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(54) **METHODS AND SYSTEMS FOR CONSERVING POWER DURING HOVER FLIGHT**

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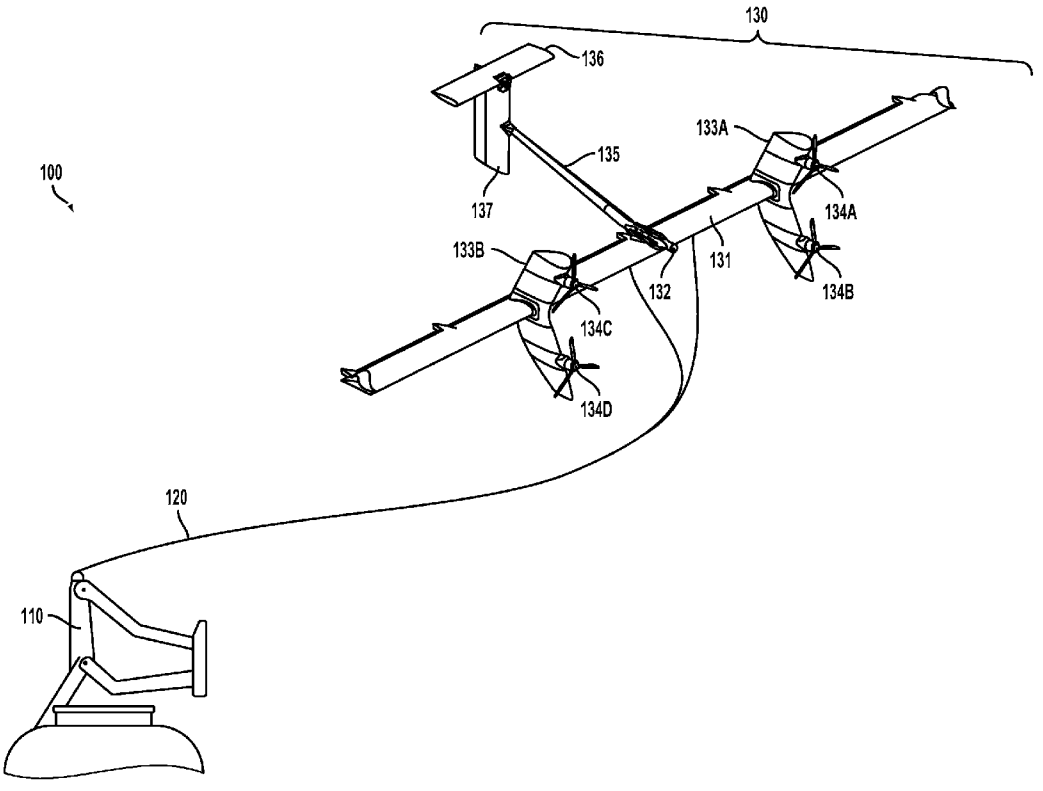
(57) **ABSTRACT**

An example method may include determining a drag force of an apparent wind on an aircraft that is coupled to a ground station via a tether. The method also includes determining a trajectory of the aircraft to a point downwind of the ground station such that the aircraft travelling the trajectory causes the tether to unfurl along a catenary path above ground. The method further includes determining an orientation of the aircraft to travel the trajectory in the apparent wind so that an actuator of the aircraft is configured to provide a vertical thrust in a direction substantially perpendicular to the ground. The method also includes determining a vertical thrust for the aircraft at the orientation to travel the trajectory in the apparent wind. The method also includes providing instructions to cause the actuator of the aircraft to provide the vertical thrust to move the aircraft along the trajectory.



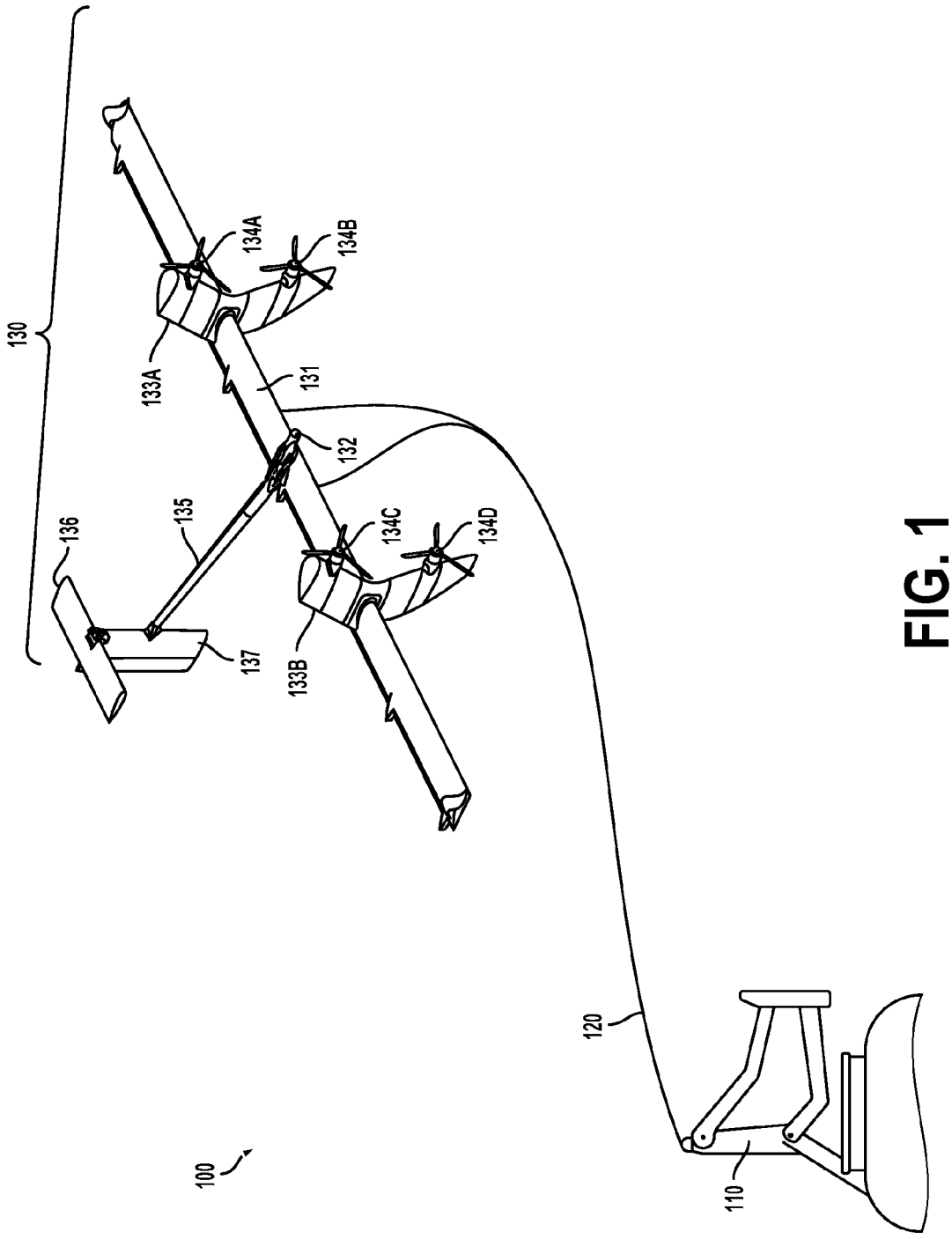

130
134A
134B
133A
131
132
135
136
134C
134D
137
133B
120
110
100

FIG. 1

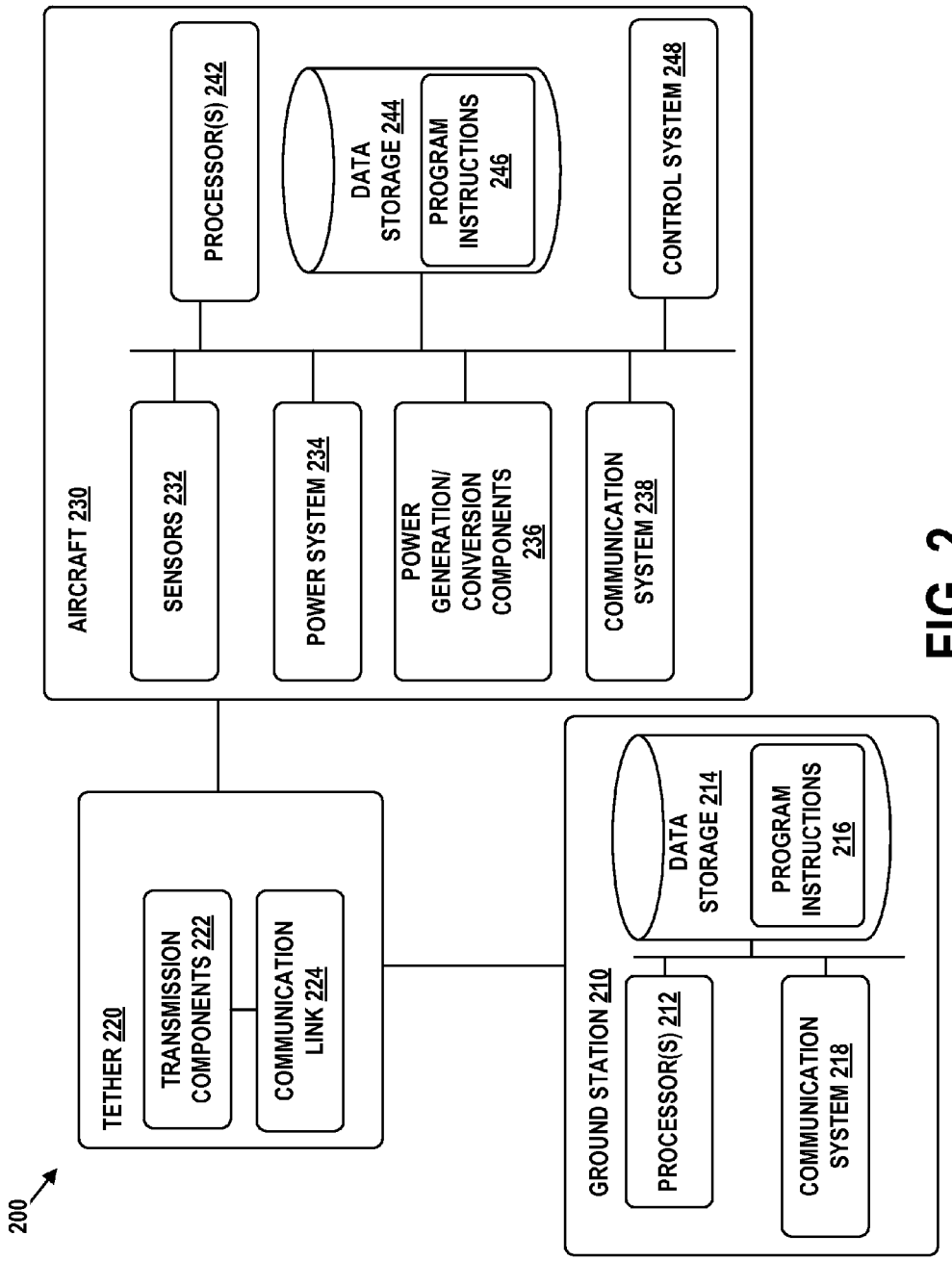

200
AIRCRAFT 230
PROCESSOR(S) 242
DATA STORAGE 244
PROGRAM INSTRUCTIONS 246
CONTROL SYSTEM 248
SENSORS 232
POWER SYSTEM 234
POWER GENERATION/ CONVERSION COMPONENTS 236
COMMUNICATION SYSTEM 238
TETHER 220
TRANSMISSION COMPONENTS 222
COMMUNICATION LINK 224
GROUND STATION 210
DATA STORAGE 214
PROGRAM INSTRUCTIONS 216
PROCESSOR(S) 212
COMMUNICATION SYSTEM 218

FIG. 2

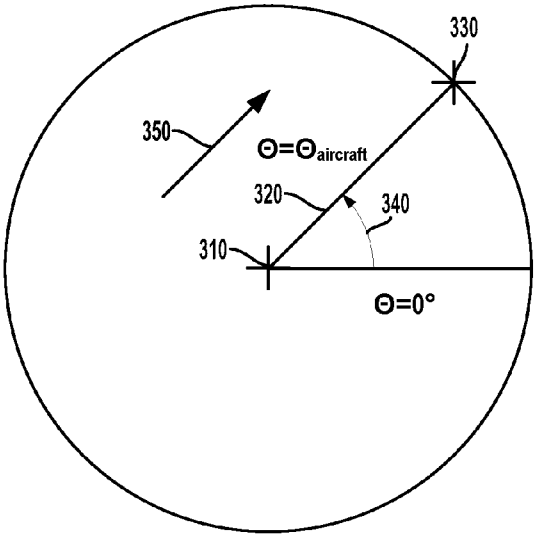

330
350
Θ=Θaircraft
320
340
310
Θ=0°

FIG. 3A

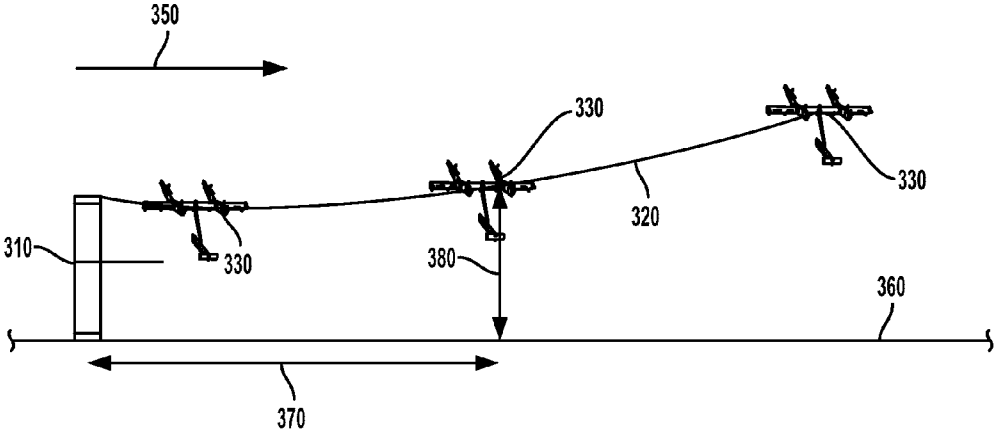

350
330
330
320
310
330
380
360
370

FIG. 3B

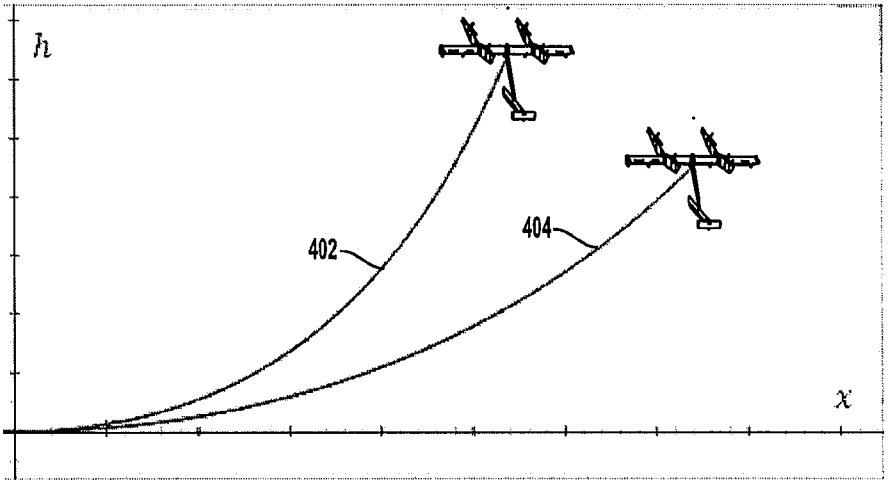


FIG. 4A

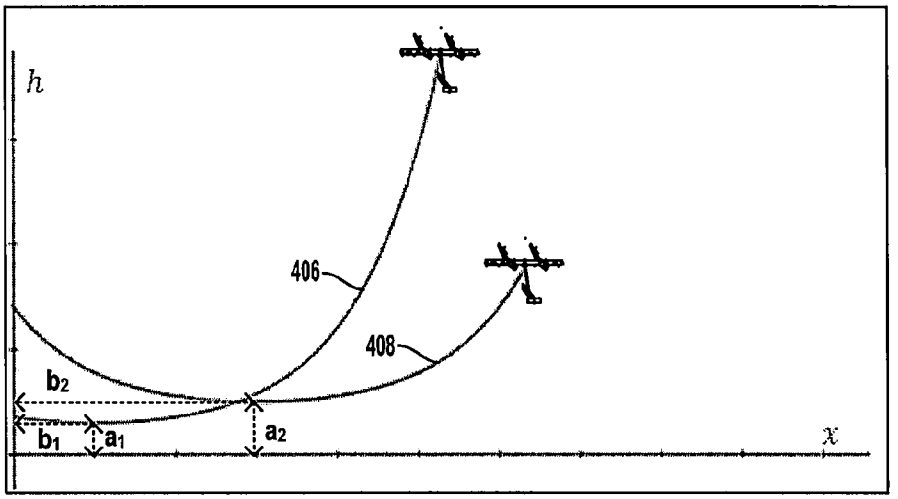


FIG. 4B

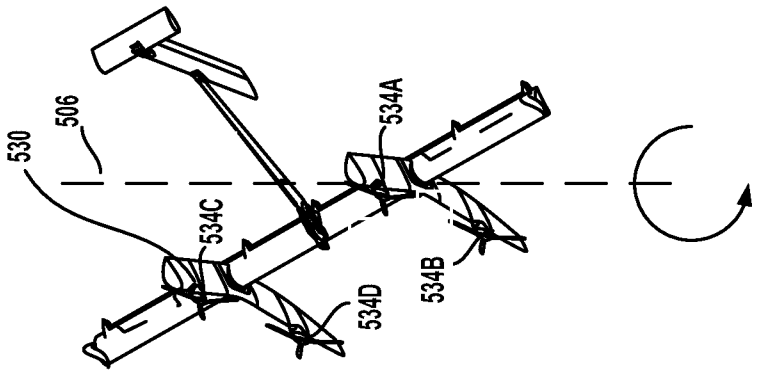


FIG. 5C

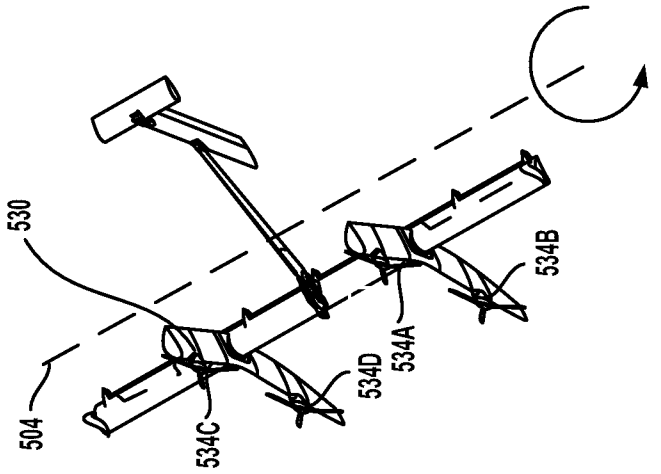


FIG. 5B

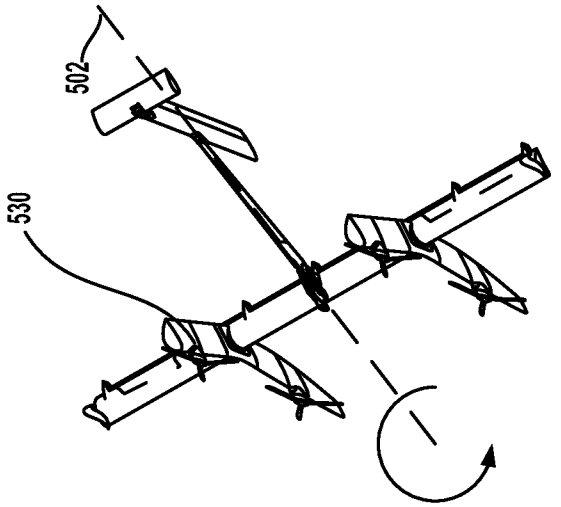


FIG. 5A

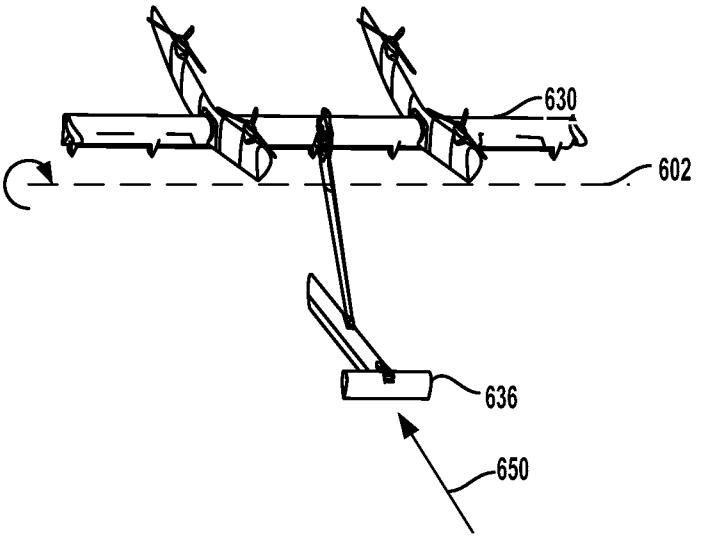


FIG. 6A

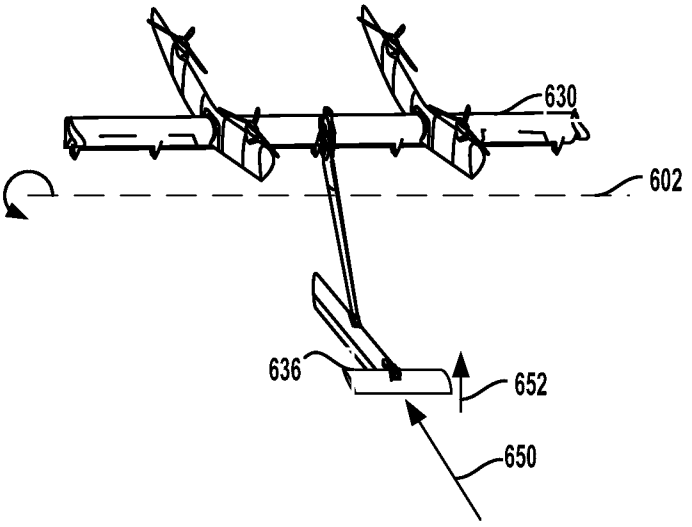


FIG. 6B

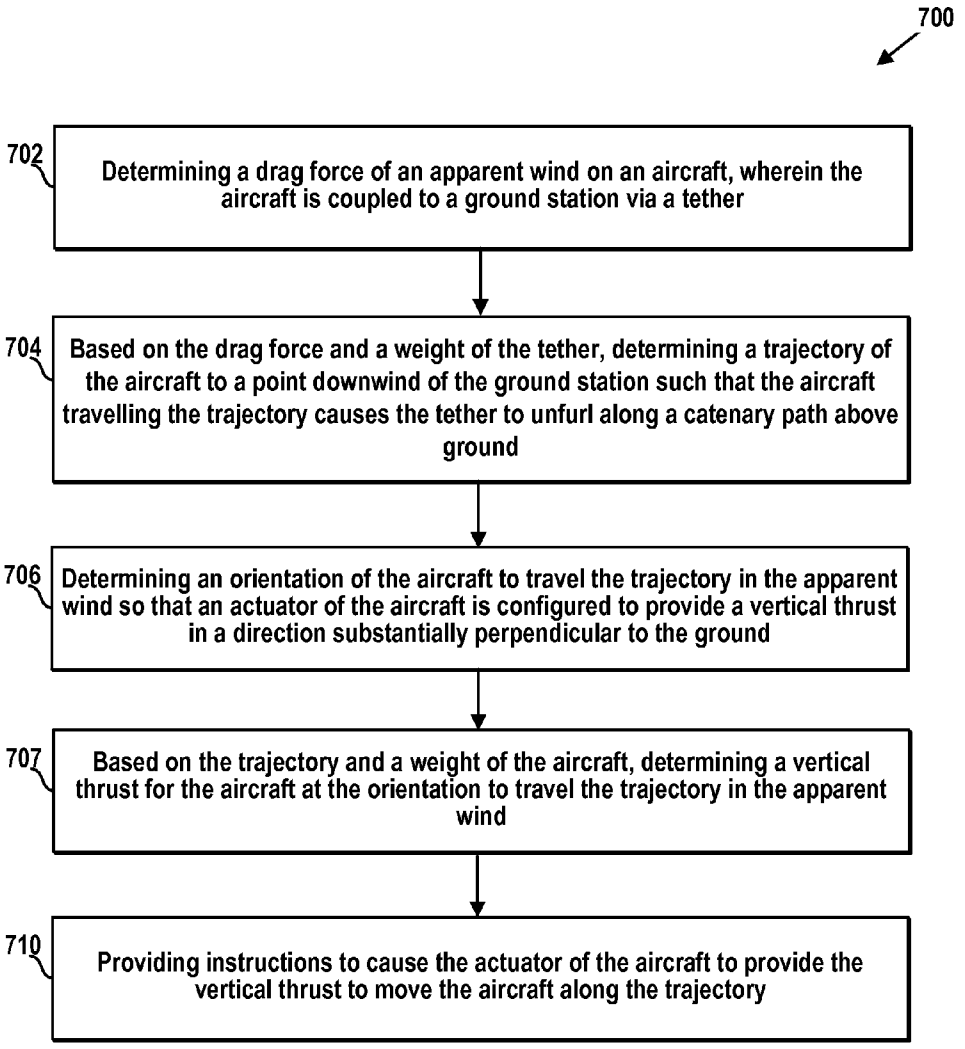

700
702
Determining a drag force of an apparent wind on an aircraft, wherein the aircraft is coupled to a ground station via a tether
704
Based on the drag force and a weight of the tether, determining a trajectory of the aircraft to a point downwind of the ground station such that the aircraft travelling the trajectory causes the tether to unfurl along a catenary path above ground
706
Determining an orientation of the aircraft to travel the trajectory in the apparent wind so that an actuator of the aircraft is configured to provide a vertical thrust in a direction substantially perpendicular to the ground
707
Based on the trajectory and a weight of the aircraft, determining a vertical thrust for the aircraft at the orientation to travel the trajectory in the apparent wind
710
Providing instructions to cause the actuator of the aircraft to provide the vertical thrust to move the aircraft along the trajectory

FIG. 7

METHODS AND SYSTEMS FOR CONSERVING POWER DURING HOVER FLIGHT

BACKGROUND

[0001] Unless otherwise indicated herein, the materials described in this section are not prior art to the claims in this application and are not admitted to be prior art by inclusion in this section.

[0002] Many techniques and systems exist for controlling a flight path of an aircraft. Generally, an ability to change a position or an attitude of the aircraft will depend on the location and functionality of actuators included as part of the aircraft.

SUMMARY

[0003] In one example, a method is provided that includes determining a drag force of an apparent wind on an aircraft coupled to a ground station via a tether. The method also includes, based on the drag force and a weight of the tether, determining a trajectory of the aircraft to a point downwind of the ground station such that the aircraft travelling the trajectory causes the tether to unfurl along a catenary path above ground. The method further includes determining an orientation of the aircraft to travel the trajectory in the apparent wind so that an actuator of the aircraft is configured to provide a vertical thrust in a direction substantially perpendicular to the ground. The method also includes, based on the trajectory and a weight of the aircraft, determining a vertical thrust for the aircraft at the orientation to travel the trajectory in the apparent wind. The method also includes providing instructions to cause the actuator of the aircraft to provide the vertical thrust to move the aircraft along the trajectory.

[0004] In another example, a computer readable storage memory having stored therein instructions, that when executed by a computing device that includes one or more processors, cause the computing device to perform functions is provided. The functions comprise determining a drag force of an apparent wind on an aircraft coupled to a ground station via a tether. The functions further comprise, based on the drag force and a weight of the tether, determining a trajectory of the aircraft to a point downwind of the ground station such that the aircraft travelling the trajectory causes the tether to unfurl along a catenary path above ground. The functions further comprise determining an orientation of the aircraft to travel the trajectory in the apparent wind so that an actuator of the aircraft is configured to provide a vertical thrust in a direction substantially perpendicular to the ground. The functions further comprise based on the trajectory and a weight of the aircraft, determining a vertical thrust for the aircraft at the orientation to travel the trajectory in the apparent wind. The functions further comprise providing instructions to cause the actuator of the aircraft to provide the vertical thrust to move the aircraft along the trajectory.

[0005] In still another example, a system is provided that comprises one or more processors and memory configured to store instructions, that when executed by the one or more processors, cause the system to perform functions. The functions comprise determining a drag force of an apparent wind on an aircraft coupled to a ground station via a tether. The functions further comprise, based on the drag force and a weight of the tether, determining a trajectory of the aircraft to a point downwind of the ground station such that the aircraft travelling the trajectory causes the tether to unfurl along a catenary path above ground. The functions further comprise determining an orientation of the aircraft to travel the trajectory in the apparent wind so that an actuator of the aircraft is configured to provide a vertical thrust in a direction substantially perpendicular to the ground. The functions further comprise, based on the trajectory and a weight of the aircraft, determining a vertical thrust for the aircraft at the orientation to travel the trajectory in the apparent wind. The functions further comprise providing instructions to cause the actuator of the aircraft to provide the vertical thrust to move the aircraft along the trajectory.

[0006] In yet another example, a system is provided that includes a means for determining a drag force of an apparent wind on an aircraft coupled to a ground station via a tether. The system further comprises means for, based on the drag force and a weight of the tether, determining a trajectory of the aircraft to a point downwind of the ground station such that the aircraft travelling the trajectory causes the tether to unfurl along a catenary path above ground. The system further comprises means for determining an orientation of the aircraft to travel the trajectory in the apparent wind so that an actuator of the aircraft is configured to provide a vertical thrust in a direction substantially perpendicular to the ground. The system further comprises means for, based on the trajectory and a weight of the aircraft, determining a vertical thrust for the aircraft at the orientation to travel the trajectory in the apparent wind. The system further comprises means for providing instructions to cause the actuator of the aircraft to provide the vertical thrust to move the aircraft along the trajectory.

[0007] These as well as other aspects, advantages, and alternatives, will become apparent to those of ordinary skill in the art by reading the following detailed description, with reference where appropriate to the accompanying figures.

BRIEF DESCRIPTION OF THE FIGURES

[0008] FIG. **1** depicts a tethered flight system, according to an example embodiment.

[0009] FIG. **2** is a simplified block diagram illustrating example components of the tethered flight system.

[0010] FIG. **3**A depicts a downward looking view of an example tethered flight system.

[0011] FIG. **3**B depicts examples of the aircraft engaging in hover flight at various horizontal positions and altitudes.

[0012] FIG. **4**A depicts a first example catenary path and a second example catenary path.

[0013] FIG. **4**B depicts a third example catenary path and a fourth example catenary path.

[0014] FIG. **5**A depicts an example roll axis of an aircraft.

[0015] FIG. **5**B depicts an example pitch axis of the aircraft.

[0016] FIG. **5**C depicts an example yaw axis of the aircraft.

[0017] FIG. **6**A depicts examples of a pitch axis of an aircraft, a tail wing, and an apparent wind.

[0018] FIG. **6**B depicts examples of a pitch axis of an aircraft, a tail wing, and an apparent wind.

[0019] FIG. **7** is a block diagram of an example method for determining a trajectory and an orientation of the aircraft that causes a tether to unfurl along a catenary path above ground.

DETAILED DESCRIPTION

[0020] The following detailed description describes various features and functions of the disclosed systems and meth-

ods with reference to the accompanying figures. In the figures, similar symbols identify similar components, unless context dictates otherwise. The illustrative system and method embodiments described herein are not meant to be limiting. It may be readily understood that certain aspects of the disclosed systems and methods can be arranged and combined in a wide variety of different configurations, all of which are contemplated herein.

[0021] Within examples, a processor may be configured to determine a drag force of an apparent wind on an aircraft tethered to a ground station. The processor may determine the drag force based on a density of air, a drag coefficient of the aircraft, a reference area of the aircraft, or a speed of the apparent wind. The drag coefficient may represent a tendency of the aircraft to resist movement of air moving over the surface of the aircraft based on the shape of the aircraft. The reference area of the aircraft may represent a cross sectional area of the aircraft in a plane perpendicular to the apparent wind, but may also represent any area of the aircraft.

[0022] Next, the processor may determine a trajectory of the aircraft to a point downwind of the ground station such that by moving along the trajectory, the aircraft pulls the tether along a catenary path above ground as the tether is unfurled. The processor may determine the trajectory based on the drag force and a weight of the tether, such that a tension of the tether is caused by the drag force of the apparent wind. For example, a decrease in the weight of the tether or an increase in the drag force may cause the point downwind of the ground station to be at a lower altitude. By further example, an increase in the weight of the tether or a decrease in the drag force may cause the point downwind of the ground station to be at a higher altitude.

[0023] The processor may also determine an orientation of the aircraft for the aircraft to travel toward the point downwind of the ground station. The aircraft may include an actuator and while the aircraft is in the orientation the actuator may be configured to provide a vertical thrust in a direction substantially perpendicular to the ground. The orientation may be referred to as zero pitch. The aircraft being in the orientation may allow the actuator to move the aircraft in a substantially vertical direction, while the drag force from the apparent wind moves the aircraft in a substantially horizontal direction.

[0024] Based on the trajectory and a weight of the aircraft, the processor may determine a vertical thrust for the aircraft at the orientation to travel the trajectory in the apparent wind. The processor may determine a vertical acceleration to travel the trajectory, and may determine the vertical thrust based on the vertical acceleration, the weight of the aircraft, a weight of a portion of the tether supported by the aircraft, and gravitational forces acting on the aircraft and the tether. The processor may further provide instructions to the actuator to provide the vertical thrust to move the aircraft along the trajectory.

[0025] Referring now to the figures, FIG. **1** depicts a tethered flight system **100**, according to an example embodiment. The tethered flight system **100** may include a ground station **110**, a tether **120**, and an aircraft **130**. As shown in FIG. **1**, the aircraft **130** may be connected to the tether **120**, and the tether **120** may be connected to the ground station **110**. The tether **120** may be attached to the ground station **110** at one location on the ground station **110**, and attached to the aircraft **130** at two locations on the aircraft **130**. However, in other examples, the tether **120** may be attached at multiple locations to any part of the ground station **110** or the aircraft **130**.

[0026] The ground station **110** may be used to hold or support the aircraft **130** until the aircraft **130** is in a flight mode. The ground station **110** may also be configured to reposition the aircraft **130** such that deploying the aircraft **130** is possible. Further, the ground station **110** may be further configured to receive the aircraft **130** during a landing. The ground station **110** may be formed of any material that can suitably keep the aircraft **130** attached or anchored to the ground while in hover flight, forward flight, or crosswind flight.

[0027] In addition, the ground station **110** may include one or more components (not shown), such as a winch, that may vary a length of the tether **120**. For example, when the aircraft **130** is deployed, the one or more components may be configured to pay out or reel out the tether **120**. In some implementations, the one or more components may be configured to pay out or reel out the tether **120** to a predetermined length. As examples, the predetermined length could be equal to or less than a maximum length of the tether **120**. Further, when the aircraft **130** lands on the ground station **110**, the one or more components may be configured to reel in the tether **120**.

[0028] The tether **120** may transmit electrical energy generated by the aircraft **130** to the ground station **110**. In addition, the tether **120** may transmit electricity to the aircraft **130** to power the aircraft **130** for takeoff, landing, hover flight, or forward flight. The tether **120** may be constructed in any form and using any material which allows for the transmission, delivery, or harnessing of electrical energy generated by the aircraft **130** or transmission of electricity to the aircraft **130**. The tether **120** may also be configured to withstand one or more forces of the aircraft **130** when the aircraft **130** is in a flight mode. For example, the tether **120** may include a core configured to withstand one or more forces of the aircraft **130** when the aircraft **130** is in hover flight, forward flight, or crosswind flight. The core may be constructed of high strength fibers. In some examples, the tether **120** may have a fixed length or a variable length.

[0029] The aircraft **130** may include various types of devices, such as a kite, a helicopter, a wing, or an airplane, among other possibilities. The aircraft **130** may be formed of solid structures of metal, plastic, polymers, or any material which allows for a high thrust-to-weight ratio and generation of electrical energy which may be used in utility applications. Additionally, the materials may allow for a lightning hardened, redundant or fault tolerant design which may be capable of handling large or sudden shifts in wind speed and wind direction. Other materials may be possible as well.

[0030] As shown in FIG. **1**, the aircraft **130** may include a main wing **131**, a front section **132**, actuator connectors **133**A-B, actuators **134**A-D, a tail boom **135**, a tail wing **136**, and a vertical stabilizer **137**. Any of these components may be shaped in any form which allows for the use of lift to resist gravity or move the aircraft **130** forward.

[0031] The main wing **131** may provide a primary lift for the aircraft **130** during forward flight, wherein the aircraft **130** may move through air in a direction substantially parallel to a direction of thrust provided by the actuators **134**A-D so that the main wing **131** provides a lift force substantially perpendicular to a ground. The main wing **131** may be one or more rigid or flexible airfoils, and may include various control surfaces or actuators, such as winglets, flaps, rudders, elevators, etc. The control surfaces may be used to steer or stabilize the aircraft **130** or reduce drag on the aircraft **130** during hover flight, forward flight, or crosswind flight. The main wing **131**

may be any suitable material for the aircraft **130** to engage in hover flight, forward flight, or crosswind flight. For example, the main wing **131** may include carbon fiber or e-glass. Moreover, the main wing **131** may have a variety dimensions. For example, the main wing **131** may have one or more dimensions that correspond with a conventional wind turbine blade. The front section **132** may include one or more components, such as a nose, to reduce drag on the aircraft **130** during flight.

[0032] The actuator connectors **133**A-B may connect the actuators **134**A-D to the main wing **131**. In some examples, the actuator connectors **133**A-B may take the form of or be similar in form to one or more pylons. In the example depicted in FIG. **1**, the actuator connectors **133**A-B are arranged such that the actuators **134**A and **134**B are located on opposite sides of the main wing **131** and actuators **134**C and **134**D are also located on opposite sides of the main wing **131**. The actuator **134**C may also be located on an end of the main wing **131** opposite of the actuator **134**A, and the actuator **134**D may be located on an end of main wing **131** opposite of the actuator **134**B.

[0033] In a power generating mode, the actuators **134**A-D may be configured to drive one or more generators for the purpose of generating electrical energy. As shown in FIG. **1**, the actuators **134**A-D may each include one or more blades. The actuator blades may rotate via interactions with the wind and could be used to drive the one or more generators. In addition, the actuators **134**A-D may also be configured to provide a thrust to the aircraft **130** during flight. As shown in FIG. **1**, the actuators **134**A-D may function as one or more propulsion units, such as a propeller. Although the actuators **134**A-D are depicted as four actuators in FIG. **1**, in other examples the aircraft **130** may include any number of actuators.

[0034] In a forward flight mode, the actuators **134**A-D may be configured to generate a forward thrust substantially parallel to the tail boom **135**. Based on the position of the actuators **134**A-D relative to the main wing **131** depicted in FIG. **1**, the actuators may be configured to provide a maximum forward thrust for the aircraft **130** when all of the actuators **134**A-D are operating at full power. The actuators **134**A-D may provide equal or about equal amounts of forward thrusts when the actuators **134**A-D are operating at full power, and a net rotational force applied to the aircraft by the actuators **134**A-D may be zero.

[0035] The tail boom **135** may connect the main wing **131** to the tail wing **136** and the vertical stabilizer **137**. The tail boom **135** may have a variety of dimensions. Moreover, in some implementations, the tail boom **135** could take the form of a body or fuselage of the aircraft **130**. In such implementations, the tail boom **135** may carry a payload.

[0036] The tail wing **136** or the vertical stabilizer **137** may be used to steer or stabilize the aircraft **130** or reduce drag on the aircraft **130** during hover flight, forward flight, or crosswind flight. For example, the tail wing **136** or the vertical stabilizer **137** may be used to maintain a pitch or a yaw attitude of the aircraft **130** during hover flight, forward flight, or crosswind flight. In FIG. **1**, the vertical stabilizer **137** is attached to the tail boom **135**, and the tail wing **136** is located on top of the vertical stabilizer **137**. The tail wing **136** may have a variety of dimensions.

[0037] While the aircraft **130** has been described above, it should be understood that the methods and systems described herein could involve any aircraft that is connected to a tether, such as the tether **120**.

[0038] FIG. **2** is a simplified block diagram illustrating example components of the tethered flight system **200**. The tethered flight system **200** may include the ground station **210**, the tether **220**, and the aircraft **230**. As shown in FIG. **2**, the ground station **210** may include one or more processors **212**, data storage **214**, program instructions **216**, and a communication system **218**. A processor **212** may be a general-purpose processor or a special purpose processor (e.g., digital signal processors, application specific integrated circuits, etc.). The one or more processors **212** may be configured to execute computer-readable program instructions **216** that are stored in data storage **214** and are executable to provide at least part of the functionality described herein.

[0039] The data storage **214** may include or take the form of one or more computer-readable storage media that may be read or accessed by at least one processor **212**. The one or more computer-readable storage media can include volatile or non-volatile storage components, such as optical, magnetic, organic or other memory or disc storage, which may be integrated in whole or in part with at least one of the one or more processors **212**. In some embodiments, the data storage **214** may be implemented using a single physical device (e.g., one optical, magnetic, organic or other memory or disc storage unit), while in other embodiments, the data storage **214** can be implemented using two or more physical devices.

[0040] As noted, the data storage **214** may include computer-readable program instructions **216** and perhaps additional data, such as diagnostic data of the ground station **210**. As such, the data storage **214** may include program instructions to perform or facilitate some or all of the functionality described herein.

[0041] In a further respect, the ground station **210** may include the communication system **218**. The communications system **218** may include one or more wireless interfaces or one or more wireline interfaces, which allow the ground station **210** to communicate via one or more networks. Such wireless interfaces may provide for communication under one or more wireless communication protocols, such as Bluetooth, WiFi (e.g., an IEEE 802.11 protocol), Long-Term Evolution (LTE), WiMAX (e.g., an IEEE 802.16 standard), a radio-frequency ID (RFID) protocol, near-field communication (NFC), or other wireless communication protocols. Such wireline interfaces may include an Ethernet interface, a Universal Serial Bus (USB) interface, or a similar interface to communicate via a wire, a twisted pair of wires, a coaxial cable, an optical link, a fiber-optic link, or other physical connection to a wireline network. The ground station **210** may communicate with the aircraft **230**, other ground stations, or other entities (e.g., a command center) via the communication system **218**.

[0042] In an example embodiment, the ground station **210** may include communication systems **218** that allows for both short-range communication and long-range communication. For example, the ground station **210** may be configured for short-range communications using Bluetooth and for long-range communications under a CDMA protocol. In such an embodiment, the ground station **210** may be configured to function as a "hot spot", or as a gateway or proxy between a remote support device (e.g., the tether **220**, the aircraft **230**, and other ground stations) and one or more data networks, such as a cellular network or the Internet. Configured as such, the ground station **210** may facilitate data communications that the remote support device would otherwise be unable to perform by itself.

[0043] For example, the ground station **210** may provide a WiFi connection to the remote device, and serve as a proxy or gateway to a cellular service provider's data network, which the ground station **210** might connect to under an LTE or a 3G protocol, for instance. The ground station **210** could also serve as a proxy or gateway to other ground stations or a command station, which the remote device might not be able to otherwise access.

[0044] Moreover, as shown in FIG. **2**, the tether **220** may include transmission components **222** and a communication link **224**. The transmission components **222** may be configured to transmit electrical energy from the aircraft **230** to the ground station **210** or transmit electrical energy from the ground station **210** to the aircraft **230**. The transmission components **222** may take various different forms in different embodiments. For example, the transmission components **222** may include one or more conductors that are configured to transmit electricity. And in at least one such example, the one or more conductors may include aluminum or any other material which allows for the conduction of electric current. Moreover, in some implementations, the transmission components **222** may surround a core of the tether **220** (not shown).

[0045] The ground station **210** could communicate with the aircraft **230** via the communication link **224**. The communication link **224** may be bidirectional and may include one or more wired or wireless interfaces. Also, there could be one or more routers, switches, or other devices or networks making up at least a part of the communication link **224**.

[0046] Further, as shown in FIG. **2**, the aircraft **230** may include one or more sensors **232**, a power system **234**, power generation/conversion components **236**, a communication system **238**, one or more processors **242**, data storage **244**, program instructions **246**, and a control system **248**.

[0047] The sensors **232** could include various different sensors in different embodiments. For example, the sensors **232** may include a global positioning system (GPS) receiver. The GPS receiver may be configured to provide data that is typical of GPS systems (which may be referred to as a global navigation satellite system (GNNS)), such as the GPS coordinates of the aircraft **230**. Such GPS data may be utilized by the tethered flight system **200** to provide various functions described herein.

[0048] As another example, the sensors **232** may include one or more wind sensors, such as one or more pitot tubes. The one or more wind sensors may be configured to detect apparent or relative wind. Such wind data may be utilized by the tethered flight system **200** to provide various functions described herein.

[0049] Still as another example, the sensors **232** may include an inertial measurement unit (IMU). The IMU may include both an accelerometer and a gyroscope, which may be used together to determine the orientation or attitude of the aircraft **230**. In particular, the accelerometer can measure the orientation of the aircraft **230** with respect to earth, while the gyroscope measures the rate of rotation around an axis, such as a centerline of the aircraft **230**. IMUs are commercially available in low-cost, low-power packages. For instance, the IMU may take the form of or include a miniaturized MicroElectroMechanical System (MEMS) or a NanoElectroMechanical System (NEMS). Other types of IMUs may also be utilized. The IMU may include other sensors, in addition to accelerometers and gyroscopes, which may help to better determine position. Two examples of such sensors are magnetometers and pressure sensors. Other examples are also possible.

[0050] While an accelerometer and gyroscope may be effective at determining the orientation of the aircraft **230**, errors in measurement may compound over time. However, an example aircraft **230** may be able mitigate or reduce such errors by using a magnetometer to measure direction. One example of a magnetometer is a low-power, digital 3-axis magnetometer, which may be used to realize an orientation independent electronic compass for accurate heading information. However, other types of magnetometers may be utilized as well.

[0051] The aircraft **230** may also include a pressure sensor or barometer, which can be used to determine the altitude of the aircraft **230**. Alternatively, other sensors, such as sonic altimeters or radar altimeters, can be used to provide an indication of altitude, which may help to improve the accuracy of or prevent drift of the IMU. The aircraft **230** may include a thermometer or another sensor that senses air temperature as well.

[0052] As noted, the aircraft **230** may include the power system **234**. The power system **234** could take various different forms in different embodiments. For example, the power system **234** may include one or more batteries that provide power to the aircraft **230**. In some implementations, the one or more batteries may be rechargeable and each battery may be recharged via a wired connection between the battery and a power supply or via a wireless charging system, such as an inductive charging system that applies an external time-varying magnetic field to an internal battery or a charging system that uses energy collected from one or more solar panels.

[0053] As another example, the power system **234** may include one or more motors or engines for providing power to the aircraft **230**. In one embodiment, the power system **234** may provide power to the actuators **134**A-D of the aircraft **130**, as shown and described in FIG. **1**. In some implementations, the one or more motors or engines may be powered by a fuel, such as a hydrocarbon-based fuel. In such implementations, the fuel could be stored on the aircraft **230** and delivered to the one or more motors or engines via one or more fluid conduits, such as piping. In some implementations, the power system **234** may be implemented in whole or in part on the ground station **210**.

[0054] As noted, the aircraft **230** may include the power generation/conversion components **236**. The power generation/conversion components **236** could take various different forms in different embodiments. For example, the power generation/conversion components **236** may include one or more generators, such as high-speed, direct-drive generators. The one or more generators may be driven by one or more rotors or actuators, such as the actuators **134**A-D as shown and described in FIG. **1**.

[0055] Moreover, the aircraft **230** may include a communication system **238**. The communication system **238** may take the form of or be similar in form to the communication system **218** of the ground station **210**. The aircraft **230** may communicate with the ground station **210**, other aircrafts, or other entities (e.g., a command center) via the communication system **238**.

[0056] In some implementations, the aircraft **230** may be configured to function as a "hot spot" or as a gateway or proxy between a remote support device (e.g., the ground station **210**, the tether **220**, other aircrafts) and one or more data networks,

such as cellular network or the Internet. Configured as such, the aircraft **230** may facilitate data communications that the remote support device would otherwise be unable to perform by itself.

[0057] For example, the aircraft **230** may provide a WiFi connection to the remote device, and serve as a proxy or gateway to a cellular service provider's data network, which the aircraft **230** might connect to under an LTE or a 3G protocol, for instance. The aircraft **230** could also serve as a proxy or gateway to other aircrafts or a command station, which the remote device might not be able to otherwise access.

[0058] As noted, the aircraft **230** may include the one or more processors **242**, the program instructions **244**, and the data storage **246**. The one or more processors **242** can be configured to execute computer-readable program instructions **246** that are stored in the data storage **244** and are executable to provide at least part of the functionality described herein. The one or more processors **242** may take the form of or be similar in form to the one or more processors **212**, the data storage **244** may take the form of or be similar in form to the data storage **214**, and the program instructions **246** may take the form of or be similar in form to the program instructions **216**.

[0059] Moreover, as noted, the aircraft **230** may include the control system **248**. In some implementations, the control system **248** may be configured to perform one or more functions described herein. The control system **248** may be implemented with mechanical systems or with hardware, firmware, or software. As one example, the control system **248** may take the form of program instructions stored on a non-transitory computer readable medium and a processor that executes the instructions. The control system **248** may be implemented in whole or in part on the aircraft **230** or at least one entity remotely located from the aircraft **230**, such as the ground station **210**. Generally, the manner in which the control system **248** is implemented may vary, depending upon the particular embodiment.

[0060] FIG. **3**A depicts a downward looking view of an example tethered flight system **300** which may include a ground station **310**, a tether **320**, and an aircraft **330**. Also depicted in FIG. **3**A are an azimuth angle **340** and an apparent wind **350**. As shown in FIG. **3**A, the ground station **310** may be coupled to the tether **320** at a first end of the tether **320** while the tether **320** may be coupled to the aircraft **330** at a second end of the tether **320**. The aircraft **330** may be configured to freely fly in an azimuthal direction about the ground station **310**. A position of the aircraft **330** may be characterized in part by the azimuth angle **340** between a reference angle and the azimuthal position of the aircraft **330**. The ground station **310** may be rotated so as to deploy the aircraft **330** in a direction parallel to the apparent wind **350**.

[0061] FIG. **3**B depicts examples of the aircraft **330** engaging in hover flight at various horizontal positions and altitudes. The aircraft **330** may be tethered to the ground station **310** via the tether **320**. FIG. **3**B also depicts the apparent wind **350**, a ground **360**, a horizontal distance **370**, and an altitude **380** of the aircraft.

[0062] Hover flight may be characterized by the aircraft **330** travelling at an attitude such that a primary force resisting a force of gravity on the aircraft **330** is provided by the thrust of the actuators of the aircraft **330**. The aircraft **330** may be deployed in a direction parallel to the apparent wind **350**. In such a configuration, the actuators may be oriented to provide thrust in a direction substantially perpendicular to the ground **360** and the main wing may be oriented so that the main wing is not configured to apply a lift force to the aircraft **330** in a direction perpendicular to the ground **360**. During hover flight, lift generating surfaces of the main wing, the tail wing, and the horizontal stabilizer may not be effective in generating lift as the lift generating surfaces may either be oriented to face substantially parallel to a direction of travel of the aircraft **330**, or may not be impacted with a sufficient apparent wind **350** to generate a lift force. In hover flight, forces causing the aircraft **330** to move along a flight path may include forces provided by the actuators and the apparent wind **350**.

[0063] Hover flight may begin with deploying the aircraft **330** from the ground station **310** in a hover-flight orientation. The ground station **310** may be rotated so as to deploy the aircraft **330** in an azimuthal direction parallel with the apparent wind **350**. Deploying the aircraft **330** in the direction of the apparent wind **350** may enable the aircraft **330** to travel the horizontal distance **370** from the ground station **310** while the actuators of aircraft **330** are thrusting in a substantially vertical direction. The tether **320** may be paid out or reeled out as the aircraft **330** achieves increasing horizontal distance **370** from the ground station **310**. Hover flight may include the aircraft **330** ascending, descending, or hovering over the ground **360** at an altitude **380** above the ground **360**.

[0064] FIG. **4**A depicts a first example catenary path **402** and a second example catenary path **404**. A cable, chain, tether or similar object may hang along a catenary path when the object is supported at a first end and second end, but otherwise allowed to freely hang and react to gravitational forces.

[0065] Within examples, a catenary path of the tether can be equivalent (or about equal) to the trajectory of the aircraft if a common point of the tether and the aircraft, i.e. a point where the tether connects to the aircraft, is defined to travel both the trajectory of the aircraft and the catenary path of the tether. To calculate the catenary path of the tether, the processor may determine the drag force (F) on the aircraft due to an apparent wind using an equation [1]:

$$F = \frac{\rho}{2} C_d A v^2 \qquad [1]$$

The determination may first include determining or receiving parameters of the equation [1] such as a density of air surrounding the aircraft (ρ), a drag coefficient of the aircraft (C_d), a reference area of the aircraft (A), and a speed of the apparent wind impacting the aircraft (v). The drag coefficient may be dependent on a number of variables, such as a shape of the aircraft and the speed of the apparent wind. The reference area of the aircraft may be a cross-sectional area of the aircraft in a plane perpendicular to a direction of the apparent wind. However, the reference area may be any area of the aircraft. The drag force on the aircraft may be proportional to the density of air, the drag coefficient, the reference area, and a square of the speed of the apparent wind, as depicted in the equation [1]. Data representing the parameters may be received by the processor from sensors of the aircraft or ground station, or may be stored in memory. For example, the processor may determine the density of air based on receiving data representing an air temperature and pressure, may receive data representing the speed of the apparent wind, but may retrieve data representing the drag coefficient and the

reference area from memory. Once the drag force is determined, the drag force may be used as a parameter of an equation [2]:

$$h = \frac{T_0}{\mu}\left[\cosh\left(\frac{\mu x}{T_0}\right) - 1\right] \quad [2]$$

[0066] The equation [2] may define a relationship between an altitude of the tether (h), the horizontal position of the tether (x), a tension of the tether (T_0) at a lowest point of the catenary path, and a length and a weight of the tether (or a weight per length of the tether (μ)). (T_0 may also represent a horizontal component of the tension at any point on the tether.) A "cos h" function may be a hyperbolic cosine function, which may be equivalently expressed as exponential functions as in an equation [3]:

$$h = \frac{T_0}{\mu}\left[\left(\frac{\left(e^{\left(\frac{\mu x}{T_0}\right)} + e^{-\left(\frac{\mu x}{T_0}\right)}\right)}{2}\right) - 1\right] \quad [3]$$

The equation [3] may define a relationship between an altitude of the tether (h), the horizontal position of the tether (x), a tension of the tether (T_0), and a length and a weight of the tether (or a weight per length of the tether (μ)).

[0067] The drag force (F) calculated using the equation [1] may be equated with the tension of the tether (T_0) in the equation [2] (or equation [3]). By equating the tension of the tether with the drag force, the equation [2] may represent a scenario in which any tension of the tether is due to the drag force on the aircraft and the weight of the tether. In the example, an actuator of the aircraft may be positioned to provide a thrust in a direction substantially perpendicular to the ground. By providing thrust in a substantially vertical direction, the actuator may save power for vertical propulsion that may otherwise be used to produce an additional tension on the tether. For x>0, the equation [2] generally defines a path of the tether in which the altitude (h) of the tether increases as the horizontal position (x) of the tether increases. A rate of increase of the altitude with respect to the horizontal position may increase as the horizontal position increases. It should be noted that a path of the tether will have a finite length limited by the length of the tether, whereas the equation [2] and the equation [3] define an altitude for all positive and negative values of horizontal position.

[0068] The relationship between the altitude and the horizontal position of the tether may also be expressed using the equation [3]. A constant "**ϵ**" may represent Euler's number or a base of a natural logarithm (approximately 2.71828). The equation [3] may represent a function relating the horizontal position of the tether and the altitude of the tether that is equivalent to the function represented by the equation [2]. Other equations or functions that define the relationship between the horizontal position of the tether and the altitude of the tether equivalent to the equation [2] and the equation [3] may exist.

[0069] The first example catenary path **402** and the second example catenary path **404** may be catenary paths representing relationships between a horizontal position of the tether and an altitude of the tether. The first example catenary path **402** and the second example catenary path **404** may be determined based on varying parameters of the equation [1] and the equation [2] (or the equation [3]). The horizontal position of the tether may be represented on an x-axis and the altitude of the tether may be represented on an h-axis. The first example catenary path **402** or the second example catenary path **404** may be calculated by using the equation [1] to calculate a drag force of the aircraft due to an apparent wind. Next, the equation [2] or the equation [3] may be used to calculate the first example catenary path **402** or the second example catenary path **404** by using the drag force determined with the equation [1].

[0070] As depicted in FIG. **4**A, the first example catenary path **402** and the second example catenary path **404** may have an altitude of zero (h=0) at a horizontal position defined as x=0. A designation of an origin for a two-dimensional space defined by horizontal position and altitude may be arbitrary. For example, x=0 may represent a horizontal position of the ground station, or x=0 may represent a horizontal position at which a minimum altitude of the first example catenary path **402** or the second example catenary path **404** occurs. If x=0 represents the horizontal position of the ground station and h=0 represents an altitude at which the tether couples to the ground station, the first example catenary path **402** and the second example catenary path **404** may both represent tether paths in which a minimum tether altitude occurs at the ground station (x=h=0). By further example, a maximum tether altitude for the first example catenary path **402** and the second example catenary path **404** may occur at an end of the tether coupled to the aircraft.

[0071] At least one parameter of the equation [2] (or the equation [3]) used to determine the first example catenary path **402** may differ from a parameter of the equation [2] (or the equation [3]) used to determine the second example catenary path **404**. For example, the tension of the tether (T_0) represented by the first example catenary path **402** may be less than the tension of the tether (T_0) represented by the second example catenary path **404**, while the weight per length of the tether (μ) represented by the first example catenary path **402** and the second example catenary path **404** may be equal. A difference in tether tension represented by the first example catenary path **402** and the second example catenary path **404** may be caused by a difference in the density of air (ρ), the drag coefficient (C_d), the reference area (A), or the speed of the apparent wind (v), as depicted in the equation [1]. Alternatively, the tension of the tether (T_0) represented by the first example catenary path **402** may be equal to the tension of the tether (T_0) represented by the second example catenary path **404**, while the weight per length of the tether (μ) represented by the first example catenary path **402** may be greater than the weight per length of the tether (μ) represented by the second example catenary path **404**. By further example, a quantity (T_0/μ) corresponding to the second example catenary path **404** may be twice that of a quantity (T_0/μ) corresponding to the first example catenary path **402**. The variation in (T_0/μ) for the first example catenary path **402** and the second example catenary path **404** may be based on varying weights per length of tethers (μ), or based on a difference in tether tensions T_0, which may be caused by differing drag forces (F).

[0072] An equation [4] may resemble equation [2], but may further include an h-axis parameter (a) and an x-axis parameter (b):

$$h = \frac{T_0}{\mu}\left[\cosh\left(\frac{\mu(x-b)}{T_0}\right) - \left(1 - a\frac{\mu}{T_0}\right)\right] \quad [4]$$

The h-axis parameter (a) may be determined so that a minimum altitude of a catenary path may occur at a specific altitude above (or below) a point defined as h=0. For example, if a=5, then a minimum tether altitude of a catenary path defined by the equation [4] may occur at h=5. By further example, if b=7, then a minimum tether altitude of a catenary path defined by the equation [4] may occur at x=7. An equation [5] may also include an h-axis parameter (a) and an x-axis parameter (b) that affect a catenary path similarly to the h-axis parameter (a) and the x-axis parameter (b) of the equation [4]:

$$h = \frac{T_0}{\mu}\left[\left(\frac{\left(e^{\left(\frac{\mu(x-b)}{T_0}\right)} + e^{-\left(\frac{\mu(x-b)}{T_0}\right)}\right)}{2}\right) - \left(1 - a\frac{\mu}{T_0}\right)\right] \quad [5]$$

[0073] FIG. **4**B depicts a third example catenary path **406**, and a fourth example catenary path **408**. The third example catenary path **406** may be defined by the equation [4] with an h-axis parameter (a) of a_1 and an x-axis parameter (b) of b_1. As depicted in FIG. **4**B, the third example catenary path **406** may be defined by substituting (b_1) for (b) and (a_1) for (a) in the equation [4], resulting in

$$h = \frac{T_0}{\mu}\left[\cosh\left(\frac{\mu}{T_0}(x-b_1)\right) - \left(1 - a_1\frac{\mu}{T_0}\right)\right] \quad [6]$$

which may define an altitude of $h=a_1$ at a horizontal position $x=b_1$. A point ($h=a_1$, $x=b_1$) on the third example catenary path **406** may correspond to a minimum tether altitude for the third example catenary path **406**. In this case, h=0 may represent the ground and h(x=0) may represent an altitude at which the tether couples to the ground station which, based on the equation [6], may be

$$h(x=0) = \frac{T_0}{\mu}\left[\cosh\left(\frac{\mu}{T_0}(-b_1)\right) - \left(1 - a_1\frac{\mu}{T_0}\right)\right]. \quad [7]$$

[0074] As depicted in FIG. **4**B, the fourth example catenary path **408** may have an altitude of $h=a_2$ at a horizontal position $x=b_2$, which may be a minimum tether altitude for the fourth example catenary path **408**. The fourth example catenary path **408** may be defined by the equation [4] and an h-axis parameter (a) of (a_2) and an x-axis parameter (b) of (b_2). In this case h=0 may represent the ground and h(x=0) may represent an altitude at which the tether couples to the ground station which, based on the equation [4], may be

$$h(x=0) = \frac{T_0}{\mu}\left[\cosh\left(\frac{\mu}{T_0}(-b_2)\right) - \left(1 - a_2\frac{\mu}{T_0}\right)\right] \quad [8]$$

[0075] The third example catenary path **406** and the fourth example catenary path **408** may be portions of a same curve translated to accommodate differing definitions of the origin of the two-dimensional space of altitude and horizontal position. That is, the third example catenary path **406** and the fourth example catenary path **408** may be defined by an equal tension of the tether (T_0) and weight per length of the tether (μ), but differ only in the h-axis parameters and x-axis parameters that define the third catenary path **406** and the fourth example catenary path **408**.

[0076] The catenary paths illustrated in FIG. **4** are examples only, and the catenary paths may vary based on varying parameters of Equations [1]-[8].

[0077] Causing the aircraft to travel a catenary trajectory may allow the actuator of the aircraft to provide thrust in a substantially vertical direction, allowing the drag force of the apparent wind to provide a force to move the aircraft in a horizontal direction. To maintain a hover orientation in which the actuator is configured to provide a substantially vertical thrust, a control surface of the aircraft may be used to adjust an orientation of the aircraft to the hover orientation, allowing the actuator to expend energy to produce a substantially vertical thrust.

[0078] FIG. **5**A depicts an example roll axis **502** of an aircraft **530**. In one embodiment, the aircraft **530** may include actuators positioned to apply a torque thrust to the aircraft **530** about the roll axis **502** of the aircraft **530**, causing the aircraft **530** to rotate about the roll axis **502**. To land and couple the aircraft **530** onto the ground station it may be useful for the aircraft **530** to assume a particular roll angle with respect to a reference roll angle. During forward flight, roll adjustments of aircraft **530** may be made by changing a position of flaps on the main wing of the aircraft **530**. It should be noted that the definition of the roll axis **502** is arbitrary and the roll axis **502** may constitute a different axis in another embodiment.

[0079] FIG. **5**B depicts an example pitch axis **504** of the aircraft **530**. The aircraft **530** may include actuators **534**A-D positioned to apply a torque thrust about the pitch axis **504** of the aircraft **530**. To pitch the aircraft **530** in a negative direction, the actuators **534**A and **534**C may provide thrust while the actuators **534**B and **534**D are idle. Alternatively, the aircraft **530** may be pitched in a positive direction by causing the actuators **534**B and **534**D to provide thrust and causing the actuators **534**A and **534**C to be idle. Using the actuators **534**A-D to provide pitch control for the aircraft **530** may be useful during hover flight, during which the tail wing of the aircraft **530** may not be configured to provide a torque about the pitch axis **504** of the aircraft **530**. It should be noted that definitions of positive and negative pitch and the pitch axis **504** are arbitrary and not meant to be limiting. The pitch axis **504** may constitute a different axis in another embodiment.

[0080] FIG. **5**C depicts an example yaw axis **506** of the aircraft **530**. The aircraft **530** may include the actuators **534**A-D positioned to apply a torque thrust about the yaw axis **506** of the aircraft **530**. To yaw the aircraft **530** in a negative direction, the actuators **534**C and **534**D may provide thrust while the actuators **534**A and **534**B are idle. Alternatively, the aircraft **530** may be yawed in a positive direction by causing the actuators **534**A and **534**B to provide thrust and causing the actuators **534**C and **534**D to be idle. Using the actuators **534**A-D to provide yaw control may be useful during hover flight during which the vertical stabilizer of the aircraft **530** may not be configured to provide a torque about the yaw axis **506** of the aircraft **530**. It should be noted that definitions of positive and negative yaw and the yaw axis **506** are arbitrary and not meant to be limiting. The yaw axis **506** may constitute a different axis in another embodiment.

[0081] FIG. **6**A depicts examples of a pitch axis **602** of an aircraft **630**, a tail wing **636**, and an apparent wind **650**. At times, it may be useful to change a pitch angle of the aircraft **630**. To change the pitch angle of the aircraft **630** and conserve power otherwise consumed by an actuator of the aircraft **630**, the tail wing **636** may be configured to orient a surface of the tail wing **636** to face the apparent wind **650** so that the apparent wind **650** applies a drag force to the tail wing **636**. The drag force may result in a torque moment that causes the aircraft **630** to rotate with respect to the pitch axis **602** in a direction indicated in FIG. **6**A.

[0082] FIG. **6**B depicts examples of a pitch axis **602** of an aircraft **630**, a tail wing **636**, and an apparent wind **650**. At times, it may be useful to change a pitch angle of the aircraft **630**. To change the pitch angle of the aircraft **630** and conserve power otherwise consumed by an actuator of the aircraft **630**, the tail wing **636** may be configured to orient a surface of the tail wing **636** to face substantially perpendicular to the apparent wind **650** so that the apparent wind **650** applies a lift force **652** to the tail wing **636**. The lift force **652** may result in a torque moment that causes the aircraft **630** to rotate with respect to the pitch axis **602** in a direction indicated in FIG. **6**B.

[0083] FIG. **7** is a block diagram of an example method **700** for determining a trajectory and an orientation of the aircraft that causes a tether to unfurl along a catenary path above ground, in accordance with at least some embodiments described herein. Method **700** shown in FIG. **7** presents an embodiment of a method that, for example, could be used with a computing device. Functions of the method **700** may be fully performed by a processor of a computing device, by a computing device, or may be distributed across multiple processors or multiple computing devices and/or a server. In some examples, the computing device may receive information from sensors of the computing device, or where the computing device is a server the information can be received from another device that collects the information.

[0084] Method **700** may include one or more operations, functions, or actions as illustrated by one or more blocks of **702-710**. Although the blocks are illustrated in a sequential order, these blocks may in some instances be performed in parallel, and/or in a different order than those described herein. Also, the various blocks may be combined into fewer blocks, divided into additional blocks, and/or removed based on the desired implementation.

[0085] In addition, for the method **700** and other processes and methods disclosed herein, the flowchart shows functionality and operation of one possible implementation of present embodiments. In this regard, each block may represent a module, a segment, or a portion of program code, which includes one or more instructions executable by a processor for implementing specific logical functions or steps in the process. The program code may be stored on any type of computer readable medium, for example, such as a storage device including a disk or hard drive. The computer readable medium may include a non-transitory computer readable medium, for example, such as computer-readable media that stores data for short periods of time like register memory, processor cache, and Random Access Memory (RAM). The computer readable medium may also include non-transitory media, such as secondary or persistent long term storage, like read only memory (ROM), optical or magnetic disks, or compact-disc read only memory (CD-ROM), for example. The computer readable media may also be any other volatile or non-volatile storage systems. The computer readable medium may be considered a computer readable storage medium, a tangible storage device, or other article of manufacture, for example.

[0086] In addition, for the method **700** and other processes and methods disclosed herein, each block in FIG. **7** may represent circuitry that is wired to perform the specific logical functions in the process.

[0087] At block **702**, the method **700** includes determining a drag force of an apparent wind on an aircraft coupled to a ground station via a tether. A processor may determine the drag force using a drag force equation, such as equation [1]. More specifically, the processor may calculate the drag force based on a proportionality between the drag force and a density of air, between the drag force and a reference area of the aircraft, between the drag force and a drag coefficient, or between the drag force and a square of the speed of the apparent wind. The drag coefficient may indicate a resistance of the aircraft to air moving against a surface of the aircraft and may be dependent on a shape of the aircraft or the speed of the apparent wind.

[0088] At block **704**, the method **700** includes, based on the drag force and a weight of the tether, determining a trajectory of the aircraft to a point downwind of the ground station such that the aircraft travelling the trajectory causes the tether to unfurl along a catenary path above ground. The catenary path may represent a shape of the tether caused by gravity acting on the tether while the tether is supported at a first end by the ground station and supported at a second end by the aircraft. The processor may determine the trajectory by determining an azimuth angle for the trajectory that is parallel to a direction of the apparent wind. The processor may further determine a series of altitudes that correspond to a series of horizontal positions of the tether along the azimuth angle.

[0089] The processor may determine the trajectory based on the drag force equation and a catenary equation, such as equations [1]-[8] such that the aircraft travelling the trajectory in the apparent wind causes a tension of the tether to have a horizontal component substantially equal to the drag force of the apparent wind. In this way, the trajectory may be optimized so that the tether is maintained above a minimum altitude, the apparent wind pushes the aircraft in a horizontal direction, and the actuator of the aircraft provides a vertical thrust substantially perpendicular to the ground. The trajectory determined by the processor may also cause a tension of the tether to have a vertical component equal to a weight of a portion of the tether. That is, the aircraft travelling the trajectory may restrain the tether from touching the ground or from dropping below a certain altitude, but may not require thrust to be provided by an actuator to place additional tension on the tether.

[0090] The aircraft travelling the trajectory may also cause a first portion of the tether to occupy a position on the catenary path previously occupied by a second portion of the tether. As the aircraft travels the trajectory and increases a distance of the aircraft from the ground station, the tether may be reeled out by the ground station to accommodate the increased distance of the aircraft from the ground station. An overall shape of the tether suspended by the ground station and the aircraft may remain unchanged as the tether is reeled out, except that an additional section of the catenary path adjacent to the aircraft may be added to a previous path of the tether. In this way, once a position on the catenary path has been occupied

by a portion of the tether, the position may continue to be occupied by other portions of the tether as the tether is reeled out.

[0091] The method **700** may also include the processor receiving data representing a horizontal position of the ground station, an altitude of the ground station, and a length of the tether. The processor may then determine the catenary path based on the length of the tether and a tension of the tether so that the aircraft travelling the catenary path causes a tension of the tether to be about equal to the drag force of the apparent wind on the aircraft. The tension may occur at the minimum altitude of the catenary path. By minimizing the tension of the tether caused by the actuator of the aircraft, an energy dissipated by the actuator may be minimized. The processor may then determine parameters of the catenary path that cause the catenary path to include a point defined by the horizontal position of the ground station and the altitude of the ground station. The processor may also determine the parameters so that a minimum altitude of the catenary path occurs within a range of horizontal position bounded by the horizontal position of the ground station and the point downwind of the ground station. The processor may receive data representing a minimum tether altitude and determine the parameters so that a minimum altitude of the catenary path is about equal to the minimum tether altitude.

[0092] The catenary path may be determined by the processor based on the equation [4] (or equation [5]). (T_0) may represent a tension of the tether at a lowest point of the catenary path, or a horizontal component of the tension at any point on the tether. To reduce the energy consumed by the actuator, the tension T_0 may be about equal to the drag force of the apparent wind defined by the equation [1]. (ρ) may represent a density of air, (C_d) may represent the drag coefficient of the aircraft, (A) may represent the reference area of the aircraft, and (v) may represent the speed of the apparent wind. In the catenary equation, (μ) may represent the weight per length of the tether, (a) may represent a vertical adjustment parameter, (b) may represent a horizontal adjustment parameter, (h) may represent altitude, and (x) may represent horizontal position.

[0093] For example, the horizontal position of the ground station and the altitude of the ground station may be x=0 and h=5, respectively. For purposes of illustration, a quantity (T_0/μ) may be equal to 1. In this case, the catenary equation may take a simplified form, h=cos h(x−b)−(1−a). The processor may then determine the parameters (a) and (b) such that the altitude of the tether at a horizontal position represented by x=0 is h=5. The processor may first determine (a) such that a minimum altitude of the catenary path corresponds to the minimum tether altitude. For example, to yield a catenary path in which the minimum altitude of the path is h=1, the processor may determine (a) to be equal to 1, based on a minimum value of cos h(x−b) being equal to 1. The catenary equation may then be expressed as h=cos h(x−b). Next, the processor may determine (b) such that an altitude of the catenary path at x=0 is h=5, by solving an equation 5=cos h(0−b). There may exist two such values of (b) that solve the equation, b≈2.29243 and b≈−2.29243. The processor may determine that determining (b) to be equal to 2.29243 will cause the minimum altitude of the catenary path to occur at a position between the ground station and the point downwind of the ground station (i.e. the minimum altitude may occur on a positive-x side of the x-axis). In this example, (b) may be determined to be 2.29243 by the processor. By further example, referring to FIG. **4**, the third example catenary path **406** may depict a catenary path corresponding to parameters b=1 and a=2, while the fourth example catenary path **408** may depict a catenary path corresponding to parameters b=3 and a=4. (Note that in this example, the x-axis and the h-axis may not share a common scale.) Accordingly, the altitude of the third example catenary path **406** at x=0 may be h≈2.543 and the altitude of the fourth example catenary path **408** at x=0 may be h≈13.068.

[0094] The processor may also determine a horizontal position and an altitude corresponding to an endpoint of the trajectory based on the length of the tether, the weight of the tether, and the drag force. Once the catenary path is determined, an arc length (s) of the catenary path from a horizontal position x_1 to a horizontal position x_2 can be determined using an equation [9]:

$$S = \int_{x_1}^{x_2} \sqrt{1 + \left(\frac{dh}{dx}\right)^2}\, dx \qquad [9]$$

where (h) is the altitude of the catenary path defined by the equation [4]. If a total length of the tether is known, (s) in the equation [9] can be set equal to the total tether length, and a horizontal distance between the ground station at x_1 and the point downwind of the ground station at x_2 can be determined. For purposes of illustration, the ground station may have a horizontal position $x=0=x_1$, the tether may have a length of 50 and (a) may equal 2 and (b) may equal 1, yielding equation [10]:

$$h(x)=\cos h(x-1)-(1-2) \qquad [10]$$

In this case, the endpoint of the trajectory would be determined using an equation

$$50=\int_0^{x2}\sqrt{1+\sin h^2(x-1)}\,dx \qquad [11]$$

[0095] A solution to the equation [11] may be $x_2\approx 5.582$. An altitude (h) of the endpoint of the catenary path may be determined by the processor using the equation [4] and the horizontal position of the endpoint. In the case of $x_2=5.582$, h may be approximately 49.86.

[0096] At block **706**, the method **700** includes determining an orientation of the aircraft to travel the trajectory in the apparent wind so that an actuator of the aircraft is configured to provide a vertical thrust in a direction substantially perpendicular to the ground. The processor may first receive data representing a direction in which the actuator is configured to provide thrust relative to an axis of the aircraft. Next, the processor may determine an angle of rotation of the aircraft relative to the axis of the aircraft such that at the angle of rotation, the actuator is configured to provide the vertical thrust in a direction substantially perpendicular to the ground. In other words, the processor may determine an orientation of the aircraft based on a relative orientation of the actuator with respect to the aircraft, such that the actuator is configured to provide a substantially downward thrust perpendicular to the ground. Limiting the thrust of the actuator to be in the vertical direction may allow the aircraft to rely on the force of the apparent wind to travel in the horizontal direction.

[0097] At block **708**, the method **700** includes determining a vertical thrust for the aircraft at the orientation to travel the trajectory in the apparent wind based on the trajectory and a weight of the aircraft. The processor may also receive data

representing a weight, a position, and a vertical velocity of the aircraft, and a weight of a portion of the tether supported by the aircraft. With the data, the processor may determine a gravitational force acting on the aircraft based on the weight of the aircraft and the weight of the portion of the tether supported by the aircraft. The processor may determine the weight of the portion of the tether supported by the aircraft based on a weight per length of the tether and a length of the portion of the tether. The processor may next determine a vertical acceleration of the aircraft based on the position and the vertical velocity of the aircraft, wherein the aircraft achieving the vertical acceleration and the drag force pushing the aircraft horizontally cause the aircraft to follow the trajectory. Finally, the processor may determine the vertical thrust based on a force to counteract the downward force and achieve the vertical acceleration.

[0098] At block **710**, the method **700** includes providing instructions to cause the actuator of the aircraft to provide the vertical thrust to move the aircraft along the trajectory. The processor may provide the instructions to the actuator or a control system of the aircraft that controls the actuator.

[0099] The processor may further receive data indicating an initial orientation of the aircraft, and a speed and a direction of the apparent wind. The processor may use the data to determine a position of the tail wing relative to the direction of the apparent wind configured to cause the apparent wind to produce a rotational force about a pitch axis of the aircraft. The rotational force may be configured to rotate the aircraft from the initial orientation to a hover orientation. As shown and described in FIGS. **6**A and **6**B, the tail wing **636** of the aircraft may be configured to provide pitch control while the aircraft is in a hover orientation. The tail wing **636** may provide pitch control in a first direction by orienting the tail wing so that the apparent wind produces a drag force against the tail wing. The drag force may create a pitch moment in a first direction about the pitch axis of the aircraft, as shown in FIG. **6**A. The tail wing may provide pitch control in a second direction by orienting the tail wing so that the apparent wind produces a lift force against the tail wing. The lift force may create a pitch moment in a second direction about the pitch axis of the aircraft, as shown in FIG. **6**B. Lastly, the processor may provide instructions to the control system of the aircraft (or the ground station) to move the tail wing to provide the rotational force to rotate the aircraft to the hover orientation.

[0100] The tail wing may be configured to produce the lift force based on the apparent wind achieving a threshold speed, such as 15 meters per second. The processor may provide the instructions to move the tail wing to provide the rotational force based on receiving a notification from a sensor of the aircraft that the speed of the apparent wind is greater than or equal to the threshold speed. Unless the apparent wind has a speed greater than the threshold speed, the tail wing may not be configured to provide a lift force configured for pitch control of the aircraft while the aircraft is in the hover orientation. Deploying the aircraft along the catenary path and using the tail wing for pitch control may increase a margin between a nominal actuator output and a maximum actuator output, thereby increasing an ability of the aircraft to respond to disturbances (e.g. wind gusts) that cause deviations from the catenary path or a particular attitude of the aircraft.

[0101] It should be understood that arrangements described herein are for purposes of example only. As such, those skilled in the art will appreciate that other arrangements and other elements (e.g. machines, interfaces, functions, orders, and groupings of functions, etc.) can be used instead, and some elements may be omitted altogether according to the desired results. Further, many of the elements that are described are functional entities that may be implemented as discrete or distributed components or in conjunction with other components, in any suitable combination and location, or other structural elements described as independent structures may be combined.

[0102] While various aspects and embodiments have been disclosed herein, other aspects and embodiments will be apparent to those skilled in the art. The various aspects and embodiments disclosed herein are for purposes of illustration and are not intended to be limiting, with the true scope being indicated by the following claims, along with the full scope of equivalents to which such claims are entitled. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting.

1. A method comprising:

sensing a speed of an apparent wind on an aircraft, wherein the aircraft is coupled to a ground station via a tether;

based on the sensed speed of the apparent wind and Iii) a weight of the tether, determining, by one or more processors, a trajectory of the aircraft to a point downwind of the ground station such that the aircraft travelling the trajectory pulls the tether along a catenary path above ground;

based on the trajectory and a weight of the aircraft, determining a vertical thrust for the aircraft to travel the trajectory in the apparent wind; and

providing instructions to cause an actuator of the aircraft to provide the vertical thrust to move the aircraft along the trajectory.

2. The method of claim **1**, further comprising:

determining a drag force of the apparent wind on the aircraft based on a density of air, a reference area of the aircraft, or the sensed speed of the apparent wind; and

determining the trajectory based on the drag force.

3. The method of claim **1**, further comprising:

determining a drag force of the apparent wind on the aircraft based on a drag coefficient, wherein the drag coefficient indicates a resistance of a surface of the aircraft to air moving against the surface; and

determining the trajectory based on the drag force.

4. The method of claim **1**, wherein the aircraft travelling the trajectory comprises a point common to both the tether and the aircraft travelling the trajectory.

5. The method of claim **1**, wherein determining the trajectory of the aircraft comprises:

determining an azimuth angle for the trajectory; and

determining an altitude corresponding to a horizontal position on the ground along a line defined by the azimuth angle.

6. The method of claim **1**, wherein determining the trajectory of the aircraft comprises:

determining the trajectory such that the aircraft traveling the trajectory causes a tension of the tether to have a horizontal component substantially equal to a drag force of the apparent wind on the aircraft.

7. The method of claim **1**, wherein determining the trajectory of the aircraft comprises:

determining the trajectory such that the aircraft traveling the trajectory causes a tension of the tether to have a vertical component substantially equal to a weight of the tether.

8. The method of claim **1**, wherein determining the trajectory of the aircraft comprises:

determining the trajectory such that the aircraft traveling the trajectory causes a first portion of the tether to occupy a position on the catenary path previously occupied by a second portion of the tether.

9. The method of claim **1**, wherein determining the trajectory of the aircraft comprises:

determining the catenary path based on a length of the tether and a tension of the tether, wherein the tension of the tether is about equal to a drag force of the apparent wind on the aircraft; and

determining a parameter of the catenary path so that:

the catenary path includes a point defined by the horizontal position of the ground station and the altitude of the ground station, and

a minimum altitude of the catenary path occurs within a range of horizontal position bounded by the horizontal position of the ground station and the point downwind of the ground station.

10. The method of claim **9**, wherein determining the trajectory of the aircraft further comprises:

determining the parameter of the catenary path so that the minimum altitude of the catenary path is about equal to a predetermined altitude.

11. The method of claim **1**, wherein determining the trajectory of the aircraft comprises:

determining a horizontal position corresponding to an endpoint of the trajectory based on a length of the tether, the weight of the tether, and a drag force of the apparent wind on the aircraft.

12. The method of claim **1**, wherein determining the trajectory of the aircraft comprises:

determining an altitude corresponding to an endpoint of the trajectory based on a length of the tether, the weight of the tether, and a drag force of the apparent wind on the aircraft.

13. The method of claim **1**, further comprising:

determining an orientation of the aircraft to travel the trajectory in the apparent wind so that the actuator of the aircraft is configured to provide the vertical thrust in a direction substantially perpendicular to the ground.

14. The method of claim **1**, wherein determining the vertical thrust for the aircraft comprises:

determining the vertical thrust based on a position and a vertical velocity of the aircraft, wherein the actuator providing the vertical thrust and a drag force of the apparent wind on the aircraft pushing the aircraft horizontally cause the aircraft to follow the trajectory.

15. The method of claim **1**, wherein the aircraft includes a tail wing and is engaged in hover flight, and the method further comprises:

receiving data indicating an initial orientation of the aircraft, and a speed and a direction of the apparent wind;

determining a position of the tail wing relative to the direction of the apparent wind configured to cause the apparent wind to produce a rotational force about a pitch axis of the aircraft to rotate the aircraft from the initial orientation to a hover orientation; and

providing instructions to move the tail wing to provide the rotational force to rotate the aircraft to the hover orientation.

16. The method of claim **15**, wherein providing instructions to move the tail wing to provide the rotational force to rotate the aircraft to the hover orientation comprises:

providing the instructions based on receiving a notification that a speed of the apparent wind is sufficient to produce the rotational force.

17. A non-transitory computer readable storage memory having stored therein instructions, that when executed by a computing device that includes one or more processors, causes the computing device to perform functions comprising:

sensing a speed of an apparent wind on an aircraft, wherein the aircraft is coupled to a ground station via a tether;

based on (i) the sensed speed of the apparent wind and (ii) a weight of the tether, determining a trajectory of the aircraft to a point downwind of the ground station such that the aircraft travelling the trajectory pulls the tether along a catenary path above ground;

based on the trajectory and a weight of the aircraft, determining a vertical thrust for the aircraft to travel the trajectory in the apparent wind; and

providing instructions to cause an actuator of the aircraft to provide the vertical thrust to move the aircraft along the trajectory.

18. The non-transitory computer readable storage memory of claim **17**, wherein the aircraft travelling the trajectory comprises a point common to both the tether and the aircraft travelling the trajectory.

19. A computing device comprising:

one or more processors; and

memory configured to store instructions, that when executed by the one or more processors, cause the computing device to perform functions comprising:

sensing a speed of an apparent wind on an aircraft, wherein the aircraft is coupled to a ground station via a tether;

based on (i) the sensed speed of the apparent wind and (ii) a weight of the tether, determining a trajectory of the aircraft to a point downwind of the ground station such that the aircraft travelling the trajectory pulls the tether along a catenary path above ground;

based on the trajectory and a weight of the aircraft, determining a vertical thrust for the aircraft to travel the trajectory in the apparent wind; and

providing instructions to cause an actuator of the aircraft to provide the vertical thrust to move the aircraft along the trajectory.

20. The computing device of claim **19**, wherein the aircraft travelling the trajectory comprises a point common to both the tether and the aircraft travelling the trajectory.

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