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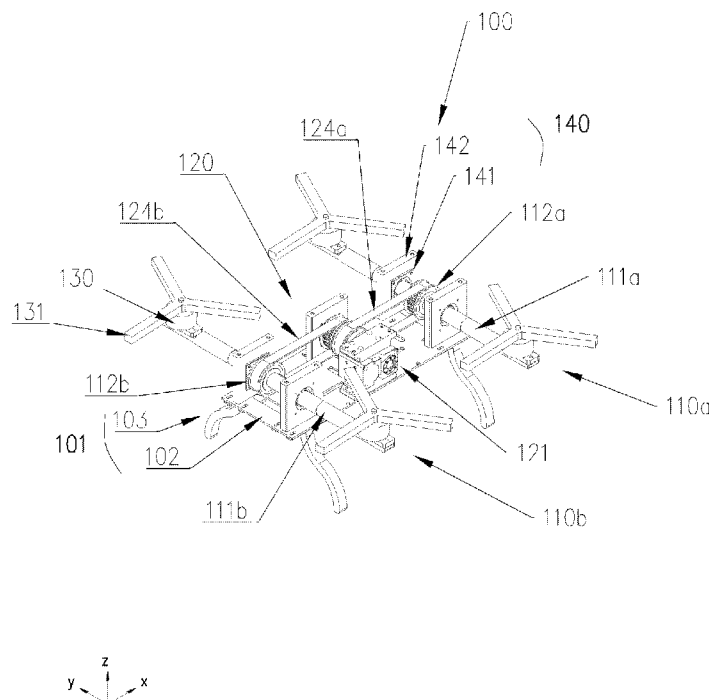
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(54) Title: 5 DEGREES-OF-FREEDOM AERIAL VEHICLE AND CONTROL METHOD



(57) Abstract: 5 DoF (degrees-of-freedom) aerial vehicle and control method disclosed. A 5 DoF (degrees-of-freedom) aerial vehicle includes a first driving unit, having a first rotor shaft disposed on a front of a body in a left-to-right direction and a pair of rotors disposed perpendicularly at left and right ends of the first rotor shaft, a second driving unit, having a second rotor shaft disposed on a rear of the body in the left-to-right direction and a pair of rotors disposed perpendicularly at left and right ends of the second rotor shaft, and a rotor tilting unit, having a servo motor disposed on a middle of the body, and transmitting a driving force of the servo motor to rotate the first rotor shaft and the second rotor shaft simultaneously to tilt an axis of rotational of the rotors.

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Description

Title of Invention: 5 DEGREES-OF-FREEDOM AERIAL VEHICLE AND CONTROL METHOD

Technical Field

- [1] The present invention relates to 5 degrees-of-freedom aerial vehicle and control method.

Background Art

- [2] In existing multirotors, regardless of the number of rotors, only 4 DoF (degrees of freedom) out of a total of 6 DoF for translational and rotational motions can be controlled (underactuatedness). In a general multirotor, the overall direction of thrust by the rotors is always fixed compared to the multirotor aerial vehicle attitude, so in order to move forward, backwards, left, and right, the aerial vehicle has to tilt its attitude. Therefore, it is not possible to perform stationary flight with the aerial vehicle tilted or forward flight without tilting the aerial vehicle.
- [3] However, considering the expected future expansion into drone taxis, it is necessary to develop an aerial vehicle that can move forward without tilting the aerial vehicle in order to provide passengers with a sense of stability and a similar experience to existing cars. In addition, considering the scalability to flying robots that perform physical interactions with the external environment, such as pushing a cart or opening a door, it is necessary to develop an aerial vehicle that can perform stationary flight with the aerial vehicle tilted.
- [4] In previously developed multi-rotor aerial vehicle to solve this problem of underactuatedness, following methods are used: (1) attaching the rotor to a surface that is inclined relative to the aerial vehicle, or (2) using an additional actuator to rotate the rotor relative to the aerial vehicle. In case (1), there is the advantage of not using an additional actuator, but there is a disadvantage that the thrust efficiency is reduced because the thrust of the rotor cannot be fully used to lift the aircraft. Among the existing methods that adopt method (2), there is also a method that uses six additional actuators, but this has a limitation in that it uses excessive actuators. There is also a method of using two additional actuators, but this method has the disadvantage of not being able to rotate the inclination of the aerial vehicle relative to the rotor beyond a certain level due to the nature of the hardware.

Disclosure of Invention

Technical Problem

- [5] The present invention is intended to provide a 5-DoF aerial vehicle and control method that converts an existing 4-DoF aerial vehicle into 5-DoF aerial vehicle by

utilizing only a minimum of additional actuators, that is, one additional actuator.

[6] The present invention is intended to provide a 5-DoF aerial vehicle and control method that can move forward without tilting the aerial vehicle or perform stationary flight in a tilted state by ensuring that there are no structural obstructions on the inclination of the rotor relative to the aerial vehicle.

[7] The present invention is intended to provide a 5-DoF aerial vehicle and control method that is economical compared to aerial vehicles that utilize an excess of actuators because only one additional actuator is used, and has high thrust efficiency in the direction of translational motion because all rotors rotate at the same inclination.

[8] The present invention is intended to provide a 5-DoF aerial vehicle and control method that can rotate the inclination of the rotor 360 degrees while fixing the position and attitude of the aerial vehicle because there is no mechanical obstructions in the rotation of all rotors relative to the aerial vehicle.

[9] Other objectives of the present invention will be readily understood through the following description.

Solution to Problem

[10] According to one aspect of the present invention, there is provided a 5 DoF (degrees-of-freedom) aerial vehicle, including a first driving unit, having a first rotor shaft disposed on a front of a body in a left-to-right direction and a pair of rotors disposed perpendicularly at left and right ends of the first rotor shaft, a second driving unit, having a second rotor shaft disposed on a rear of the body in the left-to-right direction and a pair of rotors disposed perpendicularly at left and right ends of the second rotor shaft, and a rotor tilting unit, having a servo motor disposed on a middle of the body, and transmitting a driving force of the servo motor to rotate the first rotor shaft and the second rotor shaft simultaneously to tilt an axis of rotational of the rotors.

[11] In one embodiment, the servo motor may be disposed to have an axis of rotation in the left and right directions. The rotor tilting unit may further include a servo shaft axially coupled to the axis of rotation of the servo motor, and a drive force transmission unit, configured for transmitting a rotational force of the servo shaft to the first rotor shaft and the second rotor shaft.

[12] In one embodiment, the 5 DoF aerial vehicle may further include a bearing rotatably supporting the other end of the servo shaft, and a bearing holder holding the bearing.

[13] In one embodiment, the driving force transmission unit may include a first drive pulley and a second drive pulley secured to the servo shaft, a first timing pulley secured to the first rotor shaft, a second timing pulley secured to the second rotor shaft, a first connecting device engaged between the first drive pulley and the first timing pulley, and a second connecting device engaged between the second drive pulley and

the second timing pulley.

[14] In one embodiment, each rotor is a coaxial rotor installed dually at the top and bottom.

[15] In one embodiment, a first pinion gear may be disposed at the end of the servo shaft. The driving force transmission unit may include a drive shaft on which a first ring gear meshing with the first pinion gear is secured, being disposed to extend in a front-to-back direction, and having a second pinion gear and a third pinion gear disposed at a front end and a rear end, respectively, a second ring gear secured to the first rotor shaft and meshing with the second pinion gear, and a third ring gear secured to the second rotor shaft and meshing with the third pinion gear.

[16] In one embodiment, a rotation amount of the first rotor shaft and the second rotor shaft may be controlled equally.

[17] In one embodiment, the 5 DoF aerial vehicle may further include a controller configured for outputting a tilting control signal to the rotor tilting unit. The controller may decompose dynamics of the 5 DoF aerial vehicle into an underactuated subsystem and a fully-actuated subsystem to control motion.

[18] In one embodiment, the fully-actuated subsystem may be a dynamical system corresponding to translation motion, yawing motion, and pitching motion which are independently controllable, and the underactuated subsystem may be a dynamical system corresponding to a rolling motion that is not independently controllable.

[19] In one embodiment, the controller may resolve singularity in design by defining a yaw-compensated coordinates.

[20] In one embodiment, with the first rotor shaft and the second rotor shaft rotated by a predetermined angle by the rotor tilting unit, translational motion is possible without the body being tilted, or stationary flight is possible with a tilted posture other than 0 degrees.

[21] Other aspects, features and advantages other than those described above will become apparent from the following drawings, claims and detailed description of the invention.

Advantageous Effects of Invention

[22] According to embodiments of the present invention, it is advantageous that an existing 4-DoF aerial vehicle can be converted into 5-DoF aerial vehicle by utilizing only a minimum of additional actuators, that is, one additional actuator.

[23] In addition, it is advantageous that an aerial vehicle can move forward without tilting the aerial vehicle or perform stationary flight in a tilted state by ensuring that there are no structural obstructions on the inclination of the rotor relative to the aerial vehicle.

[24] Also, it is economical compared to aerial vehicles that utilize an excess of actuators because only one additional actuator is used, and has high thrust efficiency in the

direction of translational motion because all rotors rotate at the same inclination.

- [25] Also, it is advantageous that an aerial vehicle can rotate the inclination of the rotor 360 degrees while fixing the position and attitude of the aerial vehicle because there is no mechanical obstructions in the rotation of all rotors relative to the aerial vehicle.

Brief Description of Drawings

- [26] FIG. 1 exemplarily illustrates an implementation and operation of 5-DoF aerial vehicle according to a first embodiment of the present invention;
- [27] FIG. 2 is a perspective view of 5-DoF aerial vehicle according to the first embodiment of the present invention;
- [28] FIG. 3 is a top view of 5-DoF aerial vehicle according to the first embodiment of the present invention;
- [29] FIG. 4 is a side view of 5-DoF aerial vehicle according to the first embodiment of the present invention;
- [30] FIG. 5 is a front view of 5-DoF aerial vehicle according to the first embodiment of the present invention;
- [31] FIG. 6 exemplarily illustrates a first rotor shaft and an actuator assembly to which a belt-pulley structure according to the first embodiment of the present invention is applied;
- [32] FIG. 7 is a perspective view of 5-DoF aerial vehicle according to a second embodiment of the present invention;
- [33] FIG. 8 is a perspective view of 5-DoF aerial vehicle according to a third embodiment of the present invention;
- [34] FIG. 9 is a top view of 5-DoF aerial vehicle according to the third embodiment of the present invention;
- [35] FIG. 10 exemplarily illustrates a prototype and control inputs of a tiltrotor according to the present embodiment;
- [36] FIG. 11 is a flowchart of the controller showing the inputs of the state conversion block;
- [37] FIG. 12 and FIG. 13 show a composite image and a time-lapse graph of each state of the tiltrotor following a square trajectory in the XY plane;
- [38] FIG. 14 and FIG. 15 show a captured image and a time-lapse graph of each state of the tiltrotor following time-varying, nonzero pitch angle ((a): 60 degrees, (b): -60 degrees); and
- [39] FIG. 16 and FIG. 17 show images of perching-based cart pushing operations (in order from (a) to (d)) and graphs of the normalized PWM signal for each state and each rotor (gray shading indicates time after perching).

Mode for the Invention

- [40] The invention can be modified in various forms and specific embodiments will be described below and illustrated with accompanying drawings. However, the embodiments are not intended to limit the invention, but it should be understood that the invention includes all modifications, equivalents, and replacements belonging to the concept and the technical scope of the invention.
- [41] If it is mentioned that an element is "connected to" or "coupled to" another element, it should be understood that still another element may be interposed therebetween, as well as that the element may be connected or coupled directly to another element. On the contrary, if it is mentioned that an element is "connected directly to" or "coupled directly to" another element, it should be understood that still another element is not interposed therebetween.
- [42] Terms such as first, second, etc., may be used to refer to various elements, but, these element should not be limited due to these terms. These terms will be used to distinguish one element from another element.
- [43] The terms used in the following description are intended to merely describe specific embodiments, but not intended to limit the invention. An expression of the singular number includes an expression of the plural number, so long as it is clearly read differently. The terms such as "include" and "have" are intended to indicate that features, numbers, steps, operations, elements, components, or combinations thereof used in the following description exist and it should thus be understood that the possibility of existence or addition of one or more other different features, numbers, steps, operations, elements, components, or combinations thereof is not excluded.
- [44] Elements of an embodiment described below with reference to the accompanying drawings are not limited to the corresponding embodiment, may be included in another embodiment without departing from the technical spirit of the invention. Although particular description is not made, plural embodiments may be embodied as one embodiment.
- [45] In describing the invention with reference to the accompanying drawings, like elements are referenced by like reference numerals or signs regardless of the drawing numbers and description thereof is not repeated. If it is determined that detailed description of known techniques involved in the invention makes the gist of the invention obscure, the detailed description thereof will not be made.
- [46] A 5-DoF(degree-of-freedom) multicopter aerial vehicle, which is one of the 5-DoF vehicles according to the present embodiments, is an aerial robot capable of performing Aerial Physical Interaction (APhI) while maintaining hovering flight, and for this purpose, it continuously generates non-zero thrust. Since sustaining hovering flight itself takes considerable energy, and precise and stable control during physical interaction is not easy, it would be preferable for the aerial robot to conduct a perching-

based APhI after perching. In other words, a stable perching and a physical interaction after perching can be enabled.

[47] The aerial robot according to the present embodiments is a minimally actuated quadrotor-based tiltrotor that can perch on an inclined surface and exert a force to the contact surface.

[48] In order to perch stably and firmly on an arbitrary orientated surface, it would be advantageous for the aerial robot to hover while maintaining its attitude parallel to the surface. This is because when attitude can be independently controlled to be parallel to the surface, only translation needs to be considered during perching. Thus, more precise control can be achieved compared to the case where both translation and rotation should be controlled simultaneously.

[49] Considering that a conventional multirotor cannot hover at nonzero roll or pitch angles and that only two DoF in orientation is sufficient for the aerial robot to hover parallel to any inclined surface, the minimum required DoF is five, and the aerial robot according to the present embodiment can meet this condition.

[50] In addition, in order to effectively generate thrust onto the contact surface regardless of the perching angle, it is necessary to control not only the magnitude of total thrust but also the direction of it, and the aerial robot according to the present embodiments enables such control.

[51] Hereinafter, a hardware structure of 5-DoF aerial vehicle and a controller structure and operation for controlling the 5-DoF of the aerial vehicle will be described with reference to accompanying drawings.

[52] First, the hardware structure will be explained

[53] FIG. 1 exemplarily illustrates an implementation and operation of 5-DoF aerial vehicle according to a first embodiment of the present invention, FIGS. 2 to 5 are a perspective view, a top view, a side view and a front view of 5-DoF aerial vehicle according to the first embodiment of the present invention, and FIG. 6 exemplarily illustrates a first rotor shaft and an actuator assembly to which a belt-pulley structure according to the first embodiment of the present invention is applied.

[54] The 5-DoF aerial vehicle 100 according to the first embodiment of the present invention may be a multirotor aerial vehicle. The 5-DoF aerial vehicle 100 according to the first embodiment is a quadrotor-based tiltrotor that utilizes a belt-pulley structure to achieve 5 DoF even when only one actuator is added to the existing 4-DoF multirotor aerial vehicle.

[55] The 5-DoF aerial vehicle 100 may have a large margin for generating interaction forces during APhI, and may have the characteristic of having no mechanical obstruction in a thrust direction rotation. Thanks to these properties, the 5-DOF aerial vehicle 100 can hover parallel to an arbitrarily oriented surface and freely adjust the

thrust direction, making it suitable for perching-based aerial physical interaction.

- [56] The 5-DoF aerial vehicle 100 may include an asymptotically stabilizing controller with stability analysis to control the 5-DoF. The control algorithm in the controller will be described later with reference to related drawings.
- [57] The 5-DoF aerial vehicle 100 may include a body 101 having a body plate 102 and legs 103 as a basic skeleton.
- [58] The body plate 102 may be a rectangular flat plate that is long in a front-to-back direction (X-axis direction) and have multiple through holes, thereby reducing its weight.
- [59] There may be four legs 103, for example, as shown in FIG. 2. Each of the four legs 103 may be coupled one by one to each corner of a lower surface of the body plate 102. The four legs 103 may be implemented with the same structure and are symmetrically coupled to the body plate 102, so that they can function as a support that allows the body plate 102 to be parallel to the flat surface.
- [60] The body plate 102 may include a first driving unit 110a, a second driving unit 110b, and a rotor tilting unit 120.
- [61] The first driving unit 110a and the second driving unit 110b may be disposed at the front and rear, respectively. Each driving unit 110a, 110b (collectively referred to as 110) may have a pair of rotors 130 disposed on the left and right, and as the rotor 130 is driven, blades 131 connected to the rotor 130 rotate to make the body 101 fly. A total of four rotors 130 may be disposed in the first driving unit 110a and the second driving unit 110b.
- [62] A first rotor shaft 111a extending in the left-to-right direction (Y-axis direction) may be arranged in the first driving unit 110a. A pair of rotors 130 may be disposed at both left and right ends of the first rotor shaft 111a so as to have an axis of rotation perpendicular to the rotor shaft.
- [63] A second rotor shaft 111b extending in the left-to-right direction (Y-axis direction) may be arranged in the second driving unit 110b. A pair of rotors 130 may be disposed at both left and right ends of the second rotor shaft 111b so as to have an axis of rotation perpendicular to the rotor shaft.
- [64] The first rotor shaft 111a and the second rotor shaft 111b may be disposed spaced apart from each other at the front and rear of the body plate 102 and may be arranged parallel to each other.
- [65] The rotor shaft (first rotor shaft 111a or second rotor shaft 111b, hereinafter also collectively referred to as 111) may be mounted for smooth rotation by a pair of bearing units 140 spaced left and right to correspond to the width of the body plate 102.
- [66] The bearing unit 140 may include a bearing holder 142 disposed perpendicularly to the body plate 102 and a bearing 141 disposed within the bearing holder 142. The

inner diameter of the bearing 141 corresponds to the outer diameter of the rotor shaft 111, and the rotor shaft 111 can smoothly rotate in the forward or reverse direction about an axis of rotation by the bearing 141.

[67] The rotor tilting unit 120 may be disposed in the middle of the body plate 102 in the front-to-back direction (X-axis direction), and can tilt the first rotor shaft 111a of the first driving unit 110a and the second rotor shaft 111b of the second driving unit 110b in a desired direction.

[68] The rotor tilting unit 120 may include a servo shaft 122, a servo motor 121, and a drive force transmission unit. The drive force transmission unit may include driving pulleys 123a, 123b (hereinafter collectively referred to as 123), timing belts 124a, 124b (hereinafter collectively referred to as 124), and timing pulleys 112a, 112b (hereinafter collectively referred to as 112). The timing belt 124 may be replaced with another type of belt or connecting device such as a chain.

[69] The servo motor 121 may generate a drive force for tilting the axis of rotation (rotor shaft) in response to a tilting control signal from the controller. That is, the servo shaft 122 may be rotated by an amount (angle) corresponding to the tilting control signal.

[70] The servo motor 121 may be disposed on the body plate 102 so that its axis of rotation is disposed in the left-to-right directions (y-axis direction) of the body plate 102.

[71] One end of the servo shaft 122 may be axially coupled to the axis of rotation of the servo motor 121, and the other end may be rotatably supported by the bearing unit 140 disposed vertically on the body plate 102. The bearing 141 of the bearing unit 140 may have a height corresponding to the axis of rotation of the servo motor 121, so that the servo shaft 122 can be maintained parallel to the body plate 102.

[72] The bearing 141 supporting the servo shaft 122 not only helps the servo shaft 122 rotate smoothly, but also distributes the force applied to the actuator (servo motor 121). It is possible to distribute a pulling force in the X-axis direction generated by the timing belt connected to the servo shaft 122 and a force in the gravity direction caused by the weight of the shaft, the pulley and so on.

[73] A first driving pulley 123a and a second driving pulley 123b may be secured to the servo shaft 122. The first driving pulley 123a and the second driving pulley 123b may be integrally coupled to the servo shaft 122 and can rotate by an amount equal to a rotation amount of the servo shaft 122.

[74] The first timing pulley 112a may be secured to the first rotor shaft 111a in correspondence to the first driving pulley 123a. The first timing belt 124a for transmitting drive force may be coupled to the first driving pulley 123a and the first timing pulley 112a.

[75] And the second timing pulley 112b may be secured to the second rotor shaft 111b in

correspondence to the second driving pulley 123b. The second timing belt 124b for transmitting drive force may be coupled to the second driving pulley 123b and the second timing pulley 112b.

[76] When the servo shaft 122 rotates by the servo motor 121, the driving pulley 123 secured to the servo shaft 122 may rotate. The rotation of the driving pulley 123 may be transmitted to the timing pulley 112 by the timing belt 124, and the rotor shaft 111 to which the timing pulley 112 is secured may rotate.

[77] In the present embodiment, the first drive force transmission unit by the first driving pulley 123a, the first timing belt 124a and the first timing pulley 112a, and the second drive force transmission unit by the second driving pulley 123b, the second timing belt 124b and the second driven pulley 112b may be implemented to make the rotor shaft 111a and the second rotor shaft 111b to rotate by the same amount in the same direction, regardless of the distance between the first rotor shaft 111a and the servo shaft 122 and the distance between the second rotor shaft 111b and the servo shaft 122. Since the connection relationship between the driving pulley, timing belt, and timing pulley is obvious to those skilled in the art to which the present invention belongs, detailed description will be omitted.

[78] In the present embodiment, the first rotor shaft 111a and the second rotor shaft 111b may rotate by the same amount in the same direction by the servo motor 121, so that the pair of rotors 130 disposed on both ends of the first rotor shaft 111a and the pair of rotors 130 disposed on both ends of the second rotor shaft 111b have the same inclination angle relative to the body plate. That is, the rotor 130 of the front axle and the rotor 130 of the rear axle can be tilted in the same direction.

[79] In this way, one additional actuator (i.e., servo motor 121) may be utilized to solve some of the underactuatedness of the multirotor-based aerial vehicle and to ensure that there are no mechanical obstructions in moving (tilting) the axis of rotation of the rotor. The four rotors 130 can freely rotate around the rotor shaft 111, solving some of the underactuatedness, eliminating the need to tilt the aerial vehicle for forward and backward translational motion. The attitude of aerial vehicle will be tilted only for translational motion to the left or the right.

[80] In addition, since there are no restrictions on the movement of the axis of rotation of the rotor 130, it is possible to rotate the axis of rotation of the rotor at various angles (including 180 degrees and 360 degrees) relative to the aerial vehicle attitude, and large acceleration in the forward and backward directions can be achieved without tilting the aerial vehicle.

[81] In addition, it is possible to reduce the weight of the aerial vehicle itself and secure economic efficiency in manufacturing the aerial vehicle, and it is possible to have a larger thrust margin when generating thrust in a specific axial direction.

- [82] In the present embodiment, the case in which the first rotor shaft 111a and the second rotor shaft 111b have the same rotation amount has been described, but it may be possible to adjust the mechanical characteristics (e.g., pulley size, belt length, etc.) of the belt-pulley structure applied to the first rotor shaft 111a and the belt-pulley structure applied to the second rotor shaft 111b so that the first rotor shaft 111a and the second rotor shaft 111b have a predetermined ratio of rotation.
- [83] FIG. 7 is a perspective view of 5-DoF aerial vehicle according to a second embodiment of the present invention.
- [84] Referring to FIG. 7, the 5-DoF aerial vehicle 200 according to the second embodiment of the present invention has the same belt-pulley structure as the 5-DoF aerial vehicle 100 according to the first embodiment.
- [85] In order to obtain a larger thrust margin compared to the first embodiment, a pair of coaxial rotors 210 may be disposed at both ends of the rotor shaft. That is, a pair of coaxial rotors 211 and 212 may be disposed on the left and right sides of one rotor shaft, respectively, to generate greater thrust.
- [86] FIG. 8 is a perspective view of 5-DoF aerial vehicle according to a third embodiment of the present invention, and FIG. 9 is a top view of 5-DoF aerial vehicle according to the third embodiment of the present invention.
- [87] Referring to FIGS. 8 and 9, the 5-DoF aerial vehicle 300 according to the third embodiment of the present invention may be equipped with a gear mechanism utilizing a bevel gear instead of the belt-pulley structure as a rotational force transmission mechanism by an additional actuator.
- [88] The bevel gear is a cone-shaped gear used to transmit power at a certain angle to another gear or axis. The bevel gear is a combination of a pinion gear and a ring gear, and the pinion gear functions as a driving side and can transmit rotational force to the ring gear.
- [89] A servo motor 321 may be disposed on one side of the center of the body plate 302 in the front-to-back direction (X-axis direction). The axis of rotation of the servo motor 321 may be arranged in the left-to-right direction (Y-axis direction).
- [90] A drive shaft 322 extending in the front-to-back direction (X-axis direction) of the body plate 302 may be disposed to be rotatable along an axis of rotation in the X-axis direction. The front and rear ends of the drive shaft 322 may be rotatably supported by a first supporting unit 350 and a second supporting unit 351.
- [91] The first supporting unit 350 and/or the second supporting unit 351 may be a bearing unit and may include a bearing that rotationally supports the drive shaft 322 and a bearing holder for holding the bearing.
- [92] A first pinion gear 331 may be disposed at the end of the axis of rotation of the servo motor 321. A first ring gear 332 meshing with the first pinion gear 331 may be in-

tegrally coupled to the central side of the drive shaft 322.

[93] Therefore, when the first pinion gear 331 rotates, the rotational force is transmitted to the meshing first ring gear 332, and the drive shaft 322 integrally coupled to the first ring gear 332 rotates around the axis of rotation in the X-axis direction.

[94] A second pinion gear 341a and a third pinion gear 341b may be disposed at both front and rear ends of the drive shaft 322, respectively.

[95] A second ring gear 342a meshing with the second pinion gear 341a may be integrally coupled to the first rotor shaft 311a on its outer surface. A third ring gear 342b meshing with the third pinion gear 341b may be integrally coupled to the second rotor shaft 311b on its outer surface.

[96] Therefore, when the drive shaft 322 rotates, the second pinion gear 341a and the third pinion gear 341b rotate, and then the second ring gear 342a and the third ring gear 342b meshed with each pinion gear rotate, and finally, the first rotor shaft 311a and the second rotor shaft 311b rotate around the axis of rotation in the left-to-right direction (Y-axis direction).

[97] By adjusting the gear ratios of the second pinion gear 341a and the second ring gear 342a, and the third pinion gear 341b and the third ring gear 342b, the rotation amounts of the first rotor shaft 311a and the second rotor shaft 311b may be the same or may be adjusted to various ratios depending on the situation.

[98] In the third embodiment using the bevel gear, as in the belt-pulley structure, there may be no mechanical obstructions in the rotation of the two rotor shafts 311a and 311b.

[99] Next, the singularity in the controller design is resolved by defining a yaw-compensated coordinate for precise control of 5-DoF for the aerial vehicle according to the present embodiments. Because the aerial robot platform has 5-DoF, the dynamics can be decomposed into two parts to handle the underactuatedness, and controllers for both subsystems can be designed. Lastly, a motion controller with verified asymptotic stability may be included.

[100] FIG. 10 exemplarily illustrates a prototype and control inputs of a tiltrotor according to the present embodiment, FIG. 11 is a flowchart of the controller showing the inputs of the state conversion block, FIGS. 12 and 13 show a composite image and a time-lapse graph of each state of the tiltrotor following a square trajectory in the XY plane, FIGS. 14 and 15 show a captured image and a time-lapse graph of each state of the tiltrotor following time-varying, nonzero pitch angle ((a): 60 degrees, (b): -60 degrees), and FIGS. 16 and 17 show images of perching-based cart pushing operations (in order from (a) to (d)) and graphs of the normalized PWM signal for each state and each rotor (gray shading indicates time after perching).

[101] Hereinafter, notations in this specification are defined as follows.

[102] $e_1 := [1 \ 0 \ 0]^\top$, $e_2 := [0 \ 1 \ 0]^\top$ and $e_3 := [0 \ 0 \ 1]^\top$

[103] Additionally, $v_i \in \mathbb{R}$ is defined as the i^{th} element of vector v . Column vectors a and b are $[a; b] := [a^\top \ b^\top]^\top$. For a given state variable x , the desired value is denoted by x_d . Lastly, $c(\cdot)$, $s(\cdot)$, and $t(\cdot)$ are used as abbreviations for $\cos(\cdot)$, $\sin(\cdot)$, and $\tan(\cdot)$, respectively.

[104] The modeling for a 5-DoF aerial vehicle (i.e., a tiltrotor) with the above-described hardware structure is as follows.

[105] Let $p \in \mathbb{R}^3$ be the center of mass of the tiltrotor in the world fixed frame and $\omega \in \mathbb{R}^3$ be the body angular velocity. The rotation matrix $R \in \text{SO}(3)$ and ZYX Euler angles $\phi = [\phi_1; \phi_2; \phi_3] \in \mathbb{R}^3$ denote the orientation of the tiltrotor. Control input is regarded as $u = [\eta_d; F_1; F_2; F_3; F_4] \in \mathbb{R}^5$, where η_d is the desired servomotor angle, and $F_i \in \mathbb{R}_+$ $i = 1, \dots, 4$ is the rotor thrust. For the ease of controller design, a virtual control input of $\tilde{u} = [f_x; f_z; \tau] \in \mathbb{R}^5$ will be considered, where $f_x, f_z \in \mathbb{R}^2$ are x and z directional forces described in the body frame, and $\tau \in \mathbb{R}^3$ is a torque in the body frame. Then, system dynamics of the tiltrotor according to the present embodiment can be written as

[106]
$$m\ddot{p} = R(f_x e_1 + f_z e_3) - mge_3 \quad (1a)$$

[107]
$$I_b \dot{\omega} = -\omega \times I_b \omega + \tau \quad (1b)$$

[108] where $m \in \mathbb{R}_+$ and $I_b \in \mathbb{R}^{3 \times 3}$ are the tiltrotor's mass and moment of inertia measured in the body frame. g is a gravitational acceleration constant, and $a \times b$ denotes the cross product of $a, b \in \mathbb{R}^3$.

[109] Before deriving a control law, it is essential to find a mapping between u and $\tilde{u}$ so that the actual control input u can be calculated whenever a control law for $\tilde{u}$ is established. Considering the kinematic configuration of the tiltrotor illustrated in FIG. 10, the mapping between u and $\tilde{u}$ can be defined as $\tilde{u} = C(\eta)F$ where

[110]
$$C(\eta) = \begin{bmatrix} s\eta & s\eta & s\eta & s\eta \\ c\eta & c\eta & c\eta & c\eta \\ -L_h c\eta - k_f s\eta & L_h c\eta + k_f s\eta & L_h c\eta - k_f s\eta & -L_h c\eta + k_f s\eta \\ -L_v c\eta & -L_v c\eta & L_v c\eta & L_v c\eta \\ L_h s\eta - k_f c\eta & -L_h s\eta + k_f c\eta & -L_h s\eta - k_f c\eta & L_h s\eta + k_f c\eta \end{bmatrix}$$

[111] and $F = [F_1; F_2; F_3; F_4] \in \mathbb{R}^4$. $L_h, L_v \in \mathbb{R}_+$ are rotor-to-rotor distances divided by two in body y and x axes, respectively. $k_f \in \mathbb{R}_+$ denotes a thrust to torque ratio of a single rotor. Since servomotors show sufficiently fast tracking

response in practice, i.e. $\eta \approx \eta_d$, the following relationship for designing a controller is assumed: $\tilde{u} = C(\eta_d)F$.

[112] The controller design process is as follows.

[113] First, control allocation is required.

[114] A control allocation problem is to find a mapping from $\tilde{u}$ to u , which is the inverse of $u \mapsto \tilde{u} = C(\eta_d)F$. A closedform solution for $u = [\eta_d; F]$ can be obtained as

$$\begin{aligned} \eta_d &= \text{atan2}(f_x, f_z) \\ F &= D(\eta_d) \begin{bmatrix} \sqrt{f_x^2 + f_z^2} \\ \tau \end{bmatrix} \end{aligned} \quad (2)$$

$$D(\eta_d) = \frac{1}{4} \begin{bmatrix} 1 & -\frac{1}{k_f} s\eta_d - \frac{1}{L_h} c\eta_d & -\frac{1}{L_v c\eta_d} & -\frac{1}{k_f} c\eta_d + \frac{1}{L_h} s\eta_d \\ 1 & \frac{1}{k_f} s\eta_d + \frac{1}{L_h} c\eta_d & -\frac{1}{L_v c\eta_d} & \frac{1}{k_f} c\eta_d - \frac{1}{L_h} s\eta_d \\ 1 & -\frac{1}{k_f} s\eta_d + \frac{1}{L_h} c\eta_d & \frac{1}{L_v c\eta_d} & -\frac{1}{k_f} c\eta_d - \frac{1}{L_h} s\eta_d \\ 1 & \frac{1}{k_f} s\eta_d - \frac{1}{L_h} c\eta_d & \frac{1}{L_v c\eta_d} & \frac{1}{k_f} c\eta_d + \frac{1}{L_h} s\eta_d \end{bmatrix}.$$

[117] $D(\eta_d) \in \mathbb{R}^{4 \times 4}$ is well-defined if $\eta_d \in (-\pi/2, \pi/2)$, which can be assured if $f_z \neq 0$, is restricted. Note that the fact of $D(\eta_d)$ not being able to be defined at $\eta_d = \pm\pi/2$, which occurs only when $f_z = 0$, is consistent with the hardware configuration since when $\eta_d(\approx \eta) = \pm\pi/2$, τ_2 cannot be arbitrarily generated but zero.

[118] The controller design for $\tilde{u}$ is as follows.

[119] Thanks to the tilting mechanism, unlike a conventional multirotor, the pitching motion of the tiltrotor can be independently controlled regardless of any translational motion thus enabling 5-DoF motion. However, rolling motion cannot be independently controlled, and to consider this underactuatedness, the system dynamics can be decomposed into an underactuated subsystem and a fully-actuated subsystem. Furthermore, since the control input $\tilde{u}$ is defined in the body frame, simply designing a controller in the world-fixed frame could result in singularity. Therefore, to avoid singularity in controller design, a controller may be designed using a new state variable $\tilde{p} = R_z(\phi_3)^\top p$ where $R_z(\theta) \in \text{SO}(3)$ denotes a rotation matrix with the angle θ along the body Z-axis.

[120] Remark 1: Singularity occurs in the input matrix of the fully-actuated subsystem. Rather than resorting to the proposed transformation $\tilde{p} = R_z(\phi_3)^\top p$, one may naively choose a configuration of the fully-actuated subsystem as $[p_1; p_3; \phi] \in \mathbb{R}^5$. Then, the dynamics of $[p_1; p_3]$ can be obtained from (1a) as

$$[121] \quad \begin{bmatrix} \ddot{p}_1 \\ \ddot{p}_3 \end{bmatrix} = \frac{1}{m} B(\phi) \begin{bmatrix} f_x \\ f_z \end{bmatrix} + \begin{bmatrix} 0 \\ -g \end{bmatrix}$$

[122] where

$$[123] \quad B(\phi) = \begin{bmatrix} c\phi_2 c\phi_3 & s\phi_1 s\phi_3 + c\phi_1 s\phi_2 c\phi_3 \\ -s\phi_2 & c\phi_1 c\phi_2 \end{bmatrix}.$$

[124] Since $\det(B) = c\phi_1 c\phi_3 + s\phi_1 s\phi_2 s\phi_3$, it can be concluded that the input matrix $B(\phi)$ becomes singular whenever $\phi_3 = \pm\pi/2$ and ϕ_1 or $\phi_2 = 0$. Considering that matrix inverse of the input matrix B is widely adopted in controller design, this singularity issue is critical.

[125] Let $Q \in \mathbb{R}^{3 \times 3}$ denote a Jacobian matrix satisfying $\omega = Q\dot{\phi}$, then rotational dynamics with respect to ϕ can be derived from (1b) as

$$[126] \quad \ddot{\phi} = h_\phi + g_\phi \tau \quad (3)$$

[127] where $h_\phi = (I_b Q)^{-1} \{-I_b \dot{Q}\dot{\phi} - \omega \times (I_b \omega)\}$ and $g_\phi = (I_b Q)^{-1}$.

Dynamics with respect to $\tilde{p}$ can be computed from (1a) as

$$[128] \quad \ddot{\tilde{p}} = \frac{1}{m} R_y(\phi_2) R_x(\phi_1) (f_x e_1 + f_z e_3) - g e_3 + h_p + g_p \tau \quad (4)$$

[129] where $R_x(\theta), R_y(\theta) \in \text{SO}(3)$ denote X, Y-directional rotation matrices with the angle θ . $h_p \in \mathbb{R}^3$, $g_p \in \mathbb{R}^{3 \times 3}$ are terms resulting from state transformation and are defined as follows

$$[130] \quad \begin{aligned} h_p &= -\hat{e}_3 R_z(\phi_3)^\top (2\dot{\phi}_3 \dot{p} + e_3^\top h_\phi p) - \hat{e}_3^2 R_z(\phi_3)^\top \dot{\phi}_3^2 p \\ g_p &= -\hat{e}_3 R_z(\phi_3)^\top p e_3^\top g_\phi. \end{aligned}$$

[131] $(\hat{\cdot})$ is a hat operator mapping a vector in $\mathbb{R}^3$ to a skewsymmetric matrix in $\mathbb{R}^{3 \times 3}$.

Then, in order to decompose underactuated and fully-actuated dynamics, their configurations can be defined as $q_u = \tilde{p}_2 \in \mathbb{R}$ and $q_f = [\tilde{p}_1; \tilde{p}_3; \phi] \in \mathbb{R}^5$, respectively. Defining $\bar{f}_z := c\phi_1 f_z$, both dynamics can be arranged as follows:

$$[132] \quad \ddot{q}_u = h_u + g_u u_u - \frac{1}{m} (t\phi_1 - t\phi_{1,d}) \bar{f}_z \quad (5a)$$

$$[133] \quad \ddot{q}_f = h_f + g_f u_f \quad (5b)$$

[134] where $h_u = e_2^\top (h_p + g_p \tau) \in \mathbb{R}$, $g_u = -\frac{1}{m} \bar{f}_z \in \mathbb{R}$, $h_f =$

$[e_1^\top h_p; e_3^\top h_p; h_\phi] \in \mathbb{R}^5$, t is tan function, and

$$[135] \quad g_f = \begin{bmatrix} \frac{1}{m} \begin{bmatrix} c\phi_2 & s\phi_2 \\ -s\phi_2 & c\phi_2 \end{bmatrix} & \begin{bmatrix} e_1^\top \\ e_3^\top \end{bmatrix} g_p \\ 0_{3 \times 2} & g_\phi \end{bmatrix} \in \mathbb{R}^{5 \times 5}.$$

[136] $u_u := t\phi_{1,d}$ and $u_f := [f_x; \bar{f}_z; \tau]$ are control inputs to each subsystem. For $\phi_1, \phi_2 \in (-\pi/2, \pi/2)$, g_f is always invertible, and f_z exists for any given $\bar{f}_z$. Then, with error states $e_u := q_u - q_{u,d}$ and $e_f := q_f - q_{f,d}$, a control law can be proposed as

$$[137] \quad u_u = g_u^{-1} \left(\ddot{q}_{u,d} - h_u - K_{up}e_u - K_{ud}\dot{e}_u - K_{ui} \int e_u dt \right) \quad (6a)$$

$$[138] \quad u_f = g_f^{-1} \left(\ddot{q}_{f,d} - h_f - K_{fp}e_f - K_{fd}\dot{e}_f - K_{fi} \int e_f dt \right). \quad (6b)$$

[139] Proposition 1: For positive-definite, diagonal matrices K_{up} , K_{ud} , K_{ui} , K_{fp} , K_{fd} , K_{fi} satisfying $K_{up}K_{ud} > K_{ui}$ and $K_{fp}K_{fd} > K_{fi}$, the closed-loop system consisting of the system dynamics (5) and control input (6) is asymptotically stable.

[140] Proof: The closed-loop system can be written as

$$[141] \quad \ddot{e}_u + K_{ud}\ddot{e}_u + K_{up}\dot{e}_u + K_{ui}e_u = -\frac{1}{m} \frac{d}{dt} \{ (t\phi_1 - t\phi_{1,d}) \bar{f}_z \} \quad (7a)$$

$$[142] \quad \ddot{e}_f + K_{fd}\ddot{e}_f + K_{fp}\dot{e}_f + K_{fi}e_f = 0. \quad (7b)$$

[143] Thanks to the conditions on controller gains, from Routh-Hurwitz criterion, (7b) is exponentially stable to $[e_f; \dot{e}_f] = 0$ and (7a) is also exponentially stable to $[e_u; \dot{e}_u] = 0$ if $[e_f; \dot{e}_f] = 0$. Therefore, by stability theorem for a cascade system, the entire system is asymptotically stable.

[144] Overall flow chart of the proposed controller can be found in FIG. 11. u_f to $\tilde{u}$ conversion can be easily computed by applying the definition of $\bar{f}_z = c\phi_1 f_z$.

[145] Referring to FIG. 11, the controller may include a state transformation unit 410, an underactuated subsystem control unit (U-subsys. control) 420, and a fully-actuated subsystem control unit (F-subsys. control) 430, and may include a control allocation unit 440.

[146] In the present embodiment, since the controller is configured in yaw-compensated coordinates, it is necessary to convert a target position entered into the controller into the yaw-compensated coordinates. Accordingly, the state transformation unit 410 may

be configured for performing coordinate conversion of the target position.

- [147] The target position $p_{1,d}, p_{2,d}, p_{3,d}$ of the aerial vehicle (before coordinate conversion) and the target attitude $\phi_{2,d}, \phi_{3,d}$ of the aerial vehicle (pitch and yaw angles among Euler angles) may be input to the state transformation unit 410. And the target position $\bar{p}_{1,d}, \bar{p}_{3,d}, \bar{p}_{2,d}$ of the aerial vehicle (after coordinate conversion) and the target attitude $\phi_{2,d}, \phi_{3,d}$ of the aerial vehicle (same as the input values) may be output.
- [148] $\bar{p}_{2,d}$, which is the Y-axis of the coordinate-transformed value of the target position of the aerial vehicle, may be input to the underactuated subsystem control unit 420. Additionally, $p, \phi, \dot{p}, \dot{\phi}$, which are the measured current position, attitude, speed, and angular velocity of the aerial vehicle, may also be input. Additionally, the underactuated subsystem control unit 420 may be configured for outputting a control input u_u that causes the coordinate-transformed current Y-axis position to reach the coordinate-transformed target Y-axis position. This can be understood as a target roll angle of the aerial vehicle.
- [149] Due to the nature of 5-DoF control, the roll angle must be adjusted to move in the coordinate-transformed Y-axis direction. Accordingly, the underactuated subsystem control unit 420 may be configured for determining how much the roll angle must be adjusted for the coordinate-transformed current Y-axis position to reach the desired position.
- [150] The target position $\bar{p}_{1,d}, \bar{p}_{3,d}$ of the aerial vehicle (X and Z axes of converted coordinate values) and the target attitude $\phi_{1,d}, \phi_{2,d}, \phi_{3,d}$ (roll, pitch, and yaw angles) of the aircraft may be input to the fully-actuated subsystem control unit 430. Additionally, $p, \phi, \dot{p}, \dot{\phi}$, which are the measured current position, attitude, speed, and angular velocity of the aerial vehicle, may also be input. And the fully-actuated subsystem control unit 430 may be configured for outputting a control input u_f that causes the coordinate-transformed current X-axis and Z-axis positions to reach the coordinate-transformed target X-axis and Z-axis positions, and causes the aerial vehicle's attitude to reach the target attitude. This can be understood as the force f_x, f_z and the torque τ_1, τ_2, τ_3 generated by the aerial vehicle.
- [151] The fully-actuated subsystem control unit 430 may be configured for calculating the force and torque that must be generated by the aircraft in order to move the coordinate-transformed x- and z-axis positions and attitude of the aircraft to target values.
- [152] $\hat{u}$, which represents the force and torque that must be generated by the aerial vehicle, may be input to the control allocation unit 440. And the control allocation unit 440 may be configured for outputting the force F_1, F_2, F_3, F_4 that must be generated by each rotor attached to the aerial vehicle and the angle η_d of the servomotor.
- [153] Since the aerial vehicle according to the present embodiment is composed of five actuators including four rotors and one servomotor, the force and torque to be

generated by the aerial vehicle must be converted into input values for each actuator, and this conversion may be performed in the control allocation unit 440.

[154] Plant unit 450 is related to aerial vehicle dynamics, and may be configured for receiving as input the force that must be generated by each rotor attached to the aerial vehicle and the angle of the servomotor, and outputting as output the measured current position, attitude, speed, and angular velocity of the aerial vehicle accordingly

[155] In order to first validate the proposed hardware platform and controller, the following two scenarios are conducted: 1) X, Y position tracking control while maintaining zero pitch angle and 2) non-zero pitch tracking control with no translation. These two scenarios are selected because they could illustrate maneuvers that cannot be achieved with a conventional quadrotor. Lastly, to demonstrate perching-based APhI with the tiltrotor, we conduct a scenario of perching and cart pushing. In FIGS. 13, 15, 17, the time history of actual state/input signals is plotted with solid lines while that of desired state signals with dashed lines.

[156] A. Scenario 1 - Position tracking control without pitching motion

[157] The first scenario shows that X-directional translation can be independently controlled without pitching motion. For comparison, let the tiltrotor translate in Y-direction whose motion can only be achieved with rolling motion due to underactuatedness in Y-direction. As can be found in FIGS. 12 and 13, a square reference trajectory in XY-plane (p_1 and p_2 dashed lines at the top graph of FIG. 13) is defined and let pitch and yaw desired values to be uniformly zero (ϕ_3 and ϕ_2 dashed lines in the middle graph of FIG. 13). Compared to the actual roll angle and its desired value which can be found as ϕ_1 solid and dashed lines in the middle graph, almost no pitching motion occurs, and thus independent controllability in the x-axis can be confirmed. In the bottom graph of FIG. 13, it can be found that the added servomotor rotates to keep pitch angle zero while tracking the time-varying X-directional reference.

[158] B. Scenario 2 - pitch tracking control without translation

[159] The second scenario is to show independent controllability in the pitching motion. To show this, let the desired trajectory of X be constant (the p_1 dashed line at the top graph of FIG. 15) and let the desired pitch angle be time-varying (the ϕ_2 dashed line in the middle graph of FIG. 15). As can be found in FIGS. 14 and 15, the tiltrotor could rotate in pitch direction while regulating its position. About ± 60 degrees is achieved during the experiment, and even at those states, the tiltrotor could stably hover.

[160] C. Scenario 3 - perching-based aerial physical interaction

[161] Before performing a perching-based APhI, assume that the pose of the perching site is known and that perching is passively conducted.

[162] A simple rule-based planning algorithm is applied to make the tiltrotor navigate from

the initial pose to the perching site. A linearly interpolated reference trajectory from the initial pose to the perching site is computed in the planning algorithm where the interpolation is conducted sequentially only in one axis at a time based on the sequence of $Z \rightarrow Y \rightarrow \text{yaw} \rightarrow \text{pitch} \rightarrow X$. As can be found in FIGS. 16, 17, perching can be successfully accomplished even with such simple planning method thanks to the 5-DoF property. After perching, which is indicated by the gray shaded region in FIG. 17, the controller was manually switched to perching-based APhI mode where the thrust direction rotates to be perpendicular to the perching site surface. Then, the PWM values of all four rotors are increased simultaneously to make the cart move. This PWM increase can be found at the bottom graph of FIG. 17, and the resulting cart motion can be found in the p1 solid line at the top graph representing the X-directional position of the tiltrotor.

- [163] In above-described embodiments, a hardware design of a minimally actuated 5-DoF tiltrotor and an asymptotically stabilizing controller for controlling the full 5-DoF are proposed. Features of the proposed tiltrotor are that 1) it is minimally actuated, 2) it has a high interaction force margin during aerial physical interaction (APhI), and 3) no mechanical obstruction exists in thrust direction rotation. These properties allow the platform to be specialized for perching-based APhI because it is capable of parallel hovering to any inclined surface and thrust direction tilting without any hurdle. Then, to handle singularity and underactuatedness in the controller design, the controller based on the transformed coordinate and the decomposed subsystems was designed. The asymptotic stability of the entire system was then proved. In order to validate the proposed platform and the controller, two experiments were conducted to show the performance of controlling the extra DoF compared to a conventional quadrotor. Furthermore, to demonstrate applicability of the proposed platform to perching-based APhI, a perching and cart pushing experiment was successfully conducted.
- [164] These embodiments have the following two characteristics by rotating the rotor shaft. 1) Hovering is possible in an attitude where the pitch angle is not 0 degrees and 2) it is possible to translate in the X-axis direction without tilting the pitch angle.
- [165] In addition, the above description focuses on the case where the 5-DoF aerial vehicle is a multirotor aerial vehicle. However, in addition to multirotor aerial vehicle, the tilting mechanism according to these embodiments can also be applied to aerial vehicle that combine fixed-wing airplanes and rotary-wing airplanes.
- [166] The above-described method of controlling 5-DoF aerial vehicle that is executed on the controller may also be implemented in the form of a non-transitory recording medium including instructions executable by a computer, such as an application or program module executed by a computer. Non-transitory computer-readable medium can be any available media that can be accessed by a computer and includes both

volatile and nonvolatile medium, removable and non-removable media. In addition, non-transitory computer-readable medium may include computer storage medium. Computer storage medium includes both volatile and nonvolatile, removable and non-removable media implemented in any method or technology for storage of information such as computer readable instructions, data structures, program modules or other data.

[167] The above-described method of controlling 5-DoF aerial vehicle that is executed on the controller may be executed by an application (which may include a program included in a platform or operating system by default disposed in the terminal) disposed by default in the terminal, and by an application (i.e., program) that a user manually disposed in the terminal after downloading from an application store server, or an application providing server such as a web server related to the application or service. In this sense, the above-described method of controlling 5-DoF aerial vehicle that is executed on the controller may be implemented as an application (i.e., program) disposed by default in the terminal or manually disposed by a user, and may be recorded in the non-transitory computer-readable recording medium such as the terminal.

[168] While the invention has been described above with reference to exemplary embodiments, it will be understood by those skilled in the art that the invention can be modified and changed in various forms without departing from the concept and scope of the invention described in the appended claims.

Claims

- [Claim 1] A 5 DoF (degrees-of-freedom) aerial vehicle, comprising:
a first driving unit, having a first rotor shaft disposed on a front of a body in a left-to-right direction and a pair of rotors disposed perpendicularly at left and right ends of the first rotor shaft;
a second driving unit, having a second rotor shaft disposed on a rear of the body in the left-to-right direction and a pair of rotors disposed perpendicularly at left and right ends of the second rotor shaft; and
a rotor tilting unit, having a servo motor disposed on a middle of the body, and transmitting a driving force of the servo motor to rotate the first rotor shaft and the second rotor shaft simultaneously to tilt an axis of rotational of the rotors.
- [Claim 2] The 5 DoF aerial vehicle of claim 1, wherein the servo motor is disposed to have an axis of rotation in the left and right directions, wherein the rotor tilting unit further comprises
a servo shaft axially coupled to the axis of rotation of the servo motor; and
a drive force transmission unit, configured for transmitting a rotational force of the servo shaft to the first rotor shaft and the second rotor shaft.
- [Claim 3] The 5 DoF aerial vehicle of claim 2 further comprising
a bearing rotatably supporting the other end of the servo shaft; and
a bearing holder holding the bearing.
- [Claim 4] The 5 DoF aerial vehicle of claim 2, wherein the driving force transmission unit comprises,
a first drive pulley and a second drive pulley secured to the servo shaft;
a first timing pulley secured to the first rotor shaft;
a second timing pulley secured to the second rotor shaft;
a first connecting device engaged between the first drive pulley and the first timing pulley; and
a second connecting device engaged between the second drive pulley and the second timing pulley.
- [Claim 5] The 5 DoF aerial vehicle of claim 1, wherein each rotor is a coaxial rotor installed dually at the top and bottom.
- [Claim 6] The 5 DoF aerial vehicle of claim 2, wherein a first pinion gear is disposed at the end of the servo shaft,
wherein the driving force transmission unit comprises,
a drive shaft on which a first ring gear meshing with the first pinion

gear is secured, being disposed to extend in a front-to-back direction, and having a second pinion gear and a third pinion gear disposed at a front end and a rear end, respectively;

a second ring gear secured to the first rotor shaft and meshing with the second pinion gear; and

a third ring gear secured to the second rotor shaft and meshing with the third pinion gear.

[Claim 7] The 5 DoF aerial vehicle of claim 1, wherein a rotation amount of the first rotor shaft and the second rotor shaft is controlled equally.

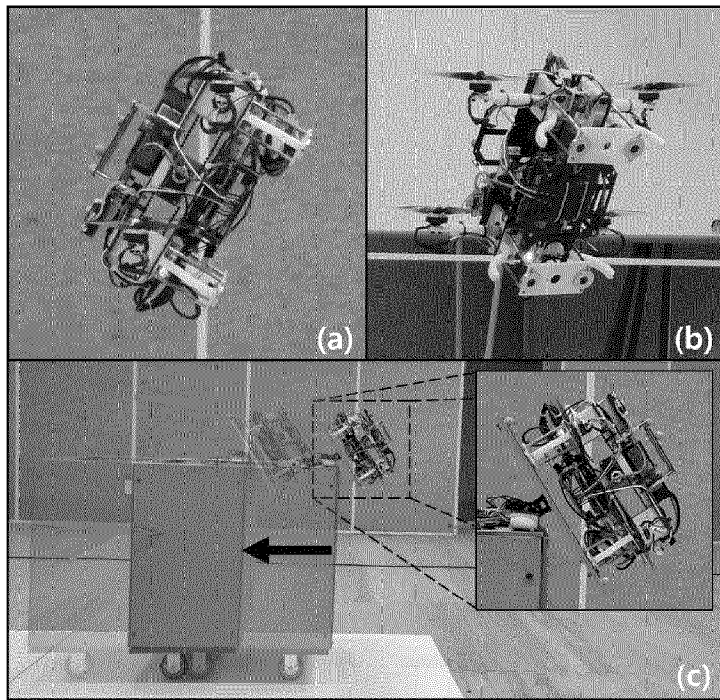
[Claim 8] The 5 DoF aerial vehicle of claim 1 further comprising a controller configured for outputting a tilting control signal to the rotor tilting unit, wherein the controller decomposes dynamics of the 5 DoF aerial vehicle into an underactuated subsystem and a fully-actuated subsystem to control motion.

[Claim 9] The 5 DoF aerial vehicle of claim 8, wherein the fully-actuated subsystem is a dynamical system corresponding to translation motion, yawing motion, and pitching motion which are all independently controllable, and the underactuated subsystem is a dynamical system corresponding to a rolling motion that is not independently controllable.

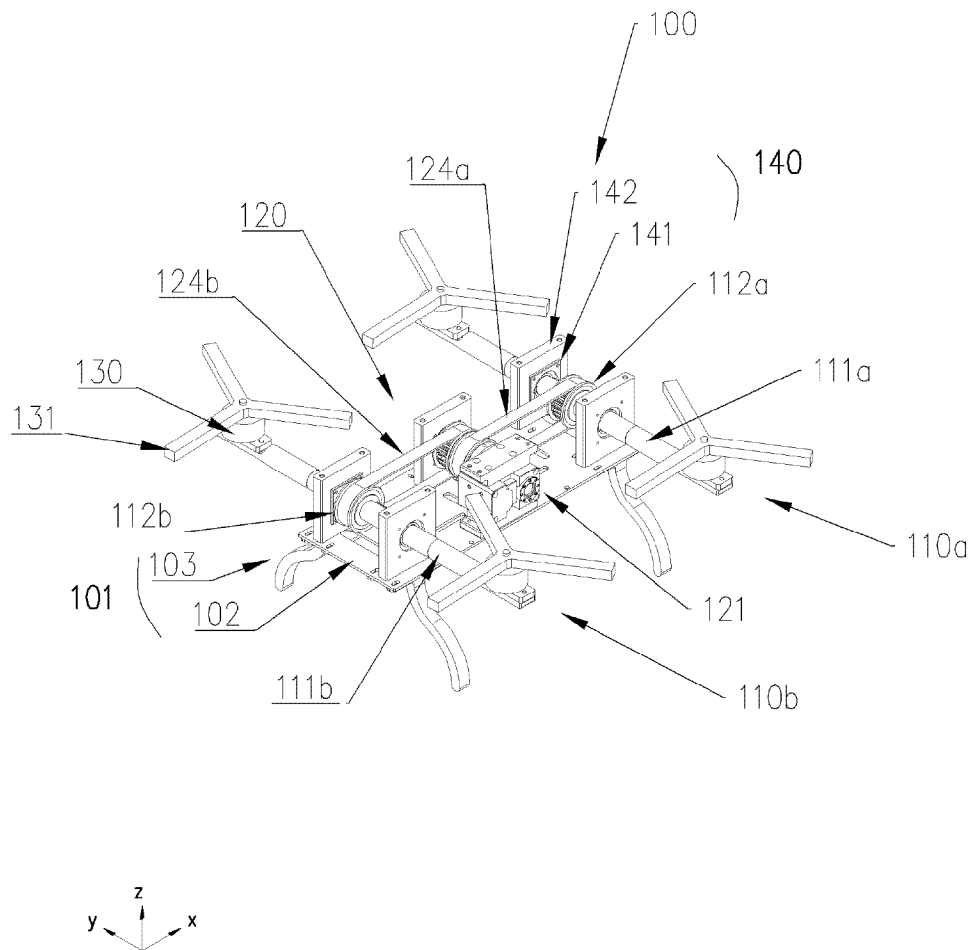
[Claim 10] The 5 DoF aerial vehicle of claim 8, wherein the controller resolves singularity in design by defining a yaw-compensated coordinates.

[Claim 11] The 5 DoF aerial vehicle of claim 1, wherein with the first rotor shaft and the second rotor shaft rotated by a predetermined angle by the rotor tilting unit, translational motion is possible without the body being tilted, or stationary flight is possible with a tilted posture other than 0 degrees.

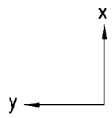
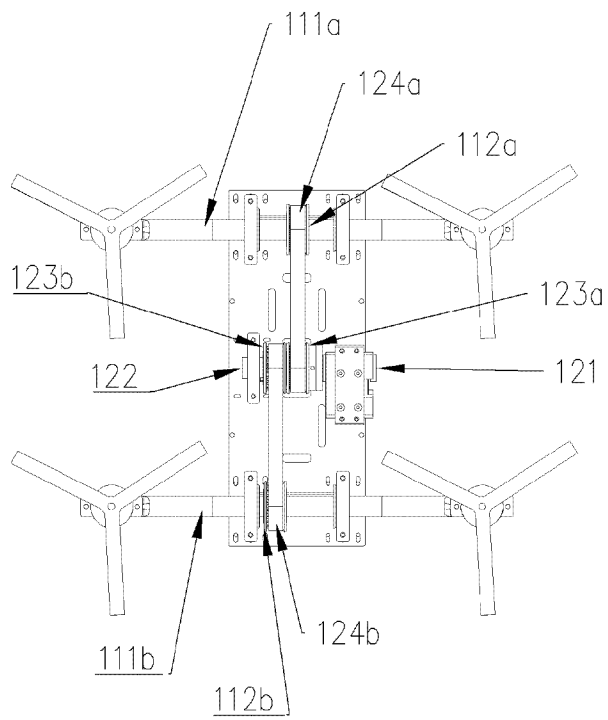
[Fig. 1]



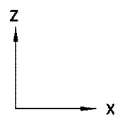
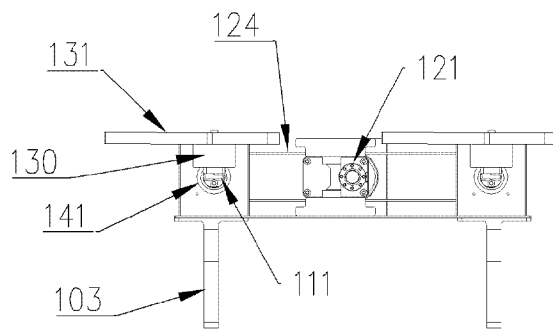
[Fig. 2]



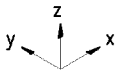
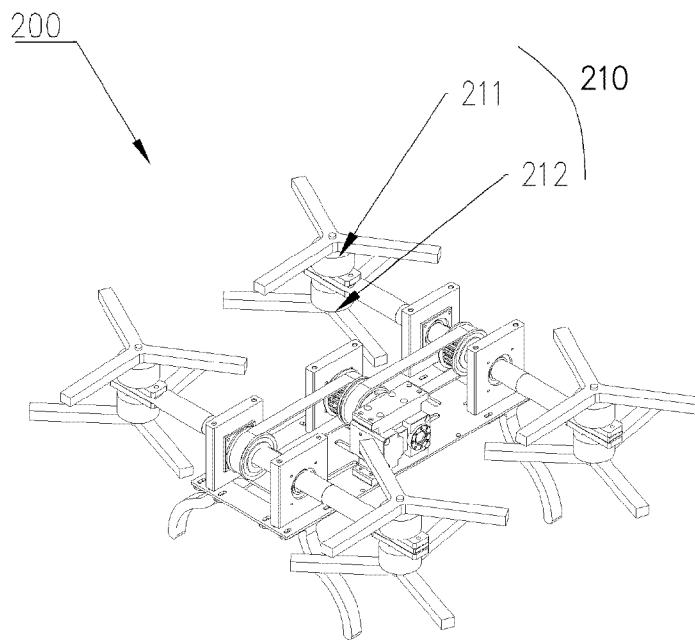
[Fig. 3]



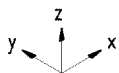
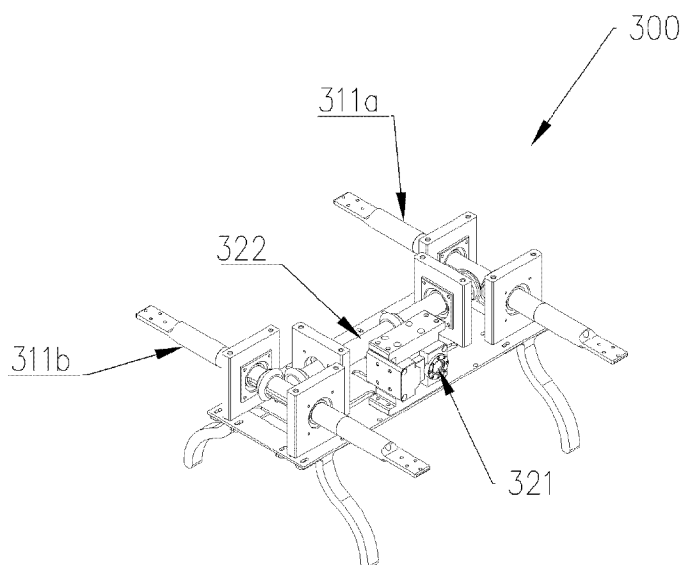
[Fig. 4]



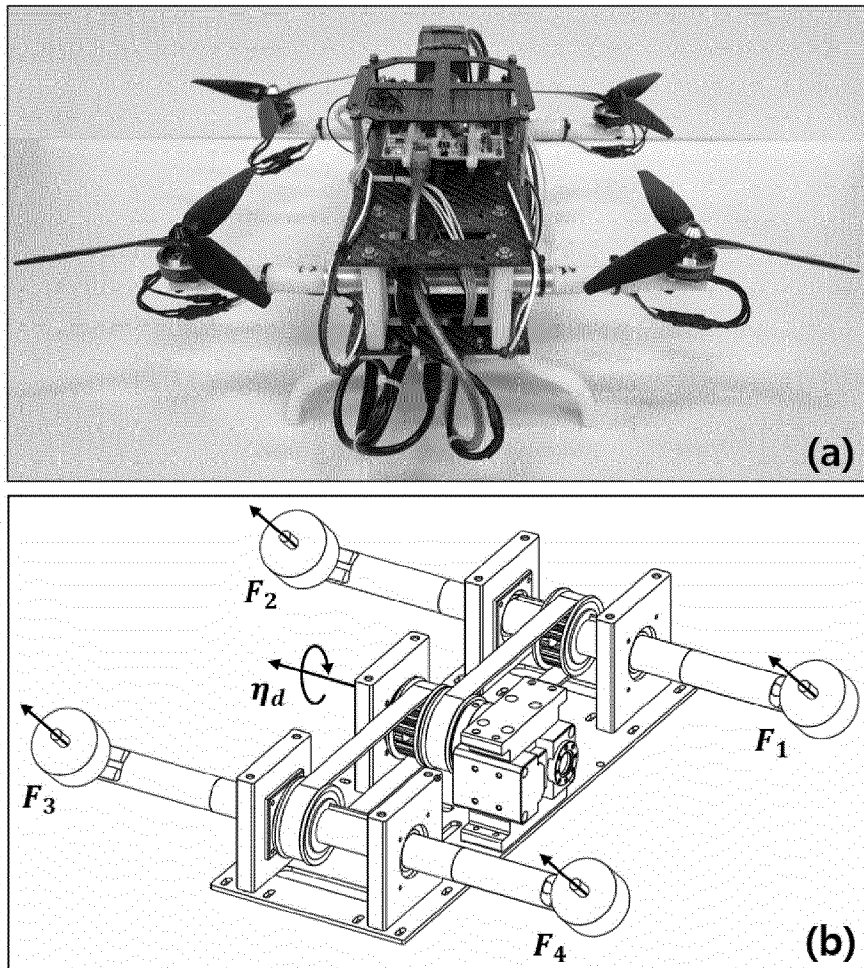
[Fig. 7]



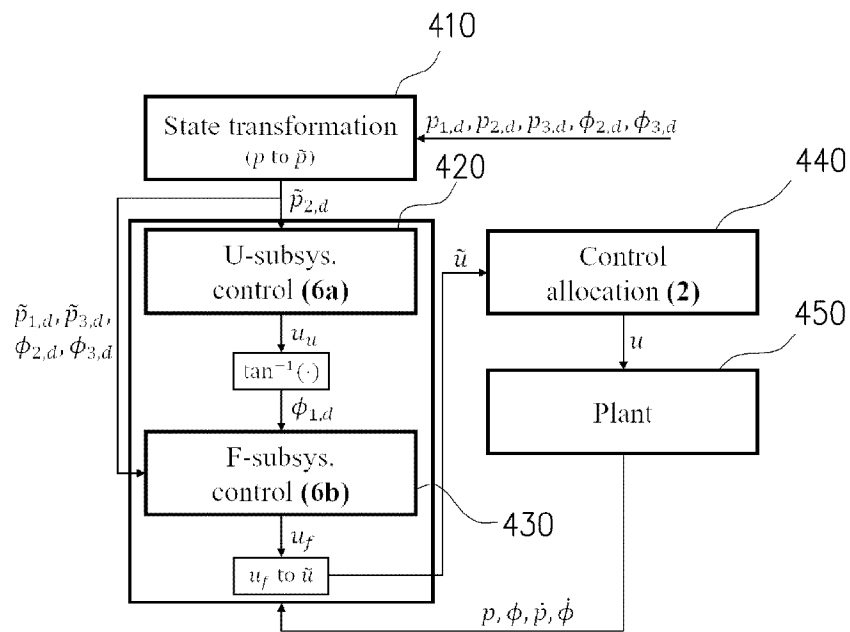
[Fig. 8]



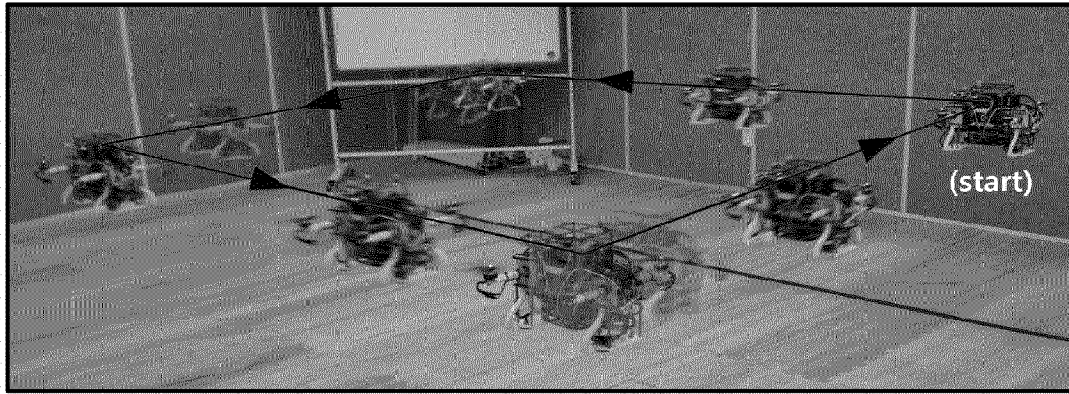
[Fig. 10]



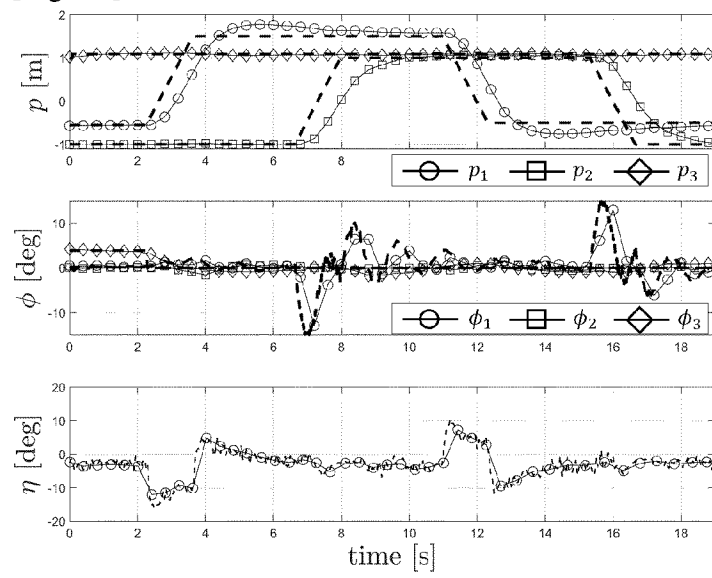
[Fig. 11]



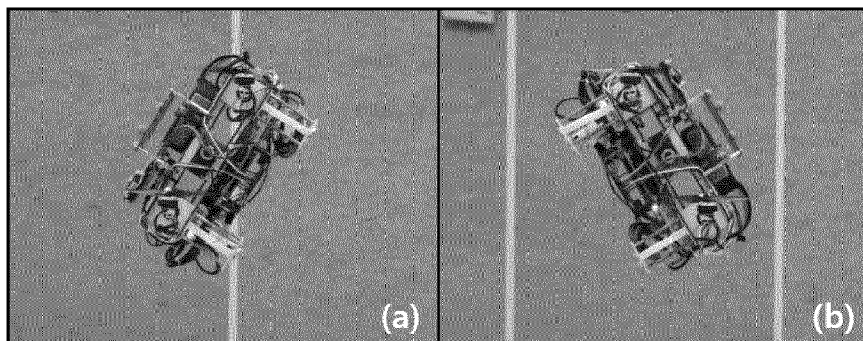
[Fig. 12]



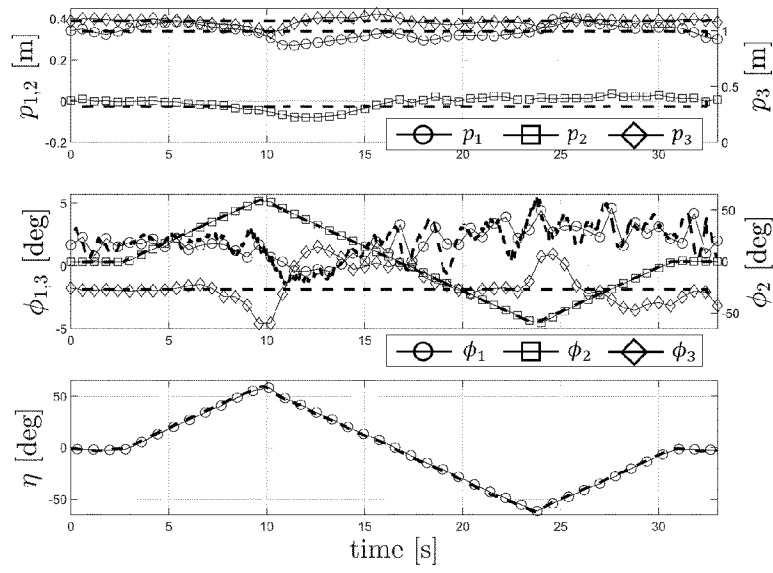
[Fig. 13]



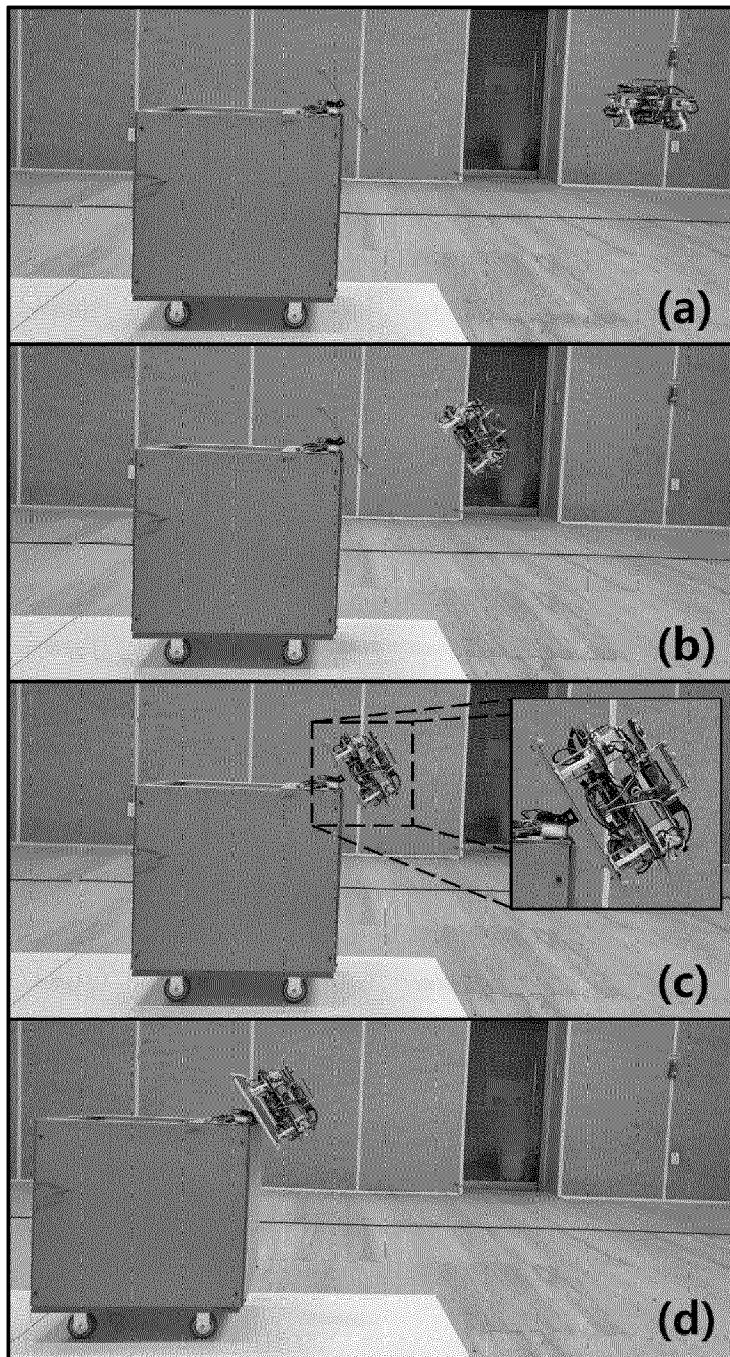
[Fig. 14]



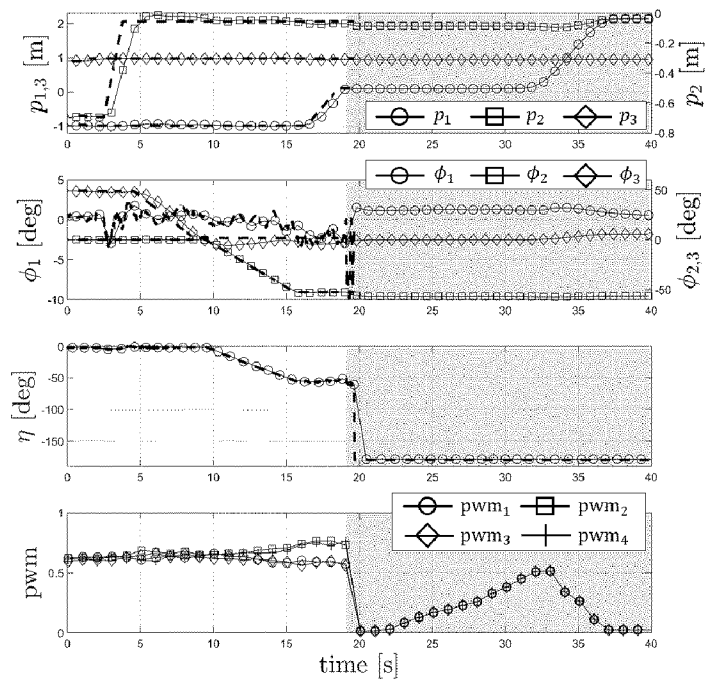
[Fig. 15]



[Fig. 16]



[Fig. 17]



INTERNATIONAL SEARCH REPORT

International application No.

PCT/KR2024/095089

A. CLASSIFICATION OF SUBJECT MATTER B64U 30/297(2023.01)i; B64U 10/14(2023.01)i; B64C 39/02(2006.01)i According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) B64U 30/297(2023.01); A63H 27/133(2006.01); A63H 30/04(2006.01); B64C 27/02(2006.01); B64C 27/08(2006.01); B64C 27/12(2006.01); B64C 27/32(2006.01); B64C 29/00(2006.01); B64C 39/02(2006.01); B64D 35/04(2006.01) Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Korean utility models and applications for utility models Japanese utility models and applications for utility models Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) eKOMPASS(KIPO internal) & Keywords: 5 degree of freedom aerial vehicle, rotor shaft, servo motor, rotor tilting unit		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 2017-063960 A (KYOSHO CORP.) 06 April 2017 (2017-04-06) paragraphs [0020]-[0029], [0061]-[0063] and figures 1-5, 9	1-4,7,11
Y		5-6
A		8-10

Y	KR 10-2022-0063070 A (VORASKY CO., LTD.) 17 May 2022 (2022-05-17) paragraph [0008] and figure 1	5

Y	CN 108146629 A (SHENZHEN CITY FLAG VISITOR'S INTELLECTUAL TECHNOLOGY CO., LTD.) 12 June 2018 (2018-06-12) paragraphs [0039]-[0041] and figures 1-2	6

A	KR 10-2022-0083671 A (TEXTRON SYSTEMS CORPORATION) 20 June 2022 (2022-06-20) figures 4a-4b	1-11

☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents: “A” document defining the general state of the art which is not considered to be of particular relevance “D” document cited by the applicant in the international application “E” earlier application or patent but published on or after the international filing date “L” document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) “O” document referring to an oral disclosure, use, exhibition or other means “P” document published prior to the international filing date but later than the priority date claimed “T” later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention “X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone “Y” document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art “&” document member of the same patent family		
Date of the actual completion of the international search 04 July 2024		Date of mailing of the international search report 04 July 2024
Name and mailing address of the ISA/KR Korean Intellectual Property Office 189 Cheongsa-ro, Seo-gu, Daejeon 35208, Republic of Korea Facsimile No. +82-42-481-8578		Authorized officer PARK, Tae Wook Telephone No. +82-42-481-3405

INTERNATIONAL SEARCH REPORT

International application No.

PCT/KR2024/095089

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	KR 10-2022-0047338 A (UNMANNED AEROSPACE LLC) 15 April 2022 (2022-04-15) figure 6	1-11

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/KR2024/095089

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
JP	2017-063960	A	06 April 2017	JP	2017-055911	A	23 March 2017
				JP	2018-001849	A	11 January 2018
				JP	5997338	B1	28 September 2016
				JP	5997342	B1	28 September 2016
				JP	6114862	B1	12 April 2017
				WO	2017-047546	A1	23 March 2017

KR	10-2022-0063070	A	17 May 2022	None			
CN	108146629	A	12 June 2018	None			
KR	10-2022-0083671	A	20 June 2022	AU	2020-332673	A1	03 March 2022
				AU	2020-332673	B2	04 April 2024
				BR	112022002861	A2	17 May 2022
				CA	3151358	A1	25 February 2021
				EP	4013677	A1	22 June 2022
				IL	290526	A	01 April 2022
				JP	2022-552431	A	15 December 2022
				US	11919630	B2	05 March 2024
				US	2021-0107640	A1	15 April 2021
				WO	2021-034640	A1	25 February 2021
				ZA	202201718	B	28 June 2023

				CA	3147197	A1	18 February 2021
				EP	3999420	A2	25 May 2022
				IL	290392	A	01 April 2022
				IL	290392	B1	01 February 2024
				IL	310129	A	01 March 2024
				JP	2022-544540	A	19 October 2022
				US	11332242	B2	17 May 2022
				US	11661182	B2	30 May 2023
				US	11873087	B2	16 January 2024
				US	2022-0119102	A1	21 April 2022
				US	2023-0037680	A1	09 February 2023
				US	2023-0271699	A1	31 August 2023
				WO	2021-030630	A2	18 February 2021
				WO	2021-030630	A3	15 April 2021
