

**Control method for controlling a yaw angle and a roll angle
of a vertical take-off aircraft**

5 The invention relates to a control method for controlling a
yaw angle and a roll angle of a vertical take-off aircraft
comprising at least two drive groups arranged in opposite
side regions of the aircraft so as to be spaced apart from
a fuselage of the aircraft, each drive group comprising at
10 least one first drive unit, the first drive unit being
arranged so as to be spaced apart from the fuselage to
pivot about a pivot angle α into a horizontal flight
position and a vertical flight position.

15 Vertical take-off aircraft are used, inter alia, as drones
and in the military field. These aircraft usually comprise
two wings arranged on opposite sides of a fuselage, with
two drive units being arranged so as to be pivotally
mounted on each of the wings in supporting elements, such
20 as gondolas, which are rigidly connected to the wings and
are adapted to the intended purpose. Aircraft are also
known in which there is no separate fuselage and the wings
are formed by two half-wings that are symmetrical along the
longitudinal axis, with two drive units being arranged so
25 as to be pivotally mounted on each of the half-wings in
supporting elements which are rigidly connected to the
half-wings and are adapted to the intended purpose.

In addition, vertical take-off aircraft are known from the
30 prior art in which the drive units are pivotally mounted
directly on the wings, for example on a supporting
structure extending within the wing. A vertical take-off

aircraft of this type is described in WO 2014/016226 A1. In this vertical take-off aircraft, it is provided that, in the horizontal flight position, the first drive unit is arranged on the wing above the wing surface and the second
5 drive unit is arranged on the wing below the wing surface, and that, in the vertical flight position, the first drive unit and the second drive unit are arranged in an approximately horizontal plane. In this way, in the vertical flight phase close to the ground, a uniform ground
10 effect of the first and second drive unit is achieved, such that smoother flight behavior is achieved, in particular in the take-off and landing phase. In the horizontal flight position, the first drive unit and the second drive unit do not flow against one another, and therefore this does not
15 bring about any loss of efficiency.

In order to control the yaw angle and roll angle, in particular of multicopters, control methods are known in which the desired yaw and roll is achieved by suitably
20 actuating the drive units, which are not pivotable on multicopters. In this case, the power provided by the respective drive units is predetermined individually to each drive, in order to generate the yaw and roll by means of the differences in lift and torque that are generated in
25 this way.

An orientation of the aircraft in three-dimensional space is usually described by the roll, pitch and yaw angles. In this case, the different angles describe rotational angles
30 of the aircraft starting from a zero position which may, for example, correspond to the orientation of the aircraft

when standing on the ground about a longitudinal, transverse and vertical axis of the aircraft.

The problem addressed by the invention is considered that
5 of providing a corresponding control method for controlling the yaw angle and roll angle by suitably actuating the drive units for vertical take-off aircraft, by means of which control is possible both in vertical flight as well as during the transition into horizontal flight, and in
10 horizontal flight.

This problem is solved according to the invention by a control method for controlling a yaw angle and a roll angle of a vertical take-off aircraft of the type described at
15 the outset,

- wherein power generated by each of the drive units is adapted in order to reach a predetermined target yaw angle and a predetermined target roll angle,
- wherein, in a determination step, a first yaw control
20 parameter g_1 and a second yaw control parameter g_2 as well as a first roll control parameter r_1 and a second roll control parameter r_2 are determined, wherein the first yaw control parameter and the first roll control parameter are vertical control parameters for reaching
25 the target yaw angle and the target roll angle in the vertical flight position, wherein the second yaw control parameter and the second roll control parameter are horizontal control parameters for reaching the target yaw angle and the target roll
30 angle in the horizontal flight position,
- wherein, in a subsequent superimposing step, an actuation parameter is determined, by means of a

superimposing rule for each drive unit, from the vertical control parameters and the horizontal control parameters on the basis of the pivot angle,

- and wherein a power of the drive units is then
5 predetermined taking into account the actuation parameters.

Different actuation parameters are required in all the pivot positions of the drive units in order to achieve the
10 desired yaw and roll behavior. By means of the continuous calculation of the horizontal control parameters and the vertical control parameters according to the invention as well as superimposition of the parameters determined for the horizontal flight and vertical flight, the control
15 method can be implemented particularly simply, since the control method only has to be designed for the two extreme horizontal and vertical flight positions. In order to determine the horizontal control parameters and the vertical control parameters, control and regulation
20 parameters that are known from the prior art can be used. According to the invention, the actuation parameters may for example be power difference values that describe the deviation from the total power required by the drive units to reach the target yaw and roll angles, the total power
25 corresponding to the power requirement requested by a pilot. The actuation parameters are advantageously determined from roll control parameters and yaw control parameters which represent absolute values for the required power difference values in horizontal flight and vertical
30 flight.

It is advantageously provided according to the invention that each drive group comprises a first drive unit and a second drive unit, the first drive unit and the second drive unit each being arranged so as to be spaced apart
5 from the fuselage to pivot about a pivot angle α into a horizontal flight position and a vertical flight position. It is advantageously provided according to the invention that the first drive units and/or the second drive units are arranged on opposite wings of the aircraft. It is,
10 however, also possible and provided according to the invention that the drive units are arranged on the fuselage, advantageously by means of supporting frames, so as to be spaced apart from the fuselage. The drive units may advantageously comprise rotors according to the
15 invention.

In a simplification of the described method, it is advantageously provided that the second yaw control parameter is determined on the basis of the first yaw
20 control parameter by multiplication by a yaw factor and/or in that the second roll control parameter is determined on the basis of the first roll control parameter by multiplication by a roll factor. It is also possible and provided according to the invention that the respective
25 first control parameters are determined by multiplying the respective second control parameters by the associated factor.

It is advantageously provided according to the invention
30 that, in the determining step, an actual yaw angle and an actual roll angle are determined, and that the control parameters are each determined by means of a control

algorithm starting from the target yaw angle and the target roll angle as well as the actual yaw angle and the actual roll angle. The actual yaw angle and the actual roll angle may advantageously be detected by means of suitable sensors
5 and may be transferred to a microcontroller or flight controller executing the control algorithm and/or the control method.

It is advantageously provided according to the invention
10 that the first yaw control parameter is determined on the basis of the target yaw angle and the actual yaw angle using a first yaw control algorithm and/or that the second yaw control parameter is determined on the basis of the target yaw angle and the actual yaw angle using a second
15 yaw control algorithm and/or that the first roll control parameter is determined on the basis of the target roll angle and the actual roll angle using a first roll control algorithm and/or that the second roll control parameter is determined on the basis of the target roll angle and the
20 actual roll angle using a second roll control algorithm. By using a plurality of separate control algorithms to determine the control parameters, the design of the individual control algorithms can be significantly simplified, since only SISO systems have to be taken into
25 account. Coupling between the output variables can then optionally be taken into account by the advantageously non-linear superimposition of the different control parameters.

In a particularly advantageous embodiment of the method
30 according to the invention, it is provided that the first yaw control algorithm and/or the second yaw control algorithm and/or the first roll control algorithm and/or

the second roll control algorithm is a linear controller having a P or PD proportion. The use of linear controllers having a P or PD proportion is particularly simple. Advantageously, the control algorithms may additionally
5 also have an I proportion.

Advantageously, the first yaw control parameter g_1 is determined using a PD controller starting from the actual yaw angle y_{yz} advantageously determined using suitable
10 sensors and from the actual yaw rate y'_{yz} advantageously also detected using sensors and starting from the predetermined target yaw angle w_{yz} , in accordance with the following provision:

$$g_1 = (P_{g_1} \cdot (w_{yz} - y_{yz}) - y'_{yz}) \cdot D_{g_1}$$

15

The factor P_{g_1} represents the P proportion of the PD controller and the factor D_{g_1} represents the D proportion of the PD controller for determining the first yaw control parameter g_1 . In a comparable manner, the first roll
20 control parameter r_1 , the second yaw control parameter g_2 and the second roll control parameter r_2 are determined in accordance with the following provisions, with the actual roll angle y_{yx} advantageously detected using suitable sensors, the actual roll rate y'_{yx} likewise advantageously
25 detected by sensors and the predetermined target roll angle w_{yx} additionally being used:

$$r_1 = (P_{r_1} \cdot (w_{yx} - y_{yx}) - y'_{yx}) \cdot D_{r_1}$$

$$g_2 = (P_{g_2} \cdot (w_{y_z} - y_{y_z}) - \dot{y}_{y_z}) \cdot D_{g_2}$$

$$r_2 = (P_{r_2} \cdot (w_{y_x} - y_{y_x}) - \dot{y}_{y_x}) \cdot D_{r_2}$$

It is advantageously provided according to the invention
5 that the P proportion P_{g_1} and the D proportion D_{g_1} for
determining the first yaw control parameter g_1 correspond
to the P proportion P_{r_2} and the D proportion D_{r_2} of the PD
controller for determining the second roll control
parameter r_2 , and that the P proportion P_{r_1} and the D
10 proportion D_{r_1} for determining the first roll control
parameter r_1 correspond to the P proportion P_{g_2} and the D
proportion D_{g_2} of the PD controller for determining the
second yaw control parameter g_2 .

15 In order to determine the actual roll angle y_{y_x} , the actual
roll rate $\dot{y}_{y_x}$, the actual yaw angle y_{y_z} and the actual yaw
rate $\dot{y}_{y_z}$, the aircraft advantageously comprises a
gyroscope, an acceleration sensor and a compass, with the
required angles and rates being determined on the basis of
20 methods known from the prior art, such as a Kalman filter
composed of measured variables detected by these sensors.

It is also provided according to the invention that the
horizontal control parameters and the vertical control
25 parameters are continuously each determined using a control
algorithm or a common control algorithm. Each control
algorithm used may be a linear or non-linear controller.

It is advantageously provided that, in the superimposing step, the vertical control parameters and the horizontal control parameters are each multiplied by a drive-unit-specific and pivot-angle-specific evaluation function and the actuation parameters for each drive unit are determined by a linear combination of the vertical control parameters multiplied by the drive-unit-specific and pivot-angle-specific evaluation function and the horizontal control parameters multiplied by the drive-unit-specific and pivot-angle-specific evaluation function. Advantageously, the evaluation function is a non-linear function based on the pivot angle. By means of the non-linear evaluation and subsequent linear combination, unconsidered couplings between the control loop can also advantageously be considered, in particular when using a plurality of separate controllers for determining the first and second yaw and roll control parameters.

It is advantageously provided according to the invention that the evaluation function of the vertical control parameters is the cosine of the pivot angle and that the evaluation function of the horizontal control parameters is the sine of the pivot angle. It has been shown that the superimposition using sine and cosine functions can achieve particularly stable flight behavior, in particular during the transition from the vertical flight position into the horizontal flight position, and vice versa.

In a particularly advantageous embodiment of the method according to the invention, it is provided that a yaw angle and a roll angle are defined in a clockwise manner about a vertical axis and a longitudinal axis, respectively, of the

aircraft, in the superimposing step, the actuation parameter AP_1 of a first drive unit arranged to the left of the longitudinal axis in a plan view of the aircraft being calculated according to the following model:

5

$$AP_1 = \cos(\alpha) \cdot r_1 + \cos(\alpha) \cdot g_1 - \sin(\alpha) \cdot r_2 + \sin(\alpha) \cdot g_2, \quad (1)$$

in the superimposing step, the actuation parameter AP_2 of a first drive unit arranged to the right of the longitudinal axis in a plan view of the aircraft being calculated according to the following model:

10

$$AP_2 = -\cos(\alpha) \cdot r_1 - \cos(\alpha) \cdot g_1 + \sin(\alpha) \cdot r_2 - \sin(\alpha) \cdot g_2, \quad (2)$$

in the superimposing step, the actuation parameter AP_3 of a second drive unit arranged to the left of the longitudinal axis in a plan view of the aircraft being calculated according to the following model:

15

$$AP_3 = \cos(\alpha) \cdot r_1 - \cos(\alpha) \cdot g_1 + \sin(\alpha) \cdot r_2 + \sin(\alpha) \cdot g_2, \quad (3)$$

20

in the superimposing step, the actuation parameter AP_4 of a second drive unit arranged to the right of the longitudinal axis in a plan view of the aircraft being calculated according to the following model:

25

$$AP_4 = -\cos(\alpha) \cdot r_1 + \cos(\alpha) \cdot g_1 - \sin(\alpha) \cdot r_2 - \sin(\alpha) \cdot g_2. \quad (4)$$

If the drive units comprise rotors, a rotational direction of the rotors is advantageously taken into account when determining the actuation parameters.

30

In order to determine power actuation values, by means of which the individual drive units are subsequently actuated, starting from the thus determined actuation parameters, 5 which advantageously represent power difference values, it is provided according to the invention that power actuation values u_1, u_2, u_3, u_4 of the drive units, by means of which the drive units are actuated, are calculated as follows, taking into account a power requirement variable F and a pitch 10 parameter n , in order to generate the desired power of the individual drive units:

$$u_1 = F - n + AP_1, \quad (5)$$

15 $u_2 = F - n + AP_2, \quad (6)$

$$u_3 = F + n + AP_3, \quad (7)$$

20 $u_4 = F + n + AP_4. \quad (8)$

According to the invention, the power requirement variable may for example be the total power requested by a pilot. The pitch parameter advantageously describes a power difference value which is required to reach a predetermined 25 target pitch angle.

It is advantageously provided according to the invention that, in the horizontal flight position, the first drive units are arranged in the direction of the vertical axis so 30 as to be spaced apart from the second drive units, and that, in the vertical flight position, the first drive units are arranged in the direction of the longitudinal

axis so as to be spaced apart from the second drive units. It is advantageously provided according to the invention that, in the horizontal flight position, the first drive units are arranged above an upper wing surface and the
5 second drive units are arranged below a lower wing surface, and that, in the vertical flight position, the first drive units and the second drive units are arranged in front of and behind the wing in the horizontal flight direction.

10 Other advantageous configurations of the method according to the invention are explained in greater detail with reference to an embodiment shown in the drawings.

Fig. 1 schematically shows a vertical take-off aircraft 1.
15 The aircraft 1 comprises two drive groups 3 arranged on opposite wings 2 of the aircraft 1, each drive group 3 comprising a first drive unit 4, 5 and a second drive unit 6, 7. The first drive unit 4, 5 and the second drive unit 6, 7 are each arranged on the wing 2 so as to pivot about a
20 pivot angle α into a horizontal flight position and a vertical flight position. In the figure, the drive units 4, 5, 6, 7 are in the horizontal flight position. The first drive units 4, 5 are arranged on the wings 2 above an upper wing surface 8 and the second drive units 6, 7 are arranged
25 on said wings below a lower wing surface 9. When the drive units 4, 5, 6, 7 are pivoted into the vertical flight position, the first drive units 4, 5 and the second drive units 6, 7 are arranged in front of and behind the wings 2 in the horizontal flight direction. A yaw angle γ_z , a roll
30 angle γ_x and a pitch angle γ_y are defined in a clockwise manner about a vertical axis, a longitudinal axis and a transverse axis, respectively, of the aircraft 1.

The drive units 4, 5, 6, 7 each comprise rotors. The rotors of the first drive unit 4 and the second drive unit 7 rotate anti-clockwise and the rotors of the first drive unit 5 and the second drive unit 6 rotate clockwise.

In order to control the yaw angle γ_z and the roll angle γ_x , in a determining step of a control method according to the invention, first and second yaw and roll control parameters g_1, g_2, r_1, r_2 are first determined starting from a predetermined target yaw angle w_{γ_z} and a predetermined target roll angle w_{γ_x} by means of linear controllers PD₁, PD₂, PD₃, and PD₄. Actuation parameters u_1, u_2, u_3, u_4 are then determined for each drive unit 4, 5, 6, 7 in a superimposing step from the roll control parameters g_1, g_2, r_1, r_2 . In the figure, the determination of the actuation parameter u_1 for the first drive unit 4 is shown by way of example. The determination takes place on the basis of the above-described formulas 1 to 8.

CLAIMS

1. Control method for controlling a yaw angle γ_z and a roll
5 angle γ_x of a vertical take-off aircraft (1) comprising at
least two drive groups (3) arranged in opposite side
regions of the aircraft (1) so as to be spaced apart from a
fuselage of the aircraft, wherein each drive group (3)
comprises at least one first drive unit (4, 5), wherein the
10 first drive unit (4, 5) is arranged so as to be spaced
apart from the fuselage to pivot about a pivot angle α into
a horizontal flight position and a vertical flight
position,
- wherein power generated by each of the drive units (4,
15 5, 6, 7) is adapted in order to reach a predetermined
target yaw angle w_{γ_z} and a predetermined target roll
angle w_{γ_x} ,
 - wherein, in a determination step, a first yaw control
parameter g_1 and a second yaw control parameter g_2 as
20 well as a first roll control parameter r_1 and a second
roll control parameter r_2 are determined, wherein the
first yaw control parameter g_1 and the first roll
control parameter r_1 are vertical control parameters
for reaching the target yaw angle w_{γ_z} and the target
25 roll angle w_{γ_x} in the vertical flight position,
wherein the second yaw control parameter g_2 and the
second roll control parameter r_2 are horizontal
control parameters for reaching the target yaw angle
 w_{γ_z} and the target roll angle w_{γ_x} in the horizontal
30 flight position,

- wherein, in a subsequent superimposing step, an actuation parameter is determined, by means of a superimposing rule for each drive unit (4, 5, 6, 7), from the vertical control parameters and the horizontal control parameters on the basis of the pivot angle α ,
- and wherein a power of the drive units (4, 5, 6, 7) is then predetermined taking into account the actuation parameters.

10

2. Control method according to claim 1, characterized in that each drive group (3) comprises a first drive unit (4, 5) and a second drive unit (6, 7), wherein the first drive unit (4, 5) and the second drive unit (6, 7) each are arranged so as to be spaced apart from the fuselage to pivot about a pivot angle α into a horizontal flight position and a vertical flight position.

3. Control method according to claim 1 or claim 2, characterized in that the second yaw control parameter g_2 is determined on the basis of the first yaw control parameter g_1 by multiplication by a yaw factor and/or in that the second roll control parameter r_2 is determined on the basis of the first roll control parameter r_1 by multiplication by a roll factor.

4. Control method according to any of the preceding claims, characterized in that, in the determining step, an actual yaw angle y_{yz} and an actual roll angle y_{yx} are determined, and in that the control parameters are each determined by means of a control algorithm starting from the target yaw

30

angle w_{y_z} and the target roll angle w_{y_x} as well as the actual yaw angle y_{y_z} and the actual roll angle y_{y_x} .

5. Control method according to claim 4, characterized in
5 that the first yaw control parameter g_1 is determined on the basis of the target yaw angle w_{y_z} and the actual yaw angle y_{y_z} using a first yaw control algorithm (PD₂) and/or in that the second yaw control parameter g_2 is determined on the basis of the target yaw angle w_{y_z} and the actual yaw
10 angle y_{y_z} using a second yaw control algorithm (PD₄) and/or in that the first roll control parameter r_1 is determined on the basis of the target roll angle w_{y_x} and the actual roll angle y_{y_x} using a first roll control algorithm (PD₁) and/or in that the second roll control parameter r_2 is
15 determined on the basis of the target roll angle w_{y_x} and the actual roll angle y_{y_x} using a second roll control algorithm (PD₃).

6. Control method according to claim 5, characterized in
20 that the first yaw control algorithm (PD₂) and/or the second yaw control algorithm (PD₄) and/or the first roll control algorithm (PD₁) and/or the second roll control algorithm (PD₃) is a linear controller having a P or PD proportion.

25

7. Control method according to any of the preceding claims, characterized in that, in the superimposing step, the vertical control parameters and the horizontal control parameters are each multiplied by a drive-unit-specific and
30 pivot-angle-specific evaluation function and the actuation parameters for each drive unit (4, 5, 6, 7) are determined

by a linear combination of the vertical control parameters multiplied by the drive-unit-specific and pivot-angle-specific evaluation function and the horizontal control parameters multiplied by the drive-unit-specific and pivot-angle-specific evaluation function.

8. Control method according to claim 7, characterized in that the evaluation function of the vertical control parameters is the cosine of the pivot angle α and in that the evaluation function of the horizontal control parameters is the sine of the pivot angle α .

9. Control method according to claim 8, characterized in that a yaw angle γ_z and a roll angle γ_x are defined in a clockwise manner about a vertical axis and a longitudinal axis, respectively, of the aircraft (1), wherein, in the superimposing step, the actuation parameter AP_1 of a first drive unit (4) arranged to the left of the longitudinal axis in a plan view of the aircraft is calculated according to the following model:

$$AP_1 = \cos(\alpha) \cdot r_1 + \cos(\alpha) \cdot g_1 - \sin(\alpha) \cdot r_2 + \sin(\alpha) \cdot g_2,$$

wherein, in the superimposing step, the actuation parameter AP_2 of a first drive unit (5) arranged to the right of the longitudinal axis in a plan view of the aircraft is calculated according to the following model:

$$AP_2 = -\cos(\alpha) \cdot r_1 - \cos(\alpha) \cdot g_1 + \sin(\alpha) \cdot r_2 - \sin(\alpha) \cdot g_2,$$

wherein, in the superimposing step, the actuation parameter AP_3 of a second drive unit (6) arranged to the left of the

longitudinal axis in a plan view of the aircraft is calculated according to the following model:

$$AP_3 = \cos(\alpha) \cdot r_1 - \cos(\alpha) \cdot g_1 + \sin(\alpha) \cdot r_2 + \sin(\alpha) \cdot g_2,$$

5 wherein, in the superimposing step, the actuation parameter AP_4 of a second drive unit (7) arranged to the right of the longitudinal axis in a plan view of the aircraft is calculated according to the following model:

$$AP_4 = -\cos(\alpha) \cdot r_1 + \cos(\alpha) \cdot g_1 - \sin(\alpha) \cdot r_2 - \sin(\alpha) \cdot g_2.$$

10

10. Control method according to claim 9, characterized in that power actuation values u_1, u_2, u_3, u_4 of the drive units (4, 5, 6, 7), by means of which the drive units (4, 5, 6, 7) are actuated, are calculated as follows, taking into
15 account a power requirement variable F and a pitch parameter n , in order to generate the desired power of the individual drive units (4, 5, 6, 7):

$$u_1 = F - n + AP_1,$$

$$u_2 = F - n + AP_2,$$

20

$$u_3 = F + n + AP_3,$$

$$u_4 = F + n + AP_4.$$