THRUST ALLOCATION 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, "Counter-Rotating Propellers for Aerial Vehicle," Attorney Docket Number XCOM-1-66313, 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;~~

~~vertical propulsion units mounted to the airframe to provide vertical propulsion and physically organized into propulsion rings including at least an inner ring and an outer ring;~~

~~a flight controller including logic that when executed by flight controller causes the aerial vehicle to perform operations including:~~

~~determining whether an initial thrust command output vector results in a thrust command clipping of one of the vertical propulsion units;~~

~~transferring torque associated with the initial thrust command output vector from each the vertical propulsion units in the outer ring to the vertical propulsion units in the inner ring when the thrust command clipping of one of the vertical propulsion units in the outer ring occurs;~~

~~determining a revised thrust command output vector after transferring the torque; and~~

~~driving the vertical propulsion units according to the revised thrust command output vector.~~

an airframe;

vertical propulsion units mounted to the airframe to provide vertical propulsion and physically organized into propulsion rings including at least an inner ring and an outer ring;

a flight controller including logic that when executed by flight controller causes the aerial vehicle to perform operations including:

determining whether an initial thrust command output vector results in a thrust command clipping of one of the vertical propulsion units;

transferring torque associated with the initial thrust command output vector from each of the vertical propulsion units in the outer ring to the vertical propulsion units in the inner ring when the thrust command clipping of one of the vertical propulsion units in the outer ring occurs;

determining a revised thrust command output vector after transferring the torque; and

driving the vertical propulsion units according to the revised thrust command output vector.

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

~~determining whether an initial thrust command output vector results in a thrust command clipping of one of the vertical propulsion units, wherein the vertical propulsion units are physically organized into propulsion rings including an inner ring and an outer ring;~~

~~transferring torque associated with the initial thrust command output vector from each the vertical propulsion units in the outer ring to the vertical propulsion units in the inner ring when the thrust command clipping of one of the vertical propulsion units in the outer ring occurs;~~

~~determining a revised thrust command output vector after transferring the torque; and~~

~~driving the vertical propulsion units according to the revised thrust command output vector.~~

determining whether an initial thrust command output vector results in a thrust command clipping of one of the vertical propulsion units, wherein the vertical propulsion units are physically organized into propulsion rings including an inner ring and an outer ring;

transferring torque associated with the initial thrust command output vector from each of the vertical propulsion units in the outer ring to the vertical propulsion units in the inner ring when the thrust command clipping of one of the vertical propulsion units in the outer ring occurs;

determining a revised thrust command output vector after transferring the torque; and

driving the vertical propulsion units according to the revised thrust command output vector.

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;~~

~~vertical propulsion units mounted to the airframe to provide vertical propulsion and physically organized into propulsion rings including at least an inner ring and an outer ring;~~

~~a flight controller including logic that when executed by flight controller causes the aerial vehicle to perform operations including:~~

~~determining whether an initial thrust command output vector results in a thrust command clipping of one of the vertical propulsion units;~~

~~transferring torque associated with the initial thrust command output vector from each the vertical propulsion units in the outer ring to the vertical propulsion units in the inner ring when the thrust command clipping of one of the vertical propulsion units in the outer ring occurs;~~

~~determining a revised thrust command output vector after transferring the torque; and~~

~~driving the vertical propulsion units according to the revised thrust command output vector.~~

~~2. The aerial vehicle of claim 1, wherein the flight controller includes further logic that when executed by the flight controller causes the aerial vehicle to perform further operations including:~~

~~scaling first thrust values associated with all of the vertical propulsion units in the outer ring when the thrust command clipping of one of the vertical propulsion units in the outer ring is determined,~~

~~wherein the torque transferred from the outer ring to the inner ring comprises an amount of torque reduced from the outer ring due to scaling all of the vertical propulsion units in the outer ring.~~

3. The aerial vehicle of claim 2, wherein the flight controller includes further logic that when executed by the flight controller causes the aerial vehicle to perform further operations including:

identifying which of the vertical propulsion units in the outer ring has a greatest amount of the thrust command clipping due to the initial thrust command output vector,

wherein all of the first thrust values of the vertical propulsion units in the outer ring are scaled based upon the greatest amount of the thrust command clipping.

4. The aerial vehicle of claim 2, wherein the flight controller includes further logic that when executed by the flight controller causes the aerial vehicle to perform further operations including:

recomputing second thrust values of the initial thrust command output vector associated with the inner ring after transferring the torque from the outer ring to the inner ring, wherein the first thrust values of the outer ring are fixed after the scaling and while recomputing the second thrust values of the inner ring.

5. The aerial vehicle of claim 1, wherein the flight controller includes further logic that when executed by the flight controller causes the aerial vehicle to perform further operations including:

determining the initial thrust command output vector,

wherein the initial thrust command output vector and the revised thrust command output vector are determined by solving for least squares solutions.

6. The aerial vehicle of claim 5, wherein the initial thrust command output vector and the revised thrust command output vector are determined by applying a Moore-Penrose Pseudoinverse allocation matrix to force command input vectors.

7. The aerial vehicle of claim 1, wherein the vertical propulsion units in the outer ring have greater mechanical advantage due to a longer lever arm to a center of mass the aerial vehicle than the vertical propulsion units in the inner ring.

8. The aerial vehicle of claim 1, wherein the flight controller includes logic that when executed by the flight controller causes the aerial vehicle to perform operations including:

monitoring an effectiveness of each of the vertical propulsion units in real-time;

identifying when the effectiveness of a given one of the vertical propulsion units falls outside of an expected operating range;

adjusting a control effectiveness matrix to reflect a reduced effectiveness for the given one of the vertical propulsion units when the effectiveness is identified as falling outside of the expected operating range; and

revising a current thrust command output vector for controlling the vertical propulsion units based upon the control effectiveness matrix after the adjusting.

9. The aerial vehicle of claim 8, wherein monitoring the effectiveness of each of the vertical propulsion units comprises monitoring drive signals to the vertical propulsion units.

10. The aerial vehicle of claim 8, further comprising:

operational sensors positioned in, on, or adjacent to the vertical propulsion units that monitor operation of the vertical propulsion units, wherein monitoring the effectiveness of each of the vertical propulsion units comprises monitoring feedback signals from the operational sensors.

11. The aerial vehicle of claim 1, wherein the aerial vehicle comprises an unmanned aerial vehicle (UAV) having two or more of the vertical propulsion units physically positioned in each of four quadrants of the airframe and wherein each of the four quadrants also includes first and second vertical propulsion units associated with the outer ring and the inner ring, respectively.

12. A method of controlling vertical propulsion units of an aerial vehicle, the method comprising:

determining whether an initial thrust command output vector results in a thrust command clipping of one of the vertical propulsion units, wherein the vertical propulsion units are physically organized into propulsion rings including an inner ring and an outer ring;

transferring torque associated with the initial thrust command output vector from each the vertical propulsion units in the outer ring to the vertical propulsion units in the inner ring when the thrust command clipping of one of the vertical propulsion units in the outer ring occurs;

~~determining a revised thrust command output vector after transferring the torque; and~~

~~driving the vertical propulsion units according to the revised thrust command output vector.~~

~~13. The method of claim 12, further including:~~

~~scaling first thrust values associated with all of the vertical propulsion units in the outer ring when the thrust command clipping of one of the vertical propulsion units in the outer ring is determined,~~

~~wherein the torque transferred from the outer ring to the inner ring comprises an amount of torque reduced from the outer ring due to scaling all of the vertical propulsion units in the outer ring.~~

~~14. The method of claim 13, further including:~~

~~identifying which of the vertical propulsion units in the outer ring has a greatest amount of the thrust command clipping due to the initial thrust command output vector,~~

~~wherein all of the first thrust values of the vertical propulsion units in the outer ring are scaled based upon the greatest amount of the thrust command clipping.~~

~~15. The method of claim 13, further including:~~

~~re-computing second thrust values of the initial thrust command output vector associated with the inner ring after transferring the torque from the outer ring to the inner ring, wherein the first thrust values of the outer ring are fixed after the scaling and while re-computing the second thrust values of the inner ring.~~

~~16. The method of claim 12, further including:~~

~~determining the initial thrust command output vector,~~

~~wherein the initial thrust command output vector and the revised thrust command output vector are determined by solving for least squares solutions.~~

~~17. The method of claim 16, wherein the initial thrust command output vector and the revised thrust command output vector are determined by applying a Moore-Penrose Pseudoinverse allocation matrix to force command input vectors.~~

~~18. The method of claim 12, wherein the vertical propulsion units in the outer ring have greater mechanical advantage due to a longer lever arm to a center of mass the aerial vehicle than the vertical propulsion units in the inner ring.~~

~~19. The method of claim 12, further including:~~

~~monitoring an effectiveness of each of the vertical propulsion units in real-time;~~

~~identifying when the effectiveness of a given one of the vertical propulsion units falls outside of an expected operating range;~~

~~adjusting a control effectiveness matrix to reflect a reduced effectiveness for the given one of the vertical propulsion units when the effectiveness is identified as falling outside of the expected operating range; and~~

~~revising a current thrust command output vector for controlling the vertical propulsion units based upon the control effectiveness matrix after the adjusting.~~

~~20. The method of claim 19, wherein monitoring the effectiveness of each of the vertical propulsion units comprises monitoring drive signals to the vertical propulsion units.~~

~~21. The method of claim 19, wherein the aerial vehicle includes operational sensors that monitor operation of the vertical propulsion units, and wherein monitoring the effectiveness of each of the vertical propulsion units comprises monitoring feedback signals from the operational sensors.~~

1. An aerial vehicle, comprising:

an airframe;

vertical propulsion units mounted to the airframe to provide vertical propulsion and physically organized into propulsion rings including at least an inner ring and an outer ring;

a flight controller including logic that when executed by flight controller causes the aerial vehicle to perform operations including:

determining whether an initial thrust command output vector results in a thrust command clipping of one of the vertical propulsion units;

transferring torque associated with the initial thrust command output vector from each of the vertical propulsion units in the outer ring to the vertical propulsion units in the inner ring when the thrust command clipping of one of the vertical propulsion units in the outer ring occurs;

determining a revised thrust command output vector after transferring the torque; and

driving the vertical propulsion units according to the revised thrust command output vector.

2. The aerial vehicle of claim 1, wherein the flight controller includes further logic that when executed by the flight controller causes the aerial vehicle to perform further operations including:

scaling first thrust values associated with all of the vertical propulsion units in the outer ring when the thrust command clipping of one of the vertical propulsion units in the outer ring is determined,

wherein the torque transferred from the outer ring to the inner ring comprises an amount of torque reduced from the outer ring due to scaling all of the vertical propulsion units in the outer ring.

3. The aerial vehicle of claim 2, wherein the flight controller includes further logic that when executed by the flight controller causes the aerial vehicle to perform further operations including:

identifying which of the vertical propulsion units in the outer ring has a greatest amount of the thrust command clipping due to the initial thrust command output vector,

wherein all of the first thrust values of the vertical propulsion units in the outer ring are scaled based upon the greatest amount of the thrust command clipping.

4. The aerial vehicle of claim 2, wherein the flight controller includes further logic that when executed by the flight controller causes the aerial vehicle to perform further operations including:

recomputing second thrust values of the initial thrust command output vector associated with the inner ring after transferring the torque from the outer ring to the inner ring, wherein the first thrust values of the outer ring are fixed after the scaling and while recomputing the second thrust values of the inner ring.

5. The aerial vehicle of claim 1, wherein the flight controller includes further logic that when executed by the flight controller causes the aerial vehicle to perform further operations including:

determining the initial thrust command output vector,

wherein the initial thrust command output vector and the revised thrust command output vector are determined by solving for least squares solutions.

6. The aerial vehicle of claim 5, wherein the initial thrust command output vector and the revised thrust command output vector are determined by applying a Moore-Penrose Pseudoinverse allocation matrix to force command input vectors.

7. The aerial vehicle of claim 1, wherein the vertical propulsion units in the outer ring have greater mechanical advantage due to a longer lever arm to a center of mass of the aerial vehicle than the vertical propulsion units in the inner ring.

8. The aerial vehicle of claim 1, wherein the flight controller includes logic that when executed by the flight controller causes the aerial vehicle to perform operations including:

monitoring an effectiveness of each of the vertical propulsion units in real-time;

identifying when the effectiveness of a given one of the vertical propulsion units falls outside of an expected operating range;

adjusting a control effectiveness matrix to reflect a reduced effectiveness for the given one of the vertical propulsion units when the effectiveness is identified as falling outside of the expected operating range; and

revising a current thrust command output vector for controlling the vertical propulsion units based upon the control effectiveness matrix after the adjusting.

9. The aerial vehicle of claim 8, wherein monitoring the effectiveness of each of the vertical propulsion units comprises monitoring drive signals to the vertical propulsion units.

10. The aerial vehicle of claim 8, further comprising:

operational sensors positioned in, on, or adjacent to the vertical propulsion units that monitor operation of the vertical propulsion units, wherein monitoring the effectiveness of each of the vertical propulsion units comprises monitoring feedback signals from the operational sensors.

11. The aerial vehicle of claim 1, wherein the aerial vehicle comprises an unmanned aerial vehicle (UAV) having two or more of the vertical propulsion units physically positioned in each of four quadrants of the airframe and wherein each of the four quadrants also includes first and second vertical propulsion units associated with the outer ring and the inner ring, respectively.

12. A method of controlling vertical propulsion units of an aerial vehicle, the method comprising:

determining whether an initial thrust command output vector results in a thrust command clipping of one of the vertical propulsion units, wherein the vertical propulsion units are physically organized into propulsion rings including an inner ring and an outer ring;

transferring torque associated with the initial thrust command output vector from each of the vertical propulsion units in the outer ring to the vertical propulsion units in the inner ring when the thrust command clipping of one of the vertical propulsion units in the outer ring occurs;

determining a revised thrust command output vector after transferring the torque; and

driving the vertical propulsion units according to the revised thrust command output vector.

13. The method of claim 12, further including:

scaling first thrust values associated with all of the vertical propulsion units in the outer ring when the thrust command clipping of one of the vertical propulsion units in the outer ring is determined,

wherein the torque transferred from the outer ring to the inner ring comprises an amount of torque reduced from the outer ring due to scaling all of the vertical propulsion units in the outer ring.

14. The method of claim 13, further including:

identifying which of the vertical propulsion units in the outer ring has a greatest amount of the thrust command clipping due to the initial thrust command output vector,

wherein all of the first thrust values of the vertical propulsion units in the outer ring are scaled based upon the greatest amount of the thrust command clipping.

15. The method of claim 13, further including:

re-computing second thrust values of the initial thrust command output vector associated with the inner ring after transferring the torque from the outer ring to the inner ring, wherein the first thrust values of the outer ring are fixed after the scaling and while re-computing the second thrust values of the inner ring.

16. The method of claim 12, further including:

determining the initial thrust command output vector,

wherein the initial thrust command output vector and the revised thrust command output vector are determined by solving for least squares solutions.

17. The method of claim 16, wherein the initial thrust command output vector and the revised thrust command output vector are determined by applying a Moore-Penrose Pseudoinverse allocation matrix to force command input vectors.

18. The method of claim 12, wherein the vertical propulsion units in the outer ring have greater mechanical advantage due to a longer lever arm to a center of mass of the aerial vehicle than the vertical propulsion units in the inner ring.

19. The method of claim 12, further including:

monitoring an effectiveness of each of the vertical propulsion units in real-time;

identifying when the effectiveness of a given one of the vertical propulsion units falls outside of an expected operating range;

adjusting a control effectiveness matrix to reflect a reduced effectiveness for the given one of the vertical propulsion units when the effectiveness is identified as falling outside of the expected operating range; and

revising a current thrust command output vector for controlling the vertical propulsion units based upon the control effectiveness matrix after the adjusting.

20. The method of claim 19, wherein monitoring the effectiveness of each of the vertical propulsion units comprises monitoring drive signals to the vertical propulsion units.

21. The method of claim 19, wherein the aerial vehicle includes operational sensors that monitor operation of the vertical propulsion units, and wherein monitoring the effectiveness of each of the vertical propulsion units comprises monitoring feedback signals from the operational sensors.