



(51) International Patent Classification:
G08G 5/06 (2006.01) *G05D 1/02* (2006.01)

(21) International Application Number:
PCT/IL2017/051340

(22) International Filing Date:
12 December 2017 (12.12.2017)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
249929 04 January 2017 (04.01.2017) IL

(71) Applicant: ISRAEL AEROSPACE INDUSTRIES LTD.
[IL/IL]; Ben-Gurion International Airport, 7010000 Lod
(IL).

(72) Inventors: ZIVAN, Lior; P.O.B. 98, 4284000 Yad Hanna
(IL). DEKEL, Guy; 3 Shdema Street, 3786800 Kazir (IL).

(74) Agent: HAUSMAN, Ehud; Reinhold Cohn and Partners,
P.O.B 13239, 6113102 Tel Aviv (IL).

(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(54) Title: AUTONOMOUS TAKEOFF AND LANDING BY AN AIRCRAFT

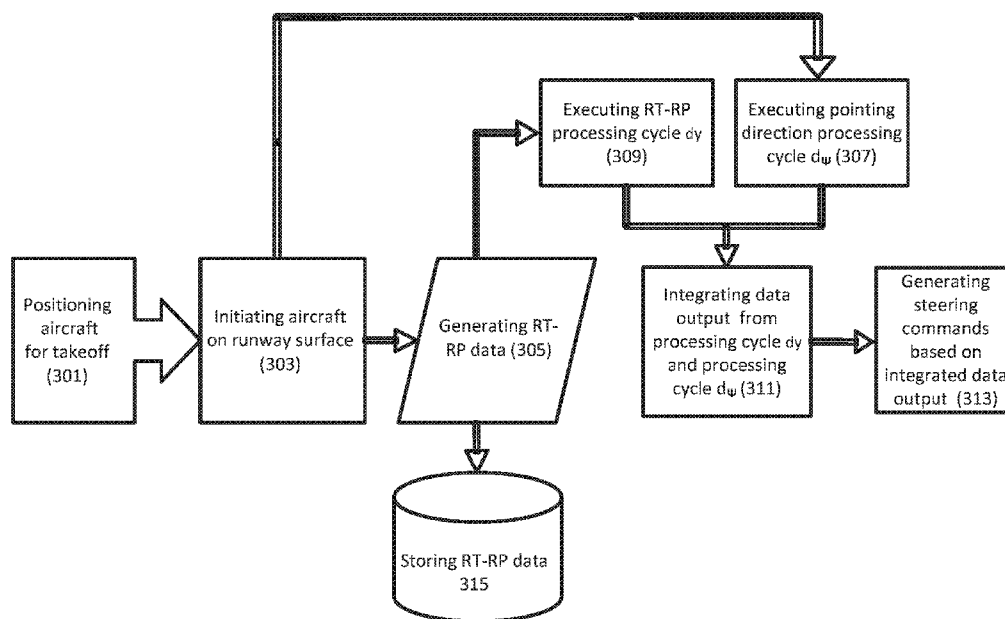


Fig. 3

(57) **Abstract:** According to the disclosed subject matter a runway path is generated, in real-time, as the aircraft proceeds in the general takeoff direction along the runway surface. As part of the initial stages of the takeoff process, one or more reference points are selected, where accurate positioning of the reference point is not necessary. The runway path is generated based on points which are sampled in real-time as the aircraft progresses along the runway surface. Sampling includes determining the relative position of points in relation to the one or more reference points. A line representing the runway path and extending in the general takeoff direction is generated based on the collection of sampled points. If the aircraft deviates from the intended takeoff direction and/or from the generated line, appropriate steering commands are generated for correcting the deviation and maintaining the aircraft on course.



(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

AUTONOMOUS TAKEOFF AND LANDING BY AN AIRCRAFT

FIELD OF THE PRESENTLY DISCLOSED SUBJECT MATTER

The presently disclosed subject matter relates to the field of aircraft control and specifically to aircraft control during takeoff and landing.

BACKGROUND

Autonomous aircraft takeoff and landing (ATOL; including both a manned and unmanned aircraft) requires a runway. For ATOL operation accurate positioning information is required in order to follow the runway during takeoff and landing. Such information is not always available and accordingly safe autonomous takeoff and landing is not always possible.

GENERAL DESCRIPTION

The term "progression course" as used herein refers to the actual path traversed by the aircraft when taking off or landing. In conventional conditions the boundaries of the progression course are usually defined by a designated "runway surface" which refers to the actual physical surface from which the aircraft takes off.

The term "real-time runway path" (abbreviated RT-RP, also referred to herein as "runway path"), as used herein, refers to a path generated in real-time along the runway surface and subsequently used for takeoff and possibly also for landing. As explained below, an RT-RP can be generated on any suitable surface and is not limited to a designated runway surface.

Conventional autonomous takeoff and landing requires an accurate position of the runway and aircraft. This can be achieved by using an accurate positioning system for determining accurate global position (defining geographical coordinates) of the aircraft and runway. In situations where accurate determination of global position is not possible, an accurately determined relative position of the aircraft and runway can be used instead. This technique requires knowledge of an accurate global position of a reference point. The relative position of the aircraft and runway are determined in relation to the accurately positioned reference point. Notably, according to some examples "accurate positioning data"

includes positioning accuracy of 1 meter or less. According to other examples "accurate positioning data" includes positioning accuracy of 1.5 meter or less. According to further examples "accurate positioning data" includes positioning accuracy of 2.5 meter or less.

A reference point is a point located in the vicinity of the runway area, which is distinguishable from the background area. Examples of reference points include any physical object including a designated physical marking positioned for this purpose as well as a physical object already located in the vicinity of the runway e.g. a tree, structure such as building or silo tank, pole, or any other distinguishable object. The location of the reference point can be accurately determined by various methods including for example a differential Global Positioning System (dGPS).

However, such methods are not always available. For example, in remote and secluded areas such as fields (where according to some examples autonomous takeoff and landing may be desired for the purpose of crop-dusting), the exact coordinates of the runway are often unknown, and accordingly it is not possible to accurately determine the global position of the runway at the time of takeoff. Furthermore, in many cases a runway does not even exist and a stretch of land is randomly used as a makeshift runway.

Even in cases where the location of a runway has been known at some point in time in the past, environmental conditions such as climatic changes, extreme weather (e.g. flooding of the runway), crop rotation, human intervention, etc., may impact the runway and consequentially it may be necessary to change the runway in order to adjust to the current environmental conditions, rendering information with respect to the previous location of the runway, irrelevant.

Also, an accurately positioned reference point many times cannot be used; for example, due to lack of accurate positioning facilities (e.g. dGPS) which is required for accurately determining the location of a reference point. In those cases where a previously determined reference point exists, it is required that the reference point or marking remains in place. This is not always possible, as many times the reference point, or marking, is moved or lost due to environmental conditions or as a result of accidental or deliberate human intervention (e.g. moving of a reference point).

The presently disclosed subject matter includes a system and method which enables autonomous takeoff and landing of an aircraft without the need for accurate positioning facilities and without requiring prior knowledge of an accurate (global) position of a reference point and/or a runway.

According to the disclosed technique a runway path is generated, in real-time, using real time relative measurements and calculations of the aircraft and its position with respect to some reference point selected in the takeoff area. According to this approach a runway path can be located almost anywhere and is not limited to a pre-designated runway surface with a known and accurate global position. For example, for takeoff, a runway surface can be an arbitrary stretch of land suitable for takeoff (e.g. in an isolated field or some other flat surface) selected before takeoff.

The RT-RP is generated in real-time as the aircraft proceeds in the general takeoff direction along the runway surface. As part of the initial stages of the takeoff process, one or more reference points are selected, where accurate positioning of the reference point is not necessary (e.g. no need to determine the exact geographical coordinates of the reference point).

A reference point can be any suitable point within the takeoff area. A reference point can be a reference point external to the aircraft (herein "external reference point") such as a physical element/object that is identifiable distinguishable from the background in the vicinity of the takeoff area. A reference point can also be a "self-reference point" whereby the system selects one or more points along the progression course of the aircraft and uses this as the reference point to enable takeoff and landing.

The runway path is generated based on points which are sampled in real-time as the aircraft progresses along the runway surface. Sampling includes determining the relative position of points in relation to the one or more reference points. A line representing the runway path and extending in the general takeoff direction is generated based on the collection of sampled points. If the aircraft deviates from the intended takeoff direction and/or from the generated line, appropriate steering commands are generated for correcting the deviation and maintaining the aircraft on course.

According to one aspect of the presently disclosed subject matter there is provided a computer-implemented method of autonomous takeoff of an aircraft from a runway surface; the method comprising:

operating a computer system while the aircraft is proceeding on the runway surface towards takeoff for executing at least the following:

a) obtaining current heading of the aircraft and calculating a first output including data related to deviation of the current heading of the aircraft from an intended takeoff direction;

b) determining respective position, relative to at least one reference point, of each one of a collection of points sampled along the aircraft progression course;

generating a runway path, based on the collection of points;

calculating a second output including data related to deviations of progression course of the aircraft from the runway path;

c) integrating the first output and second output and generating integrated data output; and

generating, based on the integrated data output, steering commands for steering the aircraft and correcting the aircraft's progression course in order to compensate for deviation in the heading of the aircraft and/or deviation of the progression course of the aircraft;

repeating each one of operations a to c;

executing takeoff sequence once the runway path is ready for takeoff.

Additional to the above features, the method according to this aspect of the presently disclosed subject matter can optionally comprise one or more of features (i) to (x) below, mutatis mutandis, in any technically possible combination or permutation.

i) wherein generating the runway path, comprises:

repeatedly sampling new points as the aircraft proceeds along the takeoff

surface to thereby repeatedly generate an updated collection of sampled points; and
calculating updated instances of the runway path based on a recently updated collection of sampled points.

ii) wherein calculating a second output comprises:

calculating current position of the aircraft relative to the runway path; calculating current speed of aircraft; and

determining deviation rate of aircraft relative to runway path based on speed and heading.

iii) wherein the generating of the runway path comprises implementing a regression analysis on the collection of points.

iv) wherein the integrating comprises:

assigning a respective weight to each one of the first output and second output, wherein each weight defines the contribution of the respective output to the integrated data output; and

adapting the weight according to progress of the runway path generation.

v) wherein the absolute position of the collection of points is unknown.

vi) wherein the at least one reference point is an external reference point located externally to the aircraft.

vii) wherein the at least one reference point is a self-reference point representing self-position of the aircraft at some point in time.

viii) The method further comprising scanning the runway surface in front of the aircraft during takeoff and detecting obstacles and aborting or circumventing an obstacle on the runway surface which obstructs the progression of the aircraft.

ix) The method further comprising executing an autonomous landing process, comprising:

while in the air, repeatedly determining position of aircraft relative to the at

least one reference point;

extracting runway path data from the data-storage device, wherein runway path data includes the position of sampled points constituting the runway path relative to the at least one reference point;

maneuvering the aircraft to a point above the runway path;

landing on the runway according to runway path data.

- x) The method further comprising autonomously determining a reference point, comprising: operating a range finder device for identifying a suitable object to serve as a reference point in the vicinity of the runway surface.

According to another aspect of the presently disclosed subject matter there is provided a system for enabling autonomous takeoff of an aircraft from a runway surface, the system comprising a computer device operatively connected to a direction finder device, and a positioning device; the system is configured, while the aircraft is proceeding on the runway surface towards takeoff, to execute at least the following:

- i. operate the direction finder device to determine current heading of the aircraft;

operate the computer device to calculate a first output including data related to deviation of the current heading of the aircraft from an intended takeoff direction;

- ii. operate the positioning device to determine respective position, relative to at least one reference point, of each of a collection of points sampled along the aircraft progression course;

operate the computer device to:

generate a runway path, based on the collection of points; and

calculate a second output including data related to deviations of progression course of the aircraft from the runway path;

operate the computer device to:

integrate the first output and second output and generate integrated data output;

and

- iii. generate, based on the integrated data output, steering commands for steering the aircraft and correcting the aircraft's progression course in order to compensate for deviation in the heading of the aircraft and/or deviation of the progression course of the aircraft;

repeat each one of operations i to iii;

execute takeoff sequence once the runway path is ready for takeoff.

According to another aspect of the presently disclosed subject matter there is provided a non-transitory program storage device readable by a computer, tangibly embodying computer readable instructions executable by the computer to perform a computer-implemented method of autonomous takeoff of an aircraft from a runway surface; the method comprising:

operating a computer system while the aircraft is proceeding on the runway surface towards takeoff for executing at least the following:

- i. obtaining current heading of the aircraft and calculating a first output including data related to deviation of current heading from an intended takeoff direction;
- ii. determining respective position, relative to at least one reference point, of each of a collection of points sampled along the aircraft progression course;
generating a runway path, based on the collection of points;
calculating a second output including data related to deviations of progression course of the aircraft from the runway path;
- iii. integrating the first output and second output and generating integrated data output; and
generating, based on the integrated data output, steering commands for steering the aircraft for correcting the aircraft's progression course in order to compensate for deviation in the heading of the aircraft and/or deviation of

the progression course of the aircraft;

repeating each one of operations i to iii;

executing takeoff sequence once the runway path is ready for takeoff.

The system and the computer storage device disclosed in accordance with the presently disclosed subject matter can optionally comprise one or more of features (i) to (ix) listed above, mutatis mutandis, in any technically possible combination or permutation.

According to another aspect of the presently disclosed subject matter there is provided an aircraft with an onboard autonomous takeoff system providing the aircraft with autonomous takeoff capability as disclosed herein, wherein the aircraft is either a UAV or a piloted aircraft.

According to some examples the autonomous takeoff system is autonomous takeoff and landing system capable of also autonomously landing the aircraft as disclosed herein.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the presently disclosed subject matter and to see how it may be carried out in practice, the subject matter will now be described, by way of non-limiting examples only, with reference to the accompanying drawings, in which:

Fig. 1 is a functional block diagram schematically illustrating a general view of an autonomous takeoff and landing system, in accordance with some examples of the presently disclosed subject matter;

Fig. 2 is a functional block diagram showing a more detailed view of some components of system **100**, in accordance with some examples of the presently disclosed subject matter;

Fig. 3 is a flowchart showing an example of operations performed during autonomous takeoff, in accordance with some examples of the presently disclosed subject matter;

Fig. 4 is a flowchart showing a more detailed view of operations performed during autonomous takeoff, in accordance with some examples of the presently disclosed subject matter;

Fig. 5 is schematic illustration (top view) demonstrating various stages of an autonomous takeoff process, in accordance with some examples of the presently disclosed subject matter;

Fig. 6 is schematic illustration (top view) demonstrating different scenarios of deviation, in accordance with some examples of the presently disclosed subject matter;

Fig. 7a is a graph exemplifying the adaptive integration of the pointing direction processing cycle $d\psi$ output and runway path processing cycle $d\gamma$ output, in accordance with some examples of the presently disclosed subject matter;

Fig. 7b is a schematic illustration of a numerical example of the integration logic of the two processing cycles, in accordance with some examples of the presently disclosed subject matter; and

Fig. 8 is a flowchart showing operations executed for autonomous landing, in accordance with some examples of the presently disclosed subject matter.

DETAILED DESCRIPTION

Elements in the drawings are not necessarily drawn to scale. Unless specifically stated otherwise, as apparent from the following discussions, it is appreciated that throughout the specification discussions utilizing terms such as "obtaining", "determining", "generating", "calculating", "integrating", "executing" or the like, include actions and/or processes of a computer that manipulate and/or transform data into other data, said data represented as physical quantities, e.g. such as electronic quantities, and/or said data representing the physical objects.

The terms "computer", "computer device", "computerized device", "computer system", "processing device" or variation thereof should be expansively construed to include any kind of electronic device with a processing circuitry capable of data processing and which includes one or more computer processors operatively connected to a computer memory (optionally including non-transitory computer memory) operating together for executing and/or generating instructions. Examples of such a device include: digital signal processor (DSP), a microcontroller, a field programmable gate array (FPGA), an application specific

integrated circuit (ASIC), a personal computer, server computer device, a dedicated processing device, etc.

As used herein, the phrase "for example," "such as", "for instance" and variants thereof describe non-limiting embodiments of the presently disclosed subject matter. Reference in the specification to "one case", "some cases", "other cases" or variants thereof means that a particular feature, structure or characteristic described in connection with the embodiment(s) is included in at least one embodiment of the presently disclosed subject matter. Thus the appearance of the phrase "one case", "some cases", "other cases" or variants thereof does not necessarily refer to the same embodiment(s).

It is appreciated that certain features of the presently disclosed subject matter, which are, for clarity, described in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features of the presently disclosed subject matter, which are, for brevity, described in the context of a single embodiment, may also be provided separately or in any suitable sub-combination.

In embodiments of the presently disclosed subject matter, fewer, more and/or different stages than those shown in Figs. 3, 4 and 8 may be executed. Also the order of execution of the described operations should not be limited to the order which is presented in the figures. For example, the operations described in Fig. 4 with reference to block 301 can in some cases start before or together with the operations described with reference to block 401.

Figs. 1 and 2 illustrate a general schematic of the system functional in accordance with an embodiment of the presently disclosed subject matter. The components in Figs. 1 and 2 may be centralized in one location or dispersed over more than one location. In other embodiments of the presently disclosed subject matter, the system may comprise fewer, more, and/or different modules than those shown in Figs. 1 and 2. For example, while computer 103 is illustrated as a single device, in other examples it may be implemented as several interconnected computerized devices distributed at different locations (e.g. some onboard the aircraft and some located elsewhere). Likewise, while control unit 102 is illustrated as a single unit in other examples it may be implemented as several distributed

computerized devices, each designated for controlling a different device onboard the aircraft. Also, image processing unit 207 may not always be necessary.

Attention is now drawn to **Error! Reference source not found.** showing a functional block diagram illustrating a general example of an autonomous takeoff and landing system. System 100 comprises aircraft 101, aircraft control unit (ACU) 102, computer 103, computer data storage 105, and sensors 107. Data-storage can include both persistent computer memory (e.g. hard disk or NVRAM) and non-persistent (e.g. RAM) computer memory.

In some examples, all of the components of system 100 (other than aircraft 101) are loaded onboard aircraft 101 and operate therefrom. In other examples part of the components of system 100 are located off the aircraft 101 and are configured to communicate with the aircraft over a communication link.

Aircraft control unit 102 is a computerized device configured *inter alia*, to generate and provide instructions to one or more flight control units onboard the aircraft for the purpose of controlling the aircraft's movement during takeoff, landing and flight. Flight control units control various aircraft controlling devices and include for example rudder control unit, ailerons control unit, flap control unit, throttle control unit, etc.

With respect to the presently disclosed subject matter, computer 103 is configured, *inter alia*, to generate the RT-RP based on data received from sensors 107. As explained further below, data is calculated and processed by computer 103 in real-time during takeoff for generating the runway path. Fig. 2 is a functional block diagram showing a more detailed view of part of system 100. According to some examples, as illustrated in Fig. 2, computer 103 can comprise one or more functional units used for calculating the RT-RP, including for example runway generator 210 and deviation calculator 220. Runway generator 210 can further comprise for example, sampling unit 202, runway path calculating unit 204 and is configured in general to generate a line representing the RT-RP. Deviation calculator 220 is configured to calculate deviation of the aircraft from the intended takeoff direction and/or from the generated RT-RP.

Sensors 107 can include various sensing devices (some of which are illustrated in Fig. 2 by way of non-limiting example only) including positioning devices for obtaining data

related to the aircraft's position. In general, positioning devices can be divided into two types: relative and absolute. Relative positioning devices determine the position based on the distance, angle or direction between the aircraft and a certain point, and are not based on a fixed frame of reference. Absolute positioning devices determine the position with respect to a geographical reference frame. This type of sensors includes for example GPS and dGPS.

Sensors **107** can be located onboard the aircraft (**101**) and/or off the aircraft (off-board sensors), e.g. on the ground in the vicinity of the runway surface. Off-board sensors can be located in a position where they can track the aircraft during takeoff and landing. As used herein the term "positioning device" should be expansively construed to include any device which can provide data indicative of the relative or absolute position.

Examples of positioning devices include, but are not limited to, unmanned common automatic recovery system (UCARS), object position and tracking system (OPATS), instrument landing systems (ILS), etc. Such devices generally operate with a respective reflector onboard the aircraft.

Examples of positioning devices which can be loaded onboard the aircraft include, but are not limited to: Light imaging, detection and ranging (LIDAR), RADAR, image sensors (cameras), inertial navigation systems (INS), IMU, odometer(s), etc.

Examples of positioning devices which determine absolute positioning data include: global navigation satellite systems (GNSS) such as GPS, GLONASS, BDS (BeiDou navigation satellite system), Galileo, etc., or regional satellite navigation systems such as quasi-zenith satellite system (QZSS), independent regional navigation satellite (IRNSS), radio based systems such as VOR/DME, NDB, LORAN, etc.

While absolute and accurate positioning data is not necessary for accomplishing takeoff and landing, such positioning devices, if available, can be used for obtaining relative positioning data (i.e. positioning data relative to a reference point).

Sensor **107** also includes speedometer and direction finder (DF) devices which provide true or magnetic heading data (ψ). Some positioning devices can also be used to determine heading and speed of the aircraft (e.g. GPS, INS). Alternatively, dedicated direction finding devices for determining heading (e.g. magnetic compass, fluxgate/flux valve compass,

magnetometers, Dual Antenna, etc.) and speed (e.g. odometer, etc.) can be used. Thus, the specific combination of sensors in system **100** may vary as long as they are able to provide the relative position, heading and speed of the aircraft.

Real-time data gathered by the various sensing devices also contributes to determining runway validity and helps to improve the autonomous decision making process. For example, as mentioned below, angular rates [Ω_x , Ω_y , Ω_z] and linear accelerations [A_x , A_y , A_z] can be used to indicate runway condition. Additional functional components in Fig. **2** are described below.

Attention is now drawn to Fig. **3** showing a flowchart of operations performed in an autonomous takeoff, according to some examples of the presently disclosed subject matter. Operations described with reference to Fig. **3** (as well as Fig. **4** and Fig. **8** below) can be executed for example by system **100** described above with reference to Fig. **1** and Fig. **2**. However, it is noted that the specific configuration of elements in system **100** is merely a non-limiting example and various modifications to the system can be applied for executing the described operations.

At the onset of the takeoff process the aircraft is positioned on the runway surface in a desired location to commence takeoff (block **301**). The aircraft can be positioned while pointing in the desired takeoff direction, or the desired takeoff direction can be otherwise determined as described below with reference to Fig. **4**. Once the intended takeoff direction is determined, the aircraft starts to proceed along the takeoff surface in the general takeoff direction (**303**).

As the aircraft moves forward along the runway surface, runway path data is generated (block **305**). Runway path data includes points which are sampled by system **100** as it travels on the takeoff surface. Sampling includes determination of the relative position of points along the aircraft's progression route with respect to one or more reference points. The sampled points are used for generating the runway path in real-time. A more detailed description of the sampling process and runway path generation process is described below with reference to Fig. **4**.

Two processing cycles are initiated for controlling the aircraft during takeoff. One is the runway path processing cycle d_r (Block 307) and the other is the pointing direction processing cycle d_ψ (Block 309). The purpose of the pointing direction processing cycle d_ψ is to maintain the aircraft heading as closely aligned as possible with intended takeoff direction. The purpose of the runway path processing cycle d_r is to maintain the aircraft aligned with the generated runway path. The pointing direction processing cycle d_ψ begins with the initial movement of the aircraft in the intended takeoff direction. The runway path processing cycle d_r is initiated once sufficient points have been collected and the first instance of the runway path has been generated.

Output data from the pointing direction processing cycle d_ψ and output data from the runway path processing cycle d_r are integrated to generate integrated data output (block 311), and steering commands for controlling the aircraft are generated based on the integrated data output (block 313). Once it is determined that the generated runway path is adequate for takeoff (e.g. sufficiently long) the aircraft proceeds to takeoff. It is noted that the term "processing cycle" is used herein to indicate that the related operations are repeated during the takeoff process and an updated integrated data output is repeatedly calculated based on the most updated output data obtained from each processing cycle. It is also noted that in some examples each processing cycle is executed asynchronously to the other processing cycle. Integrated data output can be repeatedly generated based on the most recently available output from each processing cycle.

Fig. 4. is a flowchart showing a more detailed view of the autonomous takeoff process described above with reference to Fig. 3, according to some examples of the presently disclosed subject matter.

Information indicative of one or more reference points is obtained before the onset of the takeoff process or at the initial stages of the takeoff process (Block 401). According to one example, system 100 can be configured to autonomously identify one or more reference points by scanning the area surrounding the takeoff area (runway surface) and selecting some object that can be used as a reference point. Autonomous identification of reference points can be accomplished for example by a range finder device (e.g. laser, LIDRAR, RADAR,

or an image sensor) operable for scanning the area near the takeoff surface and providing respective scanning data output (e.g. images). Computer **103** can be configured, for example, to implement image processing (e.g. with the help of image processing unit **207**) and identify a suitable object within the image to be used as a reference point during takeoff.

Alternatively, information of one or more reference points can be provided to system **100** (e.g. by an operator located on the field who selects the reference point). Further alternatively, a self-reference point can be used instead.

According to one non-limiting example, if a reliable external reference point is not found, the system (e.g. with the help of computer **103**) is configured to autonomously switch to operate in an self-reference mode where one or more self-reference points are used.

As mentioned above, at the onset of the takeoff process the aircraft is positioned on the runway surface in a desired location to commence takeoff (block **301**). According to one example, the aircraft can be placed by a human operator in a direction with a clear path ahead. A clear path should meet certain requirements such as being obstacle free, sufficiently flat, and with a minimal taxi distance suitable for takeoff. The operator can survey the takeoff surface and surrounding area and position the aircraft on the takeoff surface with its nose pointing in the most suitable direction for takeoff.

According to another example, the system can be configured to operate in an autonomous mode for determining a suitable takeoff direction. Range data obtained from a range finder device can be used for determining if an appropriate distance required for takeoff exists ahead of the aircraft. To this end system **100** can comprise for example an autonomous takeoff direction selection unit **201** operatively connected to a range finder device such as a LIDAR, RADAR or image sensor. In some examples range finder device is located onboard aircraft **101** while in other examples it can be located elsewhere in the vicinity of the aircraft. Autonomous takeoff direction selection unit **201** can be configured to obtain range data from the range finder device and use this data to determine whether the range ahead of the aircraft meets the minimal distance requirements for takeoff.

For example, an operator can place the aircraft on the takeoff surface and once the takeoff process begins the range finder device, possibly in conjunction with the data

obtained by other sensors, provides information to computer 103 which in turn determines, based on the received data, whether the distance and surface ahead is suitable for takeoff.

If an unobstructed path ahead is not found, the takeoff process can be aborted and/or an alert can be generated indicating to the operator that the aircraft should be repositioned. Alternatively or additionally, computer 103 can be configured to generate instructions for controlling the aircraft to turn (e.g. by operating the rudder and/or wheels) and face a different direction and start over the process until a path which is suitable for takeoff is found.

According to another example, an azimuth value of a desired takeoff direction can be provided to computer 103 and the pointing direction of the aircraft can be set according to the provided azimuth. This can be done either manually by an operator or autonomously (e.g. by instructions generated by computer 103 as described above) directed for maneuvering the aircraft to turn and point in the provided azimuth.

Notably, according to some examples, the takeoff process can be aborted at any time in case an obstacle which obstructs the progression course of the aircraft is detected. A range finder device can be continuously operated during the takeoff process in order to search for obstacles in front of the aircraft and enable the computer to generate instructions for aborting the takeoff if an obstacle or some other hazard is detected. Alternatively or additionally, computer 103 can be configured to generate steering commands for directing the aircraft around the obstacle and continue with the takeoff process once the obstacle is circumvented.

Once the takeoff direction is determined, the specific direction is set as the heading at the initial time T_0 (referred to herein as "intended takeoff direction") and recorded in computer memory (e.g. stored in data-storage 105).

Calculations of deviation of the aircraft's heading during takeoff are made relative to the intended takeoff direction. According to some examples, in case the absolute azimuth value of the intended takeoff direction is known, deviations of the heading from the azimuth value can be calculated (e.g. by an onboard magnetic compass or dual antenna GPS compass or some other DF) relative to the absolute azimuth value.

According to other examples, where an absolute azimuth value of the intended takeoff direction is not used, the intended takeoff direction is pre-set as an initial (relative) heading (e.g. as point (0,0)) and deviations are determined relative to the pre-set heading.

The aircraft starts to proceed along the takeoff surface in the intended takeoff direction (Block 303) and to collect (including sensing and calculating) runway data (Block 405 and 407). Execution of the pointing direction processing cycle $d\psi$ is also initiated (Block 307).

Computer 103 can optionally be further configured to obtain from onboard sensors (e.g. from an onboard gyroscope or INS) real-time data (including for example, angular rates and linear accelerations) indicative as to whether the surface is sufficiently flat and use this data for determining whether takeoff should be allowed. This can be any time during takeoff including the initial as well as the final stages of the takeoff process.

In some examples, During the initial stages of the aircraft's progress, before sufficient points are sampled and the first instance of the runway path is available, only the pointing direction processing cycle $d\psi$ is used for maintaining the aircraft's heading aligned with the intended takeoff direction (Block 413). In the pointing direction processing cycle $d\psi$, the aircraft's actual heading is repeatedly determined and compared to the intended takeoff direction. If a deviation between the pointing direction measured in real-time and the intended takeoff direction is found (e.g. a difference which is greater than a certain threshold value), steering commands are generated (and provided to ACU 102) for compensating for the deviation and adapting the aircraft's heading according to the intended takeoff direction. Pointing direction processing cycle $d\psi$ can be executed for example, by pointing direction processing unit 221 in computer 103.

Various methods can be used for identifying deviations in the aircraft's heading. These methods depend, *inter alia*, on the type of sensor which is used.

- If an absolute azimuth value of the intended takeoff direction is available, a device such as a compass or dual antenna GPS can be used for determining the direction of the aircraft relative to the intended takeoff direction.

If an absolute azimuth value of the intended takeoff direction is not available according to some examples, the following techniques can be used:

- inertial measurements can be used. Yaw measurements integration can be executed to obtain yaw and thus the deviation relative to the pre-set pointing direction. To this end, system **100** can comprise an INS operatively connected to computer **103**. Notably, although yaw integration calculations are known to suffer from integration drift, this technique can be used where the takeoff time is short (in some examples between 10 to 15 seconds), and accordingly the drift does not raise a significant problem.

- Two odometers can be fixed to two side wheels, each to a different wheel, for measuring the ground distance travelled by the respective wheel. As each odometer calculates ground distance of the respective wheel separately, differences between the travelled distance of the two wheels can be indicative of a deviation of the aircraft from the intended takeoff direction. Based on the calculated travelled difference between the wheels, appropriate commands can be generated for steering the aircraft back to the desired direction. For example, computer **103** can be operatively connected to two odometers, each attached to a respective side wheel and receive data therefrom, and be configured to calculate the current heading of the aircraft as well as deviations of the current heading from the intended takeoff direction.

- As mentioned above, an external reference point (and possibly more than one) is identified in the vicinity of the runway surface, and the respective position (including range and angle) of sampled points is determined relative to the reference point. Computer **103** can be operatively connected to a range finder device and be configured to calculate differences in the relative position between points sampled at different times along the progression course of the aircraft (e.g. by triangulation), and thereby determine the aircraft's heading and thus deviations from the intended takeoff direction.

The autonomous takeoff process is schematically illustrated in Fig. 5. Fig. 5a shows the initial stages of the takeoff process before the first instance of the runway path has been

generated. The broken line (42) is a straight line representing the intended takeoff direction. Once the intended takeoff direction is set, the aircraft (101) begins to move on the takeoff surface in the intended takeoff direction and to sample points. The trace of sampled points (schematically represented by black dots 40 in fig. 5) indicates the actual progression course of the aircraft. Since the runway path has not yet been generated, control over the aircraft for maintaining its heading according to the intended takeoff direction is based on calculations executed by the pointing direction processing cycle Ψ .

Sampling (Block 405) which is executed as part of the calculation of the RT-RP includes the determination of the position of the aircraft along its progression course at a plurality of points P_n (each point P_i represents the relative position of the aircraft at a certain time T_i), where the position is determined relative to at least one reference point. The relative position can be defined for example, based on distance and direction between the aircraft and the reference point. As mentioned above, the reference point can be an external reference point or a self (internal) reference point.

According to one example, sampling is performed by sampling unit 202 in computer 103 operating in conjunction with one or more sensors which provide data indicative of the position of the aircraft relative to one or more reference points. According to one example, sampling frequency is equal or greater is than 5 sampled points per second.

As more points are accumulated along the aircraft's progression course, the runway path is generated (Block 407). According to one example, the runway path is represented by a line generated by implementing regression analysis for drawing a straight line through the collection of sampled points (e.g. by implementing linear regression or least squares or some other regression analysis method). This calculation is done in real-time as the aircraft moves forward on the runway surface. Generation of the runway path can be initiated, for example, once a predefined number of points have been sampled or once the aircraft has traversed a certain distance. Regression analysis for generating the runway path can be executed for example by RT-RP processing unit 223 in computer 103.

Part or all of the runway path data is stored in a computer data-storage device (block 315). The runway path data includes for example the group of sampled points (each point is

defined by its relative position and possibly also by a time stamp) and a sub-group of sampled points which are connected by a line constituting the runway path.

Fig. 5b schematically illustrates the generation of the runway path (44). As can be noted from the illustration, the runway path is generated primarily based on previously sampled points located behind the aircraft. The part of the runway path ahead of the aircraft is an extension of the calculated line 44 located at the back of the aircraft.

Once the first instance of the runway path is available (Block 409) the runway path processing cycle d_y is initiated (Block 309). As mentioned above, in the runway path processing cycle d_y , deviations of the aircraft from the calculated runway path are determined. These operations can be performed for example by RT-RP processing unit 223 in computer 103.

Deviation of the aircraft progression course from the runway path can be determined based on the current position and heading of the aircraft. Aircraft position relative to the generated runway path can be determined for example based on position of previously sampled points, which are part of the generated runway path and the position of one or more currently sampled points (relative to the reference point), representing the current position of the aircraft.

For the purpose of calculating the steering commands required for compensating for a deviation of the aircraft from the runway path, the velocity of the aircraft at the current position is also determined. The speed component is used for determining the rate of deviation from the runway path (or alternatively rate of convergence with the runway path). Compensating maneuvering commands are generated based on the current position of the aircraft, the current aircraft's heading (angle relative to runway path) and the rate of deviation. This is further exemplified with reference to fig. 7b below.

As described above, various techniques can be used for calculating heading. Some of these techniques provide sufficient data for calculating relative position of the aircraft as well as speed which are required for determining deviation of the aircraft from the runway path, while other techniques can be combined in order to enable this calculation.

In case self-reference points are used, any one of the following examples of devices (or combination of devices) can be used for calculating heading, speed and distance from runway path:

GPS device and/or an inertial measurement system (e.g. INS);

Two odometers or an odometer coupled to a DF of any type.

A range determination device (e.g. laser, LIDAR, RADAR, image sensor) can be configured to determine changes in the range between the aircraft and an external reference point. These changes can be used for calculating distance from runway path as well as speed. A DF of any type can be operated for providing the heading of the aircraft.

An airspeed sensor (e.g. an onboard pitot tube) can be used to calculate airspeed. The aircraft's speed can be calculated using airspeed minus wind speed normalize to International Standard Atmosphere (ISA) conditions, which can be measured or provided from an external source. Integration implemented on the calculated speed can provide positioning data which enables to determine distance from runway path.

Reverting to Fig. 5, Fig. 5c and 5d schematically illustrate more advanced stages of the autonomous takeoff. It can be noted that as the runway path generation process advances the progression course of the aircraft (indicated by the black dots 40) increasingly converges with the calculated runway path 44.

Fig. 6 is a schematic illustration demonstrating different deviations scenarios. Fig. 6a shows a scenario where there is no deviation between the aircraft's heading and the intended takeoff direction and there is also no deviation (or divergence) between the progression course of the aircraft and the generated runway path 44 (distance between aircraft 101 and runway path 44 is zero and angle between aircraft's heading and intended takeoff direction is zero).

Fig. 6b shows a scenario where there is a deviation between the aircraft's heading and the intended takeoff direction and there is also a deviation (or divergence) between the progression course of the aircraft and the generated runway path 44 (distance between aircraft 101 and runway path 44 is greater than zero and angle between aircraft's heading

and intended takeoff direction is greater than zero). The distance between the runway path and the aircraft is indicated by arrow **46**, which, as mentioned above, the distance can be calculated based on the difference between relative position of previously sampled points which are part of the runway path and currently sampled points.

Fig. **6c** shows a scenario where there is no deviation between the aircraft's heading and the intended takeoff direction but there is a deviation (or divergence) between the progression course of the aircraft and the generated runway path **44** (distance between aircraft **101** and runway path **44** is greater than zero and angle between aircraft's heading and intended takeoff direction is zero).

Fig. **6d** shows a scenario where there is a deviation between the aircraft's heading and the intended takeoff direction but there is no deviation (or divergence) between the progression course of the aircraft and the generated runway path **44** (distance between aircraft **101** and runway path **44** is zero and angle between aircraft's heading and intended takeoff direction is greater than zero).

Notably, deviation in either one of the processing cycles can be determined based on a difference which is greater than a predefined threshold, which may be in some cases larger than zero.

The output of the pointing direction processing cycle **dw** and the output of the runway path processing cycle, are integrated (Block **311**). If the integrated output of the two processing cycles shows that the aircraft has deviated from the intended takeoff direction and/or from the runway path, steering commands are generated, in order to correct the aircraft's heading and/or location with respect to the runway path (block **313**).

Steering commands can be generated for example by integration unit **225**. The generated instructions can be provided for example to ACU **102** which controls various control devices such as rudder, wheels, throttle, for obtaining the desired steering.

The runway path is repeatedly calculated as the aircraft advances along the takeoff surface. As more sampled points are accumulated, each calculation is made based on a larger collection of sampled points. The increasing number of points collected over time reduces

the effect of outlier points (resulting for example from measurement errors) since outlier points are averaged out in the regression analysis calculation.

Fig. 7a shows a graph demonstrating possible relation between the weight which is given to each one of the processing cycles in the integrated calculation and the amount of collected runway path data. As seen in the graph, initially, when the number of sampled points is below a threshold and the first instance of the runway path has not been generated, all weight is given to the runway path processing cycle d_y (solid line) and no weight is given to the pointing direction processing cycle d_ψ (broken line). As the process of runway path generation progresses and more points are sampled, the weight of the direction processing cycle d_ψ decreases and the weight of the runway path processing cycle d_y increases. This trend continues as newer instances of the runway path are generated, each time based on a greater number of sampled points. According to some examples, at some point the contribution of the two processing cycles becomes the same.

Fig. 7b is a schematic illustration demonstrating a numerical example of the integration logic for integrating the two processing cycles during generation of steering commands. Notably, the example provided with reference to fig. 7b is a simplified and non-limiting example and should not be construed as limiting or binding in any way.

As shown, input data in pointing direction processing cycle d_ψ includes Ψ error (i.e. difference between intended takeoff direction and actual heading of aircraft), which in this example equals 10° , and $\dot{\Psi}$ error (which is the derivative of Ψ error; i.e. rate of change of Ψ error) which in this example equals 0 i.e. the heading of the aircraft is currently unchanging.

Input in the runway path processing cycle d_y includes d_y (i.e. distance of aircraft from RT-RP) and $\dot{d}_y$. $\dot{d}_y$ gives the rate of divergence from the RT-RP and can be calculated based on the speed of the aircraft and the deviation angle (Ψ error) mathematically represented by: $V \sin^* \Psi$ error. In the current example $\dot{d}_y$ equals:

$$10 \cdot \sin(10^\circ) = 1.73 \text{ meter/second.}$$

It can be noted that the amplification coefficient of the dy and dy dot have a 1:3 ratio. This is so since this ratio provides a desired convergence angle of the aircraft back to the runway path, one which is not too sharp (which may cause crossing the runway path to the other side) but also enables converges of the aircraft with the line fast enough to allow safe takeoff.

The output from the pointing direction processing cycle $d\psi$ contribute a heading error of -10 and the output from the runway path processing cycle dy contributes positioning error of 3.28. The integrated output is therefore -6.72. The steering commands are generated based on the integrated output, in the current example 6.72° to the right to compensate for the resulting integrated error. Notably, the operator signs are based on the predefined setting of the coordinate system e.g. right of runway path are positive dy values and left of the runway path are negative dy values. In other examples, signs can be reversed.

Reverting to Fig. 4, Block 415 refers to the determination as to whether or not the generation of the runway path has been completed and the aircraft can proceed to takeoff. Thus, before takeoff is authorized, sufficient convergence between the progression course of the aircraft and the generated runway path is determined. In addition, as mentioned above, other takeoff requirement (e.g. taxiing speed and runway pitch) are checked before authorizing takeoff (e.g. by takeoff control unit 206).

If all requirements for takeoff are met, takeoff sequence is initiated and the aircraft takes off the runway surface (block 417). Takeoff sequence includes operations needed for takeoff as are well known in the art, including for example, acceleration, controlling flaps, engine control, etc. Takeoff can be executed for example by takeoff control unit 206.

In some cases, if it is determined that the runway path is not completed, the process continues to sample more points for enhancing the runway path (block 405) and/or fixing the aircraft's heading (block 307).

After takeoff the generated runway path (which has been stored in data-storage unit 105) can be used for autonomous landing. For purpose of landing, the aircraft needs information of part or all of the runway path (including the relative position of the points) and information identifying the position of the reference point(s) used for generating the

runway path. During landing the aircraft flies to some point along the runway path, which can be either the beginning of the runway path or some other point that leaves sufficient distance for landing. Once the aircraft reaches an appropriate point in the air above the runway path, execution of an autonomous landing sequence is initiated, where the runway path serves as a landing strip. Once the location of the reference point is identified, the location of the runway path can be identified based on the position of the points constituting the runway path determined relative to the reference point.

Fig. 8 is a flowchart showing a sequence of operations executed for enabling autonomous landing, according to an example of the presently disclosed subject matter.

As the aircraft travels in the air following takeoff, system **100** continues to keep track of the aircraft's position relative to the reference point. To this end, points continue to be sampled (block **801**) i.e. the position of the aircraft at different points relative to one or more reference points, is determined (e.g. by airborne tracking unit **209** in computer **103** in conjunction with an appropriate positioning device). This information continues to be stored in data storage unit (block **803**) and thus allows to preserve the position of the aircraft relative to the reference point throughout the flight.

When it is desired to land the aircraft, the aircraft uses the stored information in order to find the runway and determine the location of a touchdown point along the runway path (block **805**). The touchdown point is selected to provide sufficient taxi distance for landing. The aircraft can then return and land using the same runway path which was used for takeoff. For example, landing control unit **411** can be configured to generate maneuvering instructions for positioning the aircraft in the right place (e.g. a landing window above the runway path) for descending and landing at a touchdown point, wherein the landing window is selected to enable the aircraft to descend and reach the touchdown point. Once at the correct position, landing control unit **411** can initiate a landing sequence comprising instructions to the flight controlling device for landing the aircraft (block **807**).

In the event that the reference point has been lost (the position of the aircraft relative to the reference point is not available for some reason) system **100** can search for the reference point, and, once found, use the stored runway path for landing. For example,

computer 103 can be configured to execute dead reckoning for locating the reference point, as well known in the art.

According to other examples, where a self-reference point is used, an inertial navigation system can be used for maintaining the relative position of the aircraft during short flights, which do not introduce significant drift. In case a self-reference point is generated by a GPS, the aircraft can return to the runway point according to the GPS coordinates.

Claims:

1. A computer-implemented method of autonomous takeoff of an aircraft from a runway surface; the method comprising:
operating a computer system while the aircraft is proceeding on the runway surface towards takeoff for executing at least the following:
 - i. obtaining current heading of the aircraft and calculating a first output including data related to deviation of current heading from an intended takeoff direction;
 - ii. determining respective position, relative to at least one reference point, of each of a collection of points sampled along the aircraft progression course;
generating a runway path, based on the collection of points;
calculating a second output including data related to deviations of progression course of the aircraft from the runway path;
 - iii. integrating the first output and second output and generating integrated data output; and
generating, based on the integrated data output, steering commands for steering the aircraft for correcting the aircraft's progression course in order to compensate for deviation in the heading of the aircraft and/or deviation of the progression course of the aircraft;repeating each one of operations i to iii;
executing takeoff sequence once the runway path is ready for takeoff.
2. The method of claim 1 wherein generating the runway path, comprises:
repeatedly sampling new points as the aircraft proceeds along the takeoff surface to thereby repeatedly obtain an updated collection of sampled points; and
calculating updated instances of the runway path based on a recently updated collection of points.
3. The method of any one of the preceding claims, wherein calculating a second

output comprises:

calculating current position of the aircraft relative to the runway path; calculating current speed of aircraft; and

determining deviation rate of aircraft relative to runway path based on speed and heading.

4. The method of any one of the preceding claims, wherein the generating of the runway path comprises implementing a regression analysis on the collection of points.

5. The method of any one of the preceding claims wherein the integrating comprises:

assigning a respective weight to each one of the first output and second output, wherein each weight defines the contribution of the respective output to the integrated data output; and

adapting the weight according to progress of the runway path generation.

6. The method of any one of the preceding claims wherein the absolute position of the collection of points is unknown.

7. The method of any one of the preceding claims wherein the at least one reference point is an external reference point located externally to the aircraft.

8. The method of any one of the preceding claims wherein the at least one reference point is a self-reference point representing self-position of the aircraft at some point in time.

9. The method of any one of the preceding claims further comprising scanning the runway surface in front of the aircraft during takeoff and detecting obstacles.

10. The method of claim 9 further comprising aborting or circumventing an obstacle detected on the runway surface obstructing the runway path.

11. The method of any one of the preceding claims further comprising executing an autonomous landing process, comprising:

while in the air, repeatedly determining position of aircraft relative to the at

least one reference point;

extracting runway path data from the data-storage device, wherein runway path data includes the position of sampled points constituting the runway path relative to the at least one reference point;

maneuvering the aircraft to a point above the runway path;

landing on the runway according to runway path data.

12. The method of any one of the preceding claims further comprising autonomously determining a reference point, comprising: operating a range finder device for identifying a suitable object to serve as a reference point in the vicinity of the runway surface.

13. A system for enabling autonomous takeoff of an aircraft from a runway surface, the system comprising a computer device operatively connected to a direction finder device, and a positioning device; the system is configured, while the aircraft is proceeding on the runway surface towards takeoff, to execute at least the following:

- i. operate the direction finder device to determine current heading of the aircraft;

operate the computer device to calculate a first output including data related to deviation of the current heading of the aircraft from an intended takeoff direction;

- ii. operate the positioning device to determine respective position, relative to at least one reference point, of each of a collection of points sampled along the aircraft progression course;

operate the computer device to:

generate a runway path, based on the collection of points; and

calculate a second output including data related to deviations of progression course of the aircraft from the runway path;

operate the computer device to:

integrate the first output and second output and generate integrated data output; and

- iii. generate, based on the integrated data output, steering commands for steering the aircraft and correcting the aircraft's progression course in order to compensate for deviation in the heading of the aircraft and/or deviation of the progression course of the aircraft;

repeat each one of operations i to iii;

execute takeoff sequence once the runway path is ready for takeoff.

14. The system of claim 13 wherein the computer device is configured for generating the runway path, to:

repeatedly sample new points as the aircraft proceeds along the takeoff surface to thereby repeatedly obtain an updated collection of sampled points; and

calculate updated instances of the runway path based on a recently updated collection of points.

15. The system of any one of claims 13-14, wherein the computer device is configured for calculating a second output, to:

calculate current position of the aircraft relative to the runway path; calculate current speed of aircraft; and

determine deviation rate of aircraft relative to runway path based on speed and heading.

16. The system of any one of claims 13-15, wherein the computer device is configured, for generating of the runway path, to implement a regression analysis on the collection of points.

17. The system of any one of claims 13-16, wherein the computer device is configured for executing the integrating, to:

assign a respective weight to each one of the first output and second output, wherein

each weight defines the contribution of the respective output to the integrated data output;
and

adapt the weight according to progress of the runway path generation.

18. The system of any one of claims 13-17, wherein the absolute position of the collection of points is unknown.

19. The system of any one of claims 13-18, wherein the at least one reference point is an external reference point located externally to the aircraft.

20. The system of any one of claims 13-18, wherein the at least one reference point is a self-reference point representing self-position of the aircraft at some point in time.

21. The system of any one of claims 13-20 is further configured to execute an autonomous landing process, comprising:

while in the air, operating a position device for repeatedly determining position of aircraft relative to the at least one reference point;

extracting runway path data from the data-storage device, wherein runway path data includes the position of sampled points constituting the runway path relative to the at least one reference point;

controlling a flight subsystem for maneuvering the aircraft to a point above the runway path;

landing on the runway according to runway path data.

22. The system of any one of claims 13-21 comprises a range finder device and wherein the computer device is further configured for autonomously determining a reference point, to:

operate the range finder device to scan an area surrounding the aircraft to obtain scanning output data;

operate the computer device to process the scanning output data and identify a reference point suitable for runway path generation.

23. The system of any one of claims 13-22 comprises a range finder device and

wherein the computer device is further configured for autonomously determining the intended takeoff direction, to:

operate the range finder device to scan an area surrounding the aircraft to obtain scanning output data;

operate the computer device to process the scanning output data and determine a direction suitable for takeoff; and

set the direction suitable for takeoff as the intended takeoff direction.

24. The system of any one of claims 13-23 comprises two odometers, each fixed to a respective side wheel of the aircraft; and wherein the positioning device and direction finding device are implemented by the two odometers.

25. The system of any one of claims 13-23 comprises one odometer, fixed to a wheel of the aircraft; the positioning device is implemented by the odometer and the direction finding device.

26. The system of any one of claims 13-23 wherein the positioning device is any one of: GPS; INS; and range finder device.

27. The system of claim 26 wherein the direction finding device is any one of: GPS; INS; and range finder device.

28. The system of any one of claims 13-27 is loaded on the aircraft.

29. The system of claim 28, wherein the aircraft is a UAV.

30. An aircraft comprising the system according to any one of claims 13-27.

31. A non-transitory program storage device readable by a computer, tangibly embodying a computer readable instructions executable by the computer to perform a computer-implemented method of autonomous takeoff of an aircraft from a runway surface; the method comprising:

operating a computer system while the aircraft is proceeding on the runway surface towards takeoff for executing at least the following:

i. obtaining current heading of the aircraft and calculating a first output

including data related to deviation of current heading from an intended takeoff direction;

- ii. determining respective position, relative to at least one reference point, of each of a collection of points sampled along the aircraft progression course;

generating a runway path, based on the collection of points;

calculating a second output including data related to deviations of progression course of the aircraft from the runway path;

- iii. integrating the first output and second output and generating integrated data output; and

generating, based on the integrated data output, steering commands for steering the aircraft for correcting the aircraft's progression course in order to compensate for deviation in the heading of the aircraft and/or deviation of the progression course of the aircraft;

repeating each one of operations i to iii;

executing takeoff sequence once the runway path is ready for takeoff.

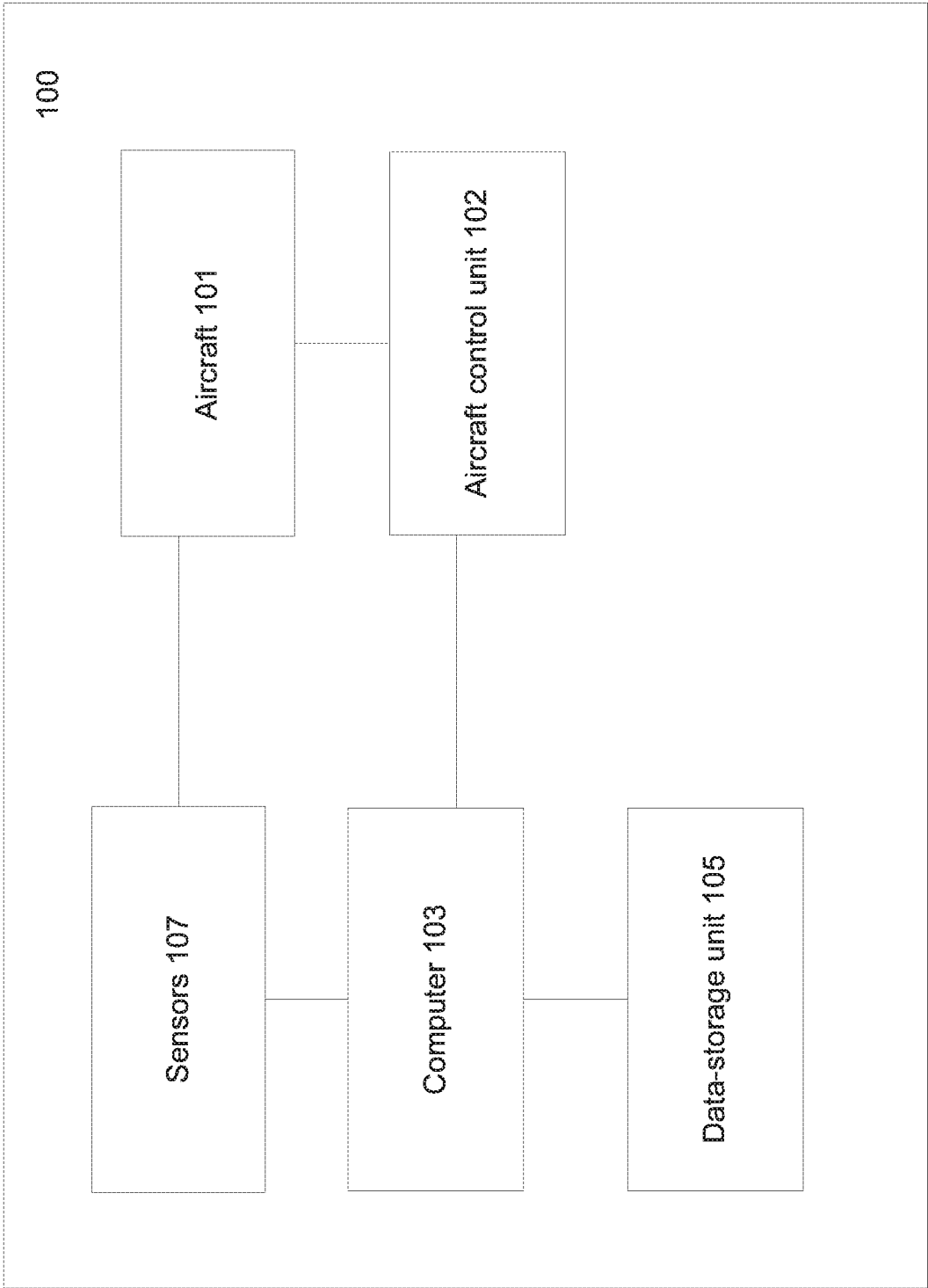


Fig. 1

2/9

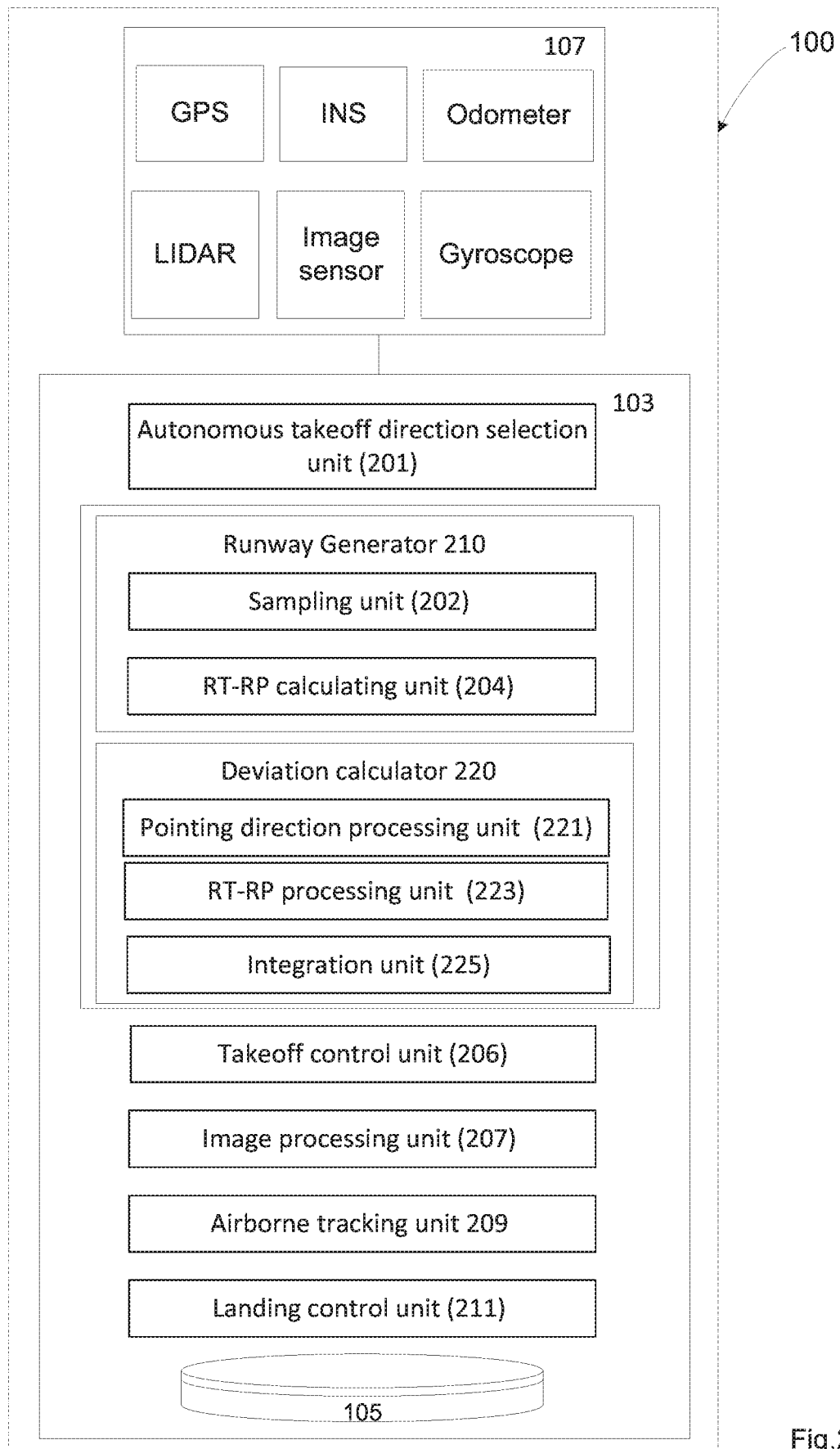


Fig.2

3/9

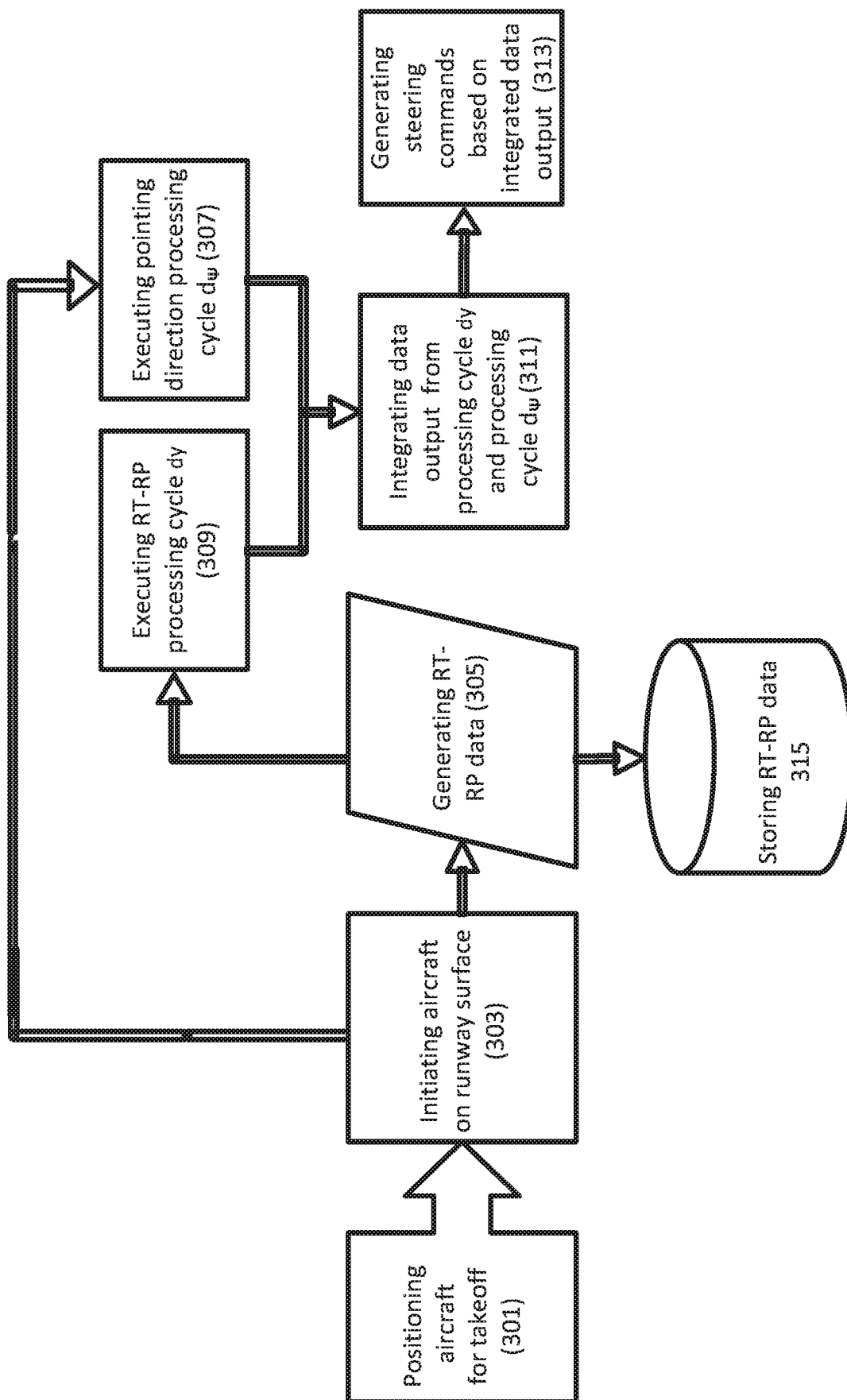


Fig. 3

4/9

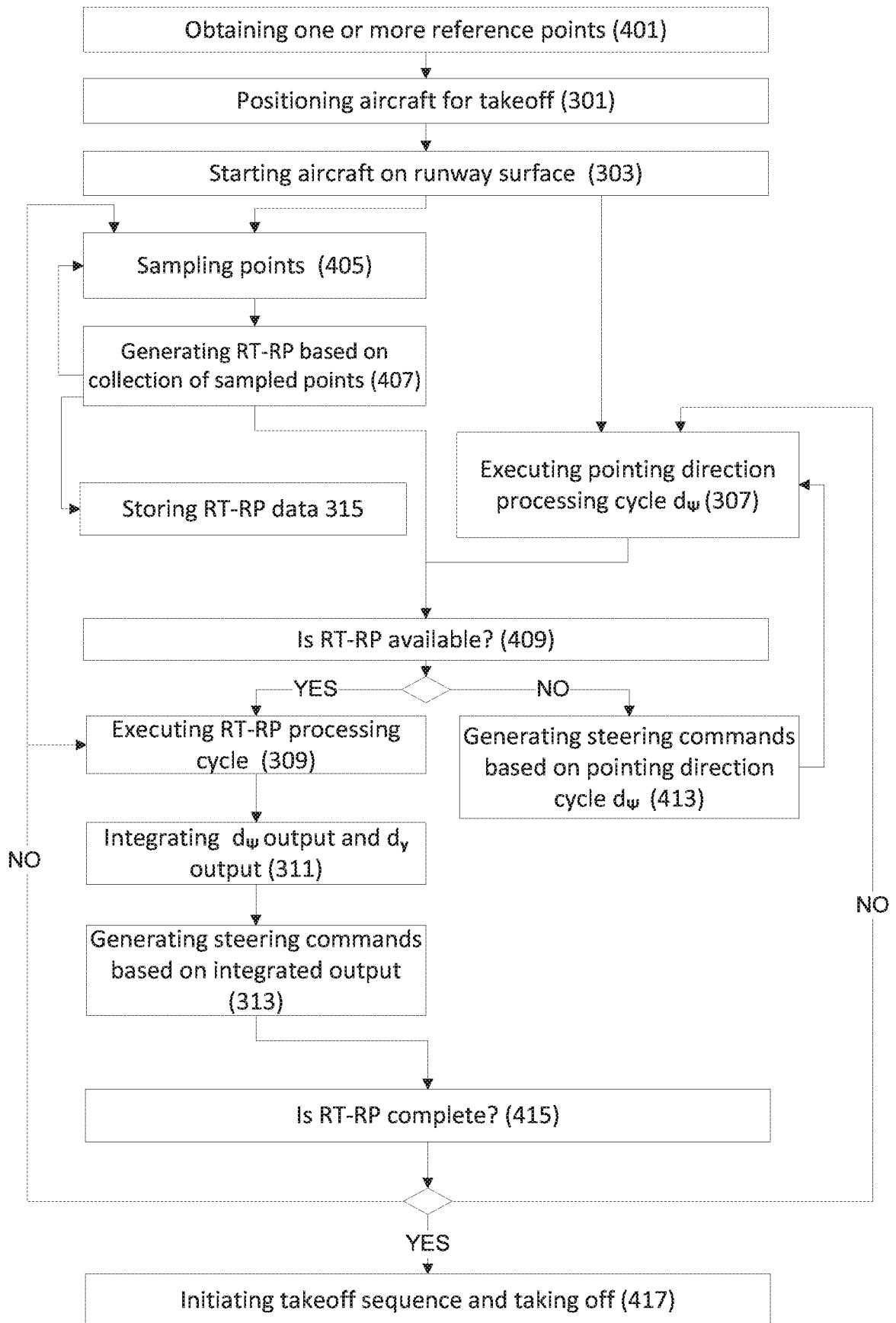


Fig. 4

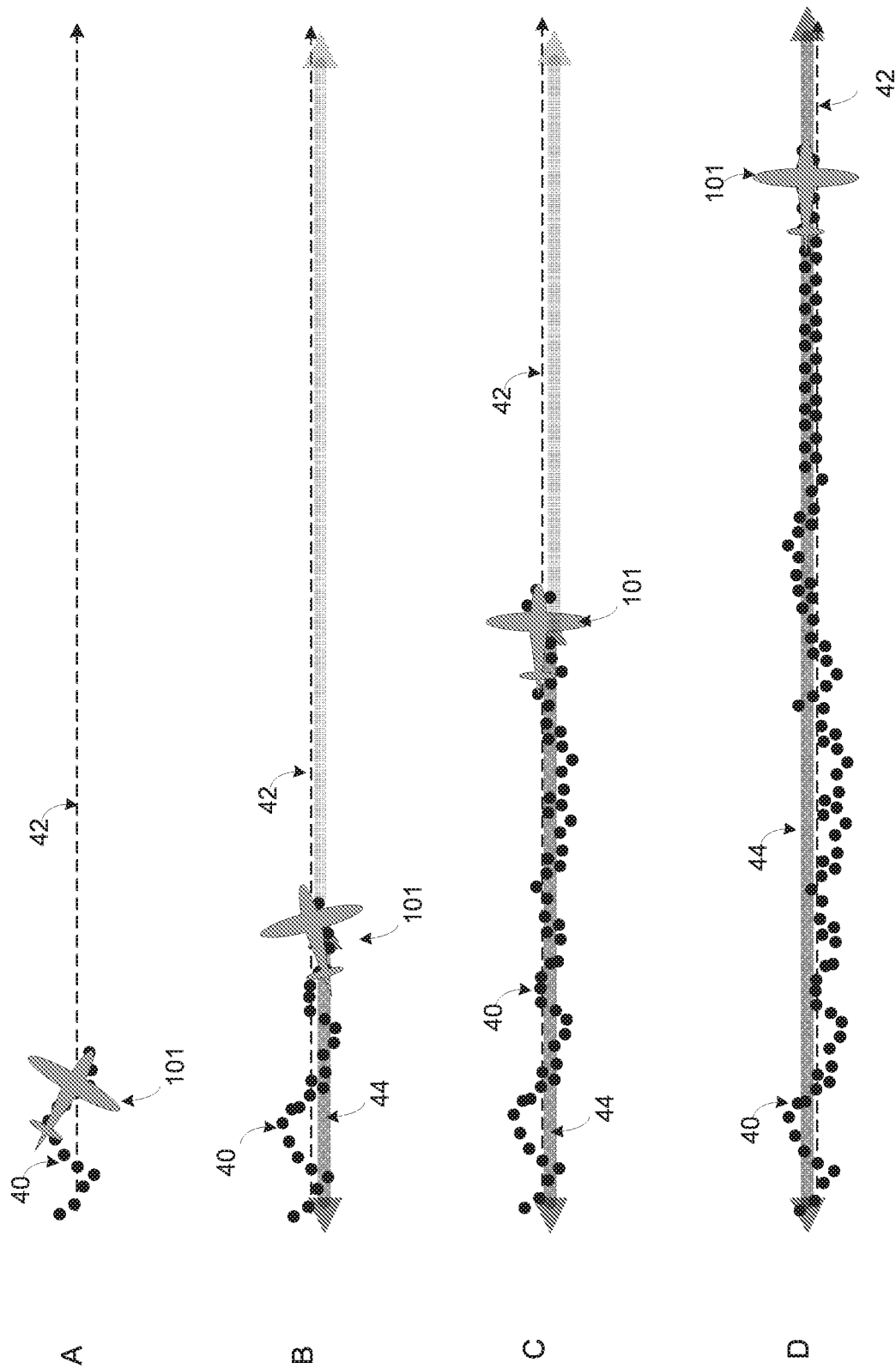


Fig. 5

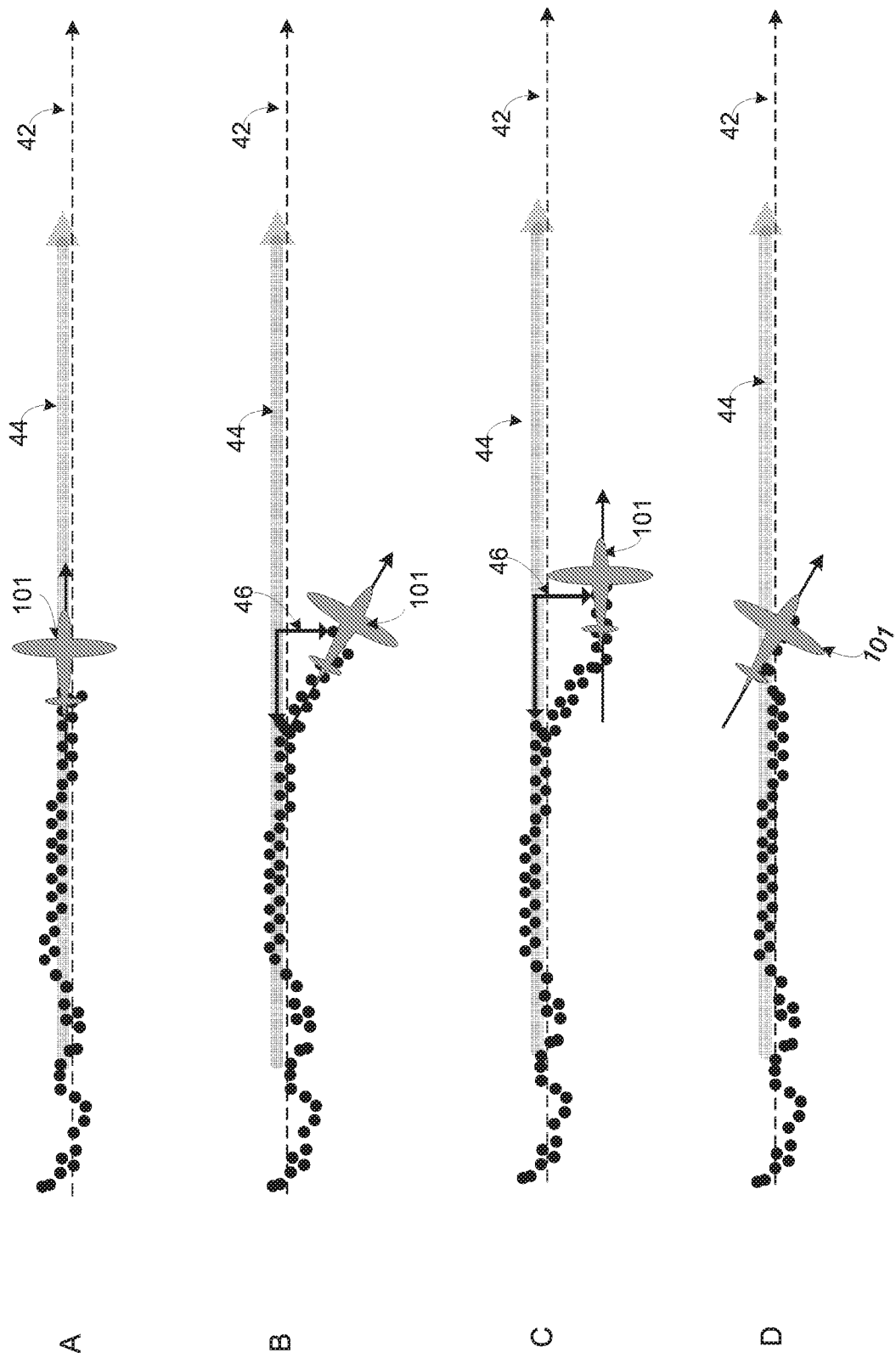


Fig. 6

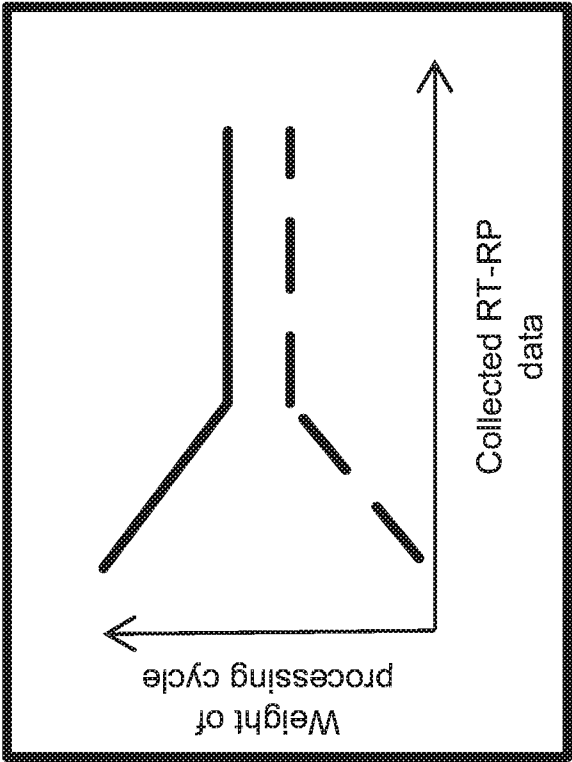


Fig. 7a

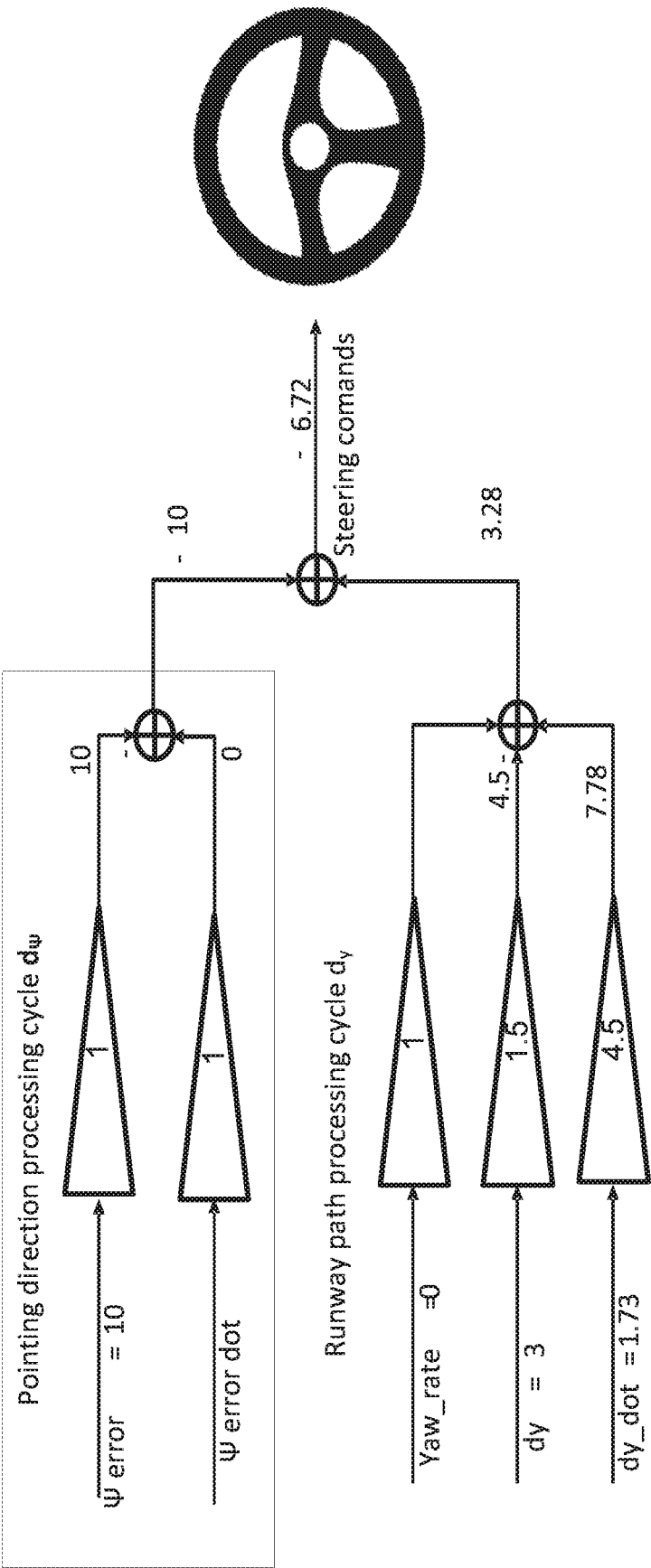


Fig. 7b

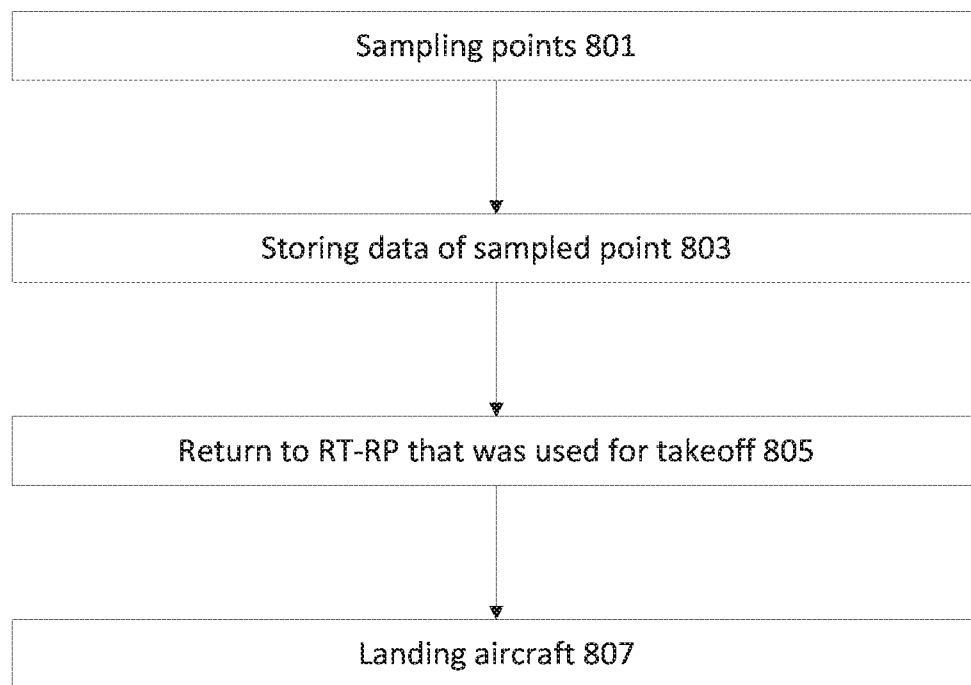


Fig. 8

INTERNATIONAL SEARCH REPORT

International application No.

PCT/IL2017/051340

A. CLASSIFICATION OF SUBJECT MATTER IPC (2018.01) G08G 5/06, G05D 1/02 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) IPC (2018.01) G08G 5/06, G05D 1/02 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) Databases consulted: Esp@cenet, Google Patents, Orbit Search terms used: autonomous, takeoff, runway, heading, position, deviation, correction		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2015142220 A1 Scacchi 21 May 2015 (2015/05/21) entire document	1-31
A	US 2015294573 A1 Conner et al. 15 Oct 2015 (2015/10/15) entire document	1-31
A	US 9132912 B2 Griffith et al. 15 Sep 2015 (2015/09/15) entire document	1-31
A	US 2006214063 A1 Firuz et al. 28 Sep 2006 (2006/09/28) entire document	1-31
A	US 8560149 B1 Ganguli et al. 15 Oct 2013 (2013/10/15) entire document	1-31
☐ Further documents are listed in the continuation of Box C. ☒ 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 "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "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 25 Mar 2018		Date of mailing of the international search report 25 Mar 2018
Name and mailing address of the ISA: Israel Patent Office Technology Park, Bldg.5, Malcha, Jerusalem, 9695101, Israel Facsimile No. 972-2-5651616		Authorized officer ROASH Yoaela Telephone No. 972-2-5657807

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/IL2017/051340

Patent document cited search report	Publication date	Patent family member(s)	Publication Date
US 2015142220 A1	21 May 2015	NONE	
US 2015294573 A1	15 Oct 2015	NONE	
US 9132912 B2	15 Sep 2015	NONE	
US 2006214063 A1	28 Sep 2006	NONE	
US 8560149 B1	15 Oct 2013	NONE	