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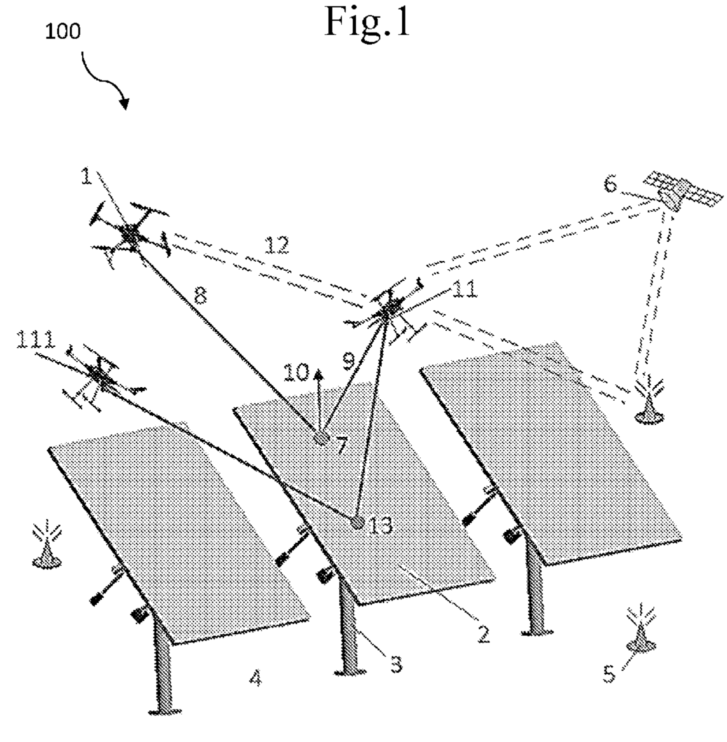
(54) **Title:** UAV-BASED SYSTEM AND METHOD FOR THE CHARACTERIZATION OF THE GEOMETRY OF SOLAR CONCENTRATING MIRRORS

Fig.1



(57) **Abstract:** The present invention relates to a system (100-300) and a method, based on the use of Unmanned Aerial Vehicles (UAVs), to characterize the reflecting surfaces of any type of Concentrating Solar systems (4). The system can be realized in two different approaches: a UAV (1) to UAV (11) measurement system using at least one on-board HD camera (16, 17) on each UAV and a single UAV (101) measurement system using an on-board array of HD cameras (24-29). The system provides information from which the exact geometry of the said reflecting surfaces (2, 18) can be interpolated and reconstructed with adequate resolution An on-board highly accurate spatial positioning unit determines the exact spatial location of the UAVs (1, 11, 101) and thus, those of the cameras (16, 17, 24-29). The on-board processing unit acquires and process the images from the cameras (16, 17, 24-29) along with their accurate spatial position while the wireless transmission unit is used to transmit the data to a ground post-processing station.

WO 2022/234315 A1

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UAV-BASED SYSTEM AND METHOD FOR THE CHARACTERIZATION OF THE GEOMETRY OF SOLAR CONCENTRATING MIRRORS

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FIELD OF INVENTION

The present invention relates to Concentrating Solar Collectors, which are integrated in any type of Concentrating Solar systems. In particular, it relates to a system and method for characterizing the geometrical shape of the reflective surfaces of a Concentrating Solar Collector, integrated in any type of Concentrating Solar systems, comprising solar thermal, photovoltaic, hybrid, thermos-ionic, thermo-chemical, a combination there of, or a new type.

In particular, the invention provides a system and a method, based on the use of Unmanned Aerial Vehicles (UAVs), to characterize the reflecting surfaces of any type of Concentrating Solar Collectors in order to reveal any deviation from the ideal optical behavior and derive its real optical behavior.

BACKGROUND

Concentrating Solar Collectors are used in Concentrating Solar Thermal (CST), in Concentrating Photovoltaic (PV), in Hybrid (CST+PV) systems to collect large amounts of direct sunlight and concentrate it onto one or more receivers. They may also be used for the same purpose in other types of systems, such as thermos-ionic, thermos-chemical, a combination there of, or a new type. There are various types of Concentrating Solar Collectors comprising the Solar Towers, Parabolic Dishes, Parabolic Troughts and Linear Fresnel.

In the present description, reference will be made to the particular case of Solar Tower systems, but, as can easily be found by a person skilled in the art, the same inventing features can also be applied to the other systems mentioned above, without straying too far from the inventive idea.

In particular, the Solar Tower uses 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.

As may be easily understood by any expert in the field, in such a large system, which bases its operation on the principles of optics, and, in particular, of the optical reflection of the solar radiation from a myriad of mirror surfaces, oriented towards the surface of the receiver, the quality and shape of the mirrors greatly influence the optical performance of the entire Concentrating Solar Collector system and modulates the distribution of the concentrated reflected solar radiation on the receiver surfaces. Any deviation from the ideal geometrical shape of said solar concentrating mirror is the source of optical errors and lead to deviation from the ideal optical behavior of the Concentrating Solar Collector system. Therefore, it is of high importance to determine the real geometry of a solar concentrating mirrors with the precision necessary to characterize their optical behavior.

Many factors influence the real shape of a solar concentrating mirror, some of which are dependent upon forces, for example the gravity induced forces, whose influence on the mirror varies with time throughout the day, in consequence of the change in orientation of the mirror. Other factors have a much larger time scale, such as the structural modification of the geometry of the supporting structure due to movements in the foundations. For this reason, a characterization of the geometry of concentrating solar mirrors is needed to be undertaken many times over the lifetime of a Concentrating Solar Collector system.

Numerous techniques have been proposed for the characterization of the geometry of concentrating solar mirrors, but all of them require either expensive equipment, or complex arrangements, which must be moved around the solar field, or both. They are not easy to deploy and adapt from one concentrating solar system to another, and furthermore, most of the time, characterization of the whole solar field is a time consuming and labor-intensive task.

All the existing solar concentrators characterization systems that are currently implemented are customized and tailored for the specific needs of each application. Most of these systems, needs to be fixed at specific locations for performing the measurements, and, in case of the presence of a big heliostat or any other reflective surface field, a complex arrangement needs be moved around through the field leading to inaccuracies and difficulties to implement the methods on large mirror surfaces. For example, when the measurement method includes a stationary laser technique, it is difficult to implement the method for long distance heliostats due to the need of an extremely high pointing precision of the laser.

For example, the paper "*Air-borne shape measurement of parabolic trough collector fields*; C.Prahl, M.Roger, and C.Hilgert, AIP Conference Proceedings, 1850(1): 020013, 2017", provides a method for the characterization of the surface of parabolic trough collectors using a distant observer method called TARMES (Trough Absorber Reflection Measurement System). Instead of a stationary camera at ground level taking pictures of a turning collector, the new approach makes use of an airborne camera vehicle which allows automated measurement of large numbers of collectors.

For example, when employing deflectometry or fringe reflection methods, like provided in the paper, "*Detecting deformations of heliostat surfaces using deflectomety with UAVs*, A.Niebrügge, L.Netze, J.Theissen, P.Peltzer, October 2017", which refers to detecting deformations of heliostat surfaces using colored pattern deflectrometry, the complex mathematical processing of data is probably the most cumbersome step of this method, while the calibration of such systems is a trouble that is encountered in the practical measurements. Furthermore, objects made of highly specular, mirror-like, materials cannot be reconstructed using photogrammetry unless they have been covered with a diffuse coating. In traditional photogrammetric techniques, the need to cover the mirror surfaces with retroreflective targets (i.e., dots and marks) is a time-consuming task, making the whole measurement procedure including preparation, data-acquisition and post-processing to takes up to several hours for a few mirrors. Moreover, these targets constitute only a finite number of points on the surface, and thus, currently, reconstruction of the heliostat surfaces is reachable only with moderate resolution. The final geometry of the surface is inferred from a 3D cloud of points (at the targets position) which may lead to significant errors in the mathematical surface reconstruction algorithms required to calculate the slopes, so any inevitable measurement deviations can lead to significant errors in the local slope calculation.

Another problem is caused by the fact that, in order to move equipment within the solar field for characterizing the mirrors, enough space is needed in between to install the equipment. The above issues become even more significant in very large plants, consisting of tens of thousands of heliostats. In tower technology, for instance, where the heliostat field is circular surrounding a cylindrical receiver on the tower, the most distant heliostat can be located 2 km away from the tower, making it extremely difficult for any system to characterize these heliostats with existing methods. In addition, an in-situ characterization of all the heliostats of a medium to large plant, which consists of more than 20,000 heliostats, is nearly impossible with the cited methods.

For this reason, methods that make use of Unmanned Aerial Vehicles (UAVs) are developed. For example, in a most recent paper, "*A non-intrusive optical approach to characterize heliostats in utility-scale power tower plants: Sensitivity study. Solar Energy*, R.A. Mitchell and G.Zhu, 207:450 – 457, 2020", the use of UAVs is proposed to acquire images of the central solar tower that are reflected through the mirrors of the heliostats within the heliostat field. These images are then post-processed to calculate the optical errors of the mirrors by comparing the reflected images to the real shape of the tower.

Among the patent literature, it worth mentioning the patent No. ES2390784T31 by Steffen Ulmer, entitled: "A method for measuring of a solar thermal concentrator", which discloses a method for measuring a solar thermal concentrator in which a target is arranged in front of it while a camera picks up and generates an image of the target reflected in the mirror, which is deformed by the shape deviations. By evaluating the pixel image generated by the camera, the surface normal to the reflection plane at different points of the concentrator is determined and compared with those of an ideal shape of the concentrator.

Another patent No. DE102011080969B4 by Christoph Prahl et al., entitled "Method for measuring solar thermal concentrator", involves recording images of solar thermal concentrator by taking pictures of the mirror with a camera wherein at least one target is arranged in front of the solar thermal concentrator. The recorded reflected images of the target along with the determined positions of the camera and camera orientation are used to determine the characteristic forms and geometric properties of the solar concentrator.

Both methods mentioned above are based on image reconstruction of the reflected deformed image of the target. The methods suffer from the complex mathematical data processing and the calibration of such a system that has to be performed in order to accurately reconstruct the geometry of the reflector. Moreover, since a target and a camera arrangement have to be positioned and adjusted in front of the reflector, the practical implementation of such a system (assuming that adequate space is available in front of each reflector) is becoming a time and labour intensive task which is practically impossible to implement in large scale solar concentrating fields. A further patent No. DE102015217086A1 by Christoph Prahl et al., entitled "Method for measuring heliostats" relates to a method for the measurement of a heliostat field of a central tower solar power plant having heliostats. A controllable aircraft is positioned above the heliostat field in a predetermined initial position and it is then moved at a predetermined flight path while taking images of a heliostat, or of a plurality of heliostats, by means of a camera at a predetermined time interval. The aircraft is equipped with a target composed of an array of Light Emitting Diodes (LED) of different colors, whose reflected image is captured by the camera. One at least normal vector on the mirror surface is then determined by means of the positions of the targets with respect to the mirror and thus the shape errors of the mirror surface are then determined. The patent above, although increases flexibility and solves issues related to space availability within the field, it is still based on the reconstruction of the reflector geometry by analyzing the reflected images of the projected LED array, with all the data processing and calibration issues that this method entails.

Of the three patents mentioned some of them are particularly best suited for just one type of concentrator (parabolic trough with a receive tube in its optical axis) and all of them make use markers and/or special targets. The proposed method does not need of any special targets or market, making it much easier to deploy and use.

SUMMARY

A general object of the present invention is, thence, to overcome the aforesaid technical problem that occurs when trying to characterize the geometry of concentrating solar mirrors, 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 reflecting mirror surfaces of a Concentrating Solar Collector, i.e., heliostat, parabolic trough and others, to be integrated in any type of Concentrating Solar system, comprising Concentrating Solar Thermal, Concentrating Photovoltaic (PV) and Hybrid (CST-PV) 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 geometry of the reflecting mirror surfaces.

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

- at least one specially mounted digital camera unit,
- a data acquisition and processing unit,
- a wireless data transmission unit and
- at least one highly accurate spatial positioning device.

Two approaches have been used within the present application; each approach needs at least a first and a second camera unit to be employed within at least one UAV.

1. According to the first approach said at least first and second camera units are mounted on two separate UAVs.
2. According to the second approach said at least first and second camera units are both mounted on the same single UAV.

A hybrid approach combining the two distinct approaches previously mentioned is also possible, i.e., a system based on the use of several UAVs each one with several cameras.

According to the first approach, which corresponds to a first embodiment of the present invention, the system comprises at least two identical UAVs, or a plurality of UAVs, each mounting a single digital camera unit, equipped with at least a high-definition camera.

A first embodiment of the present method, according to the first approach, envisages that the characterization of the mirror geometry is based upon the fact that, the at least two UAVs are flying on top of the reflective mirror surface following a predetermined flight path in a coordinated fashion. The absolute spatial position of the UAVs (and therefore the relative position between them) are continuously calculated by a spatial positioning device, which uses, for example, a differential Global Positioning System (GPS), or a three-dimensional laser positioning system, or a photogrammetric triangulation positioning system. When it happens that the at least first and second camera unit mounted on the at least two separate UAVs "see" each other reflected in the mirror, the position of the reflecting point on the mirror surface and the normal to the point vector are precisely determined by means of the on-board data acquisition and processing unit.

According to the second approach, which corresponds to a second embodiment of the present invention, the system comprises at least a single UAV mounting an array of cameras, comprising at least a first and a second high-definition digital camera unit.

A second embodiment of the present method, according to the second approach, envisages that the characterization of the mirror geometry is based upon the fact that, said at least a single UAV is flying on top of the reflective mirror surface at a predetermined flight path. The absolute spatial position of the UAV (and the relative position of each camera within the camera array) are continuously calculated by a spatial positioning device, which uses, for example, a differential Global Positioning System (GPS), or a three-dimensional laser positioning system, or a photogrammetric triangulation positioning system. When it happens that said at least first and second camera unit of the camera array of said at least single UAV "see" each other reflected in the mirror, the position of the reflecting point on the mirror and the normal to the point vector are precisely determined by means of the on-board data acquisition and processing unit. The at least a single UAV can be configured to follow an optimized flight path with respect to the mirror, in order to maximize the percentage of cameras that "see" the reflection of other cameras of the camera array in the mirror.

To speed up the characterization of the reflective mirror geometry, or for characterizing a plurality of reflective mirrors simultaneously, a plurality of UAVs, flying in a swarm mode, can be used.

According to the first or the second embodiment, the following common characteristics are provided:

- an unique distinctive feature, herein after a target, is assigned to each camera to distinguish it from the rest of the cameras, so that the on-board processing unit can recognize which camera is "seeing" in the reflection;
    - o for example, said unique distinctive characteristic comprises a small Light Emitting Diode (LED) spot of different color for each camera, so as to be visible during both daytime and night-time.
- the images acquired by the cameras along with their accurate spatial position are processed by the on-board data acquisition and processing unit and transmitted to a ground processing station for post-processing.
- a flexible supporting device, like a gimbal device, is used to hold the cameras

in order to add extra degrees of freedom to the system, so as to enable the cameras to "see" more than one reflection of other cameras from a single point of the reflecting mirror;

The following advantages over the prior art are easily recognizable by an expert in the field:

- the reflecting mirror surfaces can be directly characterized, without the needs to treat the reflecting surface by any mean, and for this reason the resulting geometry is provided with very high spatial resolution compared to the prior arts and in a timely manner;
- there are no needs to move any complex measurement arrangement within the solar reflector field and to have any ground space in between the heliostat rows for siting the measuring equipment;
- measurements can be made on individual mirrors, or on a group of mirrors, at any location of the field and at any time, irrespective of the size of the field, while being minimally intrusive to the rest of the reflector field and without causing any interruptions to the operation of the plant;
- a swarm of systems can be used simultaneously and periodically to significantly enhance the modularity of the system, providing robustness, redundancy and reliability to the measurement system; for example, in the case that a subset of systems is not available due to maintenance or charging, measurements can still be performed;
- an airborne or ground-based charging platform powered by sunlight can be used to maintain the UAVs in flying operating condition;

- both daytime and night-time operation of the system are made possible by the specific system configuration and by its special constituting components.

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 according to a first embodiment, i.e., a heliostat, within a heliostat field of a Concentrating Solar System.

- Figure 2 is a schematic close-up illustration of the airborne measurement system showing the application of the method according to a first embodiment.

- Figure 3 is a schematic close-up illustration of the airborne measurement system showing the application of the method according to a second embodiment.

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 and accurate geometry characterization of the reflective mirror surfaces of any type of Concentrating Solar System.

According to the present invention, a fully automated, fully autonomous airborne measurement system is provided, said system comprising at least two high-definition digital camera units mounted on at least one unmanned aerial vehicle (UAV).

In Fig.1 the fully automated, fully autonomous airborne measurement system according to a first embodiment of the present invention is illustrated, said system comprising at least a first and a second UAVs (1, 11), said first and second UAVs (1, 11) being both equipped with:

- a camera unit comprising a single high-definition camera, each of them characterized by a distinguish target, and configured to capture the reflected image of the target associated with the camera of the other of said first and second UAVs (1, 11) through the reflecting mirror surface;

- a data acquisition and processing unit, comprising a data logger configured to acquire and process a plurality of high-definition images coming from said camera unit of said first and a second UAVs (1, 11),

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

- a spatial positioning device being able to transmit the relative and absolute position of said first and second UAVs, 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.

The system according to the first embodiment is configured to further comprise on-board storage unit for backup and/or post-flight transmission of the acquired data to said ground processing station.

According to an embodiment of the present invention, said target associated with the camera units of said first and a second UAVs (1, 11) is a mark, or a distinctive pattern or any other type of a visible stamp associated as a unique identification signature to each camera unit, so that it can be easily identified by the on-board processing unit of each of said first and second UAVs (1, 11). For example, said target comprises a small Light Emitting Diode (LED) spot of different color for each camera, so as to be visible during both daytime and night-time

Figure 1 schematically illustrates an operating configuration of the airborne measurement system (100) according to a first embodiment of the present invention; in particular, in Fig.1 is illustrated the method for the accurate determination of the geometry of the reflective mirror (2) of a heliostat (3), within a heliostat field (4) of a Concentrating Solar System. According to the provided method two identical UAVs, (1) and (11), are flying on top of the heliostat (3) following a specific path and in a coordinated fashion so that a condition of mutual reflection, by which the reflection of UAV (1) is “seen” by the camera mounted on UAV (11) and vice versa, is achieved. When this condition is achieved, the reflecting point (7) on the surface of the reflecting mirror (2) is uniquely determined and it is registered by the on-board processing unit as a “valid” surface point. Whenever the on-board processing unit of UAV (11) identifies that the reflecting image that it “sees”, is coming from UAV (1), by identifying its unique distinctive characteristic or target, the reflecting point (7) on the surface mirror (2) is considered as a “valid” point. Since the exact spatial position of UAV (1) and UAV (11) are anytime known by using appropriate positioning techniques, comprising the Differential Global Positioning System (DGPS), both the position of the reflecting point (7) and the direction of the normal to the reflective surface at the reflecting point (10), can be accurately calculated either by the on-board processing unit or by a computer on the ground. According to an embodiment of the present method, UAV (1) and UAV (11) uses DGPS to continuously communicate with known, ground-based GPS reference stations (5) lying in fixed position and with the GPS satellite (6), to accurately calculate their spatial position, feeding this information to the on-board processing unit. For the same purpose of the present method, other appropriate positioning techniques may be employed, comprising the 3-D laser positioning system and photogrammetric triangulation positioning system.

According to another embodiment of the system (100) according to the present invention, a third UAV (111), belonging to a plurality of these UAVs, flying in swarm mode in the vicinity of the reflecting mirror surface (2) may found itself in the condition to “see” the reflection of the target associated with the camera unit if the UAV (11), so as to enable the reflecting point (13) on the reflective mirror surface (2) of the heliostat (3) to be also registered by the on-board processing unit as a “valid” point. Finally, all the points lying on the reflective mirror surface (2) are registered by all the UAVs and transmitted to a ground processing unit by the on-board transmission unit for mapping the real surface of the reflective mirror (2), by which the geometry of the said reflecting mirror (2) can be interpolated and reconstructed.

Reference is now made to Figure 2, which is a schematic close-up illustration of the airborne measurement system (100) according to a first embodiment of the present invention, and that elucidates the method (200) used by the system to accurately determine the position of point (7) on the surface of a reflective mirror (18), having a real surface profile (14). According to this method, two identical UAVs (1, 11) are flying on top of the reflective mirror (18) in a coordinated fashion so that the condition of mutual reflection is achieved, by which the reflected image of UAV (1) is “seen” by the camera (17) mounted on UAV (11) and vice versa. This condition is achieved when the reflected image of the target associated with the UAV (1) is unambiguously identified by the camera mounted on UAV (11), thus enabling the on-board processing unit to register the reflecting point (7) on the surface of the reflective mirror (14) as a “valid point”. In this case, as showed in Figure 1, the on-board processing unit accurately calculates the spatial position of the reflecting point (7) and the normal to the reflective surface on the reflecting point (10).

Both, the camera (16) of UAV (1) and camera (17) of UAV (11) are mounted on special gimbal devices (15), which provide further flexibility (i.e., extra degrees of freedom) for the movement of each camera of the system, optimizing their ability not only to "see" a single reflection, but also to “see”, in the same time and from a single flying spatial position, a plurality of reflections of different targets associated with the cameras of more than one UAV, as in the case of using a plurality of UAVs.

In Fig. 3, a fully automated, fully autonomous airborne measurement system (300) according to a second embodiment of the present invention, is illustrated, said system comprising at least one unmanned aerial vehicle (UAV), (101) equipped with:

- an array (19) of at least two high-definition cameras (24-29), configured to capture the reflected image of a target associated with said at least two high-definition cameras (24-29) through the reflecting mirror surface;

- a data acquisition and processing unit, comprising a data logger configured to acquire and process a plurality of high-definition images coming from said array of at least two high-definition cameras (24-29),

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

- a highly accurate spatial positioning device (5, 6) able to transmit with high accuracy (at each measurement spatial location) the relative and absolute position of the camera of said array of cameras, 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.

The system (300) according to the second embodiment is configured to further comprise on-board storage unit for backup and/or post-flight transmission of the acquired data to said ground processing station.

According to an embodiment of the present invention, said target associated with each of the cameras belonging to said array of cameras of said at least one UAV (101) is a mark, or a distinctive pattern or any other type of a visible stamp associated as a unique identification signature to each camera unit, so that it can be easily identified (at both, daytime and night-time) by the on-board processing unit of each camera of said array of at least two high-definition cameras (24-29)

As shown in Fig.3, a second embodiment of the method used by the system to determine simultaneously the accurate position of several reflecting points on the surface of the reflective mirror (18), having a real surface profile (14), is illustrated. According to this method, the system comprises at least a single UAV (101) equipped with an array of cameras (19), comprising at least a first (24) and a second (29) camera unit, or a plurality of cameras units (24 – 29). Said first (24) and second (29) camera unit or said plurality of cameras units (24 – 29) comprised in said array of cameras (19), are distinguished from each other by a target, which can be efficiently recognized by the on-board processing unit of said at least a single UAV (101). When it happens that the reflected image of said target associated with said first camera unit (24) is “seen” by said second camera unit (29), according to the procedure described with reference to Fig.1 and Fig.2, the position of the reflecting point (20) on the surface of the mirror (18) is accurately determined (along with the normal vector to the point) by the on-board processing unit of said at least a single UAV (101). This condition is achieved when the reflected image of the target associated with said first camera (24) is unambiguously identified by said second camera (29) of said array of cameras (19), thus enabling the on-board processing unit to register the reflecting point (20) on the surface of the reflective mirror (18) as a “valid” point. At the same time, the reflection of the target associated with camera unit (27) is “seen” by the camera unit (25) through the reflection point (22) on the surface of the mirror (18), said camera units (25) and (27) belonging to said plurality of cameras (24 – 29), thus the position of the reflecting point (22) is accurately determined; simultaneously the reflection of the target associated with camera unit (25) is “seen” by camera unit (27) through the reflecting point (23), thus the position of the reflecting point (23) is accurately determined.

According to this method, the spatial positions of a plurality of reflecting points, along with the normal to the point vectors, on the surface of the mirror (18) can be determined by the on-board processing unit of said at least a single UAV (101). By the interpolation of these data, a real reconstruction of the geometry of the said reflecting mirror (18) can be provided.

According to an embodiment of the present method, as shown in Fig.3, said at least a single UAV (101) uses DGPS system to continuously communicate with known, ground-based GPS reference stations (5) lying in fixed position and with the GPS satellite (6), to accurately calculate its spatial position, feeding this information to the on-board processing unit. In this way, the exact position of said first (24) and said second (29) camera units, or said plurality of camera units (24 – 29), on the camera array (19) are accurately determined by the on-board processing unit of said at least a single UAV (101), and, as shown Figure 1, the spatial position of said plurality of points on the surface (14) of the reflecting mirror (18) can be accurately calculated. For example, as depicted in Fig.3, since the exact distance between said first (24) and said second (29) camera units is known, the position of point (20), along with the normal to the point vector to the surface (14) of the reflecting mirror (18), can be calculated by the on-board processing unit.

According to a further embodiment of the present method, the system comprises a plurality of UAVs, said plurality of UAVs being configured to be flying simultaneously, and in swarm mode, within the area near the surface of a reflective mirror, or near a plurality of mirrors (i.e a heliostat field) to accurately determine a plurality of spatial position of points on the surface/surfaces of the said mirror/mirrors. According to this embodiment, the on-board processing unit of each UAV of said plurality of UAVs can identify the reflection of the target associated with the cameras of the other UAVs of said plurality of UAVs. The number of camera units of said array of cameras of each UAV may coincide or be different.

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 concentrating solar system is set up by utilizing said wireless data transmission unit, for feeding in regular time intervals real-time geometry information of the reflecting mirror surfaces to the control loop of the CSP plant, said method being necessary for controlling and optimizing the aiming point of the reflecting surfaces.

According to a further embodiment of the present method, a real-time, on-the-fly communication between the airborne measurement system and the control board of the sun tracking mechanisms of the reflecting mirror surfaces, i.e. heliostats, is set up by utilizing said wireless data transmission unit, for feeding in regular time intervals real-time geometry information of the reflecting mirror surfaces to said control board, said method being necessary for the real time optimization of the aiming point of the reflecting surfaces.

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 information about the geometry of the reflecting mirror surfaces of said CSP system, in order to keep repeatedly fine-tuning the modeling of the surfaces and thus the radiant field estimated by the said software.

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 CSP plant (i.e., digital twinning technology), providing a continuous stream of mirror geometry characterization 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 CSP reflector field, and hence, said airborne measurement system can be employed during operation of the CSP system with minimal to negligible impact on the operation of said CSP system.

Furthermore, the system according to the present invention, can be maintained autonomous and in flying operating condition throughout the entire operation time of the CSP 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 (100-300) for the characterization of the geometry of the reflective mirror surfaces (2, 18) of a Concentrating Solar System (4), said airborne measurement system (100-300) comprising:

- at least one unmanned aerial vehicle (UAV), (101),

- at least a first (24) and a second (29) high-definition camera unit, configured to be mounted on said at least one UAV (101) for capturing the reflected image of a target from the reflecting mirror surface (2, 18), said target being associated with said at least a first (24) and a second (29) high-definition camera unit,

- an on-board data acquisition and processing unit, configured to acquire and process a plurality of high-definition images coming from said first (24) and said second (29) high-definition camera unit,

- a wireless data transmission unit for transmitting said acquired plurality of high-definition images to a ground processing station for post-processing,

- a spatial positioning device (5, 6) for transmitting the instantaneous relative and absolute position of said at least one UAV (101) to said data acquisition and processing unit.

2. The fully automated, fully autonomous airborne measurement system (100-300) according to claim 1, wherein said at least a first (24) and a second (29) high-definition camera unit are configured to be mounted on a first UAV (1) and a second UAV (11), said first UAV (1) being configured to capture the reflected image of said second UAV

(11), said reflected image of said second UAV (11) being formed on said reflecting mirror surface (2) of said Concentrating Solar System (4).

3. The fully automated, fully autonomous airborne measurement system (100-300) according to claim 1 or 2, wherein said target associated to said at least first (24) and second (29) high-definition camera unit, is configured to be easily identified, both during daytime and night-time, by said on-board data acquisition and processing unit.

4. The fully automated, fully autonomous airborne measurement system (100-300) according to claim 1, wherein said at least a first (24) and a second (29) high-definition camera unit belong to an array of cameras (19), said first high-definition camera (24) of said array of cameras (19) being configured to capture the reflected image of said second high-definition camera (29) of said array of cameras (19), said reflected image of said second high-definition camera (29) being formed on said reflecting mirror surface (18) of said Concentrating Solar System (4).

5. The fully automated, fully autonomous airborne measurement system (100-300) 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.

6. The fully automated, fully autonomous airborne measurement system (100-300) according to any of the previous claim, further comprising an on-board storage unit for backup and/or post-flight transmission of said acquired plurality of high-definition images to said ground processing station.

7. A method for the characterization of the geometry of the reflective mirror surfaces (2) of a Concentrating Solar System (4), said method comprising:

- providing a fully automated, fully autonomous airborne measurement system (100-300) according to claim 1,

- configuring said at least one unmanned aerial vehicle (UAV), (101), to fly in a coordinated fashion within the area near the surface of a reflective mirror,

- configuring said at least a first (24) and a second (29) high-definition camera unit to capture the reflected image of a target from a plurality of reflecting points (20, 21, 22, 23) of the reflecting mirror surface (18), said target being associated with said at least a first (24) and a second (29) high-definition camera unit,

- configuring said on-board data acquisition and processing unit to register said reflecting points (20, 21, 22, 23) on the surface of the reflective mirror (18) as valid points, whenever said reflected image of said target associated with said first (24) high-definition camera unit is unambiguously identified by said second (29) high-definition camera unit,

- configuring said spatial positioning device (5, 6) to transmit the relative and absolute spatial position of said at least one UAV (101) to said on-board data acquisition and processing unit;

- configuring said on-board data acquisition and processing unit to calculate the exact position of said at least first (24) and said second (29) high-definition camera unit, based on the spatial position of said at least one UAV (101) and on the known distance between said at least first (24) and said second (29) high-definition camera unit,

- calculating the spatial positions of said plurality of reflecting points (20, 21, 22, 23), along with the normal to the point vectors on the surface (14) of the reflecting mirror (18), by which the geometry of the said reflecting mirror (18) can be interpolated and reconstructed.

8. The method according to claim 7, wherein said at least a first (24) and a second (29) high-definition camera being configured to be mounted on a first UAV (1) and on a second UAV (11), said first UAV (1) and second UAV (11) being configured to fly simultaneously within the area near the surface of the reflective mirror (18), or a plurality

of mirrors (4).

9. The method according to claim 7, wherein said at least a first (24) and a second (29) high-definition camera being configured to be mounted on a plurality of UAVs, said plurality of UAVs being configured to fly in swarm mode within the area near the surface of the reflective mirror (18), or a plurality of mirrors (4).

10. The method according to claim 7, wherein a real-time and on-the-fly communication is set-up between the airborne measurement system (100-300) and a control loop of said Concentrating Solar System (4), by utilizing said wireless data transmission unit for feeding in regular time intervals the geometry information of the reflecting mirror surfaces (18) to said control loop of said Concentrating Solar System (4).

11. The method according to claim 7, wherein a real-time and on-the-fly communication is set-up between the airborne measurement system (100-300) and a control board of a sun tracking mechanism of said reflecting mirror surface (18), by utilizing said wireless data transmission unit for feeding in regular time intervals the geometry information of the reflecting mirror surfaces (18) to said control board, for the real time optimization of the aiming point of said reflecting mirror (18) surfaces.

12. The method according to claim 7, wherein said airborne measurement system (100-300) is configured to provide continuous information about the geometry of the reflecting mirror surfaces (18) to an optical simulation software to provide a repeatedly fine-tuning of the modeling of the surfaces and of the radiant field estimated by said software.

13. The method according to claim 7, wherein said airborne measurement system (100-300) is configured to operate in conjunction with a high-fidelity real-time dynamic virtualization digital model/platform of said Concentrating Solar System (4) plant,

providing a continuous stream of mirror geometry characterization data and mapping said data to said digital model/platform for real-time optimization and enhancement of the plant's operation.

14. The method according to claim 7, wherein said airborne measurement system (100-300) 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 20 June 2022 (20.06.2022)

1. A fully automated, fully autonomous airborne measurement system (100-300) for the characterization of the geometry of the reflective mirror surfaces (2, 18) of a Concentrating Solar System (4), said airborne measurement system (100-300) comprising:

- at least one unmanned aerial vehicle (UAV), (101),

- at least a first (24) and a second (29) high-definition camera unit, configured to be mounted on said at least one UAV (101) for capturing the reflected image of a target from the reflecting mirror surface (2, 18), said target being associated with said at least a first (24) and a second (29) high-definition camera unit,

- an on-board data acquisition and processing unit, configured to acquire and process a plurality of high-definition images coming from said first (24) and said second (29) high-definition camera unit,

- a wireless data transmission unit for transmitting said acquired plurality of high-definition images to a ground processing station for post-processing,

- a spatial positioning device (5, 6) for transmitting the instantaneous relative and absolute position of said at least one UAV (101) to said data acquisition and processing unit

characterized in that

said target associated to said at least first (24) and second (29) high-definition camera unit, is configured to be easily identified, both during daytime and night-time, by said on-board data acquisition and processing unit.

2. The fully automated, fully autonomous airborne measurement system (100-300) according to claim 1, wherein said at least a first (24) and a second (29) high-definition camera unit are configured to be mounted on a first UAV (1) and a second UAV (11),

said first UAV (1) being configured to capture the reflected image of said second UAV (11), said reflected image of said second UAV (11) being formed on said reflecting mirror surface (2) of said Concentrating Solar System (4).

3. The fully automated, fully autonomous airborne measurement system (100-300) according to claim 1, wherein said at least a first (24) and a second (29) high-definition camera unit belong to an array of cameras (19), said first high-definition camera (24) of said array of cameras (19) being configured to capture the reflected image of said second high-definition camera (29) of said array of cameras (19), said reflected image of said second high-definition camera (29) being formed on said reflecting mirror surface (18) of said Concentrating Solar System (4).

4. The fully automated, fully autonomous airborne measurement system (100-300) 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.

5. The fully automated, fully autonomous airborne measurement system (100-300) according to any of the previous claim, further comprising an on-board storage unit for backup and/or post-flight transmission of said acquired plurality of high-definition images to said ground processing station.

6. A method for the characterization of the geometry of the reflective mirror surfaces (2) of a Concentrating Solar System (4), said method comprising:

- providing a fully automated, fully autonomous airborne measurement system (100-300) according to claim 1,

- configuring said at least one unmanned aerial vehicle (UAV), (101), to fly in a coordinated fashion within the area near the surface of a reflective mirror,

- configuring said at least a first (24) and a second (29) high-definition camera unit to capture the reflected image of a target from a plurality of reflecting points (20, 21, 22, 23) of the reflecting mirror surface (18), said target being associated with said at least a first (24) and a second (29) high-definition camera unit,

- configuring said on-board data acquisition and processing unit to register said reflecting points (20, 21, 22, 23) on the surface of the reflective mirror (18) as valid points, whenever said reflected image of said target associated with said first (24) high-definition camera unit is unambiguously identified by said second (29) high-definition camera unit,

- configuring said spatial positioning device (5, 6) to transmit the relative and absolute spatial position of said at least one UAV (101) to said on-board data acquisition and processing unit;

- configuring said on-board data acquisition and processing unit to calculate the exact position of said at least first (24) and said second (29) high-definition camera unit, based on the spatial position of said at least one UAV (101) and on the known distance between said at least first (24) and said second (29) high-definition camera unit,

- calculating the spatial positions of said plurality of reflecting points (20, 21, 22, 23), along with the normal to the point vectors on the surface (14) of the reflecting mirror (18), by which the geometry of the said reflecting mirror (18) can be interpolated and reconstructed.

7. The method according to claim 6, wherein said at least a first (24) and a second (29) high-definition camera being configured to be mounted on a first UAV (1) and on a second UAV (11), said first UAV (1) and second UAV (11) being configured to fly simultaneously within the area near the surface of the reflective mirror (18), or a plurality of mirrors (4).

8. The method according to claim 6, wherein said at least a first (24) and a second (29) high-definition camera being configured to be mounted on a plurality of UAVs, said

plurality of UAVs being configured to fly in swarm mode within the area near the surface of the reflective mirror (18), or a plurality of mirrors (4).

9. The method according to claim 6, wherein a real-time and on-the-fly communication is set-up between the airborne measurement system (100-300) and a control loop of said Concentrating Solar System (4), by utilizing said wireless data transmission unit for feeding in regular time intervals the geometry information of the reflecting mirror surfaces (18) to said control loop of said Concentrating Solar System (4).

10. The method according to claim 6, wherein a real-time and on-the-fly communication is set-up between the airborne measurement system (100-300) and a control board of a sun tracking mechanism of said reflecting mirror surface (18), by utilizing said wireless data transmission unit for feeding in regular time intervals the geometry information of the reflecting mirror surfaces (18) to said control board, for the real time optimization of the aiming point of said reflecting mirror (18) surfaces.

11. The method according to claim 6, wherein said airborne measurement system (100-300) is configured to provide continuous information about the geometry of the reflecting mirror surfaces (18) to an optical simulation software to provide a repeatedly fine-tuning of the modeling of the surfaces and of the radiant field estimated by said software.

12. The method according to claim 6, wherein said airborne measurement system (100-300) is configured to operate in conjunction with a high-fidelity real-time dynamic virtualization digital model/platform of said Concentrating Solar System (4) plant, providing a continuous stream of mirror geometry characterization data and mapping said data to said digital model/platform for real-time optimization and enhancement of the plant’s operation.

13. The method according to claim 6, wherein said airborne measurement system (100-300) 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

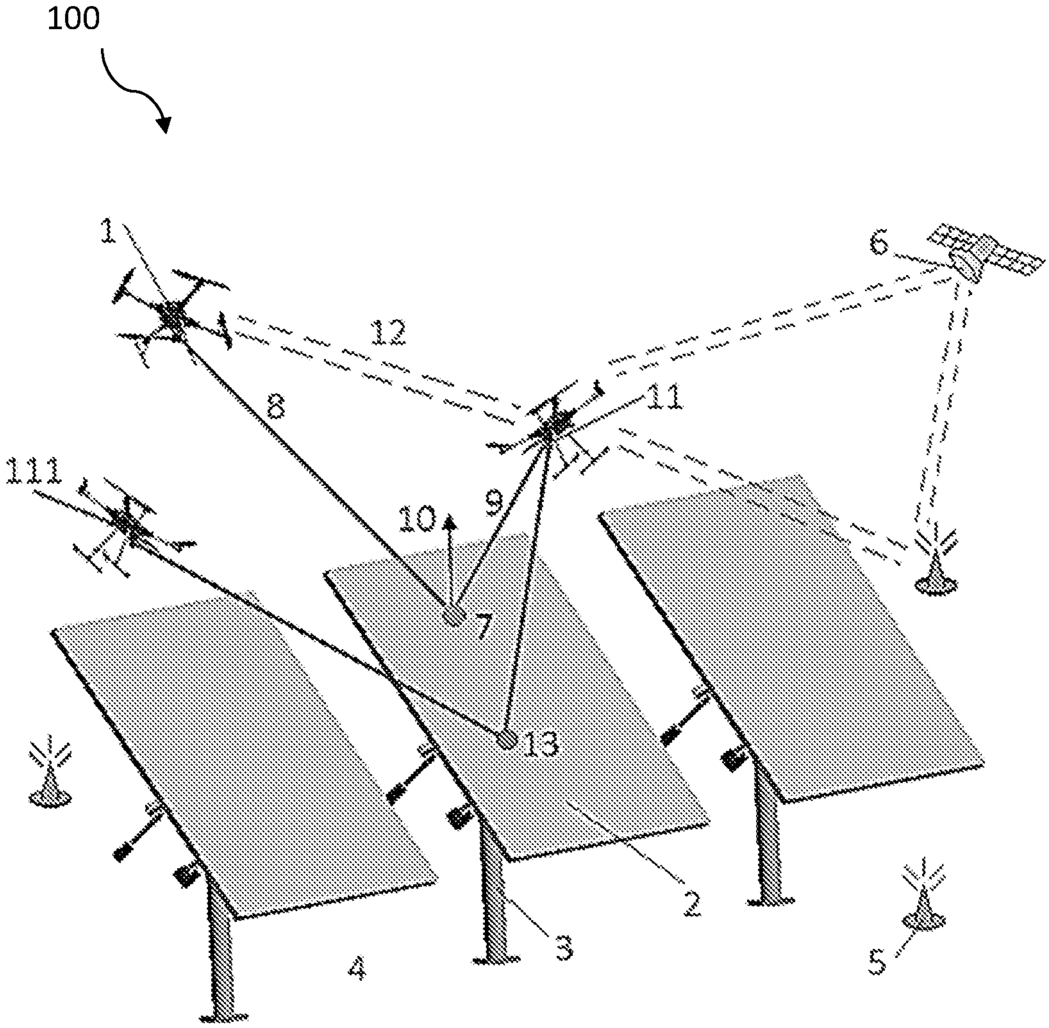


Fig.2

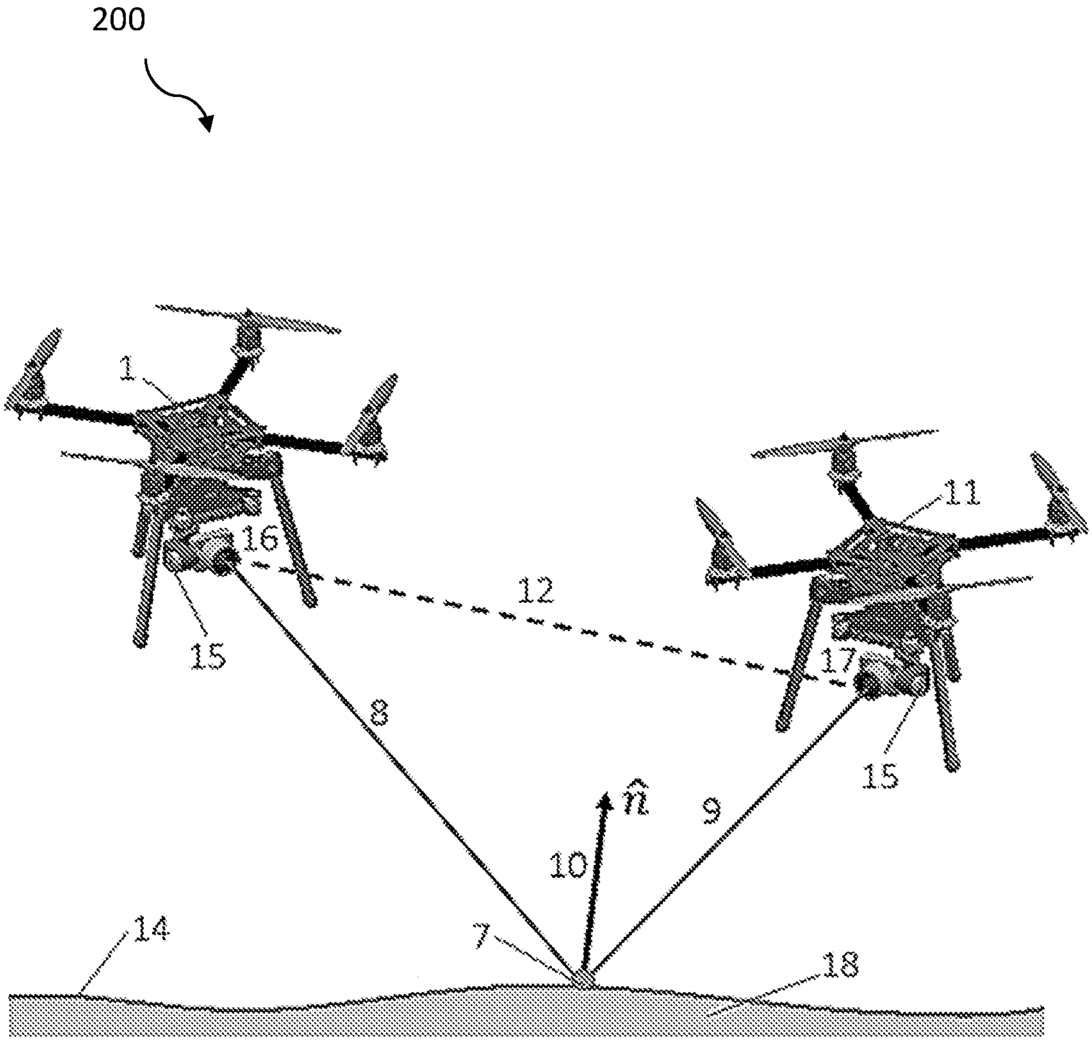
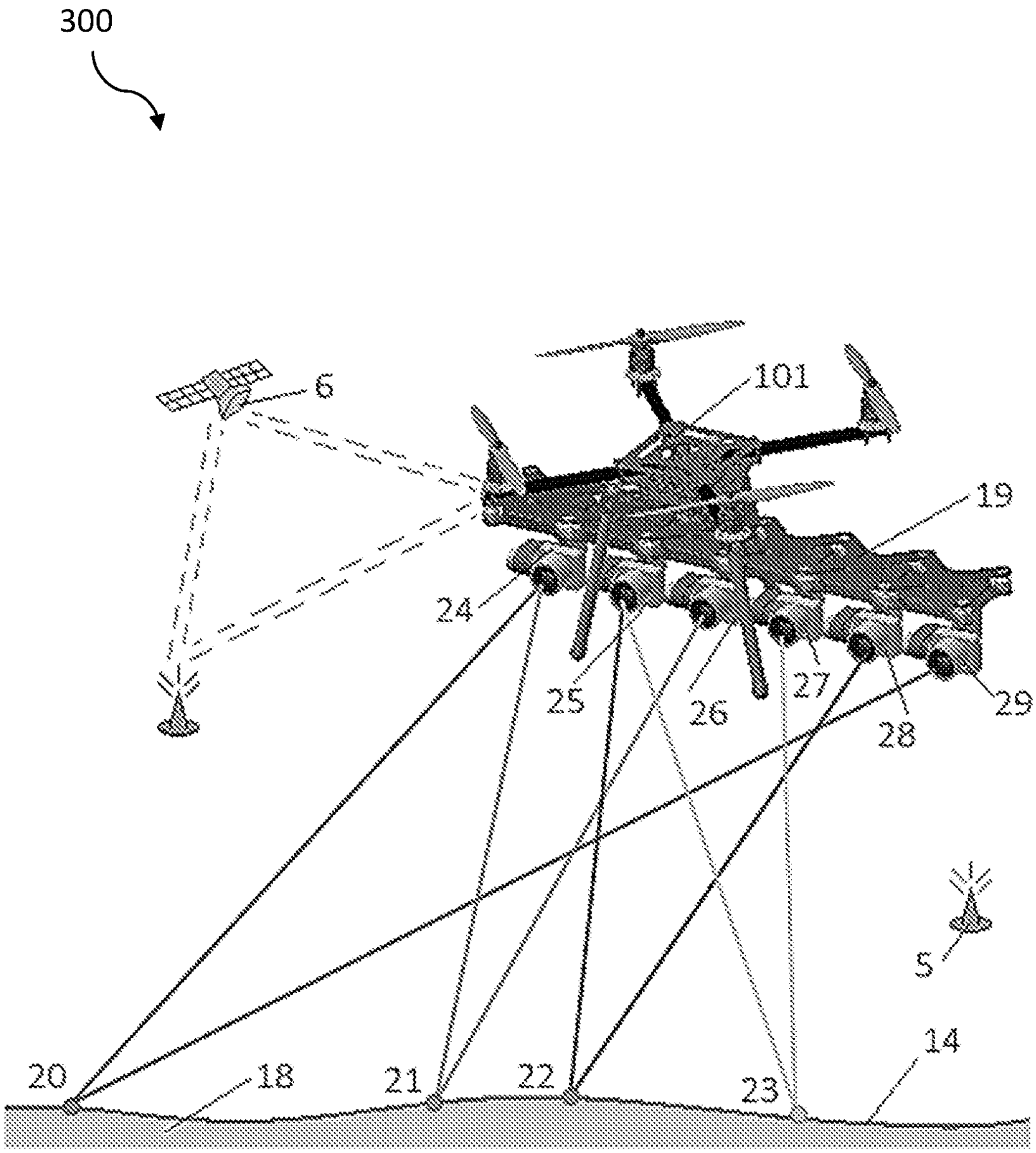


Fig.3



INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2021/053674

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 G01M

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 Y	CN 109 596 212 B (ZHEJIANG SUPCON SOLAR ENERGY TECHNOLOGY CO LTD) 12 January 2021 (2021-01-12) figure 1 paragraph [0010] paragraph [0013] paragraph [0021] paragraph [0032] paragraph [0051] -----	1,2,4,6 5
Y	ES 2 390 784 T3 (DEUTSCH ZENTR LUFT & RAUMFAHRT [DE]) 16 November 2012 (2012-11-16) paragraph [0068] ----- -/--	5

[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

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

"P" document published prior to the international filing date but later than the priority date claimed

"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

"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"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	Date of mailing of the international search report
17 December 2021	07/01/2022

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Fernandez Ambres, A

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2021/053674

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	CN 210 374 127 U (UNIV NANJING) 21 April 2020 (2020-04-21) the whole document -----	1-14
A	CN 208 171 884 U (UNIV JILIANG CHINA) 30 November 2018 (2018-11-30) the whole document -----	1-14

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
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