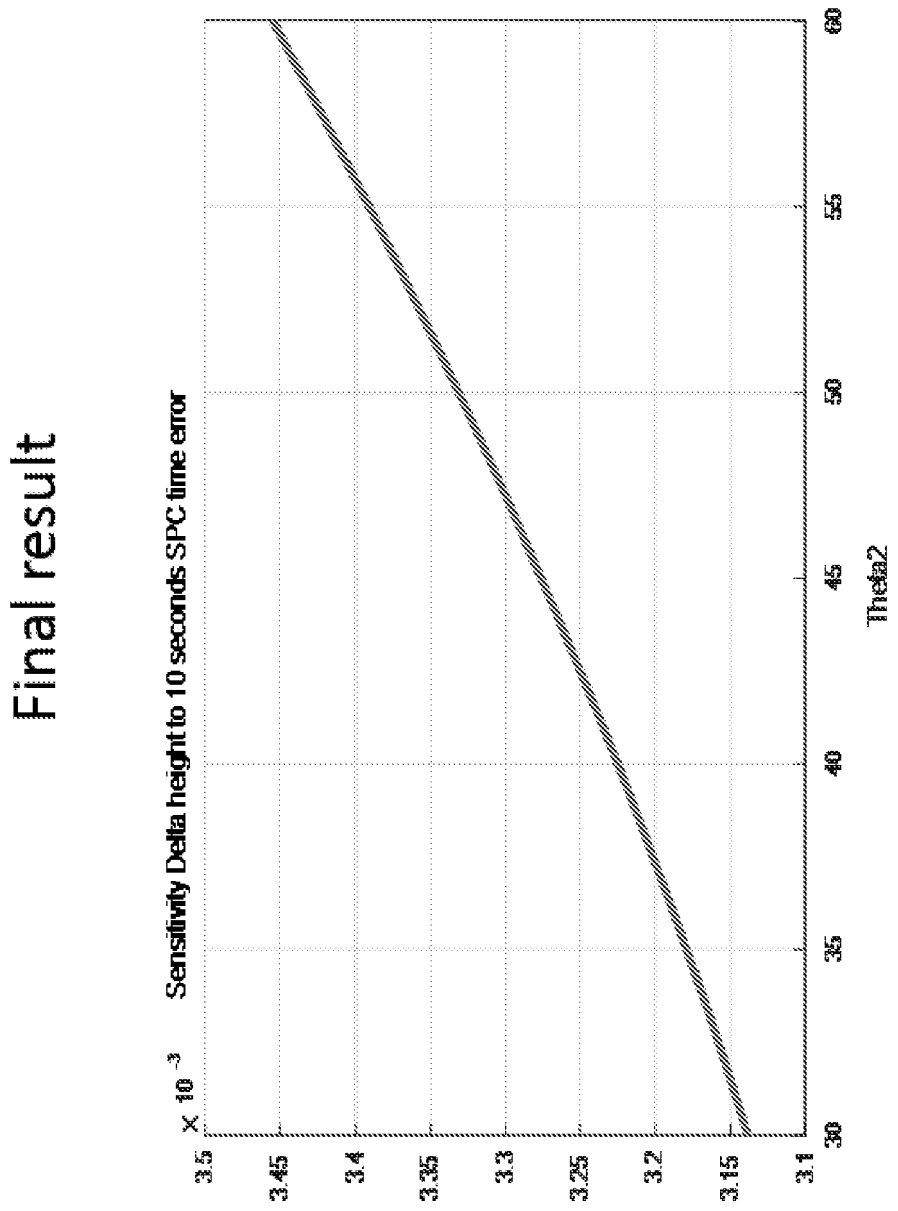

Final result
Sensitivity Delta height to 10 seconds SPC time error
× 10 -3
3.5
3.45
3.4
3.35
3.3
3.25
3.2
3.15
3.1
30
35
40
45
50
55
60
Theta2

Fig. 19

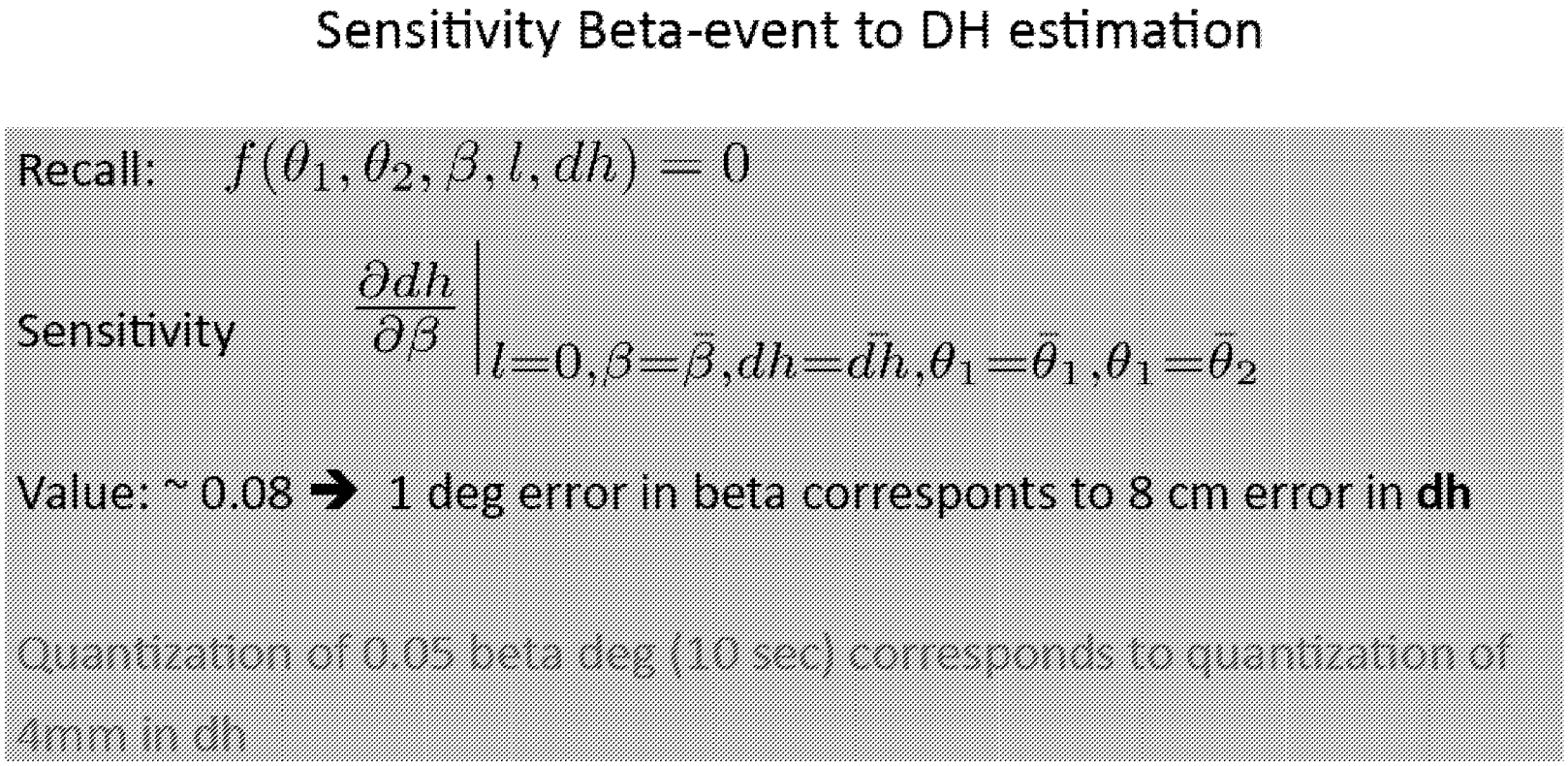

Sensitivity Beta-event to DH estimation
Recall: $f(\theta_1, \theta_2, \beta, l, dh) = 0$
Sensitivity $\left.\frac{\partial dh}{\partial \beta}\right|_{l=0,\beta=\bar{\beta},dh=\bar{dh},\theta_1=\bar{\theta}_1,\theta_1=\bar{\theta}_2}$
Value: ~ 0.08 ➔ 1 deg error in beta corresponts to 8 cm error in **dh**
Quantization of 0.05 beta deg (10 sec) corresponds to quantization of 4mm in dh

Fig. 20

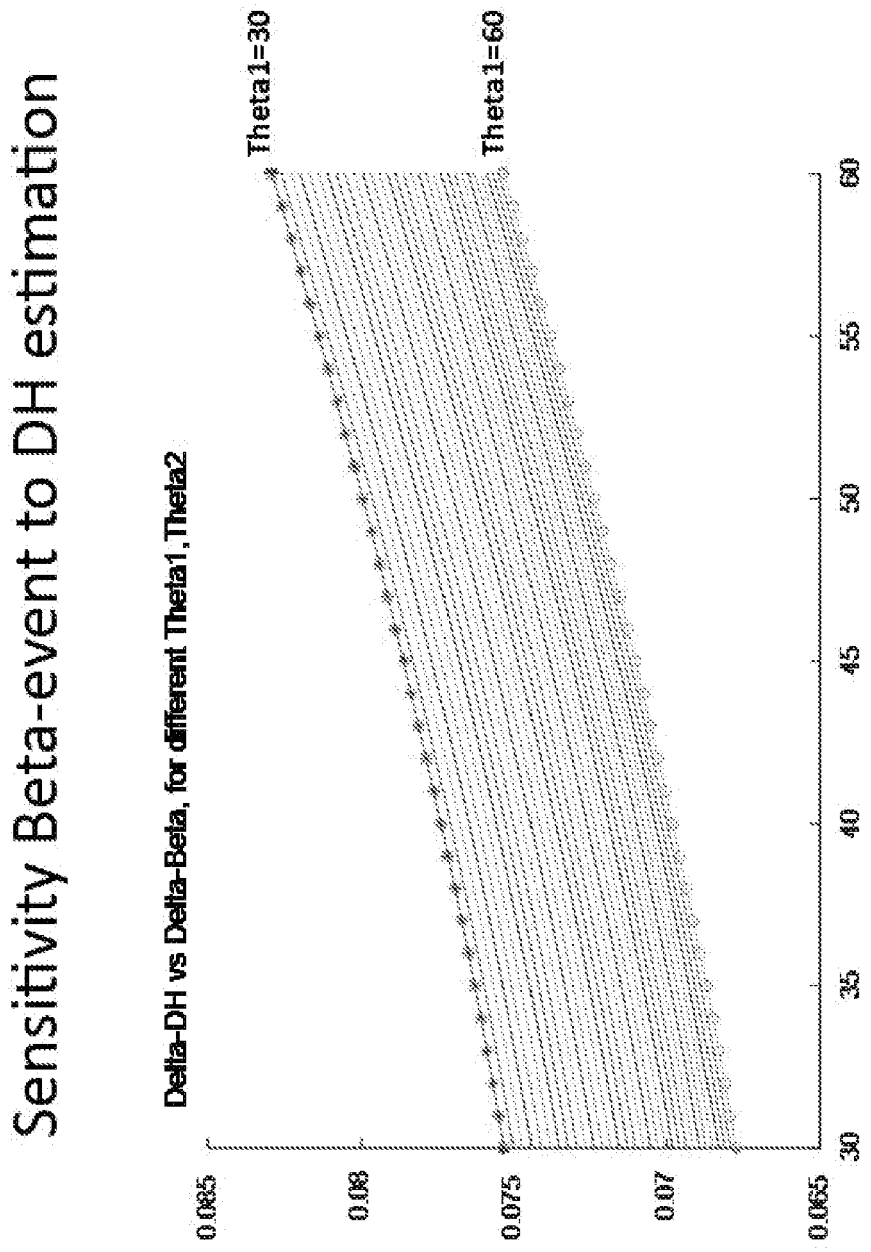
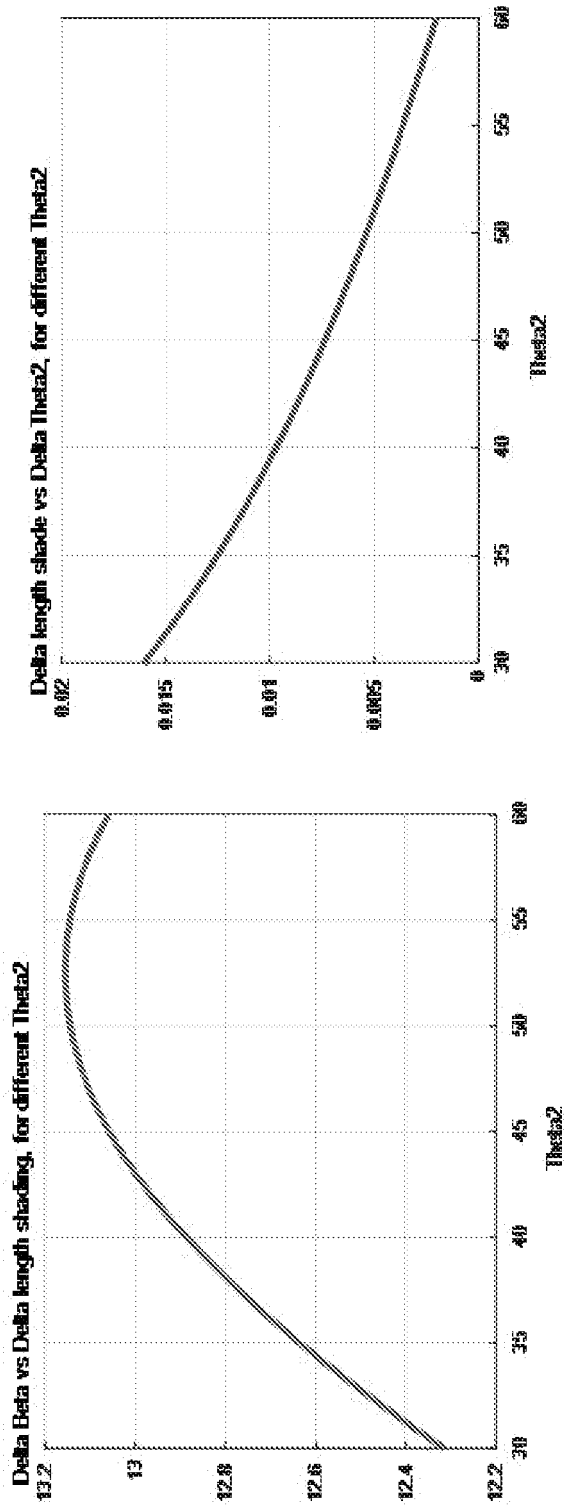

Sensitivity Beta-event to DH estimation
Delta-DH vs Delta-Beta, for different Theta1, Theta2
Theta1=30
Theta1=60
0.085
0.08
0.075
0.07
0.065
30
35
40
45
50
55
60
Theta2

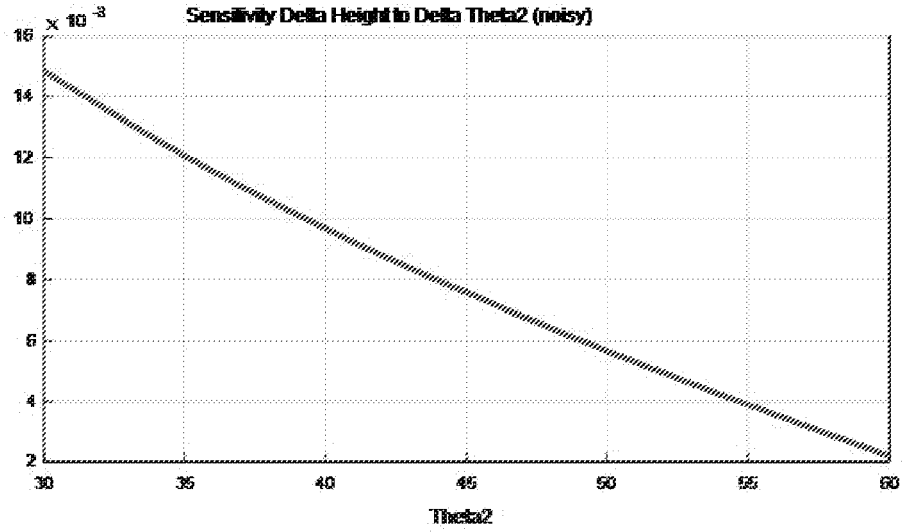
Fig. 21



$$\left.\frac{\partial dh}{\partial \theta_2}\right|_{\ldots} = \left.\frac{\partial dh}{\partial \beta}\right|_{\ldots} \left.\frac{\partial \beta}{\partial l}\right|_{\ldots} \left.\frac{\partial l}{\partial \theta_2}\right|_{\ldots}$$

Fig. 22

Final result



With Theta2 in the range of 60deg,

Value: ~ 0.002 ➔ 1 deg error in Theta 2 corresponts to 2 mm error in **dh estimation error**

Fig. 23

REFERENCES CITED IN THE DESCRIPTION

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