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Underactuated Control for a Blimp with Four-Propellers by a Logical Switching Method

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Abstract: 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. In this research, "X4-Blimp" controlled by only four propellers is proposed. Since the X4-Blimp can control its position and attitude by regulating the output of four propellers, it can realize high maneuverability, irrespective of its traveling speed. However, it is not easy to control the X4-Blimp, because it is an underactuated system. This paper proposes a method for controlling the X4-Blimp by switching two controllers, one of which is constructed by combining models that include nonlinear terms and models that only include linear terms, where those are separated from the derived dynamic model. The effectiveness of the proposed method is verified by some simulations.

Keywords: X4-Blimp, Underactuated control, Switching control

1 INTRODUCTION

In recent years, unmanned aerial vehicles are being expected to be used for the vegetational observation and the information collection of disaster sites [1]. Especially, airships that can float by its own buoyancy are attractive, because they are effective in energy consumption. 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 propsed as a blimp controlled by only four propellers without any rudders, and the objective aims at controlling it.

This paper is organized as folllows: the proposed X4-Blimp is explained in section 2. A dynamic model is derived in section 3 and partial underactuated controllers are designed in section 4. Logical switching rules are created in section 5, simulaton results are shown in section 6 and the conclusion is drawn in secton 7.

2 OVERVIEW OF THE X4-BLIMP

2.1 Structure of the X4-Blimp

The X4-Blimp proposed in this research is composed of an envelope, a gondola and propellers as shown in Fig. 1. The envelope 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 suspended from the envelope. 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.

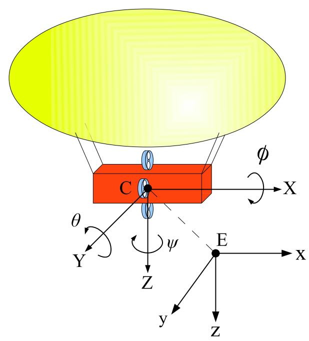

Fig. 1. Definition of the coordinates

2.2 Definition of the coordinates

In general, when rigid body motion is considered, the center of gravity of the rigid body is discussed as the representative point. However, the X4-Blimp motion is considered with the center of the gondola as a representative point in this paper. A definition of coordinates is shown in Fig. 1, and the robot coordinate C is defined 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 positive 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 $\boldsymbol{\xi} = [x, y, z]^T$ 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 attitude of the gondola is represented by $\boldsymbol{\eta} = [\phi, \theta, \psi]^T$. A rotation matrix $\boldsymbol{R}$ to transform the robot coordinate to the world coordinate is derived as follows:

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

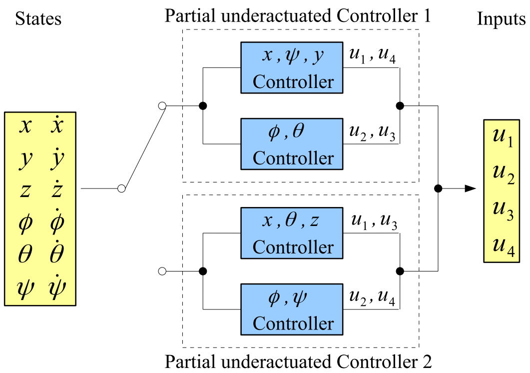

Fig. 2. Concept of the proposed controller

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

3 DERIVATION OF DYNAMIC MODEL

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

$$\left\{\begin{array}{lcl} \ddot{x} &=& (\cos\theta\cos\psi u_1)/m \\ \ddot{y} &=& (\cos\theta\sin\psi u_1)/m \\ \ddot{z} &=& (-\sin\theta u_1)/m \\ \ddot{\phi} &=& (\dot{\theta}\dot{\psi}(I_Y - I_Z) + u_2)/I_X \\ \ddot{\theta} &=& (\dot{\phi}\dot{\psi}(I_Z - I_X) - J_p\dot{\psi}\Omega + lu_3)/I_Y \\ \ddot{\psi} &=& (\dot{\phi}\dot{\theta}(I_X - I_Y) + J_p\dot{\theta}\Omega + lu_4)/I_Z \end{array}\right. \tag{2}$$

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 propeller 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 rotatinal 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

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

4 DESIGN OF PARTIAL UNDERACTUATED CONTROLLERS

Since the system of the X4-Blimp represented by the dynamic model of Eq. (2) is an underactuated system with four inputs and 12 states, it is different to realize underactuated control. As shown in Fig. 2, two 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 contollers. To perform a chaind from transformation, the dynamic model is partially linearized such that

$$\begin{array}{lcl} \ddot{x} &=& w_1 \\ \ddot{y} &=& \tan\psi w_1 \\ \ddot{z} &=& -\tan\theta\sec\psi w_1 \\ \ddot{\phi} &=& w_2 \\ \ddot{\theta} &=& w_3 \\ \ddot{\psi} &=& w_4 \end{array} \tag{7}$$

Then, the inputs are transformed as follows

$$w_1 = \cos\theta\cos\psi u_1/m \tag{8}$$
$$w_2 = (\dot{\theta}\dot{\psi}(I_Y - I_Z) + u_2)/I_X \tag{9}$$
$$w_3 = (\dot{\phi}\dot{\psi}(I_Z - I_X) - J_p\dot{\psi}\Omega + lu_3)/I_Y \tag{10}$$
$$w_4 = (\dot{\phi}\dot{\theta}(I_X - I_Y) + J_p\dot{\theta}\Omega + lu_4)/I_Z \tag{11}$$

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-state partial model for x, ψ and y is denoted by

$$z_{11} = h_1 = x \tag{12}$$
$$z_{12} = L_f h_1 = \dot{x} \tag{13}$$
$$z_{21} = L_{g_1} L_f h_2 = \tan\psi \tag{14}$$
$$z_{22} = L_f L_{g_1} L_f h_2 = \frac{\dot{\psi}}{\cos^2\psi} \tag{15}$$
$$z_{31} = h_2 = y \tag{16}$$
$$z_{32} = L_f h_2 = \dot{y} \tag{17}$$

Then, the inputs are transformed as follows

$$v_1 = w_1 \tag{18}$$
$$v_2 = \frac{1}{\cos^2\psi} w_4 + \frac{2\tan\psi}{\cos^2\psi}\dot{\psi}^2 \tag{19}$$

From the above results, a chained from is derived by

$$\begin{array}{lcl} \ddot{z}_{11} &=& v_1 \\ \ddot{z}_{21} &=& v_2 \\ \ddot{z}_{31} &=& z_{21} v_1 \end{array} \tag{20}$$

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

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

Then the control input v_1 is denoted by

$$v_1 = -(s_1 + s_2)x_2 - s_1 s_2 x_1 \tag{21}$$

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:

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

The Eq. (22) is rewritten as follows

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

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 $[B \ A_1B \ A_1^2B \ A_1^3B]$. 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

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

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

$$\begin{aligned} v_1 &= -(s_1+s_2)\dot{x} - s_1 s_2 x && (27)\\ v_2 &= l_1 \tan\psi + l_2 \frac{\dot{\psi}}{\cos^2\psi} + l_3\frac{y}{x} + l_4\frac{\dot{y}}{x} && (28)\end{aligned}$$

In this way, the controller for the 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

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

The partial underactuated controller 1 for a model with 4 inputs and 10 states 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

$$\begin{aligned} v_1 &= -(s_1+s_2)\dot{x} - s_1 s_2 x\\ v_2 &= l_1\left(-\frac{\tan\theta}{\cos\psi}\right) + l_2\left(-\frac{\dot{\theta}}{\cos\psi\cos^2\theta}\right) + l_3\frac{z}{x} + l_4\frac{\dot{z}}{x}\end{aligned}$$

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

$$\begin{aligned} w_1 &= v_1 && (31)\\ w_3 &= -\cos\psi\cos^2\theta \cdot v_2 - 2\tan\theta\cdot\dot{\theta}^2 && (32)\end{aligned}$$

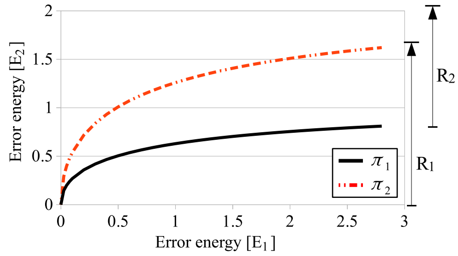

Fig. 3. Structure of energy regions

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

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

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.

5 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:

$$\begin{aligned} E_1 &= \psi^2 + y^2 && (35)\\ E_2 &= \theta^2 + z^2 && (36)\end{aligned}$$

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

$$\begin{aligned} \pi_1(E_1) &= 1 - e^{-\sqrt{E_1}} && (37)\\ \pi_2(E_1) &= 2\pi_1 && (38)\end{aligned}$$

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 regionR_2. Considering an overlapped region, switching rules are decided as follows:

Rule 1 :
If $0 < E_2 \le \pi_1(E_1)$ 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 :

Table 1. Parameters for the X4–Blimp

Parameter	Description	Value	Unit
m	Mass	0.464	kg
l	Distance	0.1	m
I_X	Roll Inertia	0.0377	$\text{kg} \cdot \text{m}^2$
I_Y	Pitch Inertia	0.0624	$\text{kg} \cdot \text{m}^2$
I_Z	Yaw Inertia	0.0309	$\text{kg} \cdot \text{m}^2$

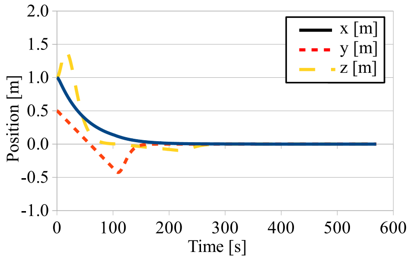

Fig. 4. Controlled positions

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, if the error energy on z becomes large when using the partial underactuated controller 1 to control states except the state z. Similarly, the partial underactuated controller 1 is used to control the state y, if the error energy on y becomes large when using the partial underactuated controller 2 to control states except the state y. It should be noted that, in this switching rule, the chattering phenomena are unlikely to occur because an overlapped region between the boundary lines π_1 and π_2 exists to switch the controllers.

6 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 $\boldsymbol{q_0} = [1, 0.5, 1, \pi/18, \pi/4, \pi/4]^T$, and the goal state is $\boldsymbol{q_r} = [0, 0, 0, 0, 0, 0]^T$. 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=1/40, s_2=0.45, l_1=−0.18, l_2=−0.68, l_3=−1.74 and l_4=−38.7 are for the partial underactuated controller 1, whereas the feedback gains k_1=0.8, k_2=1.6, k_3=1/30, k_4=0.7, s_1=1/50, s_2=0.45, l_1=−0.09, l_2=−0.48, l_3=−0.68 and l_4=−21.3 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 controller 1 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.

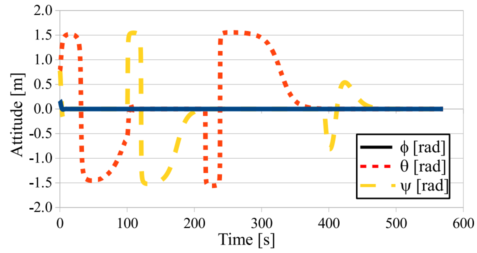

Fig. 5. Controlled attitudes

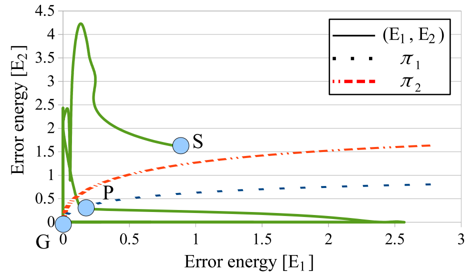

Fig. 6. Energy trajectory

7 CONCLUSION

In this paper, an underactuated controller has been proposed for stabilizing an X4-Blimp, 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 verified by the simulation. For future work, it needs to confirm the effectiveness of this approach on real robot experiments.

REFERENCES

[1] Kawabata K, Hada Y, Asama H (2006), Robotics research related to lighter than air aircraft. Journal of Robotics Society of Japan 24(8): 901–905

[2] Watanabe K, Izumi K, Okamura K, Rafiuddin S (2008), Discontinuous underactuated control for lateral X4 autonomous underwater vehicles. Proc. of the 2nd International Conference on Underwater System Technology: Theory and Applications 2008 (USYS '08) Paper ID 14

[3] Xu WL and Ma BL (2001), Stabilization of second-order nonholomic systems in canonical chained form. Robotics and Autonomous Systems 34: 223–233

[4] Laiou MC, Astolfi A (2004), Local transfomations to generalized chained forms. Proc. of the 16th International Symposium on Mathematical Theory of Networks and Systems

[5] Hespanha JP, Morse AS (1999), Stabilization of nonholonomic intergrators via logic-based switching. Automatica 35: 385–393