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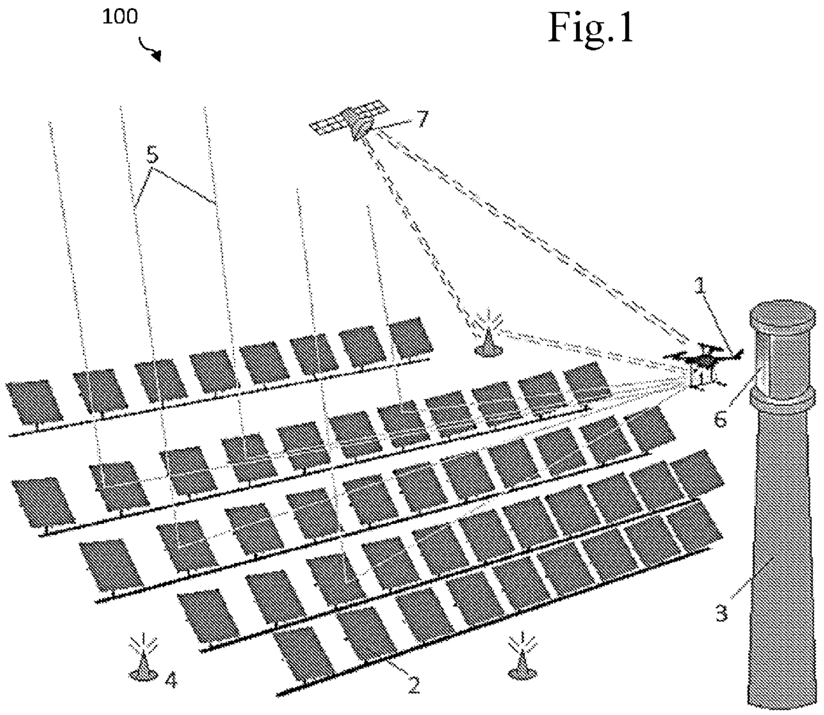

Fig.1

(57) **Abstract:** The radiant field characterization is based on an airborne measurement system (100) acquiring flux information along its flight route from within the radiant field generated by the Concentrating Solar System (4), either photovoltaic or thermal. The system is equipped with a sensor unit that incorporates at least one electronic or opto-electronic sensor, able to collect fast and direct measurement of flux data from within the radiant field along the flight route at an adequate response time. An on-board highly accurate spatial positioning unit determines the exact spatial location of the sensor and thus, the absolute and relative position of the sensor. The on-board data acquisition unit acquires the flux data from the sensor, it then matches each measurement position to the position of the sensor and through the on-board wireless data transmission unit the data is sent to a ground processing unit for post-processing.

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UAV-BASED SYSTEM AND METHOD FOR THE CHARACTERIZATION OF THE RADIANT FIELD OF REFLECTIVE CONCENTRATING SOLAR SYSTEMS

FIELD OF INVENTION

The present invention relates to the Concentrating Solar Collectors integrated in any type of Concentrating Solar System, comprising Solar Thermal (CST), Photovoltaic (PV), hybrid (CST+PV), solar chemistry. More specifically it refers to a system and method for the characterization of the optical behavior of the Concentrating Solar Collectors of a Concentrating Solar System based on the use of Unmanned Aerial Vehicles (UAV). It relates, for example, to the characterization of the radiant field of heliostat fields, or of parabolic troughs fields or of parabolic dishes or of linear Fresnel fields.

In particular, the invention provides a system and a method to estimate and characterize the radiant field of any type of Concentrating Solar Collectors, at any spatial point position on the field, or at any two-dimensional plane defined within the radiant space, or at any three-dimensional pattern within the radiant field, to obtain qualitative and quantitative estimates on how the concentrated solar flux is distributed on said radiant field.

BACKGROUND

Concentrating Solar Collectors are used in Concentrating Solar Thermal (CST), in Concentrating Photovoltaic (PV), in Hybrid (CST+PV) systems and in other Concentrating Solar systems to collect large amounts of direct sunlight and concentrate it onto one or more receivers. There are various types of Concentrating Solar Collectors, comprising the Solar Towers, Parabolic Dishes, Parabolic Troughs and Linear Fresnel.

In particular, the Solar Towers use a large field of sun-tracking mirrors known as “heliostats” to focus the solar radiation onto a central receiver, which is disposed at the top of a tower. The receiver is usually of cylindrical shape and the large heliostat field is usually composed of hundreds or thousands of heliostats distributed in surrounding patterns around the receiver's tower base. Each heliostat has at least one reflector, or concentrator, with a mirror surface, or concentrating mirror, by which solar radiation can be concentrated on the receiver surfaces.

Each reflector has a focal region, in the form of a line or a point, which is set in relation to the distance between the reflector and the receiver surface. The determination of the radiant solar energy densities and solar fluxes at the focal region and other regions of interest of the Concentrating Solar Collectors integrated in a Concentrating Solar System is of very high importance for:

- the design of the solar receiver, comprising Concentrating Photovoltaics (PV) receiver or hybrid Photovoltaic/Thermal (PVT) receiver,
- the evaluation of the solar power and the solar flux reaching the receiver,
- the assessment of risks for the safety and integrity of people, animals and equipment.

The known methods for the characterization the optical behavior of the Concentrating Solar Collectors of a Concentrating Solar systems merely measure the incident solar flux distribution on the receiver surfaces, or on a plane, or on several planes near the receiver's surface. Three different types of measurement systems are usually implemented: the direct, the indirect and the measurement-supported simulation systems.

For example, the paper "*Techniques to measure solar flux density distribution on large-scale receivers*, Roger M., Herrmnn P., Ulmer S., Prahl C., Gohring F., Journal of Solar Energy Engineering, 2014, Vol. 136/031013-1" summarizes the state of the arts and the recent research results for the techniques that can be applied to large-scale receivers. The direct system uses a single flux sensor or an array of flux sensors to directly generate a measurement signal proportional to the incident solar radiant flux. The indirect method uses a digital camera to measure the relative intensity of the image of the incident concentrated solar heat flux on a Lambertian target. Finally, the measurement-supported simulation methods use state-of-the-art ray-tracing simulation programs, whose estimates are complemented with a reduced set of flux-related measurements for validation.

One of the main constrain of these kind of systems is, for example, that they are fixed at specific locations: in fact, for example, the heat flux sensors, or the Lambertian targets have to be placed on fixed locations within the radiant field, due to the lack of mobility of the system, and thus only the concentrated solar flux (energy per unit area) reaching a surface of interest - typically a flat surface in front or at the side of the receiver - can be characterized. For this reason, these systems do not provide an overall estimate of the radiant field around the focal point or line of the Concentrating Solar Collectors, nor do they provide a full and detailed characterization of the optical behavior and performance of said system.

Most of the systems currently in use are equipped with relatively expensive equipment, comprising high-end Charged Coupled Device (CCD) or Complementary Metal Oxide Semiconductor (CMOS) cameras, to carry out the measurements. In addition, the mechanics of these systems can be quite complex, and issues such as thermal expansion and heat load by convection of hot air and radiation need to be considered in the design process. This imposes space requirements in front of the receiver where the flux measurement system is to be implemented, and, in most cases, it imposes the need for complicated cooling circuits. Furthermore, such flux measurement systems should operate in a way that does not cause relevant disruptions to the operation of the plant.

The above issues become even more significant at very large plants. For example, in large Concentrating Solar systems, like Solar Tower Systems, where the sunlight is concentrated by a large heliostat field, on the external surface of the receiver. In such a configuration it is quite complex to implement any of the traditional systems to measure the concentrated solar flux and no practical solution are available at the status of the art.

SUMMARY

A general object of the present invention is, thence, to overcome the aforesaid technical problem that occurs when trying to characterize the total solar energy incident on the solar receiver(s) of a reflective Concentrating Solar System, without resorting to either expensive equipment, or complex arrangements.

A specific object of the present invention is that of providing a system and method for the characterization of the solar radiant field in any region of interest of the Concentrating Solar Collectors integrated in a reflective Concentrating Solar System, comprising concentrating solar thermal (CST), concentrating Photovoltaics (PV), hybrid (CST-PV), solar chemistry systems.

In accordance with the present invention, there is thus provided an airborne measurement system, hereafter called ''the system'', based upon the use of Unmanned Aerial Vehicles, (UAVs), to fully characterize the solar radiant field of a reflective Concentrating Solar System.

A specific UAV designed for the purpose described above is equipped with:

- an electronic and/or opto-electronic sensor unit,
- a data acquisition and processing unit,
- a wireless data transmission unit and
- at least one highly accurate spatial positioning device.

The opto-electronic sensor/s unit is capable to determine different characteristics and quantify the flux of the radiant field at different points of the region of interest according to a predetermined flight path, whose position is accurately determined using the on-board spatial positioning device.

The spatial positioning device, which comprises Differential Global Positioning System (DGPS), three-dimensional laser positioning system, photogrammetric triangulation positioning system, or any other advanced and appropriate accurate positioning technique, is capable to transmit with high accuracy (at each measurement spatial position) the relative and absolute position of said electronic and/or opto-electronic sensor units. The data acquisition unit is used to acquire the signals (data) from said electronic and/or opto-electronic sensors along with their accurate spatial position within the radiant field. The wireless transmission unit is used to transmit the data to a ground processing station for post-processing.

Furthermore, the overall airborne system according to an embodiment of the present invention is equipped with a heat shield for protecting all the electronic components from heat and thermal stresses.

According to an embodiment of the present invention, said airborne measurement system comprises a plurality of UAVs, for example a swarm of UAVs, flying in a coordinated fashion with individual predetermined flight paths, each UAV sampling a specific region of interest of the Concentrating Solar Collectors, in this way accelerating the measurements and reducing the overall measurement time within a specific timeframe, for example within a specific sun position timeframe.

According to an embodiment of the present invention, said electronic or opto-electronic sensor unit is part of an array of electronic sensors, said array comprising thermopile or thermogage sensors, having a response time of microseconds (μs), and providing fast and direct measurement of the radiant flux. According to a further embodiment, said array of electronic or opto-electronic sensor units comprises opto-electronic video cameras coupled with optical lenses, providing not only the point estimation of the flux in space but also the angular distribution of radiance.

The airborne measurement system according to the present invention, is employable in any type of Concentrating Solar Collectors of a Concentrating Solar System.

According to the present invention, a method is provided for the characterization of the solar radiant field in any region of interest of the Concentrating Solar Collectors of a Concentrating Solar System of any kind. According to the present method, an airborne measurement system is provided, employable in any type of Concentrating Solar Collectors of a reflective Concentrated Solar System, for performing accurate measurements of:

a) the solar flux incident at any point along a specific flight path, comprising single point scanning or multiple point scanning using a predetermined point resolution,

b) the solar flux incident at predefined planes of any orientation of interest, so that the incident flux on two-dimensional planes can be interpolated and reconstructed,

c) the solar flux incident at any surface of any shape of interest, so that the incident flux on three-dimensional shapes can be interpolated and reconstructed,

d) flux information generated from single heliostats or any other reflector surface for assisting in the detailed characterization of heliostat/reflector geometry.

According to an embodiment of the present method, the airborne measurement system is configured to move at least one UAV along a predefined flying path within an area of interest of the radiant field of the Concentrating Solar Collectors of a Concentrating Solar System, simultaneously acquire solar flux data at any point along a specific flight path.

According to another embodiment of the present method, the airborne measurement system is configured to let at least one UAV to traverse a plane or several planes, located exactly in front of the receiver's inlet aperture of the Concentrating Solar Collectors, simultaneously acquiring solar flux data incident to at least a plane in front of the receiver.

According to a further embodiment of the present method, the airborne measurement system is configured to let at least one UAV to traverse a plane aligned normal to the optical axis of a single heliostat of the Concentrating Solar Collectors of a Concentrating Solar System, simultaneously acquiring solar flux data incident to at least a plane in front of the individual heliostat.

According to another further embodiment of the present method, the airborne measurement system is configured to move at least one UAV along a predefined spiral flying path in front of the cylindrical receiver of a Solar Concentration System, simultaneously acquiring solar flux data incident to at least a lateral surface of a cylinder surrounding the receiver area.

According to an embodiment of the present method, reverse engineering technique is used to reconstruct the radiant field based on the concentrated solar radiant field measurement taken by the airborne measurement system. Said reverse engineering technique is based on different methodologies, comprising ray-tracing, cone-optics or any other optical simulation software. For example, the solar radiant field can be accurately modeled by simulation software, by using specific model parameters, comprising:

- the solar Direct Normal Irradiance (DNI),
- the ground-level atmospheric transmissivity,
- the sunshape model and circumsolar ratio, and
- the reflectivity of the mirrors.

The simulation technique applies perturbations to said model parameters in order to find the set of values for said parameters that minimize the distance between the expected values and the measured values at each sampling points.

According to another embodiment, reconstruction of the radiant field in a specific plane of a region of interest is obtainable by interpolation of the field based on the measured data in any other plane.

Respect to the prior art, the provided system confers the following advantages:

- it is extremely portable and flexible,
- it is fully automated to the point to be autonomous (that is the system can be configured and programmed to perform its tasks automatically, maintaining its continuous operation through self-charging on the basis of a single or a plurality of charging stations distributed within the field,
- it is employable in any type of Concentrating Solar Collectors of a any Concentrating Solar System.

Furthermore, with the provided method the following goals are achievable:

- determine the solar flux incident in different regions of interest, for example taking the measurement while scanning a two-dimensional area within the radiant field;
- determine the full three-dimensional measurements of the entire concentrated solar radiant field generated by the Concentrating Solar Collectors of a Solar Concentrating System, for example a heliostat field, and maintain it accurately determined along the day;
- characterize the solar flux at very large plants, using, for example, a plurality of UAVs, each UAV of said plurality of UAVs having its own flight pattern, in conjunction with a ray-tracing software to keep repeatedly fine-tuning the radiant field estimated by said plurality of UAVs.

Since the provided method allows the use of a plurality of UAVs, a significant enhancement of the modularity of the system is achieved. In fact, the swarm of UAVs can be used periodically and can be alternately maintained in flying operating condition using an airborne or ground-based charging platform, which could be powered by sunlight.

Finally, at least for large heliostat fields, or large parabolic trough, the size of the airborne measurement system is negligible relative to the size of the Concentrating Solar System (and thus to the size of the radiant field), and hence, the system can be also employed during the operation of the system's plant with minimal to negligible impact on its operation. Thus, real-time assessment of the solar radiant field is provided for assessing the quality of the solar resource, feeding this data directly into the control loop of the solar system.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the present invention, preferred embodiments, which are intended purely by way of example and are not to be construed as limiting, will now be described with reference to the attached drawings, where:

- Figure 1 is a schematic illustration of the airborne measurement system (100) and the method used therein, according to an embodiment of the present invention, for the solar radiant field characterization of a Concentrating Solar Collectors integrated in a Concentrating Solar System.
- Figure 2 is a schematic illustration of the method (200) used by the airborne measurement system to characterize the radiant field of a Power Tower System.
- Figure 3 is a schematic illustration of an embodiment (300) of the method used by the airborne measurement system to characterize the radiant field of a cylindrical Concentrating Solar Tower system.

DETAILED DESCRIPTION

The following discussion is presented to enable a person skilled in the art to make and use the invention. Various modifications to the embodiments will be readily apparent to those skilled in the art, without departing from the scope of the present invention as claimed. Thus, the present invention is not intended to be limited to the embodiments described therein, but it has to be accorded the widest scope consistent with the principles and features disclosed herein and defined in the appended claims.

As it will be discussed in detail in the following, an aspect of the present invention provides a system and method for the complete characterization of the Solar Radiant Field of any Concentrating Solar System.

Reference is made to Fig.1. According to a preferred embodiment of the present invention, a fully automated, fully autonomous airborne measurement system (100) for the characterization of the solar radiant field of the Concentrating Solar Collectors of a Concentrating Solar System of any type is provided, said system comprising at least an unmanned aerial vehicle (UAV), (1) equipped with:

- a sensor unit comprising a single or an array of electronic and/or opto-electronic sensors, configured to directly measure the flux and/or the angular distribution of radiance.

- a data acquisition unit, comprising of a data logger configured to acquire a plurality of flux measurement data coming from said sensor unit,

- a wireless data transmission unit for transmitting the flux data to a ground processing station for post-processing; and

- a spatial positioning device being able to transmit the relative and absolute position of said sensor unit, said spatial positioning device comprising:

- a differential GPS system, or a three-dimensional laser positioning system, or a photogrammetric triangulation positioning system, or any other appropriate accurate positioning techniques.

Figure 1 schematically illustrates the application of the method of characterization of the solar radiant field in a LCC subsystem of a reflective Solar Tower System. As depicted in Fig.1, the sunlight represented in form of rays (5) incident on a large heliostat field (2), disposed in circular patterns around a cylindrical tower (3), is reflected from said heliostat field (2) and concentrated towards the external surface of a solar receiver (6) located on top of the solar tower (3).

According to the applied method, at least one UAV (1) of the airborne measurement system is configured to fly within the radiant field, in a position located in front of the solar receiver (6), while the on-board sensor and transmission units acquire and transmit the solar flux data to a ground post-processing station. Each of the measured data is associated with a relative and absolute spatial position, which are determined by the on-board spatial positioning device. According to a preferred embodiment, a Differential Global Positioning System (DGPS) is used, and the at least one UAV (1) continuously communicates with ground-based GPS reference stations (4) located in fixed position and with the GPS satellite (7) to calculate its spatial position at any moment within the radiant field. According to other embodiments of the present method, other conventional positioning techniques are employed, comprising, for example, a three-dimensional laser positioning system and a photogrammetric triangulation positioning system. Based on the positioning technique employed, a corresponding spatial positioning device is incorporated on-board of the at least one UAV (1). According to the present method, the airborne system is configured to communicate through the on-board wireless data transmission unit with a ground-based processing station, where the transmitted solar flux data are analyzed by a dedicated software.

Figure 2 schematically illustrates the method (200) used by the airborne measurement system to characterize the solar radiant field in a Concentrating Solar Power Tower system.

According to a first embodiment of the present method (200), the airborne measurement system performs accurate measurements of the solar heat flux distribution at any spatial position within the radiant field. According to this method, the airborne measurement system moves at least one UAV (11) according to a predetermined flight path (8), simultaneously acquiring data of the solar flux reflected from a heliostat or several heliostats by means of the on-board sensor unit at a predetermined time interval. A computing model of the radiant field of the concentrating solar system is usually performed by modeling the relevant field using advance ray-tracing simulations through appropriate optical simulation software. Though, due to the lack of physical information such as the actual atmospheric conditions and the soiling of the reflective mirrors, perturbations are only applied to few parameters of the model resulting in simulations that do not correspond to the real conditions. To overcome this problem, the at least one UAV (11) is moved according to a predetermined flight path (8), acquiring flux data at predetermined spatial points, for example at a point (10) located along the flight path (8), feeding the acquired data in real time to the corresponding ray-tracing model of the solar concentrating system, resulting into continuous calibration and validation of the ray-tracing software.

According to a second embodiment of the present method, the airborne measurement system performs accurate, fast and in-situ determination of solar flux incident at any plane of any orientation for obtaining two-dimensional flux maps on these planes. For example, as shown in Fig.2, the airborne measurement system moves at least one UAV (1) to a preferred location placed in front of the receiver's inlet aperture (13) of a Solar Tower System (12) in order to scan a two-dimensional area of at least a plane (9) or a plurality of planes (14) located perpendicular to the direction normal to the plane of the receiver, and simultaneously acquiring data of the radiant field by means of the on-board sensor unit at a predetermined time interval. In particular, the measured spatial distribution of the concentrated solar radiation in the plane (9), located exactly in front of the receiver's inlet aperture (13) is essential for estimating the solar input power and thus calculating the receiver efficiency and estimating where thermal losses incur. According to this embodiment the at least one UAV (1) is programmed to traverse the area covered by plane (9) and collect the solar flux data during its path. Several planes (14) can be traversed in a similar manner, providing thus enough information about the concentrated solar radiant flux at these planes (14) within the region of interest to be able to interpolate and reconstruct the local radiant field using reverse engineering methodologies based on the measured data.

According to a third embodiment of the present method, the airborne measurement system performs accurate measurements of the solar heat flux distribution generated by an individual heliostat. For example, as shown in Fig.2, the airborne measurement system moves at least one UAV (111) to a preferred location placed at the focal point of a specific heliostat (15) in order to scan a two-dimensional area of at least a plane (16), located normal to the optical axis of the heliostat (15), simultaneously acquiring data of the solar flux reflected from a heliostat (15) by means of the on-board sensor unit at a predetermined time interval. In particular, the accurate measurements of the solar heat flux distribution generated by an individual heliostat on a given plane is useful to characterize in detail the actual geometry of the reflective surface of the heliostat. It is also useful to monitor and control the heliostat aiming points. According to this embodiment the at least one UAV (111) is programmed to traverse the area covered by plane (16) aligned normal to the optical axis of the heliostat (15), to pass through the focal point of the heliostat (15), and to collect the solar flux data during its path needed for assisting in the characterization of individual heliostats, for example the heliostat (15).

Reference in now made to Fig.3, which a schematically illustrates an embodiment (300) of the method used by the airborne measurement system to characterize the solar radiant field generated in a cylindrical Solar Power Tower, where the heliostat field is disposed in circular shape around the tower's cylindrical receiver and absorb the sunlight from every angle.

According to this embodiment (300) of the present method, the airborne measurement system provides a flux map of the incoming solar radiation to the surface of the cylindrical receiver. Solar receivers (18) of a large surround heliostat fields (19) have very large cylindrical aperture surfaces. For those receivers, the existing methods to measure the solar flux density pose new challenges. The proposed method is suitable for overcoming these issues by providing three-dimensional flux mapping around the receiver.

According to this embodiment, as shown in Fig.3, the airborne measurement moves at least one UAV (1′) to a preferred location placed in front of the cylindrical receiver (18) of a Concentrated Solar Power Tower field (19) in order to scan a three-dimensional cylindrical area (17) surrounding the tower receiver and simultaneously acquiring data of the radiant field by means of the on-board sensor unit at a predetermined time interval. At the same time, a swarm of UAVs (11′) are flying according to an optimized flying paths within the radiant field to simultaneously acquire data from various spatial positions.

A swarm of UAVs (11′) is employed to obtain flux information of the radiant field produced by the surround heliostat field (19). The swarm of UAVs (11′) can be operational throughout the day, obtaining simultaneous data from different spatial positions within the radiant field (19) while maintaining the exact time stamp on each measurement at the exact time instant of the sun position.

This modularity of the airborne system enables real-time interconnection with ray-tracing software to keep repeatedly fine-tuning the radiant field estimated by said software for large plants. Furthermore, the airborne system results to be minimally intrusive to the operation of the plant. The swarm of UAV (11′) can be maintained operational by a self-charging, ground-based or airborne charging station, or stations. Said swarm provides robustness, redundancy and reliability to the measurement, even if a subset of the UAVs is not available due to maintenance, measurements can still be performed.

According to an embodiment of the present method, a real-time, on-the-fly communication between the airborne measurement system and the control loop of the said Solar Concentrating System is set up by utilizing said wireless data transmission unit, for feeding in real time flux information of the said radiant field to said control loop of the plant, to enhance the plant control and operation.

According to another embodiment of the present method, the airborne measurement system is configured to work in conjunction with an optical simulation software, to provide to the latter continuous solar flux information in order to keep repeatedly fine-tuning the radiant field estimated by the said optical simulation software.

According to another embodiment of the present method, solar flux information continuously fed to said optical simulation software are used to reconstruct at least a part of the entire radiant field produced by the Concentrating Solar Collectors of a Concentrating Solar System.

According to another embodiment of the present method, the airborne measurement system is configured to operate in conjunction with a high-fidelity real-time dynamic virtualization digital model/platform of the Concentrating Solar Collectors of a Concentrating Solar System, for example by using digital twinning technology, providing a continuous stream of solar flux data and mapping said data to said digital model/platform for real-time optimization and enhancement of the plant's operation.

Among the advantages offered by the present invention it is worth noting that the size of the airborne measurement system according to the any of the present embodiments is negligible relative to the size of the Concentrating Solar Collectors of the reflective Concentrating Solar System, and hence, said airborne measurement system can be employed during operation of said Concentrating Solar Collectors with minimal to negligible impact on the operation of said solar system.

Furthermore, the method according to the present invention allow the airborne measurement system (100) to operate within a short timeframe of solar position. Due to the sun position is constantly changing, it is critical to perform measurements within a relatively short timeframe that the change of the position of the sun would not alter the obtained results, in order to access the flux characteristics on that time instance.

Furthermore, the system according to the present invention, can be maintained autonomous and in flying operating condition throughout the entire operation time of the Concentrating Solar plant by using airborne or ground-based charging platforms powered by sunlight.

In the case of using a swarm of UAVs, said swarm can be configured to remain operational by optimizing their individual tasks against their charging needs, visiting the charging stations periodically and alternately providing robustness, redundancy and reliability to the system, in this way ensuring that if a subset of the UAVs is not available due to maintenance, the measurement can still be performed.

Finally, it is clear that numerous modifications and variants can be made to the present invention, all falling within the scope of the invention, as defined in the appended claims.

CLAIMS

1. A fully automated, fully autonomous airborne measurement system (100) for the characterization of the radiant field of a Reflective Concentrating Solar System (4), comprising solar thermal, photovoltaic, hybrid, solar chemistry, said system (100) comprising at least one unmanned aerial vehicle (UAV), (1, 11, 111), said UAV comprising:

- a sensor unit comprising a single or an array of electronic and/or opto-electronic sensors, configured to directly measure the flux and/or the angular distribution of radiance,

- an on-board data acquisition unit, comprising of a data logger configured to acquire a plurality of flux measurement data coming from said sensor unit,

- a wireless data transmission unit for transmitting the flux data to a ground processing station for post-processing,

- a spatial positioning device being able to transmit the relative and absolute position of said sensor unit.

2. The fully automated, fully autonomous airborne measurement system (100) according to claim 1, wherein said spatial positioning device comprises a differential Global Positioning System (GPS), or a three-dimensional laser positioning system, or a photogrammetric triangulation positioning system.

3. A method for the characterization of the solar radiant field of a Concentrating Solar System (4), said method comprising:

- providing a fully automated, fully autonomous airborne measurement system

(100) according to claim 1,

- configuring said at least one unmanned aerial vehicle (UAV), (1, 11, 111, 1′, 11′), to fly in a predefined flight path to obtain flux information from within said flight path so that the solar flux distribution within an area of interest of said radiant field can be accurately determined,

- configuring said at least on-board sensor unit to acquire data of the solar flux reflected from said Concentrated Solar System by means of the on-board sensor unit at a predetermined time interval,

- configuring said data acquisition and transmission units to acquire said solar flux data from said sensor unit and transmit them to a ground-based processing station for analyzing, interpolating and at least partially reconstructing in 2-D or 3-D said solar flux field distribution.

- configuring said spatial positioning device to transmit the relative and absolute spatial position of said sensor unit to said on-board data acquisition and processing unit in order to associate each measured solar flux data with a spatial position.

4. The method according to claim 3 wherein said at least one UAV (11) is configured to move according to a predetermined flight path (8), acquiring flux data at predetermined spatial points, for example at a point (10) located along said flight path (8), feeding the acquired data in real time to a ground-based processing station so that the flux incident at any surface of any shape and orientation within an area of interest of said radiant field can be accurately determined,

5. The method according to claim 3 wherein said at least one UAV (1) is configured to move to a preferred location placed in front of the receiver's inlet aperture (13) of a Concentrated Solar Power Tower system (12), scanning a two-dimensional area of at least a plane (9) or a plurality of planes (14) located perpendicular to the direction

normal to the plane of the receiver, simultaneously acquiring data of the radiant field by means of the on-board sensor unit at a predetermined time interval, feeding the acquired data in real time to a ground-based processing station for estimating the solar input power and thus calculating the receiver efficiency and estimating where thermal losses incur.

6. The method according to claim 3 wherein said at least one UAV (111) is configured to move to a preferred location placed at the focal point of a specific heliostat (15) of said Reflective Concentrating Solar System, scanning a two-dimensional area of at least a plane (16), located normal to the optical axis of said heliostat (15), simultaneously acquiring data of the solar flux reflected from said heliostat (15) by means of the on-board sensor unit at a predetermined time interval, feeding the acquired data in real time to a ground-based processing station for estimating the solar heat flux distribution generated by an individual heliostat on a given plane and to characterize in detail the actual geometry of the reflective surface of said heliostat (15).

7. The method according to claim 3 wherein a plurality of UAVs (11′) is configured to fly according to an optimized flying paths within the radiant field of a large Concentrated Solar Power Tower system (19) to simultaneously acquire data from various spatial positions within said radiant field, said plurality of UAVs (11′) comprising at least one UAV (1′) configured to move to a preferred location placed in front of the cylindrical receiver (18) of said Concentrated Solar Power Tower system (19) in order to scan a three-dimensional cylindrical area (17) and simultaneously acquiring data of the radiant field by means of the on-board sensor unit at a predetermined time interval, feeding the acquired data in real time to a ground-based processing station.

8. The method according to any of the previous claim wherein said airborne measurement system (100) is configured to work in conjunction with an optical simulation software, to provide to continuous solar flux information to said simulation

software to keep repeatedly fine-tuning of the radiant field estimated by the said simulation software.

9. The method according to any of the previous claims wherein said airborne measurement system (100) is configured to operate in conjunction with a high-fidelity real-time dynamic virtualization digital model/platform of the plant, comprising digital twinning technology, providing a continuous stream of solar flux data and mapping said data to the said digital model/platform for real-time optimization and enhancement of the Concentrating Solar System operation.

10. The method according to any of the previous claims wherein said airborne measurement system (100) is configured to operate within a short timeframe of solar position.

11. The method according to any of the previous claims, wherein said airborne measurement system (100) is maintained autonomous and in flying operating condition throughout the entire operation time of the Concentrating Solar System (4) plant by using airborne or ground-based charging platforms powered by sunlight.

AMENDED CLAIMS

received by the International Bureau on 22 July 2022 (22.07.2022)

1. A method for the characterization of the solar radiant field of a Concentrating Solar System (4), said method comprising:

a) providing a fully automated, fully autonomous airborne measurement system (100), said system (100) comprising at least one unmanned aerial vehicle (UAV), (1, 11, 111), said UAV comprising:

- a sensor unit comprising a single or an array of electronic and/or opto-electronic sensors, configured to directly measure the flux and/or the angular distribution of radiance,

- an on-board data acquisition unit, comprising of a data logger configured to acquire a plurality of flux measurement data coming from said sensor unit,

- a wireless data transmission unit for transmitting the flux data to a ground processing station for post-processing,

- a spatial positioning device being able to transmit the relative and absolute position of said sensor unit;

b) configuring said at least one unmanned aerial vehicle (UAV), (1, 11, 111, 1′, 11′), to fly in a predefined flight path to obtain flux information from within said flight path so that the solar flux distribution within an area of interest of said radiant field can be accurately determined;

c) configuring said at least on-board sensor unit to acquire data of the solar flux reflected from said Concentrated Solar System by means of the on-board sensor unit at a predetermined time interval;

d) configuring said data acquisition and transmission units to acquire said solar flux data from said sensor unit and transmit them to a ground-based processing station for analyzing, interpolating and at least partially reconstructing in 2-D or 3-D said solar flux field distribution;

e) configuring said spatial positioning device to transmit the relative and absolute spatial position of said sensor unit to said on-board data acquisition and processing unit in order to associate each measured solar flux data with a spatial position.

2. The method according to claim 1 wherein said at least one UAV (11) is configured to move according to a predetermined flight path (8), acquiring flux data at predetermined spatial points, for example at a point (10) located along said flight path (8), feeding the acquired data in real time to a ground-based processing station so that the flux incident at any surface of any shape and orientation within an area of interest of said radiant field can be accurately determined,

3. The method according to claim 1 wherein said at least one UAV (1) is configured to move to a preferred location placed in front of the receiver's inlet aperture (13) of a Concentrated Solar Power Tower system (12), scanning a two-dimensional area of at least a plane (9) or a plurality of planes (14) located perpendicular to the direction normal to the plane of the receiver, simultaneously acquiring data of the radiant field by means of the on-board sensor unit at a predetermined time interval, feeding the acquired data in real time to a ground-based processing station for estimating the solar input power and thus calculating the receiver efficiency and estimating where thermal losses incur.

4. The method according to claim 1 wherein said at least one UAV (111) is configured to move to a preferred location placed at the focal point of a specific heliostat (15) of said Reflective Concentrating Solar System, scanning a two-dimensional area of

at least a plane (16), located normal to the optical axis of said heliostat (15), simultaneously acquiring data of the solar flux reflected from said heliostat (15) by means of the on-board sensor unit at a predetermined time interval, feeding the acquired data in real time to a ground-based processing station for estimating the solar heat flux distribution generated by an individual heliostat on a given plane and to characterize in detail the actual geometry of the reflective surface of said heliostat (15).

5. The method according to claim 1 wherein a plurality of UAVs (11′) is configured to fly according to an optimized flying paths within the radiant field of a large Concentrated Solar Power Tower system (19) to simultaneously acquire data from various spatial positions within said radiant field, said plurality of UAVs (11′) comprising at least one UAV (1′) configured to move to a preferred location placed in front of the cylindrical receiver (18) of said Concentrated Solar Power Tower system (19) in order to scan a three-dimensional cylindrical area (17) and simultaneously acquiring data of the radiant field by means of the on-board sensor unit at a predetermined time interval, feeding the acquired data in real time to a ground-based processing station.

6. The method according to any of the previous claim wherein said airborne measurement system (100) is configured to work in conjunction with an optical simulation software, to provide to continuous solar flux information to said simulation software to keep repeatedly fine-tuning of the radiant field estimated by the said simulation software.

7. The method according to any of the previous claims wherein said airborne measurement system (100) is configured to operate in conjunction with a high-fidelity real-time dynamic virtualization digital model/platform of the plant, comprising digital twinning technology, providing a continuous stream of solar flux data and mapping said data to the said digital model/platform for real-time optimization and enhancement of the

Concentrating Solar System operation.

8. The method according to any of the previous claims wherein said airborne measurement system (100) is configured to operate within a short timeframe of solar position.

9. The method according to any of the previous claims, wherein said airborne measurement system (100) is maintained autonomous and in flying operating condition throughout the entire operation time of the Concentrating Solar System (4) plant by using airborne or ground-based charging platforms powered by sunlight.

Fig.1

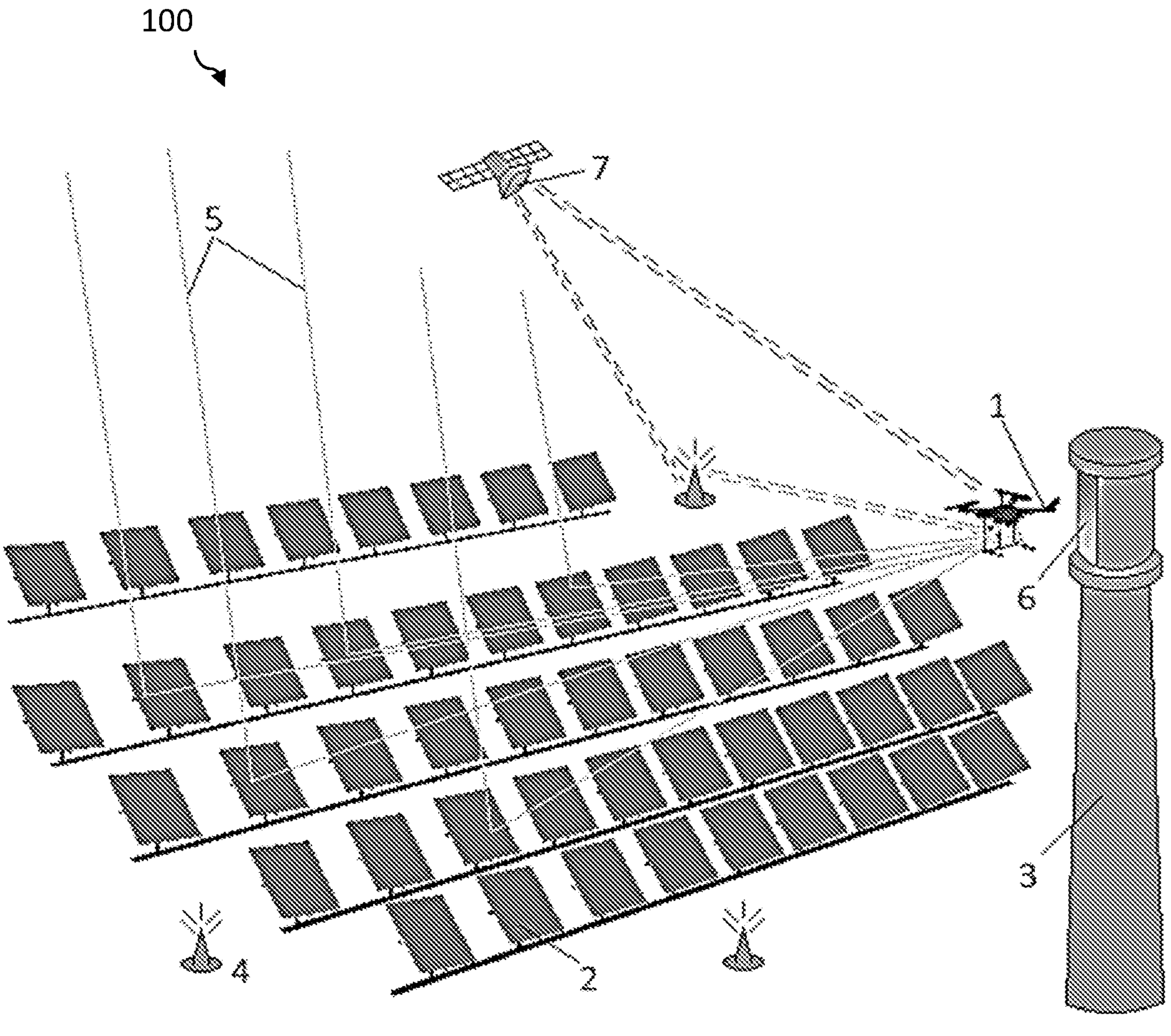


Fig.2

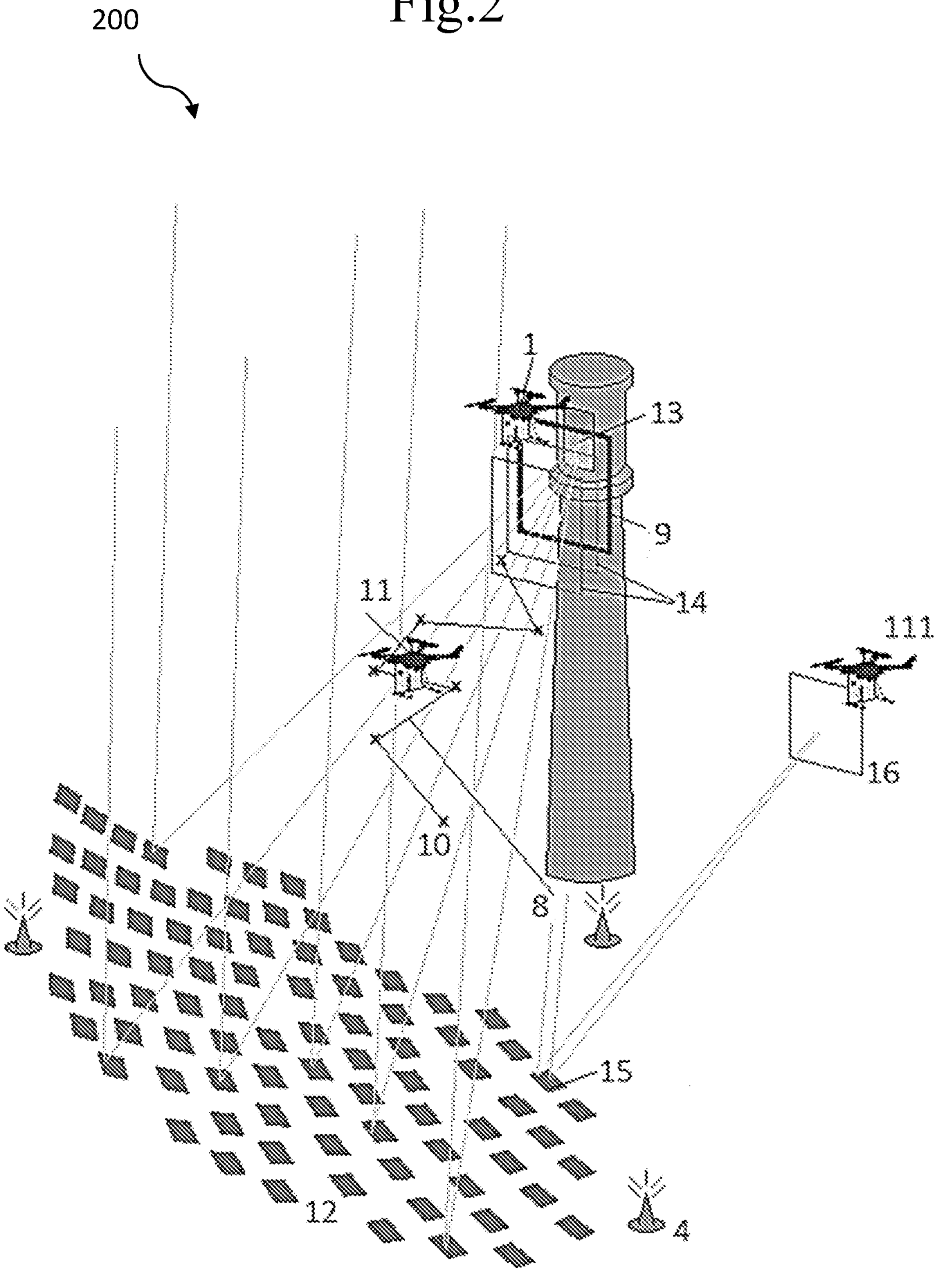
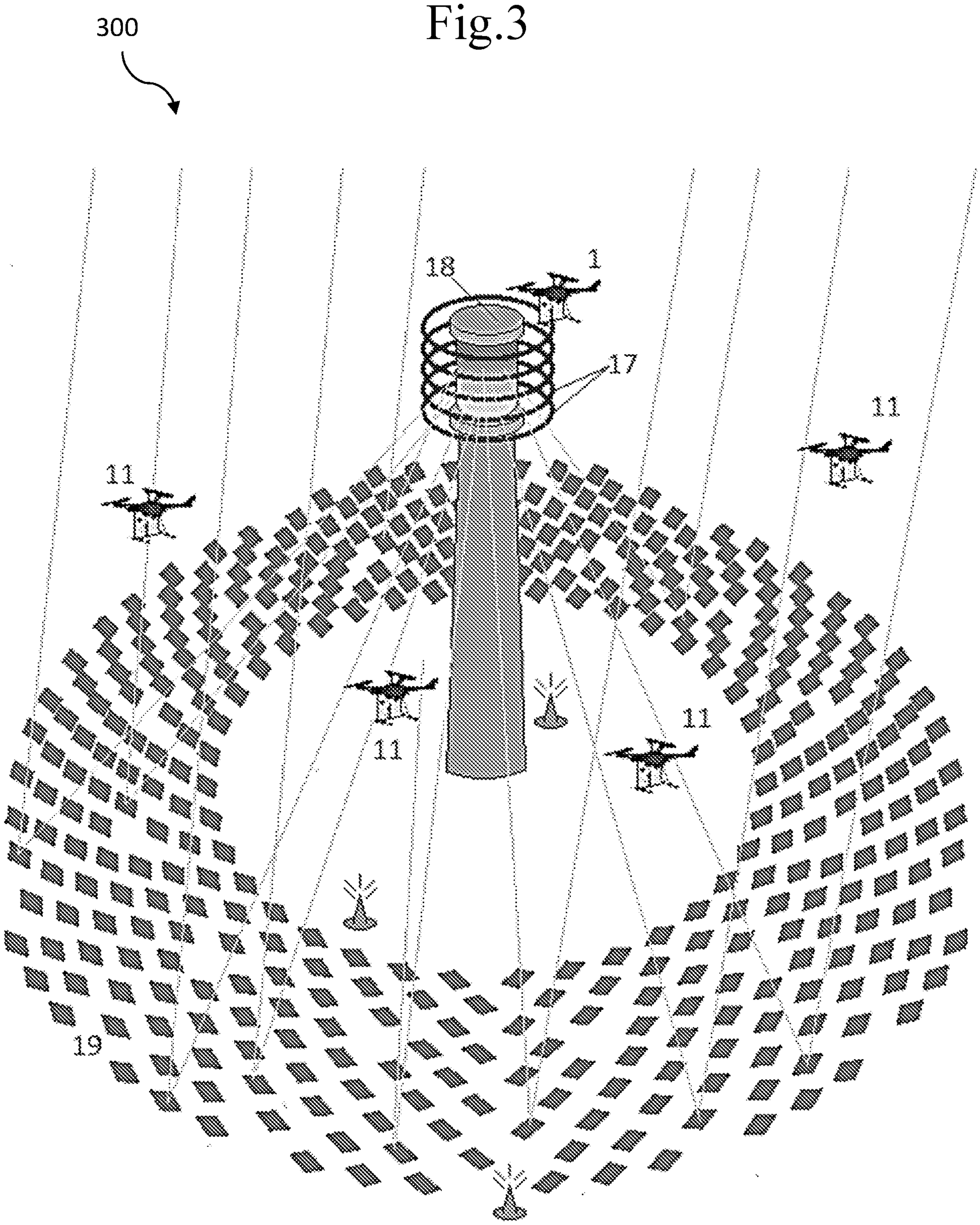


Fig.3



INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2021/053679

A. CLASSIFICATION OF SUBJECT MATTER
INV. F24S40/90
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F24S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 3 408 175 A1 (ABOVE SURVEYING LTD [GB]) 5 December 2018 (2018-12-05) figures -----	1,2
A	US 2018/003656 A1 (MICHINI BERNARD J [US] ET AL) 4 January 2018 (2018-01-04) the whole document -----	1-11
A	US 8 664 577 B1 (GHANBARI CHERYL M [US] ET AL) 4 March 2014 (2014-03-04) the whole document -----	1-11

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 17 December 2021	Date of mailing of the international search report 07/01/2022
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Fernandez Ambres, A

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2021/053679

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 3408175 A1	05-12-2018	AU 2017212024 A1	02-08-2018
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