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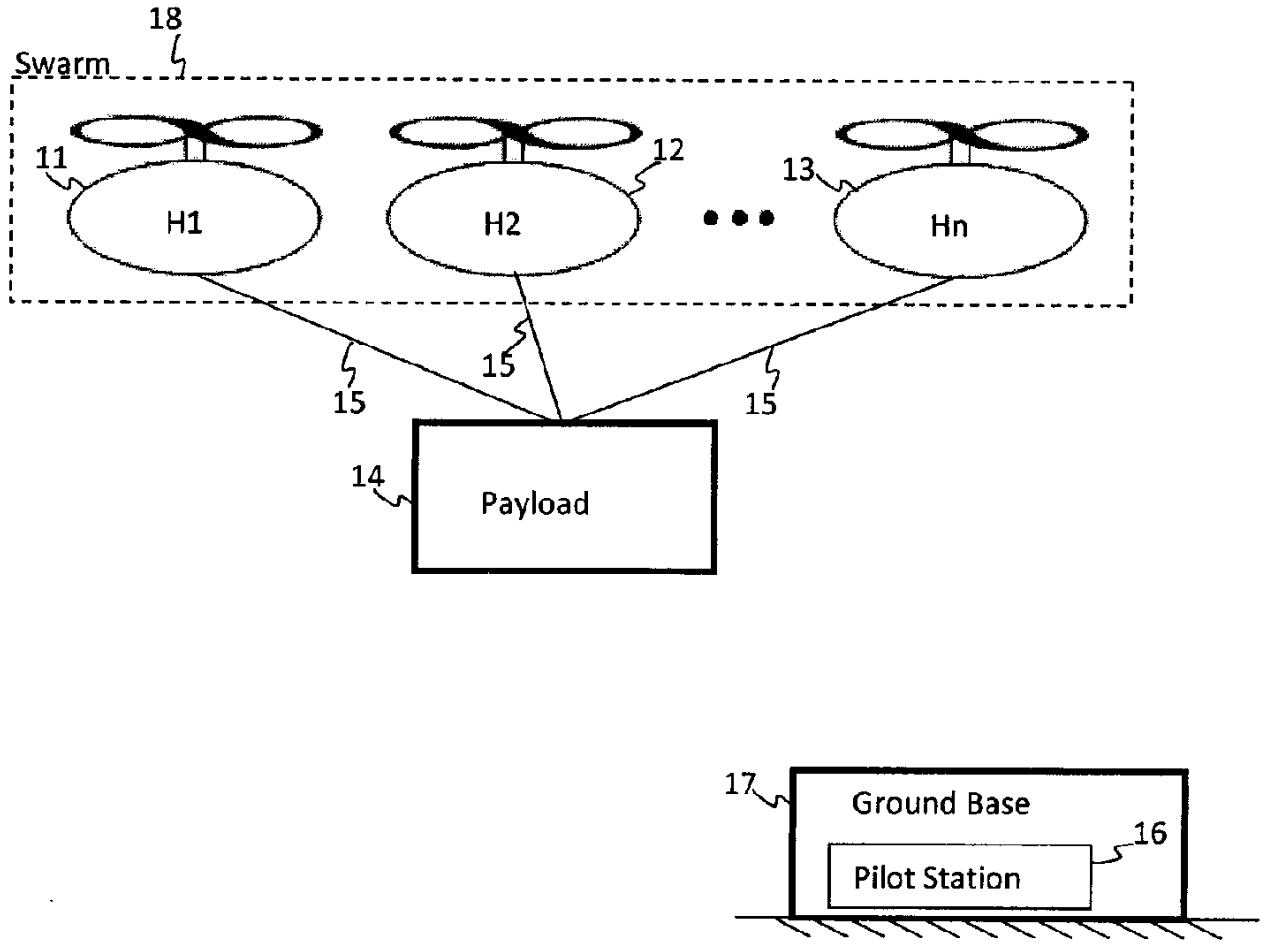


(57) **Abrégé/Abstract:**

A system and method are provided for controlling a plurality of aircraft to lift a common payload. The system comprises of multiple aircraft tethered to a common payload, where the group of said aircraft form a swarm that is controlled by a pilot station. Each said aircraft is autonomously stabilized and guided through a swarm avionics unit, which further comprises of sensor, communication, and processing hardware. At the said pilot station, a pilot remotely enters payload destinations, which is processed and communicated to each said aircraft. The method for controlling a multi-aircraft lifting system comprises of first inputting the desired location of the payload, and then determining a series of intermediary payload waypoints. Next, these payload waypoints are used by the swarm waypoint controller to generate individual waypoints for each aircraft; a flight controller for each aircraft moves the aircraft to these individual waypoints.

ABSTRACT

A system and method are provided for controlling a plurality of aircraft to lift a common payload. The system comprises of multiple aircraft tethered to a common payload, where the group of said aircraft form a swarm that is controlled by a pilot station. Each said aircraft is autonomously stabilized and guided through a swarm avionics unit, which further comprises of sensor, communication, and processing hardware. At the said pilot station, a pilot remotely enters payload destinations, which is processed and communicated to each said aircraft. The method for controlling a multi-aircraft lifting system comprises of first inputting the desired location of the payload, and then determining a series of intermediary payload waypoints. Next, these payload waypoints are used by the swarm waypoint controller to generate individual waypoints for each aircraft; a flight controller for each aircraft moves the aircraft to these individual waypoints.

SYSTEM AND METHOD FOR MULTIPLE AIRCRAFT LIFTING A COMMON PAYLOAD

FIELD OF TECHNOLOGY

[0001] The invention relates in general to autonomous control systems of aircraft, and, more particularly, to multi-aircraft lifting control systems.

DESCRIPTION OF THE PRIOR ART

[0002] Aircraft, for example helicopters and airships, that are able to perform unique maneuvers such as taking off and landing vertically or hovering in one area have many industrial and commercial applications; they are used as air ambulances, aerial cranes, and military vehicles. These aircraft are also used to transport heavy payloads to locations that are difficult or impossible to reach by ground transportation and other aircraft. The lifting capacity of an individual aircraft approaches limitations asymptotically because lifting a heavier payload requires stronger support mechanisms, larger engines, more fuel, and a larger aircraft overall. The aircraft's weight therefore increases in proportion to the weight that it is to lift. Further, constructing, maintaining and storing large aircraft becomes difficult because of size, for example in extremely large airships. Despite improving load capacities, there is still an ongoing demand to transport much greater loads in both the commercial and military sectors.

[0003] One way to transport greater loads is through the coordinated flight of multiple aircraft. In other words, multiple pilots can fly in formation to carry a common payload. This is done by tethering the payload to multiple helicopters using cables. By way of background, helicopters, for example, have rotating blades that provide lift and allow them to hover in a stationary position. However, to maintain stability in a helicopter, a pilot must constantly adjust the primary controls such as the cyclic stick, collective stick and rudder pedals. In order for the helicopters to lift the load together, they must redirect some of their thrust from lift to counter the horizontal forces pulling the helicopters together. These complex maneuvers further require a pilot to communicate his own efforts with other pilots, thereby increasing cognitive loading on the pilots. It is therefore very difficult and dangerous for multiple helicopters to fly in formation or in close proximity to one another.

[0004] Alternative methods for improving the safety and reliability of two or more helicopters operating in close proximity have been developed. For example, U.S. Patent No. 3,746,279 describes a “spreader bar” connected to a mass and tethered to each participating helicopter. The purpose of this bar is to reduce the need of the helicopters to lean away from one another while in hover. However, the spreader bar incurs the disadvantage of set-up time and effort to attach the spreader bar, while incurring a weight penalty on the payload capacity. The patent also describes a leader aircraft that is coupled to the controls of the other aircraft. The close coupling between the leader and slave aircraft creates a dependency, such that a failure in the leader aircraft may result in the overall failure of the flight system.

[0005] Further, U.S. Patent No. 3,656,723 describes a single truss network to fix all helicopters into a rigid formation. In this system, a single pilot can simultaneously direct the system using the same control signal that is relayed to the network of helicopters. This has the advantages of eliminating pilot to pilot communication error as well as preventing any mid air collisions by failed coordination. However, a truss network for helicopters does not easily accommodate variances to the type or quantity of employed helicopters in the formation. Also, if a single helicopter has a mechanical failure it not only ceases to provide lift, but becomes a liability to the rest of the system. An inoperable helicopter becomes a parasitic load because it is permanently fixed to the truss.

[0006] Other prior art include U.S. Patent No. 5,521,817, which describes a method for semi-autonomous control of multiple aircraft. This control system demonstrates how a single unmanned drone can lead a group of followers. This lead drone, which is remotely controlled from the ground, relays flight information to the followers. As the group moves, the followers react to the relative movement of surrounding drones to prevent mid air collisions. However, the drones of this system cannot function as a group to accomplish a task beyond relocation. As discussed earlier, the coordination of multiple aircraft to lift a common payload requires a more robust and precise control system that considers the dynamic and kinematic effects of a swinging payload.

[0007] Therefore, it is an object of the invention to obviate or mitigate at least one of the above-mentioned problems.

SUMMARY

[0008] The semi-autonomous system for multiple aircraft lifting a common load comprises of at least two aircraft, a single payload, and a pilot station, which allows a single pilot to control the swarm in a remote and safe environment.

[0009] The payload is connected to each aircraft through tethers and anchors. A tether extends from each aircraft's tethering anchor to the payload's tethering anchor. The anchors allow the tethers to be easily attached or released, and also prevent tangling. The location and orientation of the payload is determined through sensors, for example a Global Positioning System.

[0010] Each aircraft has autonomous flight capabilities and, therefore, can stabilize and move to different locations without a pilot. The autonomous flight functionality is implemented through a swarm avionics unit, which interacts with the aircraft's flight controller. The swarm avionics unit receives control signals from the pilot station and transmits aircraft sensory data to the pilot station. Sensory data about the aircraft and payload are used to stabilize and guide the aircraft through a flight controller algorithm.

[0011] Command of the entire multi-aircraft lifting system takes place at a remotely located pilot station. The pilot does not control the aircraft movement directly but, instead, inputs commands regarding the desired location of the payload. A payload waypoint controller calculates intermediary waypoints between the current and desired positions. These payload waypoints are used by the swarm waypoint controller to generate individual waypoints for each aircraft. These aircraft waypoints are then transmitted wirelessly to the swarm avionics unit on each aircraft.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The features of the invention will become more apparent in the following detailed description in which reference is made to the appended drawings wherein:

[0013] FIG. **1** is a schematic representation of a configuration for a multi-aircraft lifting system.

[0014] FIG. **2** is a schematic of an alternate configuration to FIG. **1**.

[0015] FIG. **3** is a schematic of yet another configuration to FIG. **1**.

[0016] FIG. **4** is a diagram of several swarm patterns for a multi-aircraft lifting system.

[0017] FIG. **5** is a schematic representation of the functionalities and hardware for a multi-aircraft lifting system.

[0018] FIG. **6** is a schematic representation of the swarm avionics.

[0019] FIG. **7** is a schematic representation of the payload avionics.

[0020] FIG. **8** is a flowchart of the control system for a multi-aircraft lifting system.

[0021] FIG. **9** is a flowchart of a detailed control system for a multi-aircraft lifting system.

[0022] FIG. **10** is a schematic of relative positioning between a swarm and a payload.

[0023] FIG. **11** is another schematic of relative positioning between a swarm and a payload.

[0024] FIG. **12** is another schematic of relative positioning between a swarm and a payload with tethers of different lengths.

[0025] FIG. **13** is another schematic of relative positioning between a swarm and a payload with aircraft in contact with one another.

[0026] FIG. **14** is another schematic of relative positioning between a swarm and a payload with tether separating structures.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0027] Referring to FIG. **1**, a semi-autonomous multi-aircraft lifting system comprises of several aircraft **11**,**12**,**13**, operating in formation attached to a single payload **14** by means of tethers **15**. Aircraft hereon refers to vehicles capable of hovering such as, by way of example, the UH-1 helicopter, V22 Osprey, F-35 Joint Strike Fighter, and a lighter-than-air airship or dirigible. Examples of heavy lifting airships include SkyHook International's JHL-40, CargoLifter's CL160 Super Heavy-Lift Cargo Airship and DARPA's Walrus heavy transport blimp. The number of aircraft in the multi-aircraft system may range from two to n units, and are labeled H_1 **11**, H_2 **12**, and H_n **13**. A multi-aircraft lifting system has the advantage over a single aircraft in being capable of lifting a payload weight that is greater than a single aircraft's lift capacity. In other words, if a single aircraft carries x kg, then n aircraft can carry a payload of up to nx kg. A group of aircraft flying together will hereon be referred to as a swarm **18**. Note that the aircraft within the swarm **18** are not required to be of the same type as to allow different aircraft to operate within the multi-aircraft lifting system.

[0028] Continuing with FIG. **1**, it should be appreciated that a pilot is not required to operate each of the aircraft **11**, **12**, **13**. Instead, a pilot station **16**, requiring a minimum of one operator or pilot, operates the multi-aircraft lifting system. The pilot station **16** may be located in a ground base **17** for remote operation. Alternatively, as shown in FIG. **2**, the pilot station **16** may be located in a vehicle, for example, an aircraft **21**, that is ancillary to the swarm **18**. In yet another embodiment, referring to FIG. **3**, the pilot station **16** may be located within one of the swarm's aircraft. These pilot configurations advantageously allows for a reduced number of human operators and can allow a human operator to remain at a safe distance from the lifting procedure. It is also appreciated that the piloting operations may not require a human perator as many control systems are well known to automatically pilot aircraft.

[0029] It should also be appreciated that the number of aircraft that compose the swarm **18** affects the flight formation pattern as shown from a top-down perspective in FIG. **4**. In a two-aircraft swarm formation **43**, comprising aircraft **11**,**12**, the aircraft are positioned 180° from each other to facilitate equal tension in the tethers and, thereby facilitating the stability in transport of the payload. Similarly, for a three-aircraft swarm formation **44** (comprising **11**,**12**,**41**), the aircraft are positioned 120° apart, while for a four-aircraft swarm formation **45**(comprising **11**,**12**,**41**,**42**), the aircraft are positioned 90° apart. Note that the number of aircraft in the swarm is not limited to four.

[0030] Moreover, any swarm formation that allows multiple aircraft to lift a common payload is applicable to the principles herein. In some situations, it may be preferable that the aircraft are configured in an irregular formation, for example, to accommodate different payload sizes and uneven weight distribution. Aircraft in a swarm may be of a different type, each with different lifting and flight performance capabilities. Thus, it may also be preferable to configure swarm lifting formations based on aircraft type.

[0031] Referring to FIG. **5**, the components of the multi-aircraft lifting system is shown in further detail. A representation of a two-aircraft swarm consisting of aircraft H_1 **11** and H_2 **12** are carrying a payload **14**. Within each aircraft **11**, **12** there is a swarm avionics unit **502** that gathers sensory and flight data to determine flight control commands. The computed flight control commands are sent to the aircraft's flight system **503**, which is an electrical interface to the aircraft's actuators **504**. By way of background, a highly complex flight system may have autopilot functionality to control the aircraft's actuators **504**. Common helicopter actuators include, but are not limited to, tail rotor motors, main rotor motors, flapping hinge actuators, and pitch control rod actuators. Common airship actuators include rotors, flaps, thrust vectoring devices, ballasts, ballonet valves, means for filling and emptying the airship with lifting gas, and devices for heating and cooling the lifting gas within the airship.

[0032] The swarm avionics unit **502** is a critical part of the swarm control system as shown in detail in FIG. **6**. The swarm avionics unit **502** comprises a sensor suite **614** that collects data about the aircraft through a variety of sensors. Specifically, the sensor suite **614** should output data directly or indirectly pertaining to an aircraft's angular and translational position, velocity, and acceleration, and any sensors able to provide such data are applicable to the principles described herein. The sensor suite **614** may include a Global Positioning System (GPS) **601**, which provides absolute position, absolute speed, and a reference of merit for the sensor suite's output data. Similarly inertial sensors **602**, typically consisting of accelerometers and gyroscopes, provide absolute speed, attitude, heading, and a reference of merit for the sensor suite's output data. Object detection sensors **605**, for example, ultrasound and infrared, provide distance measurements between the payload, aircraft, and other objects. Radar **606** provides relative distances to other aircraft. An altimeter **607** provides the altitude. A tether sensor **608** provides the magnitude and direction of force from the tether acting on the aircraft.

[0033] Data from the sensor suite **614** is sent to the swarm avionic unit's processor **609** for real-time data processing. Processed aircraft data is wirelessly transmitted to the pilot station **14** through the communication unit **611**, which includes a transceiver **612** and receiver **613**. The processor **609** also receives swarm waypoint control signals from the pilot station **16** through the receiver **613**. The control signals and the sensor suite data are inputs to the flight control algorithms, which are stored in the memory **610**. The flight control algorithms compute in real-time and output flight control commands. Details regarding the flight control algorithms are discussed further below. Flight control commands are sent from the processor **609** to the aircraft's flight system **503**.

[0034] Referring back to FIG. **5**, the payload **14** is connected to each aircraft **11**, **12** using tethers **15**. Each tether **15** is attached to the aircraft **11**,**12** through an aircraft tethering anchor **505** and similarly, is attached to the payload **14** through a payload tethering anchor **506**. Both the aircraft and payload anchors **505**,**506** have a release mechanism that detaches the tether from the aircraft and payload respectively. The anchors **505**, **506** are also used to reduce tangling during flight manoeuvres. It should be noted that the tethers **15** are not required to be at right angles to the payload tethering anchor **506** in order to maintain equal force distribution in each tether **15**. The payload tethering anchor **506** is easily attachable to variety of surfaces to facilitate short cycle times for setting up a multi-aircraft lifting system.

[0035] It can be appreciated that the tethers **15** need not be flexible and may, instead be or include rigid materials. For example, the tethers **15** may be rigid bars. Any means for attaching the payload **14** to the aircraft **11, 12** are applicable to the principles herein.

[0036] Attached to the payload **14** is a payload avionics unit **507** that gathers sensory data about the location and orientation of the payload **14**, and transmits the data to the pilot station **16** and the aircraft **11**, **12**. Turning to FIG. **7**, a detailed schematic representation shows that the payload avionics unit **507** consists of inertial sensors **71** to provide absolute speed, attitude, and heading data about the payload **14**. Examples of inertial sensors include, but are not limited to, accelerometers **72** and gyroscopes **73**. Similarly, GPS **74** determines the absolute position and speed. Data from the inertial sensors **71** and GPS **74** are collected and computed by a real-time processor **75** having on-board memory **76**. The processed data is then sent to a communication unit **77** with a transceiver **78** that is capable of transmitting the processed payload sensory data to the pilot station **16** and aircraft **11**,**12**.

[0037] Returning again to FIG. **5**, the pilot station **16** receives data about the payload **14** and individual aircraft **11**, **12** within the swarm **18** through the pilot station's communication unit **511**. Note that the communication unit **511** has a wireless receiver **515** and transceiver **514**. Wireless communication media between the aircraft **11**,**12**, payload **14** and pilot station **16** may include, for example, radio, satellite, Bluetooth, and laser. As shown in dotted lines, the communication unit **511** is in communication with the swarm avionics units **502** and the payload avionics **507**. Similarly, the payload avionics unit **502** is in communication with the swarm avionics units **502**. The received sensory data is processed in real-time by a processor **510**, which then sends the situational data to a computer display and interface **509** for the pilot **508** to view. The pilot **508** uses the current position and velocity of the swarm **18** and payload **14** to determine the flight path of the payload. The pilot **508** then inputs desired positions for the payload, called waypoints, into the computer **509** through interface devices, such as a keyboard, mouse, control stick, or control pad. The pilot's commands are sent to the processor **510**, which holds payload waypoint control algorithms and swarm waypoint control algorithms within the memory **512**. The processor uses the control algorithms to compute swarm waypoint commands for each aircraft within the swarm in order to move the payload to the desired waypoint. Details regarding the payload waypoint and swarm waypoint control algorithms are discussed further below. These waypoint commands are transmitted through the pilot station's transceiver **514** and are received by each aircraft's receiver **613**.

[0038] The above components are used to implement the multi-aircraft lifting system, which is dependent on the control system. The overall function of the multi-aircraft control system is to stabilize and guide each aircraft, while determining the flight path for each aircraft such that the payload **14** moves from its initial position to a final position as commanded by the pilot **508**. Subsidiary functions of the multi-aircraft control system include maintaining a safe distance between aircraft and proper positioning to support the payload **14**.

[0039] Referring to FIG. **8**, an overview of the multi-aircraft lifting control system is shown with respect to the pilot station processor **510** and swarm avionic processors **609**. The main components of the multi-aircraft lifting control system include the payload waypoint controller **802**, the swarm waypoint controller **803**, and the flight control system **806**. The flight control system **806** is implemented for each aircraft **11**, **12**, **13**. The payload waypoint controller **802** and the swarm waypoint controller **803** are run on the pilot station's processor **510**. Similarly, the flight controller **804** and aircraft plant model **805**, within the flight control system **806**, are run on the swarm avionics processor **609**.

[0040] A benefit of the preferred embodiment is shown more clearly in FIG. **8**. The control of the swarm is not localized to an aircraft and, instead, is ancillary to the aircraft. This mitigates or obviates the need for an aircraft leader for the swarm **18**. Therefore, in the event an aircraft fails, the multi-aircraft lifting system has the robustness to continue supporting the payload **14**. For example, four aircraft, each capable of lifting 500 kg, are transporting a 1200 kg payload in a swarm pattern **45** spaced 90° apart. If a flight control system **806** on one of the aircraft fails, the anchors **505**, **506** will allow the failed aircraft to leave the swarm **18**. The three remaining aircraft then adapt by forming a different swarm pattern **44** spaced 120° apart, while the payload waypoint controller **802** and swarm waypoint controller **803** continue to navigate the swarm **18**.

[0041] Continuing with the control system in FIG. **8**, the payload waypoint controller **802** monitors and controls the payload state variables, such as payload acceleration, velocity, position, and orientation. The payload waypoint controller **802** also generates a path along which the payload **14** will travel from its current state to the desired payload state as determined by the pilot **508**. The payload's path is formed by generating appropriate waypoints between the initial and final states, and calculates a path from the payload's initial state to the first waypoint. The path is mathematically interpolated, by way of example, through multiple splines that are used to determine the value of each state at a certain time *t*. This path is sent to the swarm waypoint controller **803**, which coordinates the individual aircraft within the swarm **18** to obtain the desired payload state at time t. It should be appreciated that other interpolation methods, such as Bezier curves, discrete steps, and linear interpolation may be used in place of splines. Other path planning controllers that may be used include fuzzy-logic and Bang-bang controllers.

[0042] The swarm waypoint controller **803** uses the previously generated payload path to determine the relative orientations and positions for all of the individual aircraft. Turning to FIG. **10**, a positioning configuration for four aircraft, by way of example, is shown. The positions on each aircraft **11**, **12**, **41**, **42**, relative to the payload **14**, is determined by two constants. The first constant is the height difference H between the payload **14** and the swarm plane **101**, and second constant is the radius R between each aircraft **11**, **12**, **41**, **42** to the center of the swarm plane **101**. It should be noted that the swarm plane **101**, as shown by the overhead view **102**, is described by a circle of radius R, in which each aircraft **11**, **12**, **41**, **42** is positioned at the circumference of the circle and separated by a constant angle Θ, where $\Theta = 360° / \text{(number of aircraft)}$. In the example of a four aircraft swarm, the angular separation Θ is 90°. Furthermore, if the length L of the tethers 15 are of the same length, then all points within the swarm plane **101**, including each aircraft, should have the same altitude. As seen by the front profile **103**, the payload **14** is located directly below the center of the swarm plane **101** by a height difference H. It should be appreciated that the R and H constants are determined by considering many factors, including, for example, the size of the aircraft, the number of aircraft, the desired horizontal to vertical force ratios, and the size of the payload. The tethers **15** between the payload **14** and aircraft **11**, **12**, **41**, **42** all have the same length, L, which is approximated by the Pythagorean relationship $L = (R^2 + H^2)^{1/2}$. Thus, the swarm waypoint controller **803** maintains the relative positioning based on the constant radius R of the aircraft and the payload's height H below the swarm plane **101**.

[0043] Turning to FIG. **11**, the payload **14** may be very large where it is advantageous for each aircraft **11**, **12** to support different portions of the payload **14**. During a straight-path transport, the swarm waypoint controller **803** ensures that each aircraft **11**, **12** maintains a relative position to each other and the payload **14**, whereby the tethers **15** remain approximately vertical.

[0044] In FIG. **12**, the payload **14** is very large and has an irregular shape. Three aircraft **11**, **12**, **13** are attached to the payload **14** using various lengths of tethers, such that each aircraft has different elevation relative to each other. The swarm waypoint controller **803** ensures that each aircraft **11**, **12**, **13** maintains their relative elevations to ensure that equal tension. It can further be appreciated that the H1 (**11**) may be a helicopter, while H2 (**12**) and Hn (**13**) may be airships. In such a case, the swarm waypoint controller **803** would also need to take into account various flight performance specifications, such as lifting power, to maintain the relative orientations of the aircraft and payload **14**. It can thus be seen that the swarm waypoint controller **803** can be configured to maintain various relative positioning formations between the aircraft in the swarm **18** and the payload **14**.

[0045] Returning to FIG. **8** , this swarm waypoint controller **803** calculates the payload states based on the states of each aircraft; the payload position may be determined from the position of all aircraft relative to ground and the Euclidian distance from each aircraft to the payload. Alternatively, the payload position may be determined by the payload avionics unit **507**. Each aircraft body **11**,**12** in the swarm **18** affects the position of the payload body **807** and consequently, the payload sensors' **507** readout. The computed payload state information is sent to the payload waypoint controller **82**.

[0046] This swarm waypoint controller **803** generates waypoints to guide each aircraft while the payload **14** moves along the desired path. These intermediate waypoints ensure that each aircraft is properly positioned relative to each other such that the payload force is equally distributed to each aircraft. In other words, where the lifting power of each aircraft is similar, the tension force in the tethers **15** should be approximately equal. Multiple spline paths are calculated to provide a means to determine each state for each aircraft at a certain time *t*. The swarm waypoint controller **803** provides the reference signal to each individual flight control system **806** within the swarm **18** using the spline paths that were previously generated.

[0047] The flight control system **806** is responsible for the flight and stability of an individual aircraft. The flight control system **806** calculates the required actuation signals necessary for the plant model **805** to track the reference control signal provided by the swarm control system **803**. The flight control system **806** is also responsible for tracking the reference signal within a specified tracking error and overshoot, as specified later in more detail. Achieving these flight control system specifications allows the aircraft actuators **504** to position the aircraft body **11**, **12** at a safe distance from each other and at the proper locations to support the payload **14**, as was determined by the swarm waypoint controller **803**. This flight control system **806** then returns the observed state of the aircraft to the swarm waypoint control system **803**.

[0048] The method for the multi-aircraft lifting control system is shown in further detail in FIG. **9**. The control algorithm is divided amongst three main controllers, being the payload waypoint controller **802**, the swarm waypoint controller **803**, and the flight controller **804**. Within the payload waypoint controller **802**, the pilot interface **509** is used to receive the desired payload destination **801**, which is then used for the next payload waypoint calculation **902**. The next payload waypoint calculation **902** and the current payload state **901** are then used to determine the spline end-conditions for position, velocity, and acceleration of the payload **903** by way of numerical methods. It should be noted that the current payload state **901** is outputted from the swarm waypoint controller **803**. The data from this spline calculation **903** is inputted back into the next payload waypoint calculation **902**, forming a recursive relationship. The spline output from step **903** is then used to compute the desired state at time *t* for the payload **904**.

[0049] With regard to the swarm waypoint controller **803** in FIG. **9**, the controller **803** uses all aircraft states **905** and the next payload waypoint **908** as inputs. The aircraft states **905** originate from the flight controller **804** of each aircraft in the swarm **18**, and the next payload waypoint originates from the step **904** in the payload waypoint controller **802**. The aircraft states **905** are used in the calculation of the current payload state **906**. The current payload state **906** and the next payload waypoint **908** are then used in step **907** for computing the desired state of each aircraft in the swarm **18**. After step **907**, the desired aircraft states are inputted into the step **909**, where the next waypoints for each helicopter are calculated and then used to generated splines for each aircraft in step **910**. These splines for position, velocity, and acceleration are used to derive the current state for each aircraft at time *t* **911**, and to calculate step **906**. Note that steps **906**, **907**, **909**, and **910** form a recursive relationship within the swarm waypoint controller **803**.

[0050] The desired states **911** for each aircraft are transmitted to the corresponding flight controllers **804**, as shown in FIG. **9** in the example of a single flight controller **804**. In other words, for an *n* aircraft swarm **18**, the swarm waypoint controller **803** will generate *n* desired aircraft states **911**, which are then transmitted to each of the *n* corresponding flight controllers **804** residing on each aircraft's processor **609**. The desired aircraft state is considered the reference signal R **916** in a flight controller **804**. It should be appreciated that the implementation of the flight controller **804** discussed herein is only one embodiment of the multi-aircraft lifting system. Alternate closed-loop control configurations may be used to stabilize and guide the movement of the aircraft.

[0051] Referring to FIG. **9**, the reference signal R **916** is compared against the observed state $\hat{X}$ of the aircraft. The difference between R and $\hat{X}$ is used to compute the gain K in step **917**, which then generates an input value u that is fed into the plant model **912** and the observer **915**. The plant model **912** represents the mechanics and dynamics of the aircraft through mathematical relations. Typical values in the plant model include the position and velocity in a Cartesian coordinate frame, and the roll, pitch, and yaw of the aircraft. The actual state variables X of the aircraft are derived from the plant model **912**, and are filtered by the observer matrix C **913**. The observer matrix **913** selects a subset of states from matrix X that are passed into the observer **915**. This embodiment of the flight controller **804** also takes into account disturbances, for example crosswinds, through the disturbance matrix D **914**. The disturbances may cause the measured state values, Y, to differ from the actual state variables, X.

[0052] The observer **915** is used to estimate state variables that may not be measured directly. The observer estimates the state of the aircraft $\hat{X}$ through the relation $\dot{\hat{X}} = A\hat{X} + BU + L\tilde{Y}$, where $\tilde{Y} = Y - \hat{Y}$. The matrices A and B represent the plant model, while matrix L is designed to drive the difference between measured state values Y and estimated measured state values $\hat{Y}$ to zero, thereby driving $\hat{X}$ to X. The estimated state $\hat{X}$ for each helicopter is sent to the swarm waypoint controller **803**, and is collected in a matrix **905**.

[0053] In another embodiment of the multi-aircraft control system, the flight controller **804** may not require an observer as enough data may be available to accurately measure the all states of the aircraft.

[0054] In another configuration of the relative positioning between aircraft, and airships in particular, the body of the aircraft may be constructed in such a way that the body of the aircraft are touching while flying in a swarm formation. In FIG. **13**, three aircraft **11**, **12**, **13** are shown flying in formation while in contact with each other. It can be appreciated that any number of aircraft may fly in such a formation. In particular, airship bodies may be in contact if the envelope, or skin, or the airship provides sufficient force to withstand the forces exerted by another airship in contact. Moreover, the thrusters, ailerons or other external structures are positioned in locations on the airship envelope where there is no contact. Such structures, for example, may be positioned towards the top region of the airship. Alternatively, the external structures may be configured or protected to allow for contact with another airship, whereby no damage is done to the airship or external structure. This swarm configuration advantageously allows multiple aircraft to lift a smaller sized payload **14**. This swarm configuration also advantageously allows for the tethers or connecting means **15** to attach on to the payload 14 at a centralized location. This is useful for allowing one of the aircraft to As can be understood, the swarm waypoint controller **803** generates waypoints to guide each aircraft, such that they maintain a certain relative positioning taking into account that the aircraft are in contact with each other.

[0055] Another configuration of multiple aircraft is shown in FIG. **14** where tether separating structures **402**, **404**, **406** are used an intermediary between the aircraft **11**, **12**, **13** and the payload **14**. For each aircraft, there is preferably a corresponding separating structure. Each separating structure is made of a rigid or semi-rigid body, whereby the separating structures can withstand external compression forces. They are preferably constructed to be light weight and, for example, include carbon fibre, steel tubing and fabrics. As the separating structures are pressing against one another, the separating structures are preferably rounded and have smooth outer surfaces to allow the separating structures to slide against each other. In particular, the tethers **15** extend from the payload **14** at a centralized location, such as a payload anchor **506**. Each tether **15** extends upward from the payload **14** at an angle towards a respective tether separating structure **402**, **404**, **406**. The tethers **15** above the separating structures extend approximately vertical towards each respective aircraft **11**, **12**, **13**. It can be appreciated that the separating structures are sufficiently large to allow an aircraft to fly without exerting additional horizontal forces to be at a distance away from another aircraft in the swarm. This configuration is used in combination with the swarm waypoint controller **803** to maintain relative positions of the aircraft and payload **14**.

[0056] Possible applications of the multi-aircraft lifting system include transporting an entire building, such as a warehouse. This has particular utility in oil and mining operations in remote locations, where drilling and mining sites are moved frequently. In remote locations where there is limited accessibility by land or water, it is advantageous to transport building structures by air. For example, for drilling operations in the Arctic or Antarctic regions, there are often little to no roads. A fleet of heavy lift airships may be deployed to transport buildings, equipment and vehicles in such remote regions. Some of the airships in the fleet are used to individually carry smaller or lighter payloads. Other airships within the fleet are used to form a swarm to carry larger or heavier payloads. The number of airships and the formation of the swarm may be configured to meet the payload's weight and size. Thus, the multi-aircraft system is flexible to the lifting operation. Further, transporting entire buildings, rather than components of a building for assembly and disassembly, reduces the assembly or set-up time for the oil and mining operations. This advantageously allowing the oil and mining operations to achieve operational status in shorter times.

[0057] In another application, the multi-aircraft lifting system may be used to transport assembled large marine vessels from land to water, and vice versa. This would advantageously allow ship and submarine manufacturers to construct or repair marine vessels inland, away from the water. Transporting large marine vessels using the multi-aircraft system would also allow marine vessels to be launched in locations that are further away from land, where the water depth is preferable.

[0058] It can be appreciated that constructing, maintaining and storing multiple smaller aircraft may be more economical. Further, the aircraft in a multi-aircraft lifting system can be used for multiple purposes, in addition to heavy lifting. For example, an aircraft in one situation is used to transport passengers. In another situation, the same aircraft cooperates with other aircraft to form a swarm for lifting a common payload. A multiple-aircraft lifting system further provides redundancy and reliability. For example, should an aircraft in the swarm fail or be removed from the swarm for other reasons, the remaining aircraft in the swarm continue to lift the payload.

[0059] Although the multi-aircraft lifting system has been described with reference to certain embodiments, various modifications thereof will be apparent to those skilled in the art without departing from the spirit and scope of the multi-aircraft lifting system as outlined in the claims.

In the claims:

1. A multiple-aircraft lifting system comprising:

a plurality of aircraft attached to a payload;

a pilot station processor in communication with a first memory for storing a payload waypoint controller and a swarm waypoint controller, wherein said pilot station processor computes a path for said payload towards a desired payload destination and computes a respective desired state for each one of said plurality of aircraft to transport said payload along said path;

a plurality of swarm avionics processors, wherein each one of said plurality of swarm avionics processors is in communication with a flight control system of a respective one of said plurality of aircraft as well as said pilot station processor, and said each one of said plurality of swarm avionics processors in communication with a respective second memory for storing a respective flight controller and a respective aircraft plant model, said each one of said plurality of swarm avionics processors computes one or more actuation signals to move said respective one of said plurality aircraft based on said respective desired state and said respective plant model.

2. The system in claim 1 wherein said pilot station processor is located in any one of a ground station, an ancillary aircraft or one of said plurality of aircraft.

3. The system in claim 1 further comprising a plurality of sensor suites, wherein said each one of said plurality of sensor suites is in communication with a respective one of said plurality of said plurality of swarm avionics processors.

4. The system in claim 3 wherein said each one of said plurality of sensor suites outputs angular and translational position, velocity, and acceleration data pertaining to said respective one of said plurality of aircraft.

5. The system in claim 1 further comprising a payload avionics unit with sensors to provide position data about said payload.

6. The system in claim 5 wherein said payload avionics unit transmits said data to said pilot station processor or to at least one of said plurality of swarm avionics processors, or both.

7. The system in claim 1 wherein said each one of said plurality of aircraft is attached to said payload using a plurality of tethers.

8. The system in claim 7 wherein said plurality of tethers are attached to said payload and said plurality of aircraft using a tethering anchor and said anchor has a release mechanism for detaching said payload from at least one of said plurality of aircraft.

9. The system in claim 1 wherein said plurality of aircraft fly in formation where at least one of said plurality of aircraft is in contact with at least another of said plurality of aircraft.

10. The system in claim 7 wherein each of said plurality of tethers are attached to a tether separating structure located between said plurality of aircraft and said payload.

11. The system in claim 1 wherein said plurality of aircraft comprise one or more helicopters, or one or more airships, or combinations thereof.

12. A method for a plurality of aircraft to lift a payload comprising:

a pilot station computing a path for said payload towards a desired payload destination;

said pilot station computing a respective desired state for each one of said plurality of aircraft to transport said payload along said path;

a plurality of swarm avionics processors, each one of said plurality of swarm avionics processors is in communication with a respective one of said plurality of aircraft, wherein each one of said plurality of swarm avionics processors receives said respective desired state from said pilot station; and

said each one of said plurality of swarm avionics processors computes one or more actuation signals to move said respective one of said plurality of aircraft based on said respective desired state and a respective plant model.

13. The method in claim 12 wherein a user provides said desired payload destination to said pilot station.

14. The method in claim 12 wherein said pilot station computes said path based on a spline path between a current payload state and said desired payload destination.

15. The method in claim 14 wherein said current payload state is calculated by first determining the position of at least on of said plurality of aircraft, and then determining the position of said payload relative to said at least one of said plurality of aircraft.

16. The method in claim 12 wherein said pilot station computes said respective desired state for each one of said plurality of aircraft 13 by determining a next waypoint for said each one of said

plurality of aircraft, and then updating a spline for position, velocity and acceleration for said each one of said plurality of aircraft.

17. The method in claim 12 wherein a swarm waypoint controller in said pilot station computes said respective desired state for each one of said plurality of aircraft to also maintain constant relative positioning between said plurality of aircraft.

18. The method in claim 12 wherein if a one or more of said plurality of aircraft are detached from said payload, then the remaining aircraft attached to said payload continue to lift said payload.

19. The method in claim 12 wherein said plurality of aircraft comprise one or more helicopters, or one or more airships, or combinations thereof.

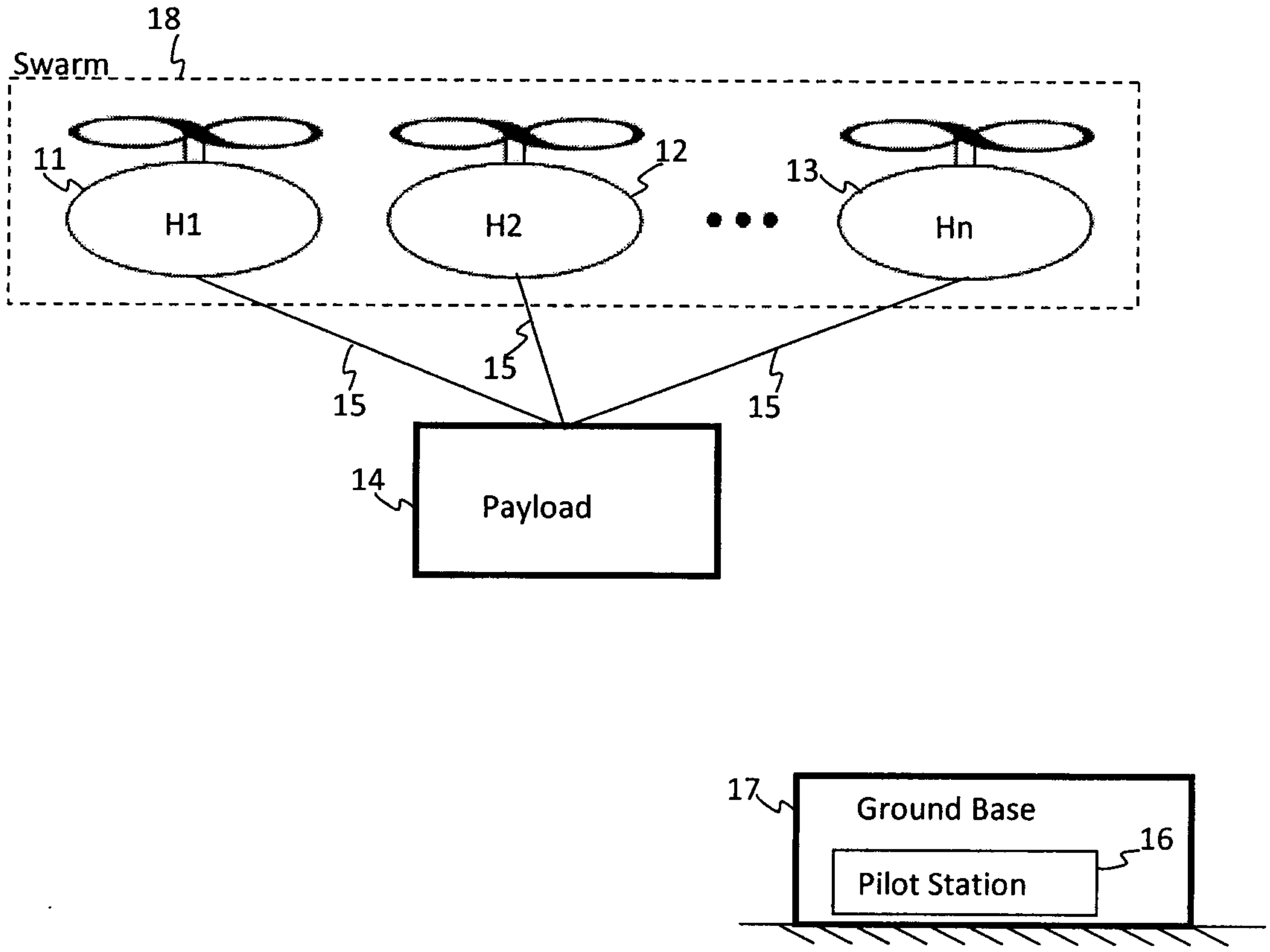

18
Swarm
11
H1
H2
12
13
Hn
15
15
15
14
Payload
17
Ground Base
16
Pilot Station

FIG. 1

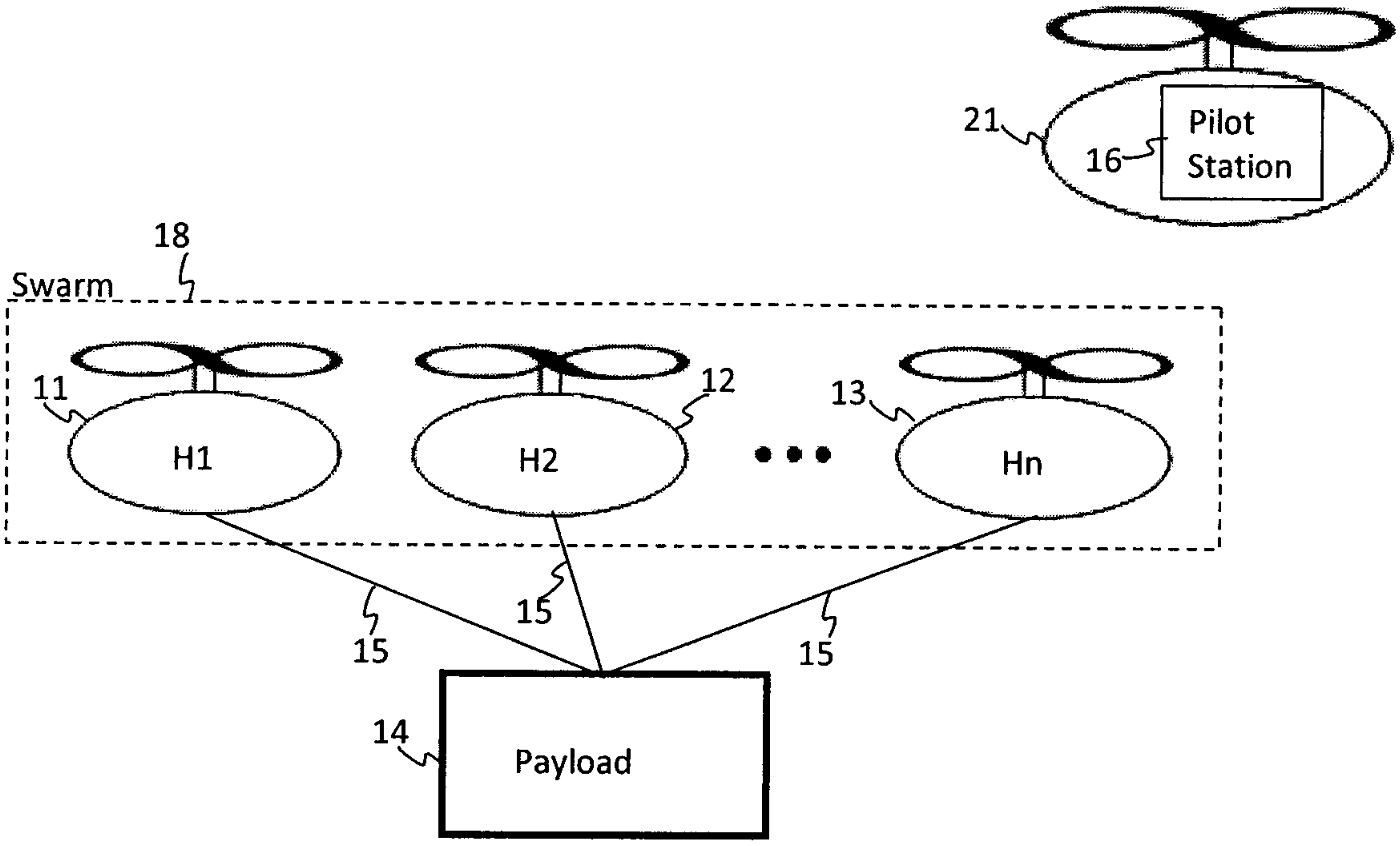

21
16
Pilot Station
18
Swarm
11
H1
12
H2
13
Hn
15
15
15
14
Payload

FIG. 2

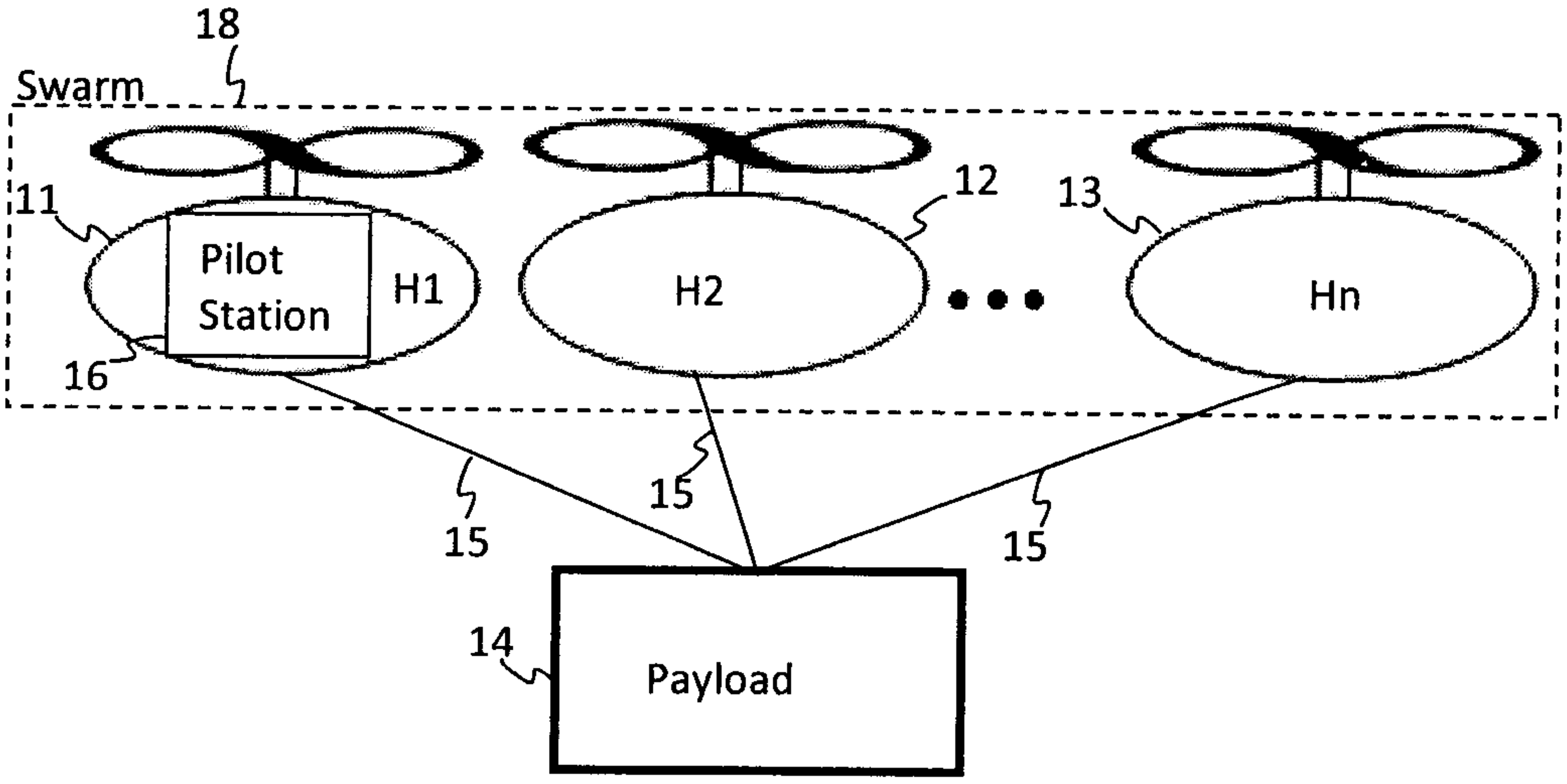

18
Swarm
11
Pilot Station
H1
16
12
H2
13
Hn
15
15
15
14
Payload

FIG. 3

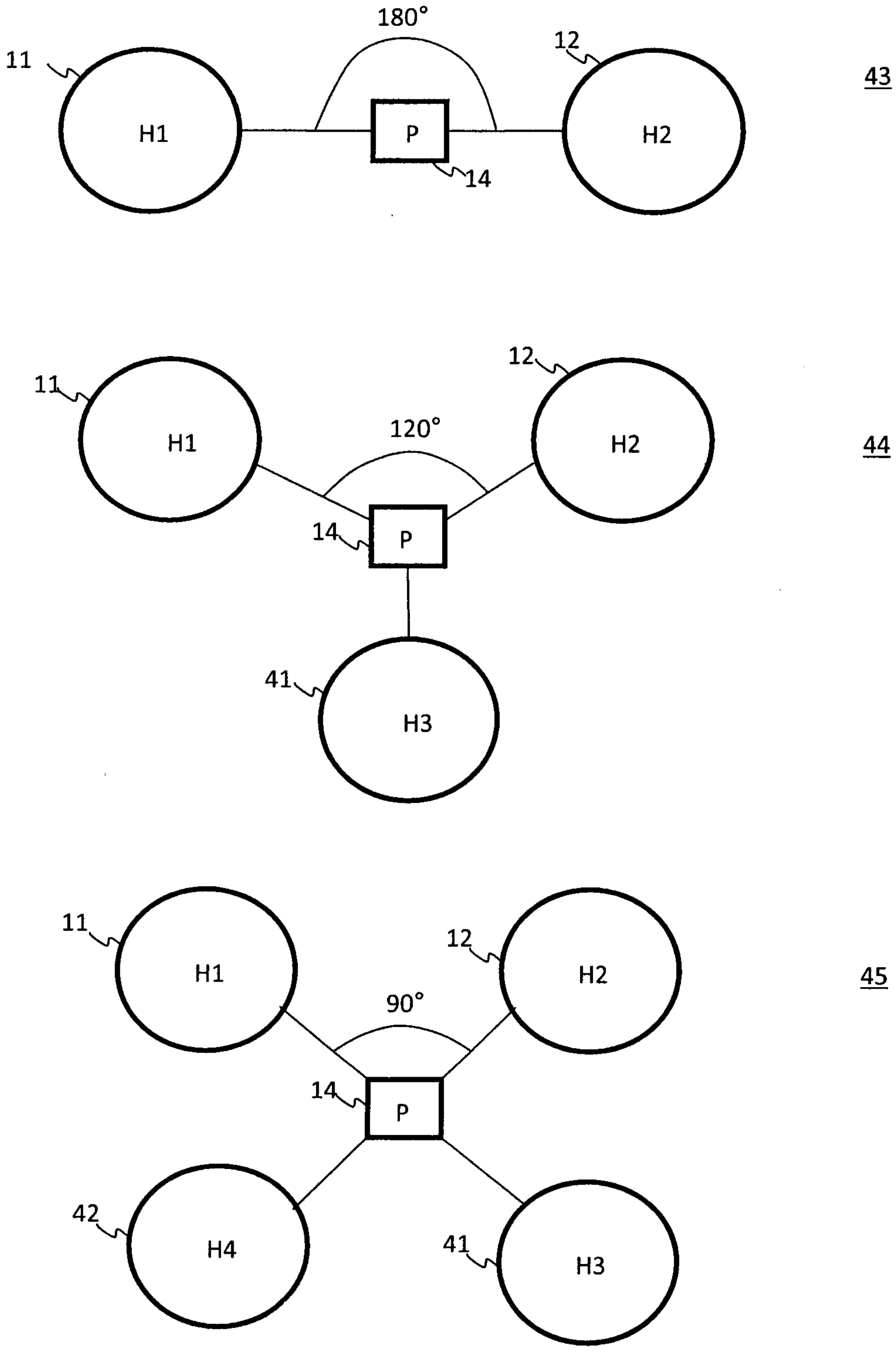

180°
11
12
43
H1
P
H2
14
12
11
44
H1
120°
H2
14
P
41
H3
11
H1
12
H2
45
90°
14
P
42
H4
41
H3

FIG. 4

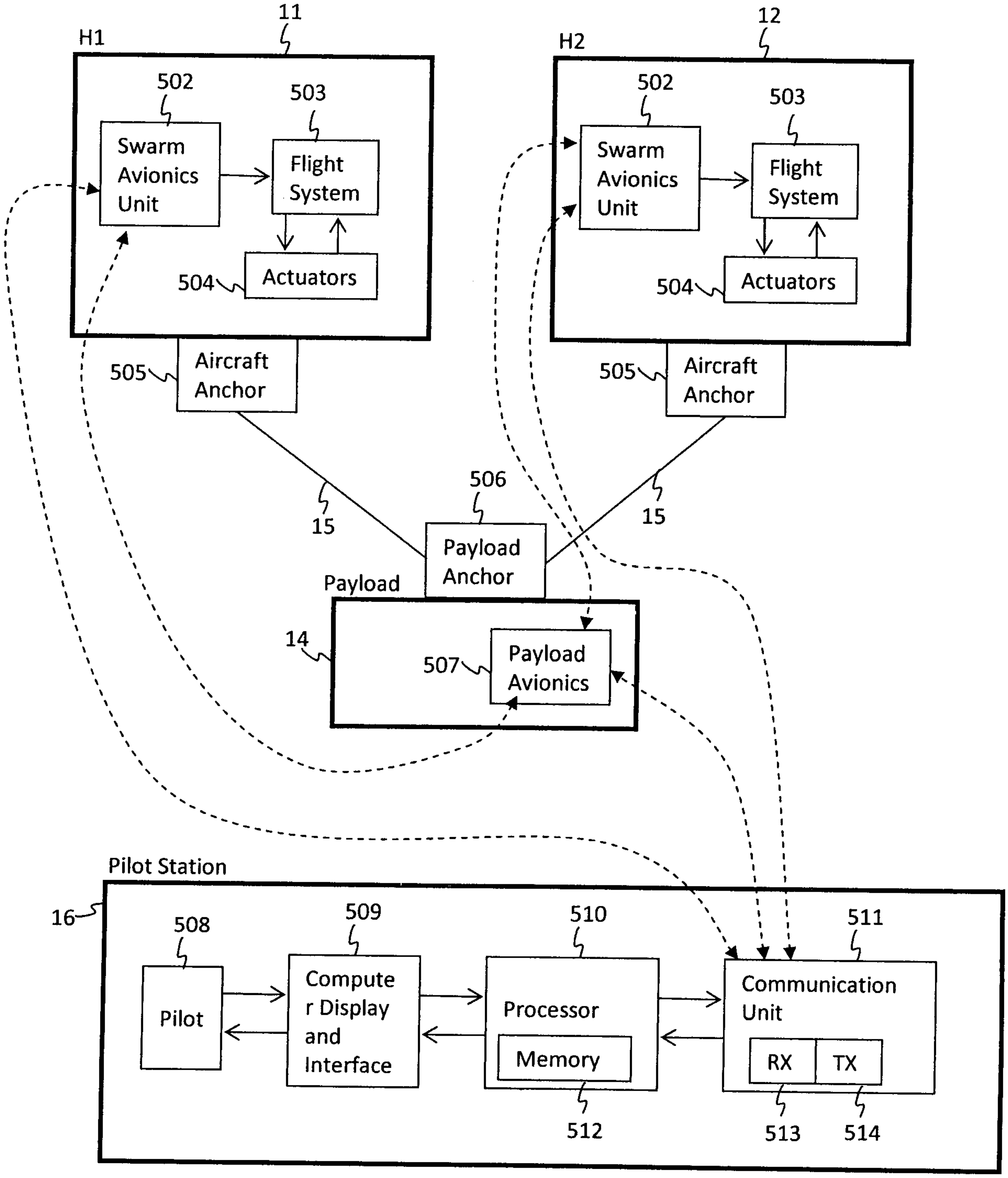

H1
11
502
Swarm Avionics Unit
503
Flight System
504
Actuators
505
Aircraft Anchor
H2
12
502
Swarm Avionics Unit
503
Flight System
504
Actuators
505
Aircraft Anchor
15
15
506
Payload Anchor
Payload
14
507
Payload Avionics
Pilot Station
16
508
Pilot
509
Computer Display and Interface
510
Processor
Memory
512
511
Communication Unit
RX
TX
513
514

FIG. 5

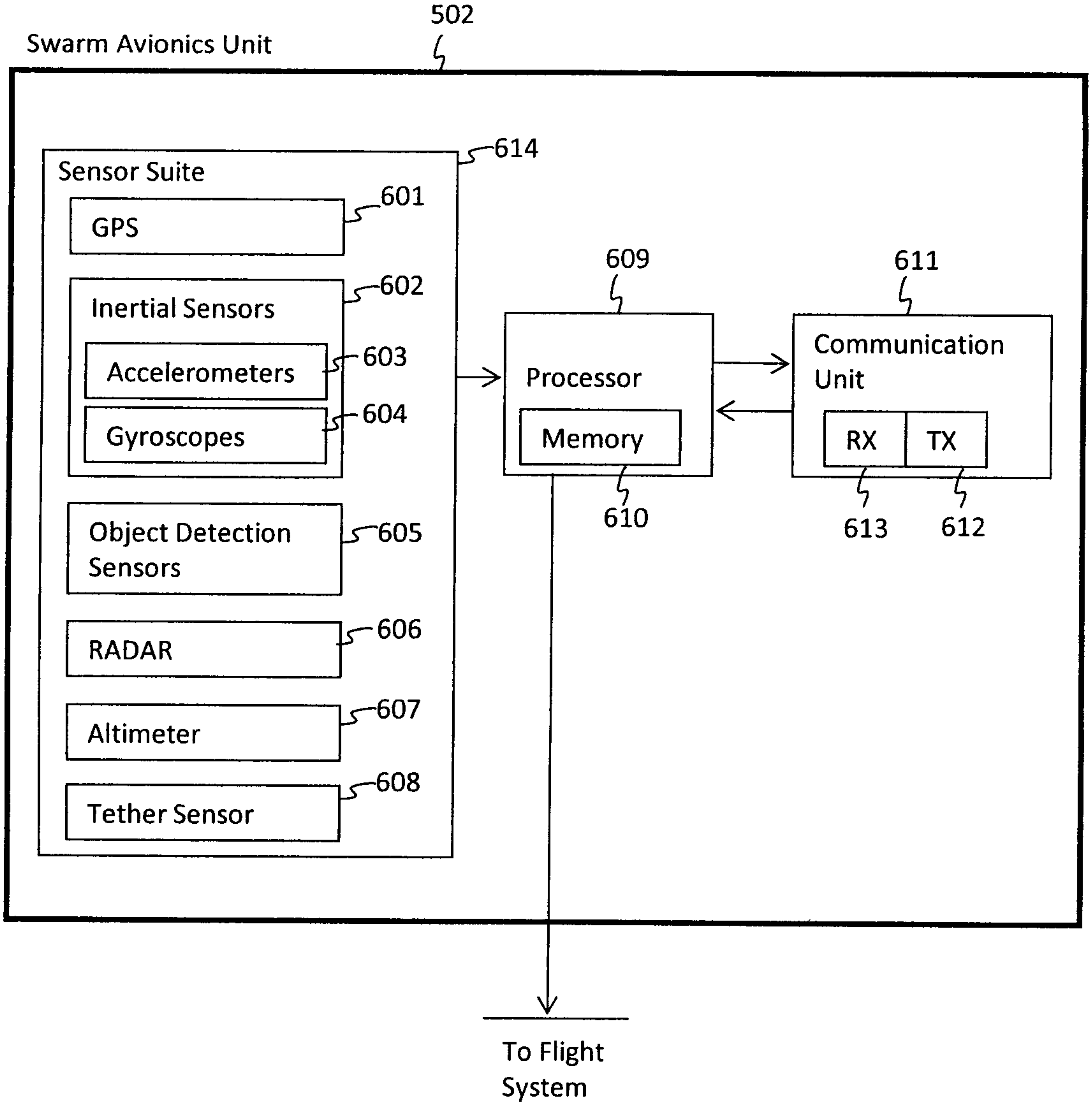

502
Swarm Avionics Unit
Sensor Suite
614
GPS
601
Inertial Sensors
602
Accelerometers
603
Gyroscopes
604
Object Detection Sensors
605
RADAR
606
Altimeter
607
Tether Sensor
608
609
Processor
Memory
610
611
Communication Unit
RX
TX
613
612
To Flight System

FIG. 6

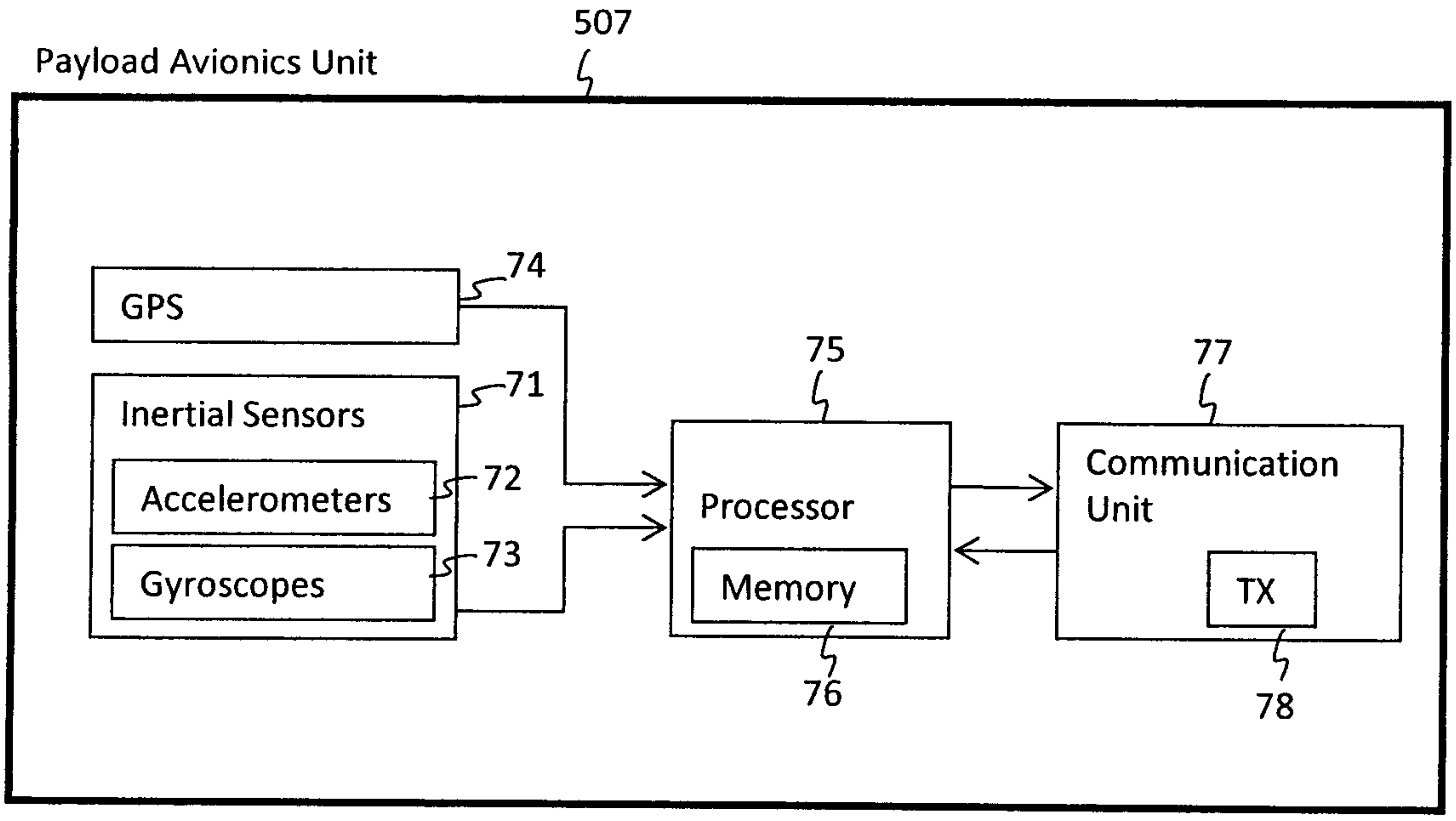

507
Payload Avionics Unit
GPS
74
Inertial Sensors
71
Accelerometers
72
Gyroscopes
73
75
Processor
Memory
76
77
Communication Unit
TX
78

FIG. 7

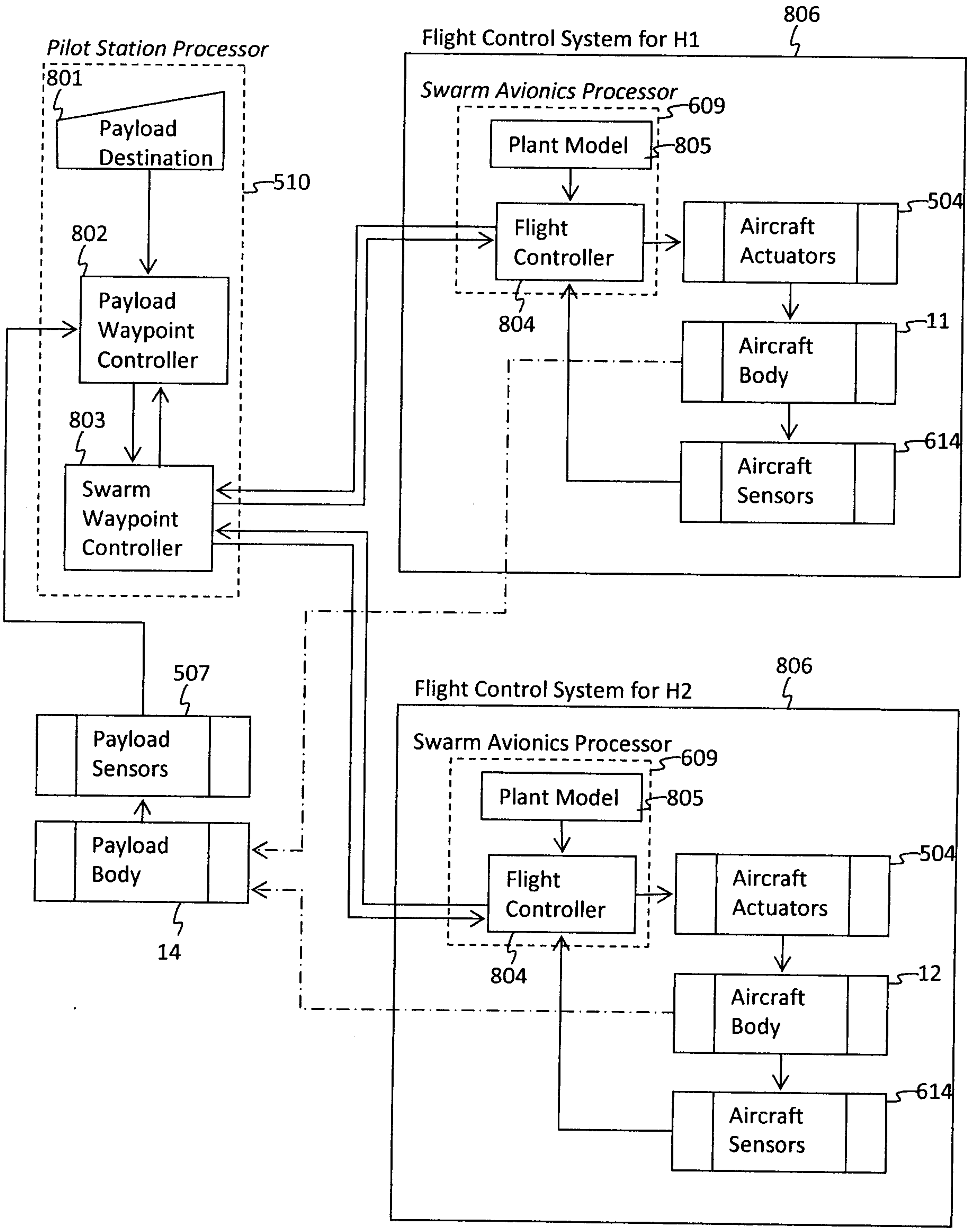

Pilot Station Processor
801
Payload Destination
510
802
Payload Waypoint Controller
803
Swarm Waypoint Controller
Flight Control System for H1
806
Swarm Avionics Processor
609
Plant Model
805
Flight Controller
804
Aircraft Actuators
504
Aircraft Body
11
Aircraft Sensors
614
507
Payload Sensors
Payload Body
14
Flight Control System for H2
806
Swarm Avionics Processor
609
Plant Model
805
Flight Controller
804
Aircraft Actuators
504
Aircraft Body
12
Aircraft Sensors
614

FIG. 8

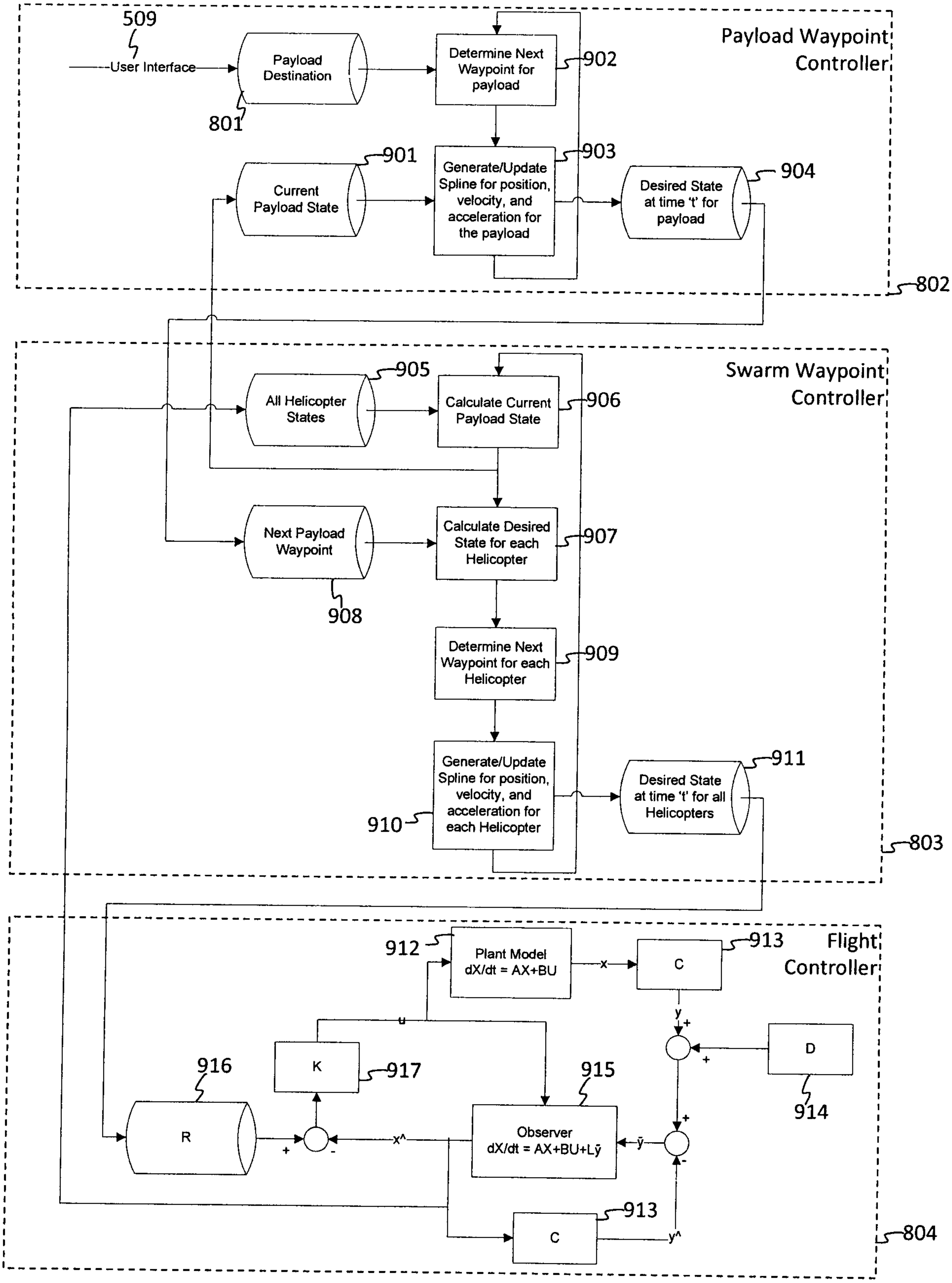

509
User Interface
Payload Destination
801
Determine Next Waypoint for payload
902
Payload Waypoint Controller
Current Payload State
901
Generate/Update Spline for position, velocity, and acceleration for the payload
903
Desired State at time 't' for payload
904
802
All Helicopter States
905
Calculate Current Payload State
906
Swarm Waypoint Controller
Next Payload Waypoint
908
Calculate Desired State for each Helicopter
907
Determine Next Waypoint for each Helicopter
909
Generate/Update Spline for position, velocity, and acceleration for each Helicopter
910
Desired State at time 't' for all Helicopters
911
803
Plant Model
dX/dt = AX+BU
912
x
C
913
Flight Controller
u
y
+
+
D
914
K
917
915
916
R
+
-
x^
Observer
dX/dt = AX+BU+Lȳ
ȳ
+
-
C
913
y^
804

FIG. 9

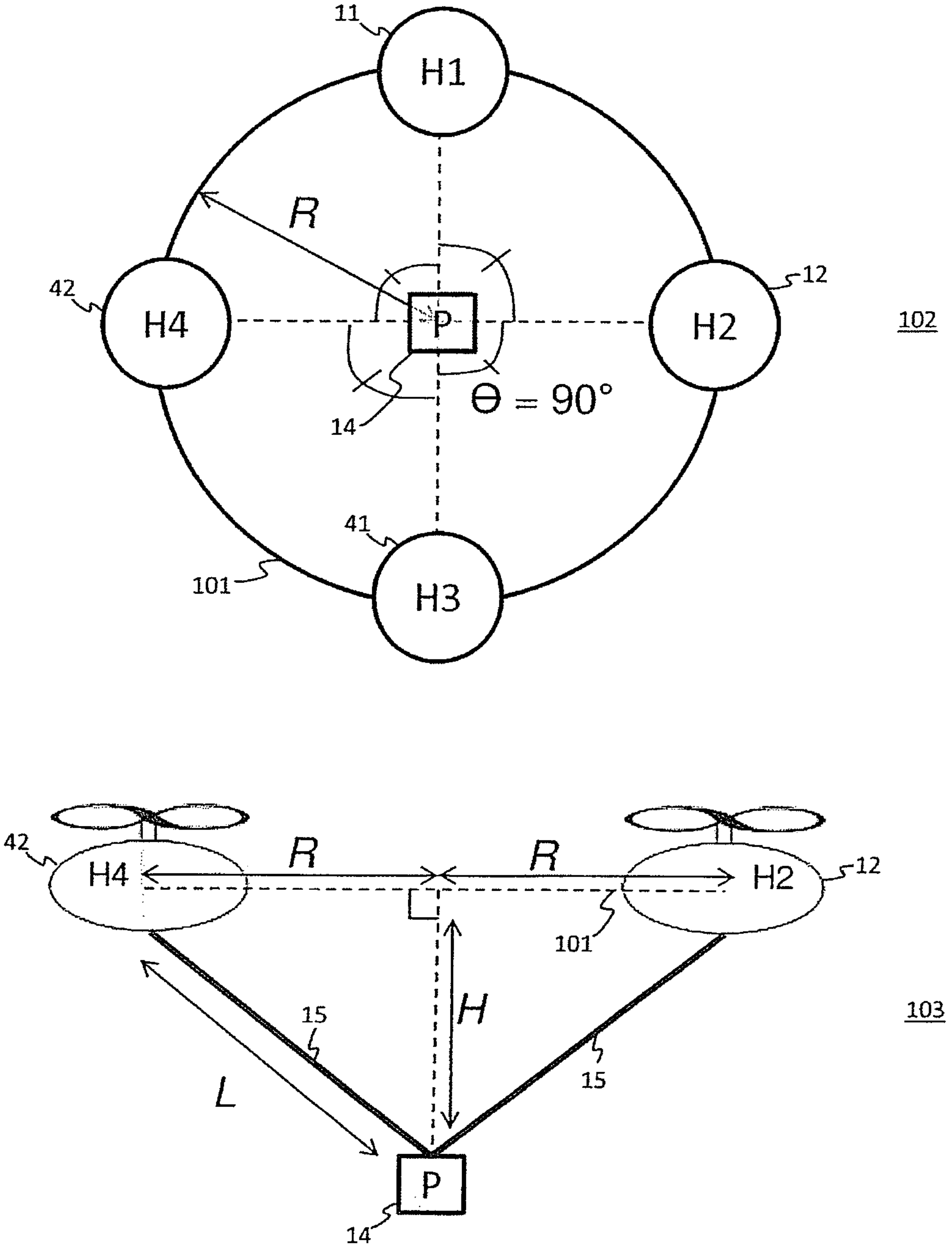

11
H1
R
42
H4
P
H2
12
102
14
Θ = 90°
41
H3
101
42
H4
R
R
H2
12
101
H
103
15
L
15
P
14

FIG. 10

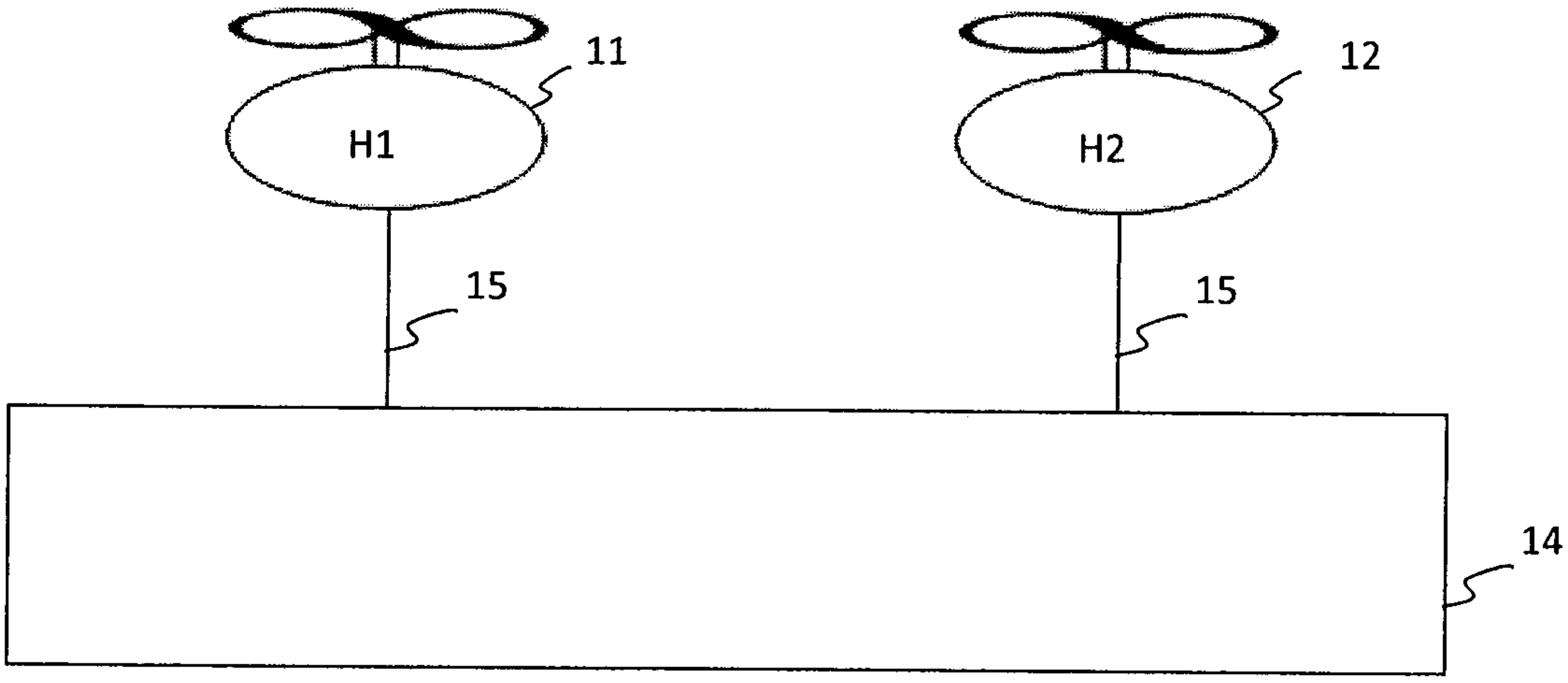


FIG. 11

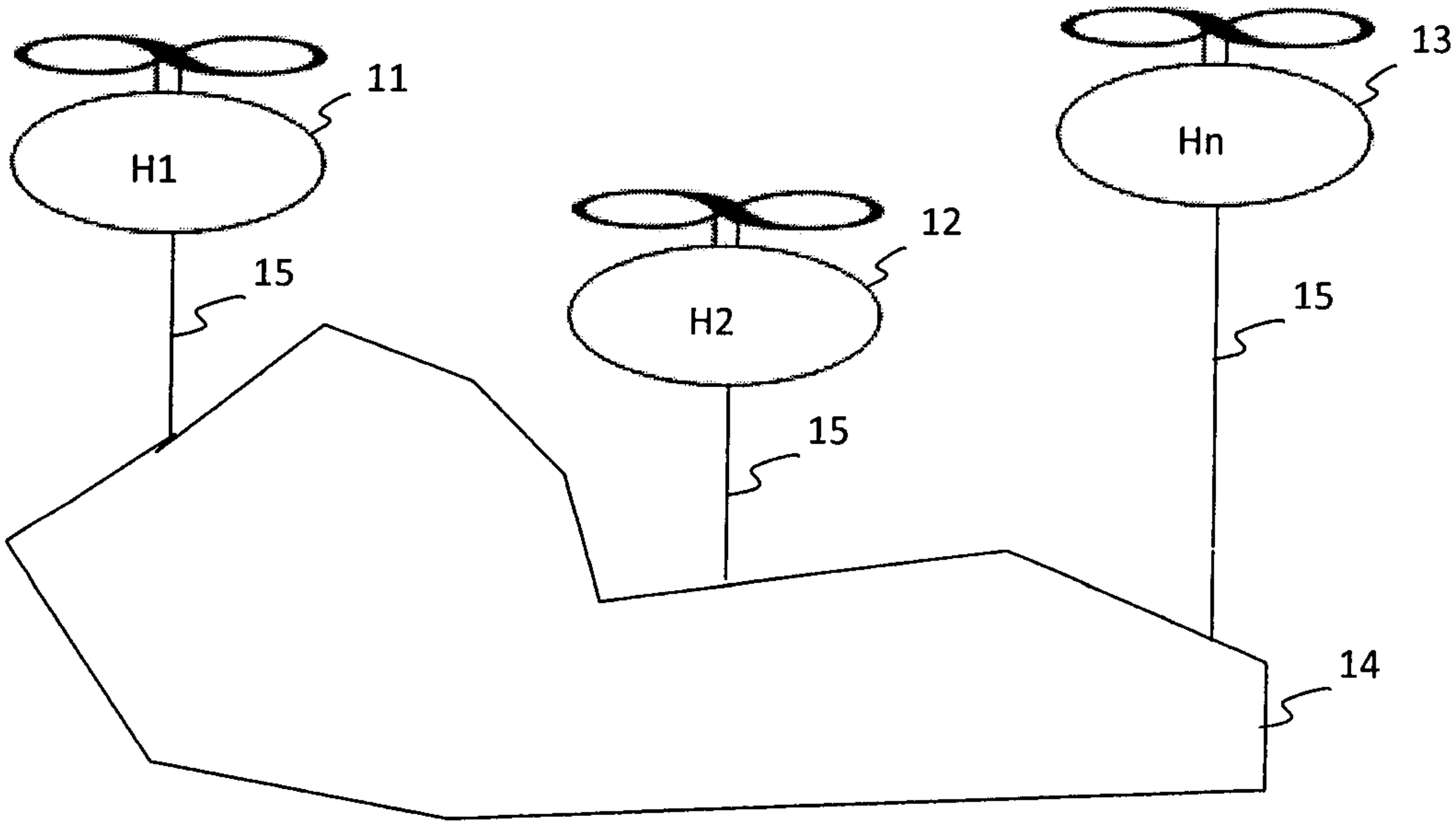


FIG. 12

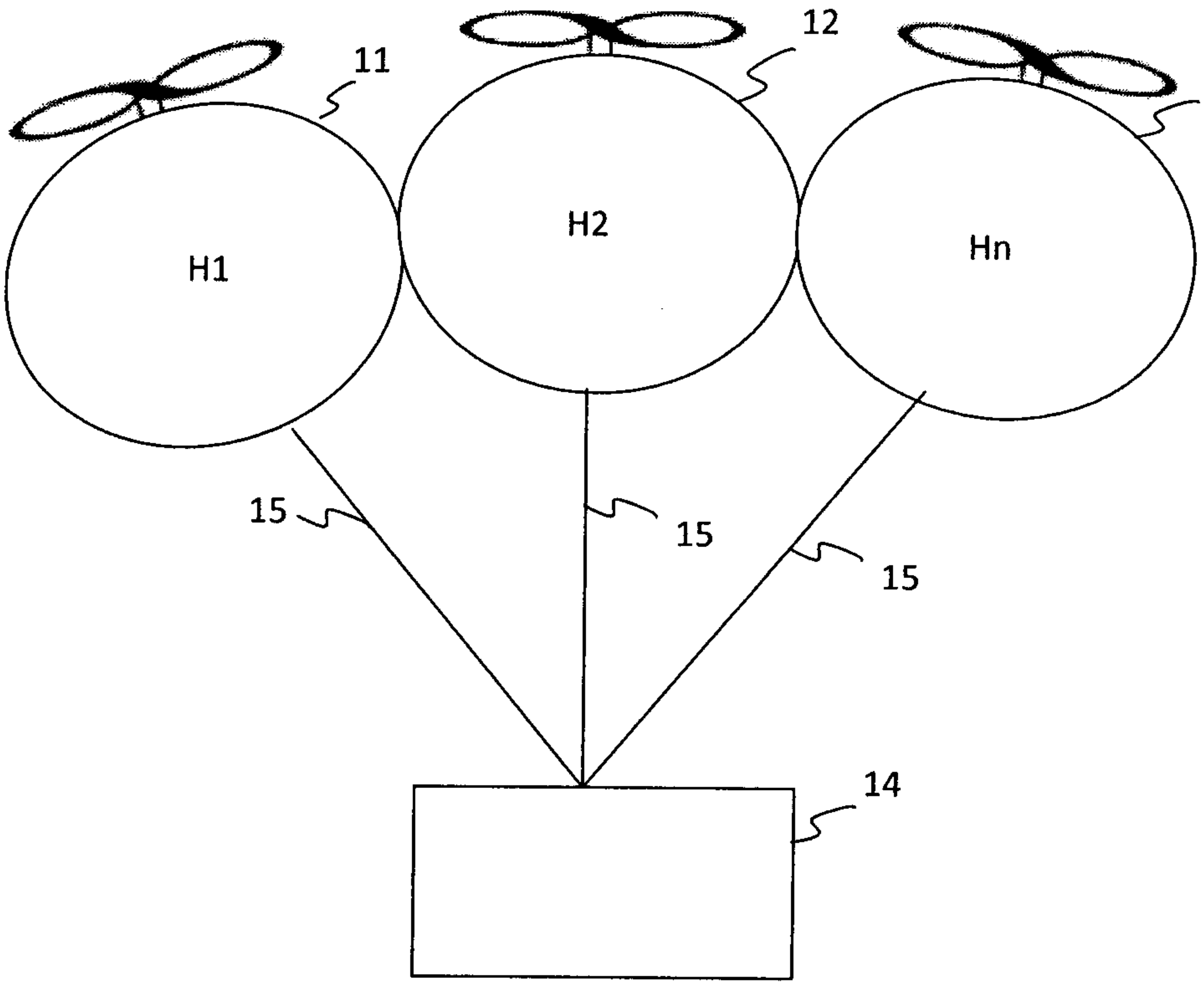


FIG. 13

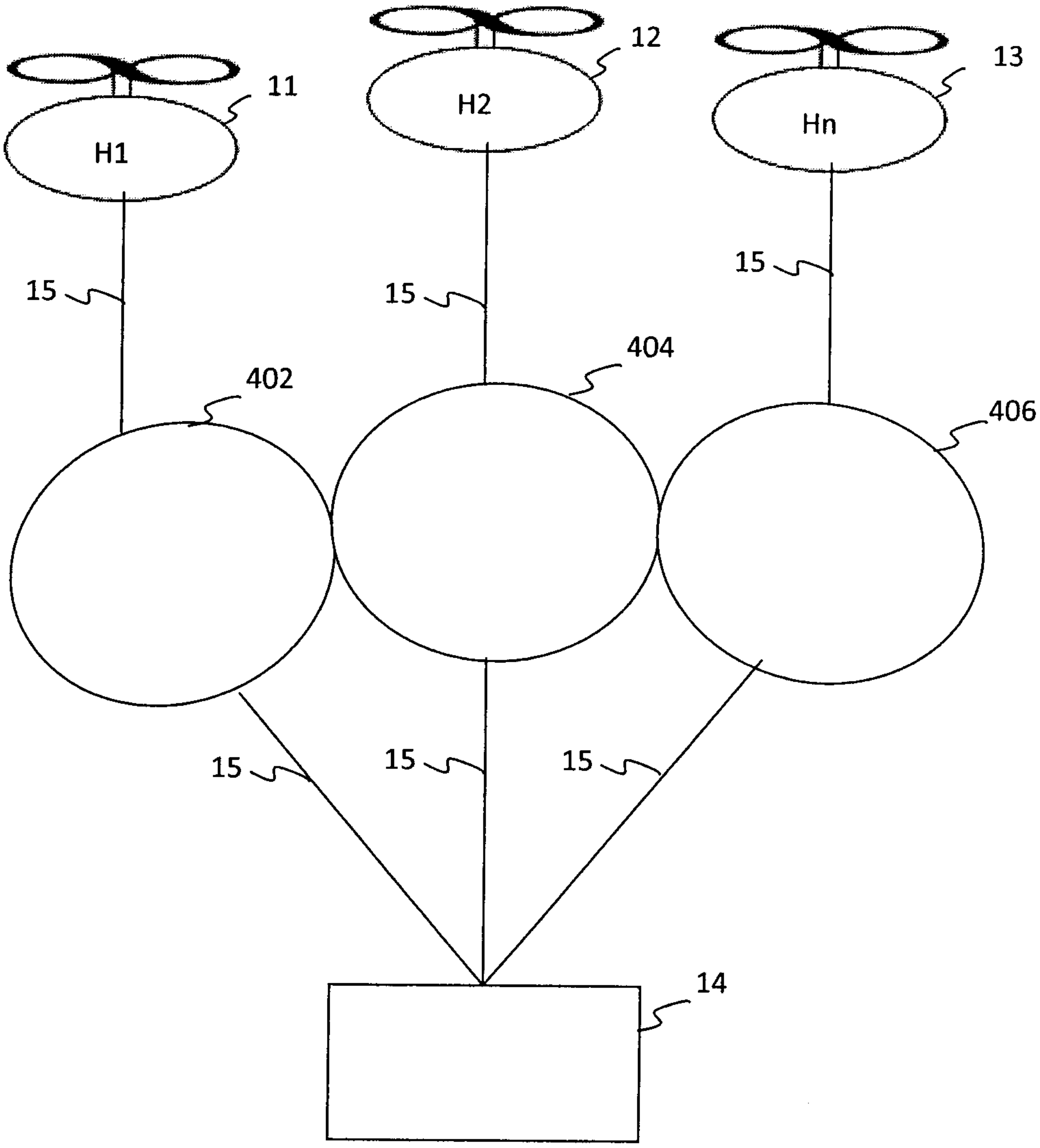
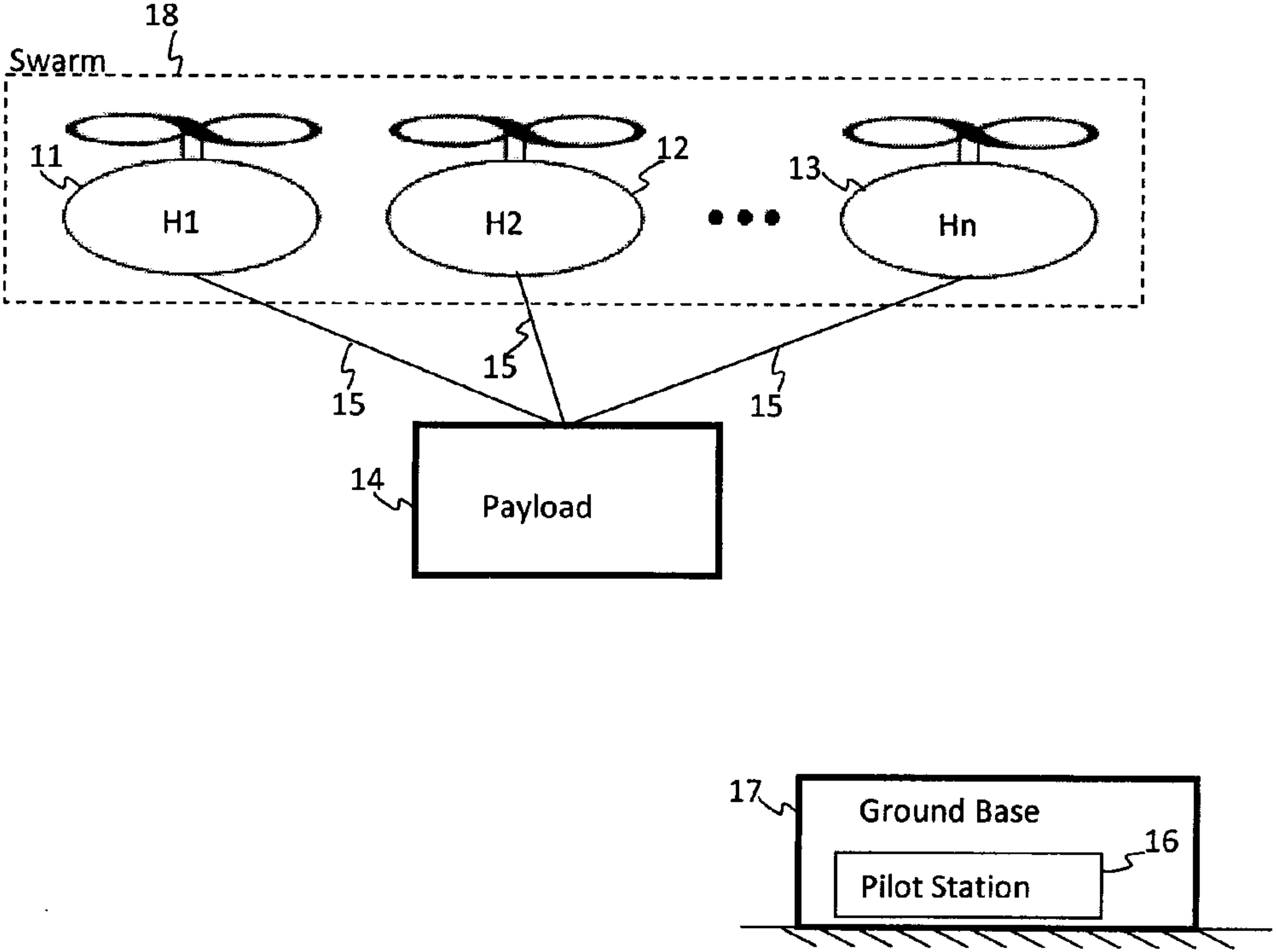


FIG. 14


18
Swarm
11
H1
12
H2
13
Hn
15
15
15
15
14
Payload
17
Ground Base
16
Pilot Station