COUNTER-ROTATING PROPELLERS FOR AERIAL VEHICLE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 62/663,503, filed April 27, 2018, which is hereby incorporated by reference in its entirety. The present application is also related to a U.S. Application entitled, "Thrust Allocation for Aerial Vehicle," Attorney Docket Number XCOM-1-66312, filed on the same day as the present application.

TECHNICAL FIELD

[0002] This disclosure relates generally to aerial vehicles, and in particular but not exclusively, relates to control systems for vertical propulsion of aerial vehicles.

BACKGROUND INFORMATION

[0003] An unmanned vehicle, which may also be referred to as an autonomous vehicle, is a vehicle capable of travel without a physically-present human operator. An unmanned vehicle may operate in a remote-control mode, in an autonomous mode, or in a partially autonomous mode.

[0004] When an unmanned vehicle operates in a remote-control mode, a pilot or driver that is at a remote location can control the unmanned vehicle via commands that are sent to the unmanned vehicle via a wireless link. When the unmanned vehicle operates in autonomous mode, the unmanned vehicle typically moves based on pre-programmed navigation waypoints, dynamic automation systems, or a combination of these. Further, some unmanned vehicles can operate in both a remote-control mode and an autonomous mode, and in some instances may do so simultaneously. For instance, a remote pilot or driver may wish to leave navigation to an autonomous system while manually performing another task, such as operating a mechanical system for picking up objects, as an example.

[0005] Various types of unmanned vehicles exist for various different environments. For instance, unmanned vehicles exist for operation in the air, on the ground, underwater, and in space. Unmanned aerial vehicles (UAVs) or drones are becoming more popular in general. As their designs are refined and their capabilities expanded, their suitability for commercial use is expected to expand. Designs that improve the efficiency, stability, reliability, and/or endurance of UAVs will expand their

mission capabilities.

SUMMARY OF INVENTION

[0005a] According to a first aspect of the present invention, there is provided an aerial vehicle, comprising:

~~an airframe;~~

~~a plurality of vertical propulsion units mounted to the airframe and including propellers oriented to provide vertical propulsion to the aerial vehicle, wherein the vertical propulsion units are physically organized in quadrants on the airframe with each of the quadrants including two or more of the vertical propulsion units; and~~

~~a controller coupled to the vertical propulsion units to control operation of the vertical propulsion units, wherein at least two of the vertical propulsion units in each of the quadrants are adapted to counter rotate from each other during flight of the aerial vehicle under influence of the controller.~~

a plurality of vertical propulsion units mounted to the airframe and including propellers oriented to provide vertical propulsion to the aerial vehicle, wherein the vertical propulsion units are physically organized in quadrants on the airframe with each of the quadrants including two or more of the vertical propulsion units; and

a controller coupled to the vertical propulsion units to control operation of the vertical propulsion units, wherein at least two of the vertical propulsion units in each of the quadrants are adapted to counter-rotate from each other during flight of the aerial vehicle under influence of the controller, wherein rotation directions of the vertical propulsion units are each selected such that a loss of a propeller reaction torque about a yaw axis due to a singular failure of any one of the vertical propulsion units in a first quadrant is counter to, and at least partially offset by, a thrust vectoring torque about the yaw axis that is induced by twisting in the airframe due to thrust asymmetries from reducing thrust of the vertical propulsion units in a second quadrant diagonally positioned relative to the first quadrant while increasing thrust of the vertical propulsion units in third and fourth quadrants to maintain stable flight.

[0005b] According to a second aspect of the present invention, there is provided a method of propelling an aerial vehicle, comprising:

~~vertically propelling the aerial vehicle with a plurality of vertical propulsion units mounted to an airframe of the aerial vehicle, wherein the vertical propulsion units are~~

~~physically mounted into quadrants on the airframe with each of the quadrants including two or more of the vertical propulsion units;~~

~~rotating first propellers of a first portion of the vertical propulsion units in a first rotational direction while the aerial vehicle is flying; and~~

~~rotating second propellers of a second portion of the vertical propulsion units in a second rotational direction opposite from the first rotational direction while the aerial vehicle is flying,~~

~~wherein at least two of the vertical propulsion units in each of the quadrants contemporaneously counter rotate from each other during the flying.~~

vertically propelling the aerial vehicle with a plurality of vertical propulsion units mounted to an airframe of the aerial vehicle, wherein the vertical propulsion units are physically mounted into quadrants on the airframe with each of the quadrants including two or more of the vertical propulsion units;

rotating first propellers of a first portion of the vertical propulsion units in a first rotational direction while the aerial vehicle is flying;

rotating second propellers of a second portion of the vertical propulsion units in a second rotational direction opposite from the first rotational direction while the aerial vehicle is flying; and

reducing thrust of the vertical propulsion units in a first quadrant when a singular failure of any one of the vertical propulsion units in a second quadrant diagonally positioned relative to the first quadrant occurs while also increasing thrust of the vertical propulsion units in third and fourth quadrants to maintain stable flight,

wherein at least two of the vertical propulsion units in each of the quadrants contemporaneously counter-rotate from each other during the flying.

[0005c] According to a third aspect of the present invention, there is provided an aerial vehicle, comprising:

an airframe;

a plurality of vertical propulsion units mounted to the airframe and including propellers oriented to provide vertical propulsion to the aerial vehicle, wherein the vertical propulsion units are physically organized in quadrants on the airframe with each of the quadrants including two or more of the vertical propulsion units; and

a controller coupled to the vertical propulsion units to control operation of the vertical propulsion units, wherein at least two of the vertical propulsion units in each of

the quadrants are adapted to counter-rotate from each other during flight of the aerial vehicle under influence of the controller, wherein the controller is configured to reduce thrust of the vertical propulsion units in a first quadrant when a singular failure of any one of the vertical propulsion units in a second quadrant diagonally positioned relative to the first quadrant occurs while also increasing thrust of the vertical propulsion units in third and fourth quadrants.

[0005d] According to a fourth aspect of the present invention, there is provided an aerial vehicle, comprising:

an airframe;

a plurality of vertical propulsion units mounted to the airframe and including propellers oriented to provide vertical propulsion to the aerial vehicle, wherein the vertical propulsion units are physically organized in quadrants on the airframe with each of the quadrants including two or more of the vertical propulsion units; and

a controller coupled to the vertical propulsion units to control operation of the vertical propulsion units, wherein at least two of the vertical propulsion units in each of the quadrants are adapted to counter-rotate from each other during flight of the aerial vehicle under influence of the controller,

wherein the plurality of vertical propulsion units consist of three propulsion units in each of the quadrants,

wherein the vertical propulsion units are organized into starboard propulsion units and port propulsion units and each of the starboard propulsion units counter-rotates to a corresponding one of the port propulsion units that has a mirrored position about a fore-aft axis of the aerial vehicle,

wherein the vertical propulsion units are further organized into fore propulsion units and aft propulsion units and each of the fore propulsion units counter-rotates to a corresponding one of the aft propulsion units that has a mirrored position about a port-starboard axis of the aerial vehicle.

CLAIMS

~~The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:~~

~~1. An aerial vehicle, comprising:~~

~~an airframe;~~

~~a plurality of vertical propulsion units mounted to the airframe and including propellers oriented to provide vertical propulsion to the aerial vehicle, wherein the vertical propulsion units are physically organized in quadrants on the airframe with each of the quadrants including two or more of the vertical propulsion units; and~~

~~a controller coupled to the vertical propulsion units to control operation of the vertical propulsion units, wherein at least two of the vertical propulsion units in each of the quadrants are adapted to counter rotate from each other during flight of the aerial vehicle under influence of the controller.~~

~~2. The aerial vehicle of claim 1, wherein the vertical propulsion units are organized into starboard propulsion units and port propulsion units and wherein each of the starboard propulsion units counter rotates to a corresponding one of the port propulsion units that has a mirrored position about a fore-aft axis of the aerial vehicle.~~

~~3. The aerial vehicle of claim 2, wherein the vertical propulsion units are further organized into fore propulsion units and aft propulsion units and wherein each of the fore propulsion units counter rotates to a corresponding one of the aft propulsion units that has a mirrored position about a port-starboard axis of the aerial vehicle.~~

~~4. The aerial vehicle of claim 1, wherein the plurality of vertical propulsion units consist of two propulsion units in each of the quadrants.~~

~~5. The aerial vehicle of claim 4, wherein the vertical propulsion units consist of eight vertical propulsion units organized into a fore-starboard quadrant (Q1), an aft-port quadrant (Q2), a fore-port quadrant (Q3), and an aft-starboard quadrant (Q4), wherein a first half of the vertical propulsion units are organized into an outer propulsion ring (R1) and a second half are organized into an inner propulsion ring (R2), and wherein the vertical propulsion units have the following rotational directions:~~

~~a first rotational direction for those of the vertical propulsion units in positions: Q1 R1, Q2 R1, Q3 R2, Q4 R2, and~~

~~a second rotational direction parallel to but opposite from the first rotational direction for those of the vertical propulsion units in positions: Q1 R2, Q2 R2, Q3 R1, Q4 R1.~~

~~6. The aerial vehicle of claim 1, wherein the plurality of vertical propulsion units consist of three propulsion units in each of the quadrants.~~

~~7. The aerial vehicle of claim 1, wherein the controller is coupled to independently control rotation rates of each of the vertical propulsion units within a given one of the quadrants.~~

~~8. The aerial vehicle of claim 1, wherein rotation directions of the vertical propulsion units are each selected such that a loss of a propeller reaction torque about a yaw axis due to a singular failure of any one of the vertical propulsion units is counter to, and at least partially offset by, a thrust vectoring torque about the yaw axis that is induced by twisting in the airframe due to thrust asymmetries from a remainder of the vertical propulsion units still functioning.~~

~~9. The aerial vehicle of claim 1, wherein the aerial vehicle comprises a fixed wing, vertical takeoff and landing (VTOL) unmanned aerial vehicle (UAV).~~

~~10. The aerial vehicle of claim 9, wherein the aerial vehicle further comprises horizontal propulsion units mounted to the airframe to provide horizontal propulsion.~~

~~11. A method of propelling an aerial vehicle, comprising:~~

~~vertically propelling the aerial vehicle with a plurality of vertical propulsion units mounted to an airframe of the aerial vehicle, wherein the vertical propulsion units are physically mounted into quadrants on the airframe with each of the quadrants including two or more of the vertical propulsion units;~~

~~rotating first propellers of a first portion of the vertical propulsion units in a first rotational direction while the aerial vehicle is flying; and~~

~~rotating second propellers of a second portion of the vertical propulsion units in a second rotational direction opposite from the first rotational direction while the aerial vehicle is flying,~~

~~wherein at least two of the vertical propulsion units in each of the quadrants contemporaneously counter rotate from each other during the flying.~~

~~12. The method of claim 11, wherein the vertical propulsion units are organized into starboard propulsion units and port propulsion units and wherein rotating the first and second propellers further comprises:~~

~~counter rotating each of the starboard propulsion units to a corresponding one of the port propulsion units that has a mirrored position about a fore aft axis of the aerial vehicle.~~

~~13. The method of claim 12, wherein the vertical propulsion units are further organized into fore propulsion units and aft propulsion units and wherein rotating the first and second propellers further comprises:~~

~~counter rotating each of the fore propulsion units to a corresponding one of the aft propulsion units that has a mirrored position about a port starboard axis of the aerial vehicle.~~

~~14. The method of claim 11, wherein the plurality of vertical propulsion units consist of two propulsion units in each of the quadrants.~~

~~15. The method of claim 14, wherein the vertical propulsion units consist of eight vertical propulsion units organized into a fore starboard quadrant (Q1), an aft port quadrant (Q2), a fore-port quadrant (Q3), and an aft-starboard quadrant (Q4), wherein a first half of the vertical propulsion units are organized into an outer propulsion ring (R1) and a second half are organized into an inner propulsion ring (R2), and wherein the first propellers are mounted in positions Q1-R1, Q2-R1, Q3-R2, Q4-R2 and the second propellers are mounted in positions Q1-R2, Q2-R2, Q3-R1, Q4-R1.~~

~~16. The method of claim 11, wherein the plurality of vertical propulsion units consist of three propulsion units in each of the quadrants.~~

~~17. The method of claim 11, further comprising:~~

~~independently controlling rotation rates of each of the vertical propulsion units within a given one of the quadrants.~~

~~18. The method of claim 11, wherein rotation directions of the vertical propulsion units are each selected such that a loss of a propeller reaction torque about a yaw axis of the aerial vehicle due to a singular failure of any one of the vertical propulsion units is counter to and at least partially offset by a thrust vectoring torque about the yaw axis that is induced by twisting in the airframe due to thrust asymmetries from a remainder of the vertical propulsion units still functioning.~~

~~19. The method of claim 11, wherein the aerial vehicle comprises a fixed wing, vertical takeoff and landing (VTOL) unmanned aerial vehicle (UAV).~~

~~20. The method of claim 19, further comprising:~~

~~horizontally propelling the aerial vehicle with a plurality of horizontal propulsion units mounted to the airframe.~~

1. An aerial vehicle, comprising:

an airframe;

a plurality of vertical propulsion units mounted to the airframe and including propellers oriented to provide vertical propulsion to the aerial vehicle, wherein the vertical propulsion units are physically organized in quadrants on the airframe with each of the quadrants including two or more of the vertical propulsion units; and

a controller coupled to the vertical propulsion units to control operation of the vertical propulsion units, wherein at least two of the vertical propulsion units in each of the quadrants are adapted to counter-rotate from each other during flight of the aerial vehicle under influence of the controller, wherein rotation directions of the vertical propulsion units are each selected such that a loss of a propeller reaction torque about a yaw axis due to a singular failure of any one of the vertical propulsion units in a first quadrant is counter to, and at least partially offset by, a thrust vectoring torque about the yaw axis that is induced by twisting in the airframe due to thrust asymmetries from reducing thrust of the vertical propulsion units in a second quadrant diagonally positioned relative to the first quadrant while increasing thrust of the vertical propulsion units in third and fourth quadrants to maintain stable flight.

2. The aerial vehicle of claim 1, wherein the vertical propulsion units are organized into starboard propulsion units and port propulsion units and wherein each of

the starboard propulsion units counter-rotates to a corresponding one of the port propulsion units that has a mirrored position about a fore-aft axis of the aerial vehicle.

3. The aerial vehicle of claim 2, wherein the vertical propulsion units are further organized into fore propulsion units and aft propulsion units and wherein each of the fore propulsion units counter-rotates to a corresponding one of the aft propulsion units that has a mirrored position about a port-starboard axis of the aerial vehicle.

4. The aerial vehicle of claim 1, wherein the plurality of vertical propulsion units consist of two propulsion units in each of the quadrants.

5. The aerial vehicle of claim 4, wherein the vertical propulsion units consist of eight vertical propulsion units organized into a fore-starboard quadrant (Q1), an aft-port quadrant (Q2), a fore-port quadrant (Q3), and an aft-starboard quadrant (Q4), wherein a first half of the vertical propulsion units are organized into an outer propulsion ring (R1) and a second half are organized into an inner propulsion ring (R2), and wherein the vertical propulsion units have the following rotational directions:

a first rotational direction for those of the vertical propulsion units in positions: Q1-R1, Q2-R1, Q3-R2, Q4-R2, and

a second rotational direction parallel to but opposite from the first rotational direction for those of the vertical propulsion units in positions: Q1-R2, Q2-R2, Q3-R1, Q4-R1.

6. The aerial vehicle of claim 1, wherein the plurality of vertical propulsion units consist of three propulsion units in each of the quadrants.

7. The aerial vehicle of claim 1, wherein the controller is coupled to independently control rotation rates of each of the vertical propulsion units within a given one of the quadrants.

8. The aerial vehicle of claim 1, wherein the aerial vehicle comprises a fixed wing, vertical takeoff and landing (VTOL) unmanned aerial vehicle (UAV).

9. The aerial vehicle of claim 8, wherein the aerial vehicle further comprises horizontal propulsion units mounted to the airframe to provide horizontal propulsion.

10. A method of propelling an aerial vehicle, comprising:

vertically propelling the aerial vehicle with a plurality of vertical propulsion units mounted to an airframe of the aerial vehicle, wherein the vertical propulsion units are physically mounted into quadrants on the airframe with each of the quadrants including two or more of the vertical propulsion units;

rotating first propellers of a first portion of the vertical propulsion units in a first rotational direction while the aerial vehicle is flying;

rotating second propellers of a second portion of the vertical propulsion units in a second rotational direction opposite from the first rotational direction while the aerial vehicle is flying; and

reducing thrust of the vertical propulsion units in a first quadrant when a singular failure of any one of the vertical propulsion units in a second quadrant diagonally positioned relative to the first quadrant occurs while also increasing thrust of the vertical propulsion units in third and fourth quadrants to maintain stable flight,

wherein at least two of the vertical propulsion units in each of the quadrants contemporaneously counter-rotate from each other during the flying.

11. The method of claim 10, wherein the vertical propulsion units are organized into starboard propulsion units and port propulsion units and wherein rotating the first and second propellers further comprises:

counter-rotating each of the starboard propulsion units to a corresponding one of the port propulsion units that has a mirrored position about a fore-aft axis of the aerial vehicle.

12. The method of claim 11, wherein the vertical propulsion units are further organized into fore propulsion units and aft propulsion units and wherein rotating the first and second propellers further comprises:

counter-rotating each of the fore propulsion units to a corresponding one of the aft propulsion units that has a mirrored position about a port-starboard axis of the aerial vehicle.

13. The method of claim 10, wherein the plurality of vertical propulsion units consist of two propulsion units in each of the quadrants.

14. The method of claim 13, wherein the vertical propulsion units consist of eight vertical propulsion units organized into a fore-starboard quadrant (Q1), an aft-port quadrant (Q2), a fore-port quadrant (Q3), and an aft-starboard quadrant (Q4), wherein a first half of the vertical propulsion units are organized into an outer propulsion ring (R1) and a second half are organized into an inner propulsion ring (R2), and wherein the first propellers are mounted in positions Q1-R1, Q2-R1, Q3-R2, Q4-R2 and the second propellers are mounted in positions Q1-R2, Q2-R2, Q3-R1, Q4-R1.

15. The method of claim 10, wherein the plurality of vertical propulsion units consist of three propulsion units in each of the quadrants.

16. The method of claim 10, further comprising:

independently controlling rotation rates of each of the vertical propulsion units within a given one of the quadrants.

17. The method of claim 10, wherein rotation directions of the vertical propulsion units are each selected such that a loss of a propeller reaction torque about a yaw axis of the aerial vehicle due to the singular failure is counter to and at least partially offset by a thrust vectoring torque about the yaw axis that is induced by twisting in the airframe due to thrust asymmetries from a remainder of the vertical propulsion units still functioning.

18. The method of claim 10, wherein the aerial vehicle comprises a fixed wing, vertical takeoff and landing (VTOL) unmanned aerial vehicle (UAV).

19. The method of claim 18, further comprising:

horizontally propelling the aerial vehicle with a plurality of horizontal propulsion units mounted to the airframe.

20. An aerial vehicle, comprising:

an airframe;

a plurality of vertical propulsion units mounted to the airframe and including propellers oriented to provide vertical propulsion to the aerial vehicle, wherein the vertical propulsion units are physically organized in quadrants on the airframe with each of the quadrants including two or more of the vertical propulsion units; and

a controller coupled to the vertical propulsion units to control operation of the vertical propulsion units, wherein at least two of the vertical propulsion units in each of the quadrants are adapted to counter-rotate from each other during flight of the aerial vehicle under influence of the controller, wherein the controller is configured to reduce thrust of the vertical propulsion units in a first quadrant when a singular failure of any one of the vertical propulsion units in a second quadrant diagonally positioned relative to the first quadrant occurs while also increasing thrust of the vertical propulsion units in third and fourth quadrants.

21. An aerial vehicle, comprising:

an airframe;

a plurality of vertical propulsion units mounted to the airframe and including propellers oriented to provide vertical propulsion to the aerial vehicle, wherein the vertical propulsion units are physically organized in quadrants on the airframe with each of the quadrants including two or more of the vertical propulsion units; and

a controller coupled to the vertical propulsion units to control operation of the vertical propulsion units, wherein at least two of the vertical propulsion units in each of the quadrants are adapted to counter-rotate from each other during flight of the aerial vehicle under influence of the controller,

wherein the plurality of vertical propulsion units consist of three propulsion units in each of the quadrants,

wherein the vertical propulsion units are organized into starboard propulsion units and port propulsion units and each of the starboard propulsion units counter-rotates to a corresponding one of the port propulsion units that has a mirrored position about a fore-aft axis of the aerial vehicle,

wherein the vertical propulsion units are further organized into fore propulsion units and aft propulsion units and each of the fore propulsion units counter-rotates to a

corresponding one of the aft propulsion units that has a mirrored position about a port-starboard axis of the aerial vehicle.

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