The Stabilization of Position and Attitude for a Blimp by a Switching Controller

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Abstract—In recent years, the development of unmanned air vehicles aiming at vegetation observation, information gathering of a disaster site, etc. is increasing. Among them, airships are attractive because of good energy efficiency and it is possible to be employed for a long time cruise. Especially, small airships called "blimp" have been developing to make the management easy. Although most of existing airships employ control methods by combining propellers and rudders, such a control approach has the problem that the maneuverability is deteriorated if their traveling speed is slow because the airflow received by rudders is weakened. In this research, "X4-Blimp" is proposed as a blimp controlled by only four propellers without any rudders, and it is controlled by a switching controller.

Index Terms—X4-Blimp, underactuated control, switching control.

I. INTRODUCTION

In recent years, unmanned aircrafts are expected to play an important role in observing vegetation and gathering information on disaster sites etc.[1] where it is hard for human to enter. Especially, airships that can float by its own buoyancy are attractive for good energy efficiency to travel for long time. However, a big airship requires a wide space and cost for maintenance. Thus, small airships which are called "blimp" have been developed, because it is easy to maintain and use it. Most of existing airships have propellers and rudders for controlling them. In this control method, the airframe is controlled by the rudders, using the airflow flowing on its surface. Such a method has a problem that if the traveling speed is slowed down, then the operability is deteriorated because of the weak airflow. Thus, it is desired to develop a blimp controlled without using rudders.

In this research, a controller method is proposed for an "X4-Blimp" where the airframe is controlled by only four propellers without any rudders. Since the X4-Blimp can control the positions and attitudes in three-dimensional space by regulating the output of the propellers, it can realize high operability, irrespective of its traveling speed. However, it is not easy to control the X4-Blimp, because it is an underactuated system. From an actual experiment, we have found that it was hard for a conventional X4-Blimp [2], in which the envelope is placed at the upper part of the airframe whereas the gondola is placed at the lower part of the airframe to fly downward.
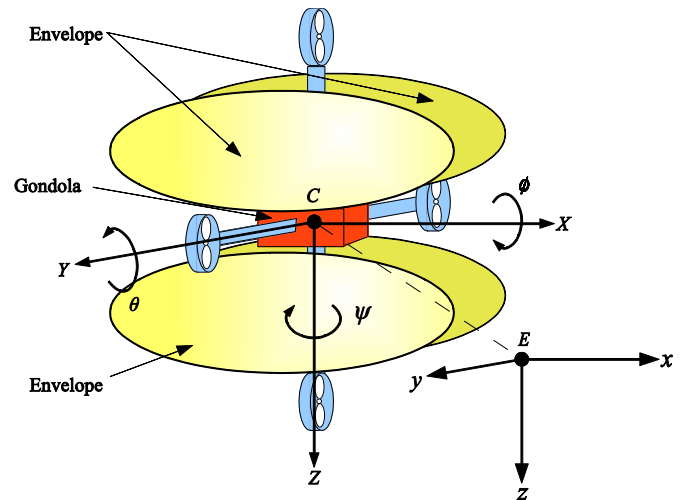

Fig. 1. Definition of the coordinates

When the airframe is inclined, the righting moment prevents the X4-Blinp from being controlled, because the conventional X4-Blimp has the center of gravity and the center of buoyancy in different point. This paper proposes a new X4-Blimp, which is symmetric in structure. The new X4-Blmip can fly stable because the new X4-Blmip has the center of gravity and the center of buoyancy in the same point. A method for controlling the X4-Blimp by switching two controllers is adopted, one of which is designed by using a model that includes nonlinear parts or a model that only includes linear parts, where those are separated from the derived dynamical model. The effectiveness of the proposed method is verified by some simulations.

II. OVERVIEW OF THE X4-BLIMP

A. Structure of the X4-Blmip

The X4-Blimp proposed in this research is composed of envelopes, a gondola and propellers as shown in Fig. 1. The envelopes is filled with helium gas to balance airframe mass with the buoyancy. The envelope form is a spheroid to decrease air resistance for traveling direction. The gondola includes batteries and controllers, and it is placed on the center of the airframe. The gondola form is a rectangular solid to maintain the space for the controllers etc. and simplify a calculation of the moment of inertia. The four propellers are attached on up, down, left and right sides of the gondola with the same distance from the center of the gondola. This airframe is designed symmetrically at a point C so as to be controlled easily.

B. Definition of the coordinates

A definition of coordinates is shown in Fig. 1, and the robot coordinate C is difined such that the origin is the center of the gondola, positive X-axis is set as the forward direction of the airframe, positive Y-axis is set as the right direction of the airframe, and Z-axis is set to be downward perpendicular to the airframe. Similarly, the world coordinate E is a right-handed coordinate where positive z-axis is set to be vertically downward. The center position of the gondola is represented by $\xi = [x, y, z]^T$ in the world coordinate, and the rotational angles for roll, pitch, and yaw in the robot coordinate system are represented as ϕ, θ and ψ respectively, then the sttitude of the gondola is represented by $\eta = [\phi, \theta, \psi]^T$. A rotation matrix R to transform the robot coordinate to the world coordinate is derived as follows:

$$R = \begin{bmatrix} c\theta c\psi & s\phi s\theta c\psi - c\phi s\psi & c\phi s\theta c\psi + s\phi s\psi \\ c\theta s\psi & s\phi s\theta s\psi + c\phi c\psi & c\phi s\theta s\psi - s\phi c\psi \\ -s\theta & s\phi c\theta & s\phi c\theta \end{bmatrix} \quad (1)$$

where cA is $\cos A$ and sA is $\sin A$.

III. DERIVATION OF DYNAMICAL MODEL

A dynamical model of the X4-Blimp is derived by referring to X4-AUV studied in Watanabe et al. [2], the dynamical model of the X4-Blimp is derived as

$$\begin{cases} \ddot{x} = (\cos\theta \cos\psi\, u_1)/m \\ \ddot{y} = (\cos\theta \sin\psi u_1)/m \\ \ddot{z} = (-\sin\theta u_1)/m \\ \ddot{\phi} = (\dot{\theta}\dot{\psi}(I_Y - I_Z) + u_2)/I_X \\ \ddot{\theta} = (\dot{\phi}\dot{\psi}(I_Z - I_X) - J_p\dot{\psi}\Omega + lu_3)/I_Y \\ \ddot{\psi} = (\dot{\phi}\dot{\theta}(I_X - I_Y) + J_p\dot{\theta}\Omega + lu_4)/I_Z \end{cases} \quad (2)$$

where the mass of the airframe is m, the moment of inertia for each axis is represented by I_X, I_Y and I_Z respectively, the moment of inertia of the propellers is J_p and $\Omega = \omega_2 + \omega_4 - \omega_1 - \omega_3$. When four propellers are numbered from 1 to 4 in the clockwise from the upper propeller and the direction of rotational velocity of each propeller is positive if it is defined as clockwise. And the input u_1 of translational motion, the input u_2 of roll motion, the input u_3 of pitch motion and the input u_4 of yaw motion are represented by

$$\begin{align} u_1 &= b(\omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2) & (3) \\ u_2 &= d(-\omega_2^2 - \omega_4^2 + \omega_1^2 + \omega_3^2) & (4) \\ u_3 &= b(\omega_1^2 - \omega_3^2) & (5) \\ u_4 &= b(\omega_2^2 - \omega_4^2) & (6) \end{align}$$

where the thrust coefficient is b and the resistance coefficient is d.

IV. DESIGN OF PARTIAL UNDERACTUATED CONTROLLERS

Since the system of the X4-Blimp represented by the dynamical model of Eq. (2) is an underactuated system with four inputs and 12 states, it is different to realize underatuated control .As shown in Fig. 2, tow partial underactuated controllers for a model with 4 inputs 10 states are designed by combining a controller for a 2-input/4-state partial model with a controller for a 2-input/6-state partial model. The whole system is controlled by switching these two partial underactuated controllers. To perform a chained form transformation, the dynamic model is partially linearized such that
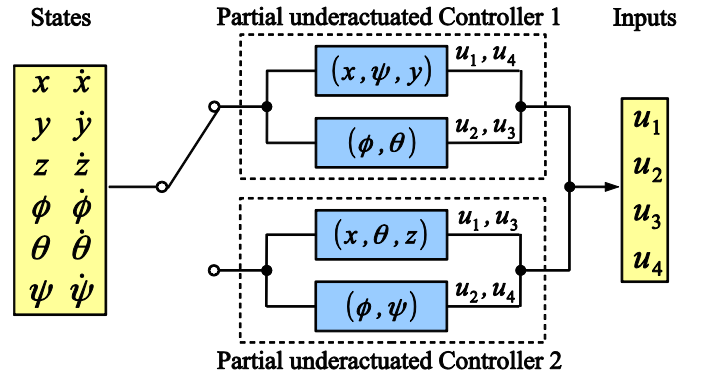

Fig. 2. Concept of the proposed controller

$$\begin{align} \ddot{x} &= \omega_1 \\ \ddot{y} &= \tan\psi\, \omega_1 \\ \ddot{z} &= -\tan\theta \sec\psi\, \omega_1 \\ \ddot{\phi} &= \omega_2 \\ \ddot{\theta} &= \omega_3 \\ \ddot{\psi} &= \omega_4 \end{align} \quad (7)$$

Then, the inputs are transformed as follows

$$\begin{align} \omega_1 &= \cos\theta\cos\psi\, u_1/m & (8) \\ \omega_2 &= (\dot{\theta}\dot{\psi}(I_Y - I_Z) + u_2)/I_X & (9) \\ \omega_3 &= (\dot{\phi}\dot{\psi}(I_Z - I_x) - J_p\dot{\psi}\Omega + lu_3)/I_Y & (10) \\ \omega_4 &= (\dot{\phi}\dot{\theta}(I_X - I_Y) + J_p\dot{\theta}\Omega + lu_4)/I_Z & (11) \end{align}$$

The partial underactuated controller 1 is designed from a 2-input/6-state partial model for *x*, ψ and *y*, and from a 2-input/4-state partial model for ϕ and θ. The partial underactuated controller 2 is designed from a 2-input/6-state partial model for *x*, θ and *z*, and from a 2-input/4-state partial model for ϕ and ψ. When a chained form transformation in [4] is applied, the 2-input/6-statepartial model for *x*, ψ and *y* is denoted by

$$\begin{align} z_{11} &= h_1 = x & (12) \\ z_{12} &= L_f h_1 = \dot{x} & (13) \\ z_{21} &= L_{g_1} L_f h_2 = \tan\psi & (14) \\ z_{22} &= L_f L_{g_1} L_f h_2 = \dot{\psi}/\cos^2\psi & (15) \\ z_{31} &= h_2 = y & (16) \\ z_{32} &= L_f h_2 = \dot{y} & (17) \end{align}$$

Then, the inputs are transformed as follows

$$v_1 = w_1 \quad (18)$$

$$v_2 = \frac{1}{\cos^2\psi} w_4 + \frac{2\tan\psi}{\cos^2\psi} \dot{\psi}^2 \quad (19)$$

From the above results, a chained form is derived by

$$\begin{align} \ddot{z}_{11} &= v_1 \\ \ddot{z}_{21} &= v_2 \\ \ddot{z}_{31} &= z_{21}v_1 \end{align} \quad (20)$$

To apply a method in Xu and Ma [3] to Eq. (20), it is rewritten for state variables such as

$$\begin{align} \dot{x}_1 &= x_2, & \dot{x}_2 &= v_1 \\ \dot{x}_3 &= x_4, & \dot{x}_4 &= v_2 \\ \dot{x}_5 &= x_6, & \dot{x}_6 &= x_3 v_1 \end{align}$$

Then the control input v_1 is denoted by

$$v_1 = -(s_1 + s_2)x_2 - s_1 s_2 x_1 \quad (21)$$

where $s_2 > s_1 > 0$. To control the underactuated system, a coordinate transformation is performed to design a controller based on a discontinuous model:

$$z_i = x_i \ (i = 1,2,3,4), \quad z_i = \frac{x_i}{x_1} \ (i = 5,6) \qquad (22)$$

The Eq. (22) is rewritten as follows

$$\dot{z}_1 = z_2 \qquad (23)$$
$$\dot{z}_2 = -(s_1 + s_2)z_2 - s_1 s_2 z_1 \qquad (24)$$
$$\dot{Z}_{3-6} = \left(A_1 + A_2(t)\right)Z_{3-6} + Bv_2 \qquad (25)$$

where $Z_{3-6} = [z_3, z_4, z_5, z_6]^T$. Here, A_1 , $A_2(t)$ and B are denoted by

$$A_1 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & s_1 & 1 \\ s_1^2 & 0 & 0 & s_1 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}$$

$$A_2(t) = C \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ -(s_1 + s_2) & 0 & 0 & -1 \end{bmatrix}$$

where $C = \frac{z_2}{z_1} + s_1$. The controllability of $[A_1, B]$ is confirmed. A controllable matrix is represented as $[B \ A_1 B \ A_1^2 B \ A_1^3 B]$. It is regular because $s_1 > 0$. Since $A_1 + BL$ is controllable, the feedback gain $L = [l_1, l_2, l_3, l_4]$ is calculated to make matrix $A_1 + BL$ as the Hurwitz matrix by the pole placement method. The control input v_2 is denoted by

$$v_2 = LZ_{3-6} = l_1 z_3 + l_2 z_4 + l_3 z_5 + l_4 z_6 \qquad (26)$$

Thus, since it can be stabilized to the origin, the control input for the chained form are derived as follows

$$v_1 = -(s_1 + s_2)\dot{x} - s_1 s_2 x \qquad (27)$$

$$v_2 = l_1 \tan \psi + l_2 \frac{\dot{\psi}}{\cos^2 \psi} + l_3 \frac{y}{x} + l_4 \frac{\dot{y}}{x} \qquad (28)$$

In this way, the controller for 2-input/6-state partial model for x, ψ and y is designed. Next, the controller for the 2-input/6-state partial model for ϕ and θ is designed by a linear feedback such as

$$w_2 = -k_1 \phi - k_2 \dot{\phi} \quad (k_1, k_2 > 0) \qquad (29)$$
$$w_3 = -k_3 \theta - k_4 \dot{\theta} \quad (k_3, k_4 > 0) \qquad (30)$$

The partial underactuated controller 1 for a model with 4 input and 10 state is designed by combining the controllers for x, ψ and y with the controller for ϕ and θ.

Similarly, the partial underactuated controller 2 is designed by combining the controller for the 2-input/6-state partial model for x, θ and z with the controller for the 2-input/4-state partial model for ϕ and ψ. When the partial model for x, θ and z is transformed to a chained form, the input transformation is denoted by

$$v_1 = -(s_1 + s_2)\dot{x} - s_1 s_2 x$$

$$v_2 = l_1 \left(-\frac{\tan \theta}{\cos \psi} \right) + l_2 \left(-\frac{\dot{\theta}}{\cos \psi \cos^2 \theta} \right) + l_3 \frac{z}{x} + l_4 \frac{\dot{z}}{x}$$

The control inputs based on the chained form transformation is denoted by

$$w_1 = v_1 \qquad (31)$$
$$w_2 = -\cos \psi \cos^2 \theta \cdot v_2 - 2 \tan \theta \cdot \dot{\theta}^2 \qquad (32)$$

The 2-input/4-state partial model for ϕ and ψ is derived by a linear feedback such as

$$w_2 = -k_1 \phi - k_2 \dot{\phi} \quad (k_1, k_2 > 0) \qquad (33)$$
$$w_4 = -k_3 \psi - k_4 \dot{\psi} \quad (k_3, k_4 > 0) \qquad (34)$$

The partial underactuated controller 2 for the model with 4 inputs and 10 states is designed by combining the controller for x, θ and z with the controller for ϕ and ψ.
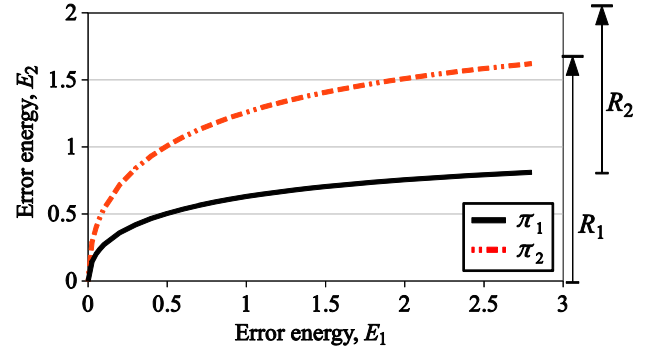

Fig. 3. Structure of energy regions

V. ENERGY REGION BASED SWITCHING METHOD

Switching the two partial underactuated controllers for 4 inputs 10 states is considered to control an underactuated system with 4 inputs 12 states. However, if input chattering phenomena occur when controllers are switched, an excessive burden is placed on motors. Therefore, a switching method[5] that has multiple boundary regions is used to prevent the chattering phenomena.

The energy is defined from the errors of generalized coordinates. Since the state x is doubly generated from the set of (x, ψ, y) and (x, θ, z), and similarly the corresponding attitude angle ϕ is also doubly generated from the set of (ϕ, θ) and (ϕ, ψ), the errors for the stabilization to the origin are directly represented by ψ, y, θ and z because both partial underactuated controllers always stabilize the state x and the angle ϕ to the origin. Then, the energy based on the errors is defined as follows:

$$E_1 = \psi^2 + y^2 \qquad (35)$$
$$E_2 = \theta^2 + z^2 \qquad (36)$$

In Fig. 3, a two–dimensional plane is represented by E_1 and E_2, and hysteresis like boundary lines π_1 and π_2 to separate the energy plane are represented respectively by

$$\pi_1(E_1) = 1 - e^{-\sqrt{E_1}} \qquad (37)$$
$$\pi_2(E_1) = 2\pi_1 \qquad (38)$$

In Fig. 3, the partial underactuated controller 1 is used on the region R_1, whereas the partial underactuated controller 2 is used on the region R_2. Considering an overlapped region, switching rules are decided as follows:

Rule 1:
  If $0 < E_2 \leq \pi_1(E_1)$ then $s_t = y$
Rule 2
  If $\pi_1(E_1) < E_2 < \pi_2(E_1)$ and $s_{t-1} = y$ then $s_t = y$
Rule 3:
  If $\pi_1(E_1) < E_2 < \pi_2(E_1)$ and $s_{t-1} = z$ then $s_t = z$
Rule 4:
  If $\pi_2(E_1) < E_2$ then $s_t = z$

Where s_t represents the controller used for each rule. When $s_t = y$, the partial underactuated controller 1 is used, whereas when $s_t = z$, the partial underactuated controller 2 is used. s_{t-1} represents the controller used before one-sampling time. According to this switching rule, the partial underactuated controller 2 is used to control the state z. Similarly, the partial underactuated controller1 is used to control the state y. It should be noted that, in this switching rule, the chattering phenomena

TABLE I.   PARAMETERS FOR THE X4-BLIMP

Parameter	Description	Value	Unit
m	Mass	0.8	kg
l	Distance	0.50	m
I_X	Roll Inertia	1.10	$kg \cdot m^2$
I_Y	Pitch Inertia	1.43	$kg \cdot m^2$
I_Z	Yaw Inertia	1.43	$kg \cdot m^2$
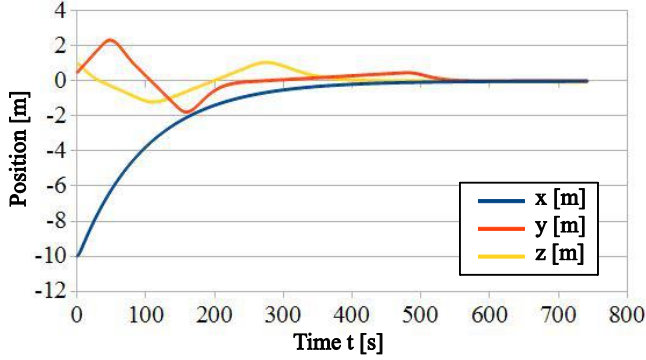
Fig. 4. Controlled positions

Fig. 5. Controlled attitudes

Fig. 6. Energy trajectory

are unlikely to occur because an overlapped region between the boundary lines π_1 and π_2 exists to switch the controllers.

VI. SIMULATION

This simulation is intended to verify that the state variables related to the position and attitude of the airframe converge to the origin by switching the two partial underactuated controllers using the switching rules created in previous section. The initial state of X4-Blimp is $q_0 = [-10.0, 0.5, 1.0, \pi/18, \pi/9, \pi/4]^T$, and the goal state is $q_r = [0, 0, 0, 0, 0, 0]^T$. The physical parameters used for simulation are shown in Table 1. The feedback gains $k_1 = 0.8, k_2 = 1.2, k_3 = 0.6, k_4 = 0.7, s_1 = 1/100, s_2 = 0.45, l_1 = -0.005, l_2 = -0.37, l_3 = -0.80,$ and $l_4 = -35.1$ are for the partial underactuated controller 1, whereas the feedback gains $k_1 = 0.8, k_2 = 1.2, k_3 = 0.6, k_4 = 0.7, s_1 = 1/100, s_2 = 0.45, l_1 = -0.02, l_2 = -0.25, l_3 = -0.14$ and $l_4 = -10.08$ are for the partial underactuated controller 2.

It is found from Fig. 4 that the positions, i.e., the states x, y and z converge from the initial positions to the goal positions. Similarly, it is seen from Fig. 5 that all the attitudes ϕ, θ and ψ converge to the desired angles. Fig. 6 shows the energy trajectory, where it starts from the point S. It is found that the controller 2 was switched to the controller1 at the point P and the energy finally converges to the origin at the point G. Switching of controllers occurs at the point P and the state variables are changed suddenly, if the energy trajectory exceeds the boundary line π_1. Thus, it is confirmed that the positions and attitudes of the X4-Blimp can be stabilized by switching the two partial underactuated controllers.

VII. CONCLUSION

In this paper, an underactuated controller has been proposed for stabilizing an X4-Blimp whose structure is symmetric at a point, where two partial underactuated controllers were
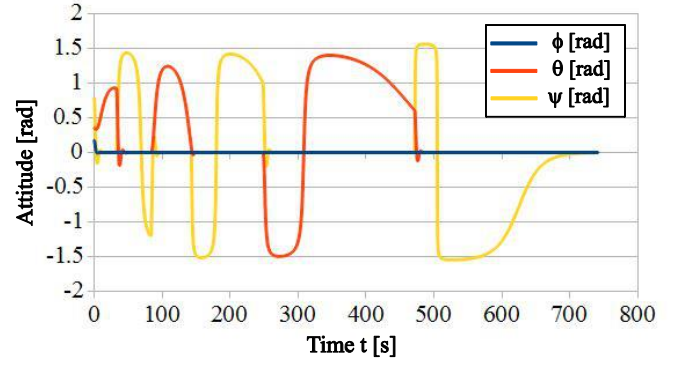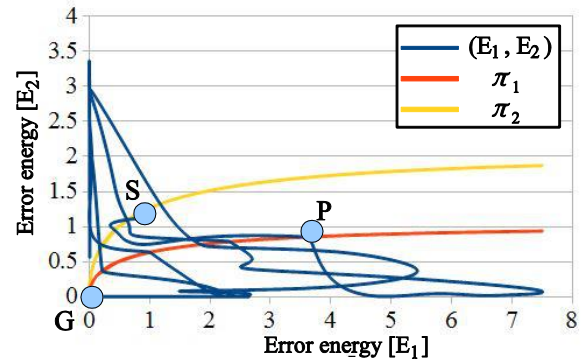
designed from the derived dynamic model, and switching rules for switching two such controllers were constructed by applying the conventional logical rules based on hysteresis-like switching boundaries. The effectiveness of the proposed method was checked by simulations. For future work, we will apply this approach to a level flight for an X4 tail-sitter.

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