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(54) **FLIGHT CONTROL SYSTEM FOR A HYBRID AIRCRAFT IN THE YAW AXIS**

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(73) Assignee: **Sikorsky Aircraft Corporation**, Stratford, CT (US)

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This patent is subject to a terminal disclaimer.

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(52) **U.S. Cl.** .... **244/195**; 244/76 B; 244/17.13
(58) **Field of Search** .... 244/195, 185, 244/23 B, 6, 182, 76 B, 225, 17.13, 190; 701/301.4, 7, 10; 340/967, 969, 970

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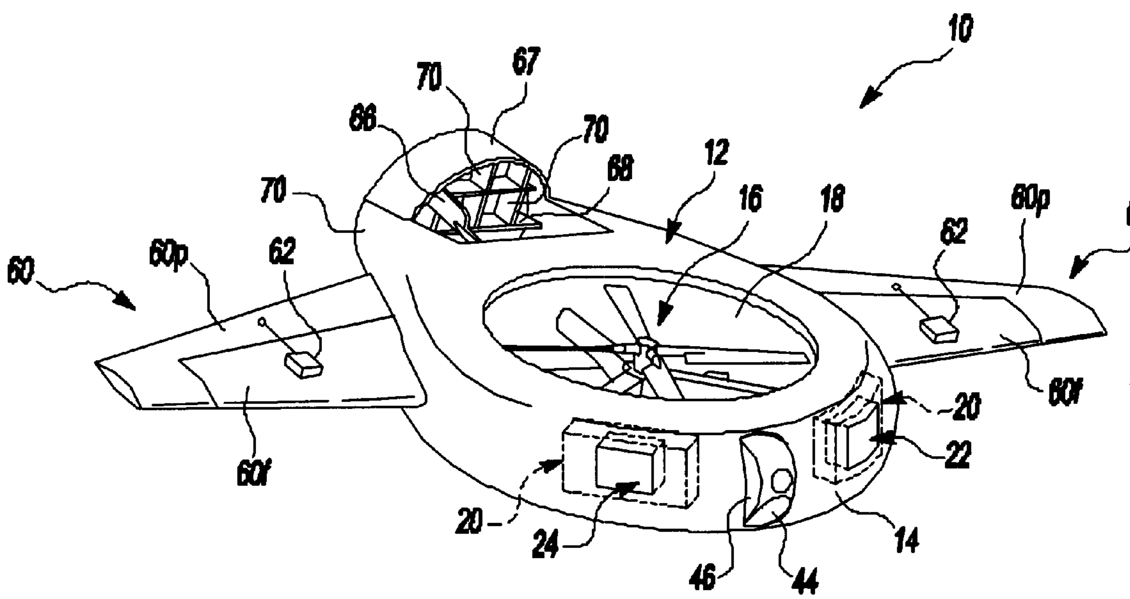
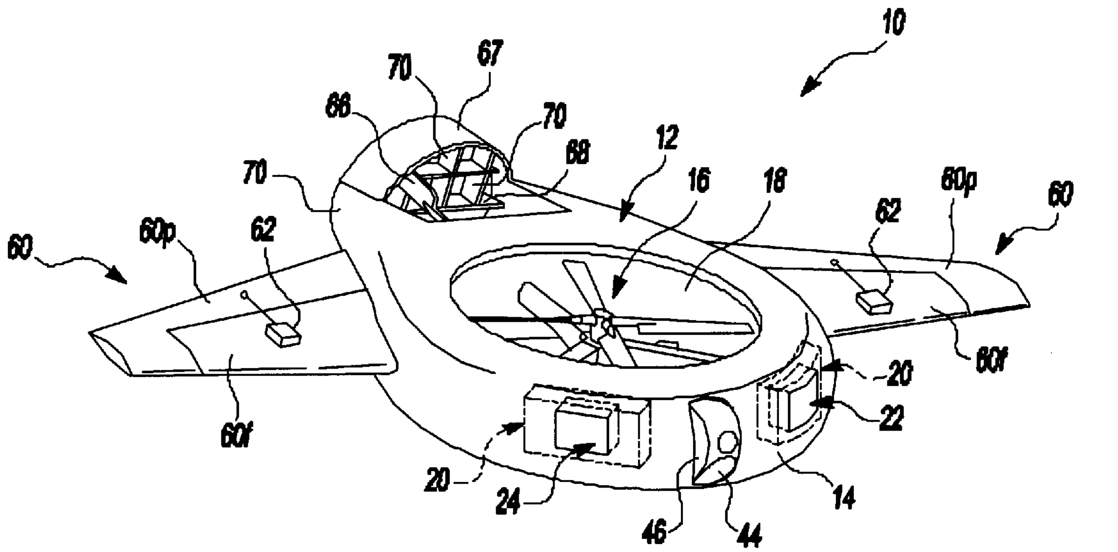
(57) **ABSTRACT**

A flight control system includes a blending algorithm which evaluates the current flight regime and determines the effectiveness of the flight controls to effect the rotational moment of a hybrid vehicle about the yaw axis. Gain schedules for both differential collective and rudder control provide a quantitative measure of control effectiveness. Based on the respective gain schedules, the algorithm determines how much of the control commands should be sent to each control surface. The result is that for a given control command, the same amount of yaw moment will be generated regardless of flight regime. This simplifies the underlying flight control law since the commands it generates are correct regardless of flight regime.

19 Claims, 5 Drawing Sheets

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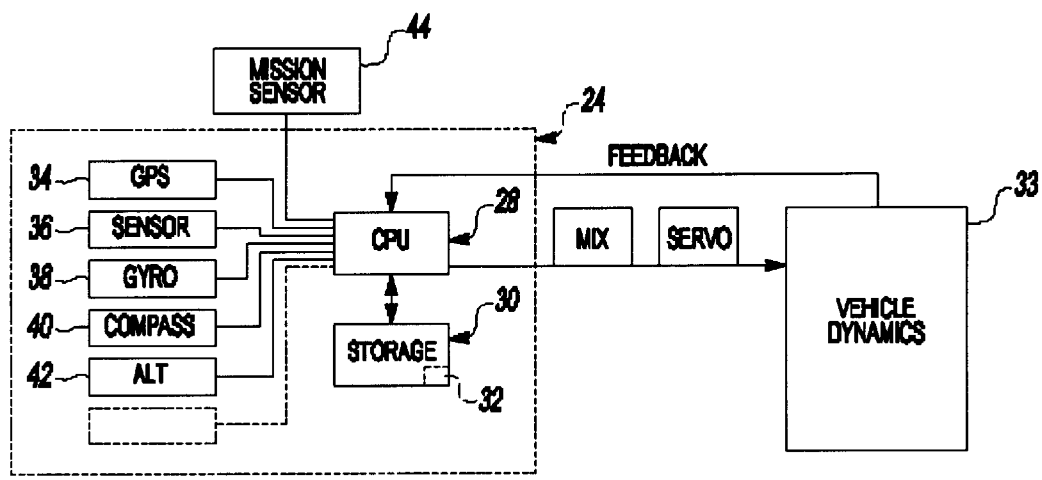
46
44

Fig-1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GYRO
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ALT
CPU
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MIX
SERVO
33
VEHICLE DYNAMICS
STORAGE
30
32

Fig-1A

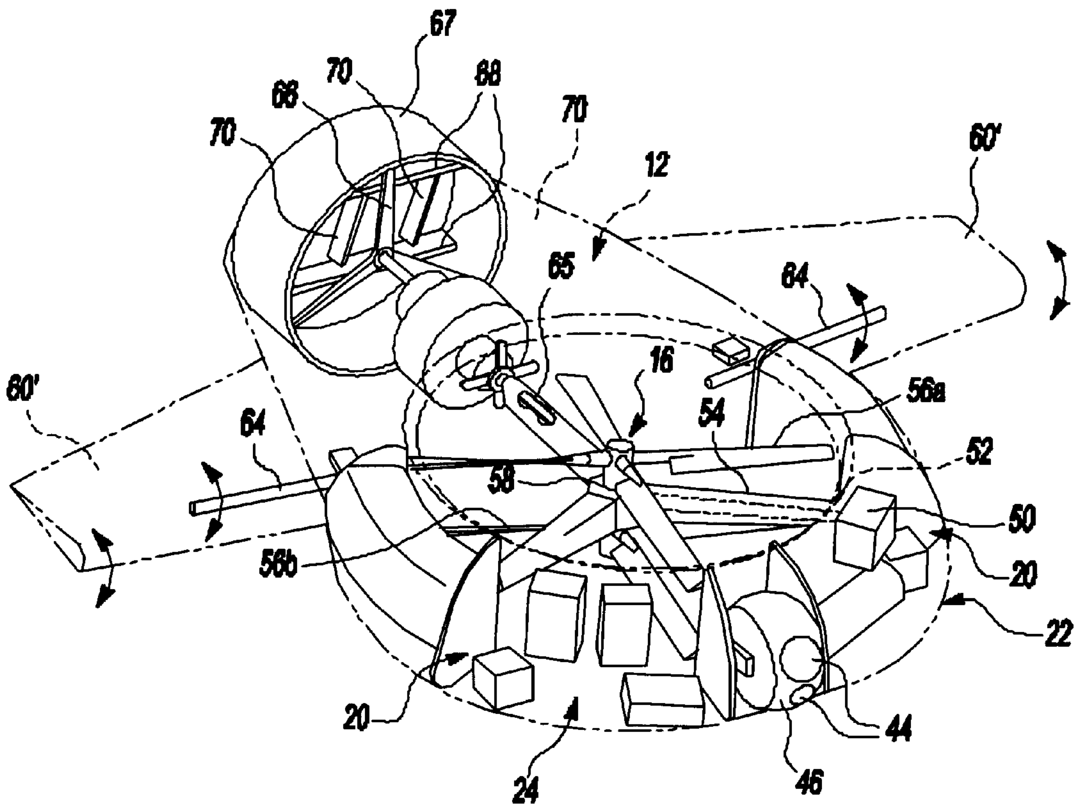
67
70
68
68
70
70
12
60'
65
64
16
60'
56a
64
54
52
58
50
56b
20
22
20
44
24
46

Fig-1B

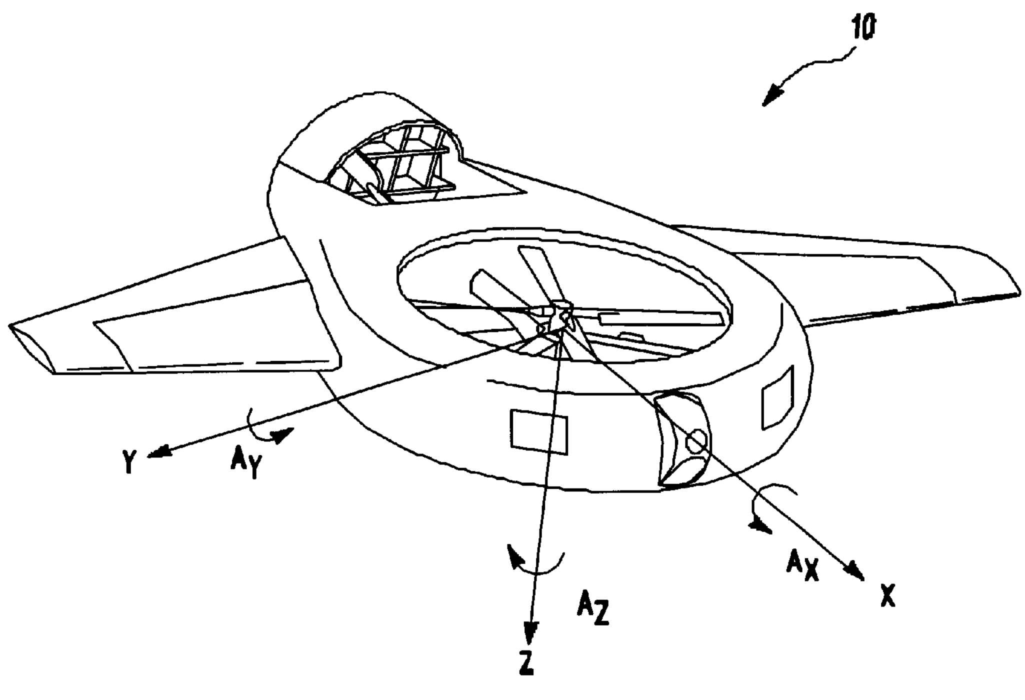
10
Y
A_Y
A_X
X
A_Z
Z

Fig-2A

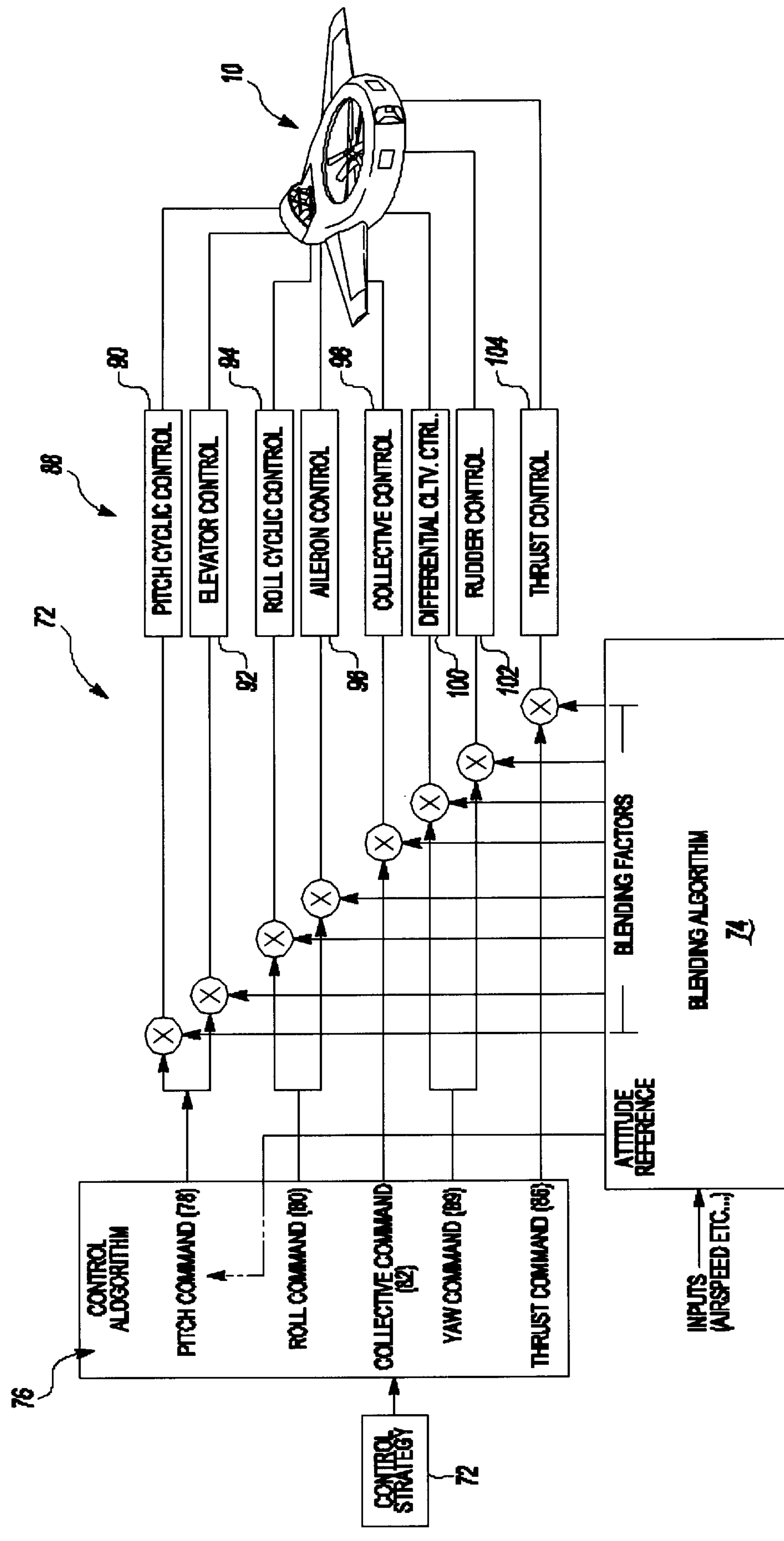
10
88
72
PITCH CYCLIC CONTROL
ELEVATOR CONTROL
ROLL CYCLIC CONTROL
AILERON CONTROL
COLLECTIVE CONTROL
DIFFERENTIAL CLTV. CTRL.
RUDDER CONTROL
THRUST CONTROL
90
92
94
96
98
100
102
104
BLENDING FACTORS
ATTITUDE REFERENCE
BLENDING ALGORITHM
74
CONTROL ALOGORITHM
PITCH COMMAND (78)
ROLL COMMAND (80)
COLLECTIVE COMMAND (82)
YAW COMMAND (86)
THRUST COMMAND (86)
76
CONTROL STRATEGY
72
INPUTS (AIRSPEED ETC...)

Fig-2

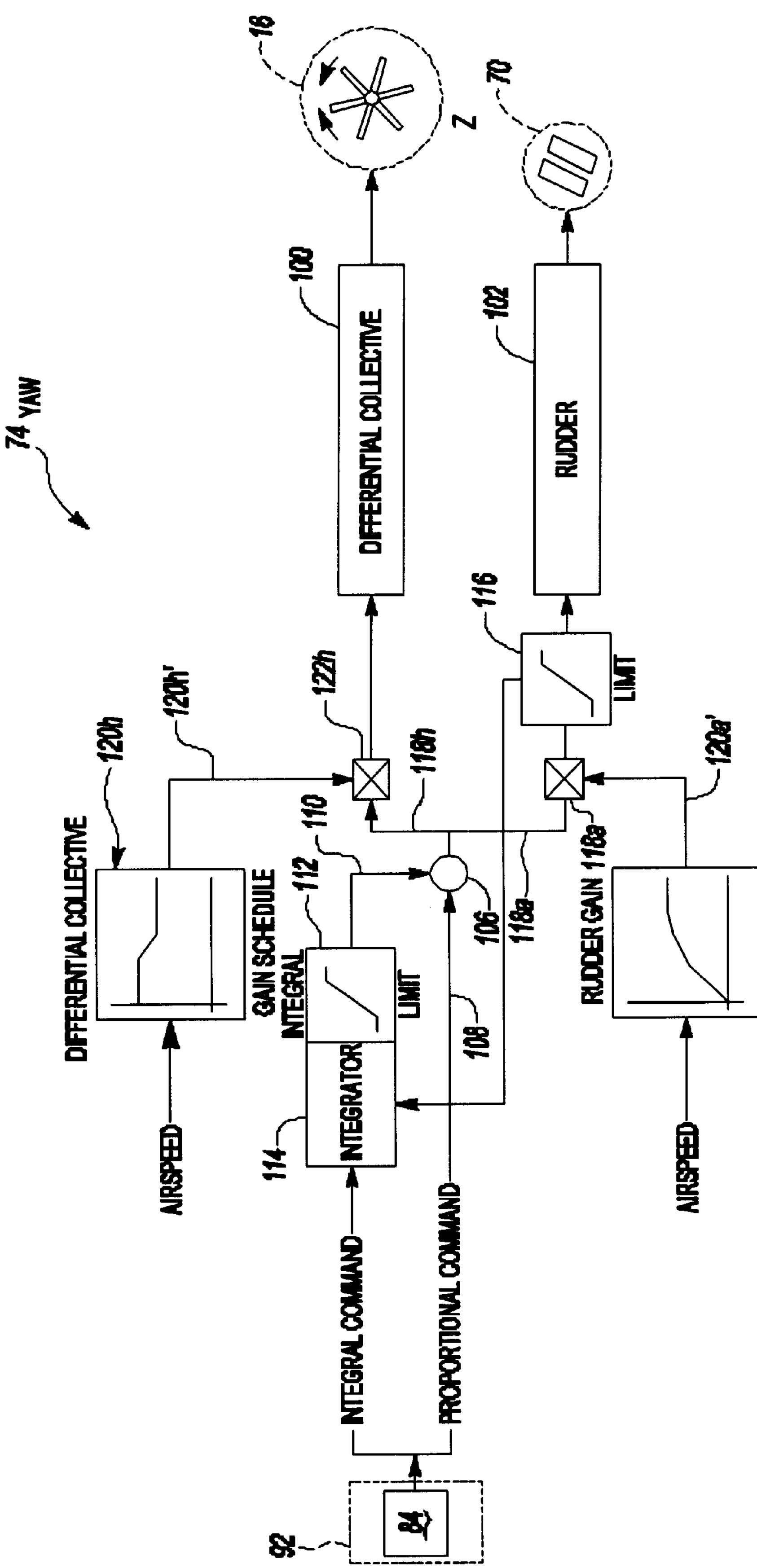
74 YAW
16
Z
70
DIFFERENTIAL COLLECTIVE
100
RUDDER
102
116
LIMIT
122h
120h'
120h
DIFFERENTIAL COLLECTIVE GAIN SCHEDULE
118h
110
112
INTEGRAL LIMIT
INTEGRATOR
114
106
108
118a
RUDDER GAIN 118a
120a'
120a
SCHEDULE
AIRSPEED
AIRSPEED
INTEGRAL COMMAND
PROPORTIONAL COMMAND
84
92

Fig-3

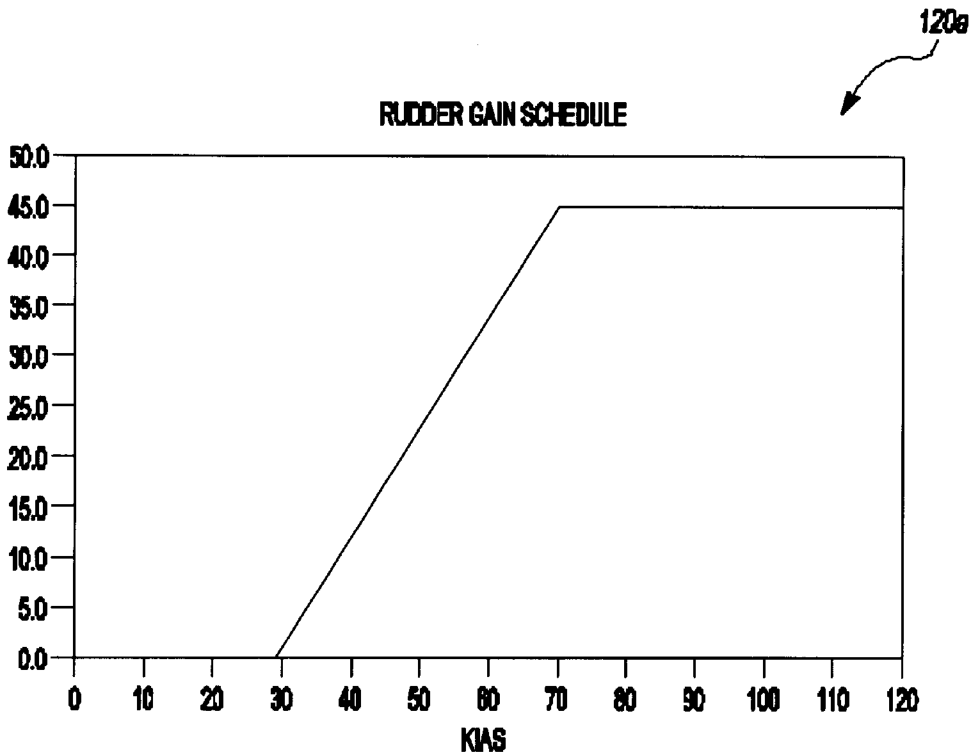
120a
RUDDER GAIN SCHEDULE
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0
10
20
30
40
50
60
70
80
90
100
110
120
KIAS

Fig-4

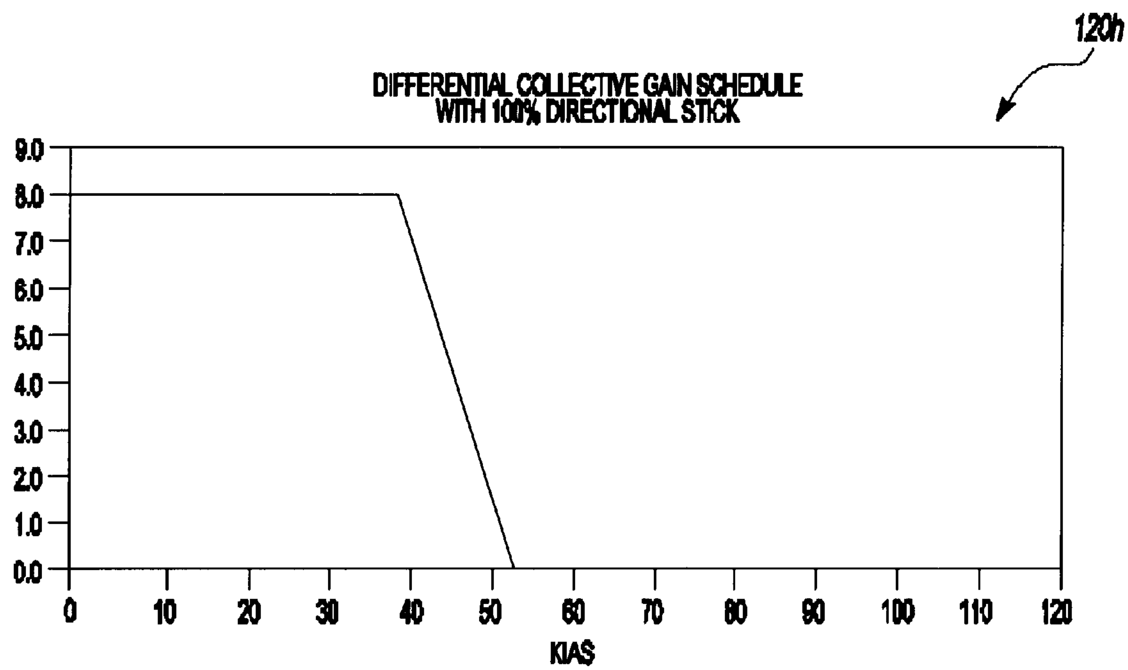
120h
DIFFERENTIAL COLLECTIVE GAIN SCHEDULE
WITH 100% DIRECTIONAL STICK
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
10
20
30
40
50
60
70
80
90
100
110
120
KIAS

Fig-5

FLIGHT CONTROL SYSTEM FOR A HYBRID AIRCRAFT IN THE YAW AXIS

This invention was made with government support under Contract No.: M67854-99C-2081 awarded by the Department of the Army. The government therefore has certain rights in this invention.

BACKGROUND OF THE INVENTION

The present invention relates to a flight control system for a hybrid aircraft, and more particularly, to a flight control system for a hybrid unmanned aerial vehicle (UAV) which blends command signals to a multiple of vehicle control surfaces during transition between rotor borne and wing borne flight.

There is an increased emphasis on the use of UAVs for performing various activities in both civilian and military situations where the use of manned flight vehicles may not be appropriate. Such missions include surveillance, reconnaissance, target acquisition, target designation, data acquisition, communications relay, decoy, jamming, harassment, ordinance delivery, or supply.

A hybrid aircraft provides the hover and low-speed maneuverability of a helicopter with the high-speed forward flight and duration capabilities of a winged aircraft. Typically, hybrid aircraft include a helicopter control surface system which provides cyclic pitch, collective pitch and differential rotation to generate lift, pitch, roll, and yaw control when operating in a hover/low-speed environment. Additionally, the hybrid aircraft includes a conventional fixed wing aircraft control surface system such as aileron, elevator, rudder and flaps to provide control when operating in a high-speed environment. Hybrid aircraft also typically include a separate translational propulsive system.

When the hybrid aircraft is operating in a hover/low-speed environment, maneuverability is achieved by controlling the helicopter control system. When the hybrid aircraft is operating in a high-speed environment, the hybrid aircraft operates as a fixed wing aircraft and maneuverability is achieved by controlling the aircraft flight control surfaces. As the hybrid aircraft transitions between helicopter and aircraft control surface systems, however, neither the helicopter nor the aircraft control systems are completely effective. Moreover, the relationship between control displacement and control moment is nonlinear and the aerodynamic forces on the aircraft change most dramatically. Flight control within this region is therefore rather complex.

Accordingly, it is desirable to provide a hybrid aircraft flight control systems which automatically blends command signals to a multiple of vehicle flight control surfaces during transition between rotor borne and wing borne flight. It is further desirable to provide the same amount of vehicle control regardless of the vehicle's flight regime.

SUMMARY OF THE INVENTION

Hybrid aircraft include a flight control system according to the present invention. A hybrid aircraft can hover like a helicopter using a rotor system or fly like a fixed wing aircraft using conventional fixed wing controls such that it is operable in four flight regimes:

1. Hover—Defined as low speed operation. The rotor generates control and lift.
2. Forward Flight—Lift is generated by the wings and all control is through the fixed wing surfaces (elevator, ailerons, rudder)
3. Transition Up—This mode guides operation of a multiple of control surfaces when flying from Hover to Forward Flight.
4. Transition Down—This mode guides operation of a multiple of control surfaces when flying from Forward Flight to Hover.

The flight control system according to the present invention includes a blending algorithm which evaluates the current flight regime and determines the effectiveness of the various flight control surfaces. In the yaw axis, gain schedules for both differential collective (rotor) and rudder control are used as a quantitative measure of control effectiveness. Based on the respective gain schedules, the blending algorithm determines how much of an input command is sent to each control surface. The result is that for a given command, the same amount of yaw moment will be generated regardless of flight regime. This simplifies the underlying flight control laws since the commands it generates are correct regardless of flight regime.

The present invention therefore provides a hybrid aircraft flight control system which automatically blends yaw command signals between differential collective and rudder flight control surfaces during transition between rotor borne and wing borne flight.

BRIEF DESCRIPTION OF THE DRAWINGS

The various features and advantages of this invention will become apparent to those skilled in the art from the following detailed description of the currently preferred embodiment. The drawings that accompany the detailed description can be briefly described as follows:

FIG. **1** is a general perspective view of an exemplary hybrid aircraft having a flight control system according to the present invention;

FIG. **1A** is a block diagram of the flight control system;

FIG. **1B** is a partially phantom view of another exemplary hybrid aircraft having a flight control system according to the present invention;

FIG. **2** is a general schematic block diagram of the flight control law strategy provided by the flight control system of FIG. **2**;

FIG. **2A** is a schematic representation of vector axes superimposed on the vehicle of FIG. **1**;

FIG. **3** is a detailed block diagram of one embodiment of a blending algorithm;

FIG. **4** is one embodiment of an exemplary rudder gain schedule for the vehicle of FIG. **1**; and

FIG. **5** is one embodiment of an exemplary differential collective gain schedule for the vehicle of FIG. **1**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. **1** illustrates a hybrid aircraft **10**, such as the CYPHER**2** UAV developed by Sikorsky Aircraft Corporation. For further understanding of the UAV embodiment and associated components thereof, attention is directed to U.S. patent application Ser. No. 09/296,624 filed Apr. 22, 1999 and entitled "Unmanned Aerial Vehicle With Counter-Rotating Ducted Rotors and Shrouded Pusher-Prop," which is assigned to the assignee of the instant invention and which is hereby incorporated herein in its entirety. It should be further understood that other hybrid aircraft (manned and unmanned) having multiple flight control surfaces will also benefit from the instant invention.

The aircraft **10** includes a fuselage **12** with a toroidal portion **14** having a generally hemi-cylindrical aerodynamic profile. A rotor assembly **16** is mounted within a duct **18** that extends substantially vertically through the fuselage **12**. The fuselage **12** includes a plurality of accessible internal bays **20** for housing and/or storing aircraft flight and mission components. Preferably, the bays house a powerplant system **22** and a flight control system **24**.

The flight control system **24** preferably includes a CPU **28** and storage device **30** connected to the CPU **28** (FIG. 1A). The storage device **30** may include a hard drive, CD ROM, DVD, RAM, ROM or other optically readable storage, magnetic storage or integrated circuit. As will be further described, the storage device **30** contains a database **32** including preprogrammed flight control law strategy associated with a blending algorithm for the control of the vehicle dynamics (illustrated schematically at **33**) through servo actuators and a mixing circuit or the like. The control strategy preferably maintains parameters such as pitch attitude, roll attitude and heading at a desired point to provide control of the vehicle **10**.

The flight control system **24** may alternatively or additionally include a Primary Flight Control System (PFCS) and an Automatic Flight Control Systems (AFCS) as are well known. The AFCS and PFCS software algorithms may be stored in the storage device **30** or alternatively in removable ROM, RAM or flash memory. The AFCS and PFCS provide feedback mechanisms having linear control system logic such as proportional, integral, derivative (PID) paths to achieve the desired response and compensate for undesired destabilization forces acting on the vehicle **10**.

The flight control system further includes transmitters, receivers, navigation, sensors and attitude sensors, such as a GPS receiver **34** and multi-axis accelerometers **36**. The flight control system **24** may alternatively or additionally include one or more gyros **38**, a compass **40**, and an altimeter **42**, all connected to the CPU **28** to detect vehicle dynamics and flight path parameters. The sensors may also include any device capable of outputting an acceleration vector signal representing sensed vehicle motion and/or receiving control surface displacement. Such devices (as well as others) are well known in the aircraft field.

Other mission related sensors **44** (also illustrated in FIG. **1**), such as a camera system, forward looking infrared radar (FLIR) sensor, laser designator, thermal imager, or the like are also preferably located in a trainable turret **46** (FIG. **1**) in a forward area of the vehicle **10**. It should be understood that although a particular component arrangement is disclosed in the illustrated embodiment, other arrangements will benefit from the instant invention.

Referring to FIG. 1B, a drive train assembly **48** is operative for transferring power developed by an engine (illustrated schematically at **50**) to the rotor assembly **16** by a drive shaft **52**. A plurality of hollow struts **54** extend between the fuselage **12** and the rotor assembly **16** to support the rotor assembly **16** therein. The support struts **54** provide structural rigidity to the aircraft duct **18** to prevent flight and ground loads from distorting the fuselage **12** and provide conduits for interconnecting operating elements of the aircraft **10** such as the engine drive shaft **52** and electrical wiring for various operating components.

The rotor assembly **16** includes a pair of multi-bladed, counter-rotating rotors **56***a*, **56***b*, coaxially aligned with the duct **18**, and a coaxial transmission subassembly therebetween (illustrated somewhat schematically at **58**). Each counter-rotating rotor **56***a*,**56***b* preferably includes a plurality of blade assemblies in which blade pitch changes induced in the counter-rotating rotor systems **56***a*,**56***b*, i.e., cyclic and/or collective pitch inputs, can be utilized to generate lift, pitch, roll, and yaw control of the aircraft **10**. Yaw control is preferably provided by differential collective of the counter-rotating rotors **56***a*,**56***b*.

Wings **60** extend laterally outward from the aircraft fuselage **12** to provide high lifting forces. Those skilled in the art would readily appreciate the diverse wing arrangements that can be incorporated into a UAV according to the present invention. Preferably, each wing **60** includes a fixed stub portion **60**F and a pivotal flight control surface portion **60**P. The flight control surface portion **60**P preferably includes a flaperon hingedly mounted to the trailing edge of the wing **60**. A servo actuator **62** mounted within the fixed portion **60**F controls the pivoting of the pivotal portion **60**P. Alternatively, or in addition, the entire wing **60**' may pivot such that a drive rod **64** independently changes the angle of attack of the wing **60**' (FIG. 1B).

In order to provide translational thrust, the aircraft **10** includes a pusher prop **66** mounted to the rear of the vehicle **10**. The propeller **66** is mounted to a drive shaft **65** which, in turn, is engaged with the powerplant subsystem through a flexible coupling or the like. The prop **66** is preferably mounted to the rear of the aircraft with its rotational axis oriented substantially horizontal.

A prop shroud **67** is formed on the aft fuselage **70** and around the pusher prop **66**. The cross-sectional shape of the shroud **67** is preferably configured as an airfoil to provide the shroud **68** with some lift component. Mounted on the shroud **68** aft of the pusher prop **66** are one or more horizontal and vertical control surfaces **68**, **70**. Preferably, the control surfaces **68**, **70** are pivotally mounted to the shroud **67** to permit the exhausted air to be channeled in a controllable manner such that the horizontal control surfaces **68** function as elevators and the vertical control surfaces **70** function as rudders. It is primarily the elevator that provides the pitch nose down moment required to counteract the nose up moment generated by the rotor shroud during transition.

Referring to FIG. **2**, a block diagram of the inventive flight control law strategy **72** having a blending algorithm **74** is schematically illustrated. The blending algorithm **74** insures smooth, controllable flight in all flight regimes. This is of particular importance in the transition flight region. Below transition, the aircraft maneuvers like a helicopter utilizing the rotor exclusively for yaw control. Above transition, the aircraft maneuvers like a fixed wing airplane utilizing the rudder exclusively for yaw control. During transition, the aircraft uses both the rotor and rudder to control yaw. In this region, the relationship between control displacement and control moment is most nonlinear. Transition is also the region where the aerodynamic forces on the aircraft change most dramatically. The blending algorithm compensates for these effects and thereby improves control.

A control algorithm **76** preferably outputs a pitch command **78**, a roll command **80**, a collective command **82**, a yaw command **84** and a thrust command **86**. The flight control commands **78**–**86** are generated by manual input from a remote operator, the flight control system **24** or a combination thereof. Orthogonal vector axes superimposed on the vehicle **10** (FIG. **2**A) illustrate that the pitch command **78** provides angular moment about the Y axis (Ay); the roll command **80** provides angular moment about the X axis (Ax); the collective command **82** provide thrust moment along the Z axis; the yaw command **84** provides angular moment about the Z axis (Az); and the thrust command **86** provides thrust moment about the X axis. It should be understood that numerous hybrid aircraft flight control systems will benefit from the blending algorithm of the instant invention.

The flight control command **78–86** are output to a multiple of movable control surfaces **88** to achieve the desired moment about the desired axis or axes. In the disclosed embodiment, the movable control surfaces **88** include a pitch cyclic control **90**, elevator control **92**, roll cyclic control **94**, aileron control **96**, collective control **98**, differential collective control **100**, rudder control **102**, and thrust control **104**.

Each flight control command **78–86** is output to one or more movable control surfaces **90–104** to control the vehicle in a particular axis. The control commands **78–86** are actuating commands which are sent to a servo actuator, a mixing circuit for a plurality of servos which control a swashplate or the like and which are suitably arranged to control the rotor blades and/or otherwise adjust the deflection of a control surface of the vehicle **10**. Preferably, one of the control surfaces **90–104** is primarily a helicopter flight control surface, while the other is primarily a conventional aircraft flight control surface.

In the disclosed embodiment, the pitch command **78** is associated with the pitch cyclic control **90** and the elevator control **92**; the roll command **80** is associated with the roll cyclic control **94**, and the aileron control **96**; the collective command **82** is associated with the collective control **98**; the yaw command **84** is associated with the differential collective control **100** and the rudder control **102**; and the thrust command **86** is associated with the thrust control **104** (FIGS. 1A and 1B; pusher prop **66**). Although particular control surfaces are disclosed in the illustrated embodiment, it should be understood that other combinations of control surfaces, and other types of control surfaces such as slats, flaps, flaperons, puffer ducts, articulatable nozzles, elevons, and the like will also benefit from the instant invention depending on the aerodynamic arrangement of the vehicle.

Referring to FIG. **3**, the blending algorithm **74** in the yaw axis (**74**yaw) is schematically illustrated. The yaw blending algorithm **74**yaw is preferably operable when the vehicle is in the transition flight region.

Yaw summing circuit **106** receives the yaw command input **84** (also shown in FIG. **2**) preferably in proportional plus integral form. The proportional and integral commands are the primary control commands and are computed by the underlying control laws within the flight control strategy **72**. That is, a proportional yaw command **108** is summed with an integral yaw command **110** which has been limited by a limiting circuit **112**.

As generally known, limiting circuits prevents a signal from exceeding a certain specified magnitude or dropping below a certain magnitude thereby providing authority limits. Limit **112** controls the rate of the output of the yaw integrator **114**. Yaw integrator unit **114** is used to maintain a desired differential collective control **100** and/or rudder control **102** without the necessity of constant displacement of the yaw command **84**. To further assure that the yaw integrator **114** does not exceed the maximum travel of the rudder **70** a second limiter **116** is provided in a feed back path. If limiter **116** is reached, the yaw integrator **114** is held in the limited direction to prevent exceeding control surface limits and integrator windup.

From the yaw summing circuit **106**, the yaw command **84** is split into separate command paths **118***a* and **118***h*. Each command path **118***a*, **118***h* is respectively multiplied by a rudder gain **120***a*' and a differential collective gain **120***h*' at multipliers **122***a*, **122***h*. The rudder gain **120***a*' is determined by a rudder gain schedule **120***a* (FIG. **4**) which relates the velocity (air speed) of the vehicle **10** to allowable rudder control **102** deflection. The differential collective gain **120***h*' is determined by a differential collective gain schedule **120***h* (FIG. **5**) which relates the velocity (air speed) of the vehicle **10** to the allowable differential collective control deflection. The gain schedules are preferably quantitative measures of control effectiveness.

Based upon the respective gain schedule **120**A, **120***h*, the yaw blending algorithm **74**yaw determines how much of the yaw input command **84** is sent to each movable control surface (differential collective control **100** and/or rudder control **102**.)

For example only, in the illustrated embodiment, no rudder deflection is provided until the vehicle **10** reaches a velocity of 30 kias. Likewise, no differential collective control is used when the velocity of the vehicle **10** exceeds 55 kias. If the vehicle **10** is travelling at a velocity of 65 kias, the entire yaw command **84** is sent to the rudder (differential collective gain **120***h*'=0). The rudder deflection, however, is scaled to provide only +/−40 degrees of deflection. Preferably, the gain schedules **120***a*, **120***h* are determined so that for any given control command, the same amount of vehicle moment will be generated regardless of flight regime. That is, the gain schedules assure that the vehicle responds in a substantially identical manner independent of it velocity. This simplifies the underlying flight control system laws since the command the flight control system generates provide the desired moment regardless of flight regime.

Preferably, the blending algorithm **74**yaw manages control limits so that if one control surface is at its maximum limit of travel, the other control surface assists the saturated surface. This minimizes the possibility of entering uncontrolled flight due to unavailable control authority. The main limit is that of the yaw integrator **114**. When the differential collective **100** reaches its full deflection (full saturation), rudder control **102** is added in by the flight control system **24**. For example only, if the vehicle is traveling forward at a relatively low velocity, and a large yaw input command **84** is provided, differential collective control **100** may not provide the necessary control authority commanded by the flight control system **24**. The blending algorithm **74**yaw responds by maintaining the differential collective control **100** at full deflection while adding in rudder control **102** to achieve the desired response.

Furthermore, while it is understood it still is worth stating that the present invention is not limited to a microprocessor based control system. The system may be implemented in a non-microprocessor based electronic system (either digital or analog).

The foregoing description is exemplary rather than defined by the limitations within. Many modifications and variations of the present invention are possible in light of the above teachings. The preferred embodiments of this invention have been disclosed, however, one of ordinary skill in the art would recognize that certain modifications would come within the scope of this invention. It is, therefore, to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described. For that reason the following claims should be studied to determine the true scope and content of this invention.

What is claimed is:

1. A flight control system for a hybrid aircraft comprising:

a movable first control surface not operably connected to a rotor system operable to direct an aircraft about a yaw axis;

a movable second control surface on a rotor system operable to direct the aircraft about said yaw axis;

a storage device having a blending algorithm, said blending algorithm determining a first gain for said first control surface according to a first gain schedule, and determining a second gain for said second control surface according to a second gain schedule in response to a control input for said yaw axis; and

a controller in communication with said first control surface, said second control surface, and said storage device, said controller operable to receive a control command for said yaw axis and actuate said first control surface according to said first gain and said second control surface according to said second gain.

2. The flight control system as recited in claim **1**, wherein said first gain schedule and said second gain schedule relate control surface deflection to vehicle airspeed.

3. The flight control system as recited in claim **1**, wherein said first control surface is a rudder.

4. The flight control system as recited in claim **3**, wherein said rudder is mounted within a shroud.

5. The flight control system as recited in claim **1**, wherein said second control surface includes a coaxial counter rotating rotor system having differential collective pitch.

6. The flight control system as recited in claim **5**, wherein said coaxial counter rotating rotor system is mounted within a duct.

7. The flight control system as recited in claim **1**, wherein said hybrid aircraft is an unmanned aerial vehicle.

8. A method of controlling a hybrid aircraft about a first axis comprising the steps of:

(1) providing a control command for a first vehicle axis;

(2) splitting said control command to provide a first control command and a second control command;

(3) multiplying said first control command by a first gain according to a first gain schedule to provide a first scaled control command;

(4) multiplying said second control command by a second gain according to a second gain schedule to provide a second scaled control command;

(5) communicating said first scaled control command to a first movable control surface not operably connected to a rotor system for control of the hybrid aircraft about the first vehicle axis; and

(6) communicating said second scaled control command to a second movable control surface, on a rotor system, for control of the hybrid aircraft about the first vehicle axis.

9. A method as recited in claim **8**, wherein said step (1) includes a proportional plus integral control command.

10. A method as recited in claim **9**, further including limiting said integral control command.

11. A method as recited in claim **9**, further including limiting said second scaled control command.

12. A method as recited in claim **11**, further including:

identifying when the limit of said second scaled control command is reached; and

holding an integral control command of said second control command in a limited direction in response to said identifying step.

13. A method as recited in claim **11**, further including:

identifying when the limit of said second control command is reached; and

adding in said first control command to assist said second control command.

14. A method as recited in claim **8**, wherein said first and second scaled control command provide the same amount of aircraft yaw moment about the yaw axis independent of the hybrid aircraft flight regime.

15. A method of controlling a hybrid unmanned aerial vehicle (UAV) about a yaw axis within a transition flight region comprising the steps of:

(1) providing a control command for a yaw axis;

(2) splitting said control command to provide a first control command and a second control command;

(4) multiplying said first control command by a first gain according to a first gain schedule to provide a first scaled control command;

(4) multiplying said second control command by a second gain according to a second gain schedule to provide a second scaled control command;

(7) communicating said first scaled control command to a rotor system for control of the UAV about the yaw axis; and

(8) communicating said second scaled control command to a aileron for control of the UAV about the yaw axis.

16. A method as recited in claim **15**, wherein said step (1) includes a proportional plus integral control command.

17. A method as recited in claim **15**, wherein said first and second scaled control command provide the same amount of yaw moment about the yaw axis independent of the UAV flight regime.

18. A method as recited in claim **15**, further including limiting said second scaled control command.

19. A method as recited in claim **18**, further including:

identifying when the limit of said second control command is reached; and

adding in said first control command to assist said second control command.

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