An Autonomous Blimp for the Wall Following Control.

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Abstract: This paper presents the wall following control of a small indoor airship (blimp). The purpose of the wall following control is that a blimp maintains its position and pose and flies along the wall. A blimp has great inertia and it is affected by temperature, atmospheric pressure, disturbance and air flow around blimp. In order to fly indoors, a volume of blimp should be small. The volume of a blimp becomes small then the buoyancy of a blimp should be smaller. Therefore, it is difficult to attach additional equipments on the blimp which are necessary to control blimp. For these reasons, it is difficult to control the pose and position of the blimp during the wall following. In our research, to cope with its defects, we developed new blimp. Generally, a blimp is controlled by using rudders and elevators, however our developed blimp has no rudders and elevators, and it has faster responses than general blimps. Our developed blimp is designed to smoothly follow the wall by using low-cost small ultra sonic sensors instead of high-cost sensors. Finally, the controller is designed to robustly control the pose and position of the blimp which could control in spite of arbitrary disturbance during the wall following, and the effectiveness of the controller is verified by experiment.

Keywords: Autonomous Blimp, Wall Following , Decoupling control

1. INTRODUCTION

Recently, there are many challenges in the field of unmanned aerial vehicle (UAV) research. Amongst them, a small indoor blimp airship (blimp) has unique advantage since it can pass over the terrain that may be impossible for land-based robots to explore. Therefore we need not consider the state of floor. And it has an effect that can attract attention from observers since it flies in the air higher than the ground vehicle. And a blimp needs no energy to maintain an altitude, as it relies on its neutral buoyancy to stay aloft. [1]

However, it is very difficult to control a blimp autonomously for the following reasons. Firstly, blimp's payload is restricted. Therefore, it is difficult to install additional equipments on the blimp which are necessary to control its pose and position (i.e. gyro sensor, GPS device, on board controller, actuators etc). Secondly, a blimp has great inertia and it is greatly affected by temperature, atmosphere, air flow around the blimp and disturbance. In order to resolve difficulties on its control, various researches have been performed to control autonomously by using vision system [2-4], stationary position control system which has passive wheeled mechanism [5], and navigation system using ultra sonic sensors [6]. However, the blimp control using vision system is greatly affected by surrounding conditions such as illumination. The blimp control which has passive wheeled mechanism can control only three degrees of freedom, not all degrees of freedom. Finally, the navigation system using ultra sonic sensors has complex structure.

However, our developed blimp has advantages which could control the pose and position of the blimp at the same time using low-cost small ultra sonic sensors instead of high-cost sensors. It was designed to have a simple structure and have faster response capability than the general blimp which is controlled by rudders and elevators.

This paper deals with the wall following control by using newly developed blimp which is not affected by its surroundings. The dynamic equation of the blimp is derived, and its controller is designed to robustly control the pose and position of the blimp. Finally, the effectiveness of the controller is verified by experiments that arbitrary disturbances are applied to the developed blimp during the wall following.

This paper is organized as follows Section 2 explains the structure of blimp. Section 3 presents the dynamic equation of the blimp and its linearization. Section 4 deals with decoupling techniques for the controller design. Section 5 shows the controller design for self positioning and posing of the blimp for the wall following. Section 6 demonstrates experimental results. Finally, section 7 contains conclusions and future works.

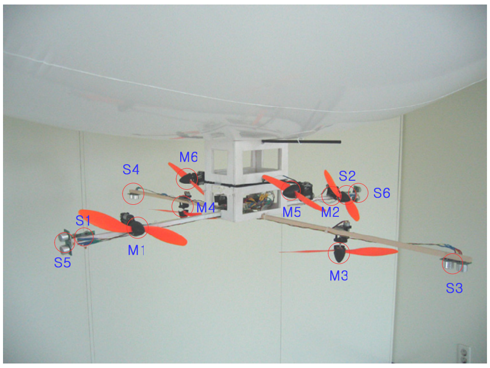
2. DESCRIPTION OF SYSTEM DESIGN

A general indoor blimp is controlled by electric motors. Also the volume of the blimp should be enough small to fly indoors. If the volume of a blimp becomes small then its buoyancy should be smaller. Because of this reason, it is difficult to install additional equipments such as the sensors, the actuators, a battery, and the on-board controller. In order to overcome these constrained conditions, we made the gondola which is made of the light materials. Also, low-cost small ultra sonic sensors and actuators are installed on the gondola

Fig. 1 shows the structure of the blimp. The length of blimp is 7 ft and the material is light, highly elastic polyurethane and it is filled with helium gas. The gondola is designed its weight to be small. The weight of the gondola is 800gram. A general blimp is controlled using rudders and elevators, however our developed blimp is not controlled using rudders and elevators. Our blimp has 6 ultra sonic sensors and 6 motors on the structures in the longitudinal and the lateral direction respectively, as shown in fig 1.

(a) Front View

(b) Side View



(c) The gondola of the blimp

Fig. 1 Autonomous blimp structure

In the lateral control, the ultra sonic sensor S1 and S2 measure yaw angle and the distance from the wall. Based on the measured values, the on-board controller calculates yaw angle and distance between the blimp and the wall and controls them through the motor M1 and M2. In the same way, in the altitude control, the ultra sonic sensor S3 and S4 measure the roll angle and the altitude of the blimp. Based on the measured values, the on-board controller calculates roll angle and altitude of the blimp and controls them through the motor M3 and M4. Finally, in the longitudinal control, sensor S5 and S6 detect the wall or the obstacles, and the motor M5, M6 are control the trajectory of the blimp.

3. DYNAMICS AND KINEMATICS OF BLIMP

3.1 Nonlinear Dynamic Equation

A full six degree of freedom mathematical model for this blimp is derived based on [1, 7, 8].

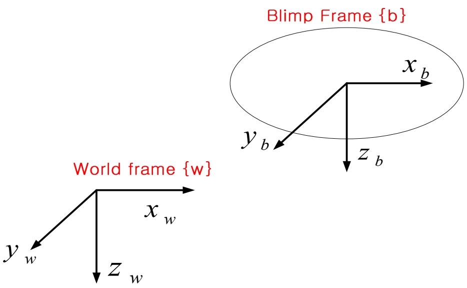


Fig. 2 The placement of reference frames.

The kinematic description of the vehicle is based on two frames. One is placed in the blimp's body, at the buoyancy centre (blimp frame {b}), and the other in the ground plane, (the world frame {w}). The referred frames are presented in Fig. 2. To describe the position and orientation of the blimp with respect to the world frame {w}, the following physical variables are used:

$$\eta=\left[\eta_1^T,\eta_2^T\right];\quad \eta_1^T=\left[x,y,z\right]^T,\quad \eta_2^T=[\phi,\theta,\psi]^T$$

$$v=\left[v_1^T,v_2^T\right];\quad v_1^T=[v_x,v_y,v_z]^T,\quad v_2^T=\left[w_x,w_y,w_z\right]^T$$

$$\tau=\left[\tau_1^T,\tau_2^T\right];\quad \tau_1^T=[F_x,F_y,F_z]^T,\quad \tau_2^T=\left[N_x,N_y,N_z\right]^T$$

Where,

$\eta=\left[\eta_1^T,\eta_2^T\right]$ represents the pose and position vector of the blimp with respect to the world frame {w}. $v=\left[v_1^T,v_2^T\right]$ describes the velocity and angular velocity vectors in the blimp frame{b}. $\tau=\left[\tau_1^T,\tau_2^T\right]$ represents the force vector in the blimp frame{b}. Assuming the blimp is rigid body, the dynamic equation could be derived as following two equations. The first one models the dynamic equation with respect to the blimp frame {b} and the second equation represents the kinematic relation between the blimp frame {b} and the world frame {w}.

$$M\dot{v}_b+C(v_b)v_b+D(v_b)v_b+g(\eta_b)=\tau_b \qquad (1)$$

$$\begin{bmatrix}\dot{\eta}_1\\ \dot{\eta}_2\end{bmatrix}=\begin{bmatrix}J_1(\eta_2) & [0]_{3\times 3}\\ [0]_{3\times 3} & J_2(\eta_2)\end{bmatrix}\begin{bmatrix}v_1\\ v_2\end{bmatrix}\Leftrightarrow \dot{\eta}=J(\eta)v$$

Where,

- $v=\left[v_x,v_y,v_z,w_x,w_y,w_z\right]^T$ is the 6×1 matrix which contains linear velocity(v_x,v_y,v_z) vector and angular velocity vector (w_x,w_y,w_z) with respect to the world frame{w}.

- $M=M_{RB}+M_A$ is the 6×6 mass matrix containing all masses and inertias of the rigid body (M_{RB}) and the added mass and the inertia terms (M_A). Assuming that the blimp is symmetry and non-deformable, cross-coupling inertial terms in M_{RB} can be neglected. And (x_g,y_g,z_g) represents the location of the center of the mass with respect to the origin of the blimp frame {b}. And then we can derive the equation that describes the rigid body matrix, where:

$$M_{RB}=\begin{bmatrix}m[I]_{3\times 3} & -mS\\ mS & I_b\end{bmatrix},\qquad S=\begin{bmatrix}0 & -z_g & y_g\\ z_g & 0 & -x_g\\ -y_g & x_g & 0\end{bmatrix}$$

$$M_A=diag\left[a_{11},a_{22},a_{33},a_{44},a_{55},a_{66}\right]$$

- $C=C_{RB}(v_b)+C_A(v_b)$ is the 6×1 dynamic force matrix. Where, $C_{RB}(v_b)$, $C_A(v_b)$ contain the Coriolis force and the centrifugal term of the dynamic model. Assuming the blimp moves slowly then $C_{RB}(v_b)$ becomes zero.

- $D(v_b)$ is the aerodynamic damping matrix. Assuming the blimp moves slowly, nonlinear damping terms could be erased. Consequently, only linear damping terms exist.

- $g(\eta_b)$ is the restoring force vector, which expresses the influence of the gravity and buoyancy forces in the dynamic behavior. Assuming the blimp is symmetric, the pitch angle of blimp becomes zero.

- τ_b contains the disturbance , the actuation forces and the torque vector.

3.2 Linearized Equation

For the purpose of simplifying the analysis of dynamic characteristic and the controller design process, equation (1) could be linearized. Assuming the blimp motion to be constrained to small perturbation about some equilibrium conditions, a considerably simplified linear model can be obtained. In order to obtain the linearized model of the blimp, it is necessary to define equilibrium values for velocity and pose. These are defined as:

$$\eta_0(t) = [x_0(t),\quad y_0(t),\quad z_0(t),\quad \phi_0(t),\quad \theta_0(t),\quad \psi_0(t)]$$
$$v_0(t) = \left[v_{x0}(t),\ v_{y0}(t),\ v_{z0}(t),\ w_{x0}(t),\ w_{y0}(t),\ w_{z0}(t)\right]$$

Therefore the linearized dynamic equation becomes the following equation:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}-M^{-1}(\ C(t)+D(t)\ ) & -M^{-1}G(t)\\ J(t) & [0]_{6\times 6}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}M^{-1}B\\ 0\end{bmatrix}u \tag{2}$$

Where:

$$\left\{\begin{matrix} C(t) = \left.\dfrac{\partial C(v)}{\partial}\right|_{v_0(t)};\ D(t) = \left.\dfrac{\partial\, D(v)}{\partial}\right|_{v_0(t)};G(t) = \left.\dfrac{\partial g(v)}{\partial}\right|_{\eta_0(t)} \\ J(t)\ =\ J(\ \eta_0\ \ (t)\ ) \end{matrix}\right\},$$
$$x_1 = v(t) - v_0(t)\ ,\quad x_2 = \eta(t) - \eta_0(t)$$

4. DECOUPLING FOR CONTROLLER DESIGN

In section 3, the dynamic equations were derived and linearized. In order to easily analyze and control the flight of the blimp, the equation (2) could be decoupled into three modes, i.e., the lateral mode, the altitude model and the longitudinal mode.

4.1 Lateral Mode

The perturbed state variables for the lateral mode are $x(t) = \left[\,y(t)\ \ \psi(t)\ v_y(t)\ \ \ w_z(t)\right]^T$. The mode is described by the state space model in equation (3)

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}-M^{-1}D & -M^{-1}G\\ J & [0]_{2\times 2}\end{bmatrix}\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} + \begin{bmatrix}M^{-1}B\\ [0]_{2\times 2}\end{bmatrix}u$$
$$y = \begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&0\\0&0&0&0\end{bmatrix}\begin{bmatrix}y\\ \psi\\ v_y\\ w_z\end{bmatrix} \tag{3}$$

4.2 Altitude Mode

The perturbed state variables for the altitude mode are $x(t) = [z(t)\ \phi(t)\ v_z(t)\ w_x(t)]^T$. The mode is described by the state space model in equation (4)

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}-M^{-1}D & -M^{-1}G\\ J & [0]_{2\times 2}\end{bmatrix}\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} + \begin{bmatrix}M^{-1}B\\ [0]_{2\times 2}\end{bmatrix}u$$
$$y = \begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&0\\0&0&0&0\end{bmatrix}\begin{bmatrix}z\\ \phi\\ v_z\\ w_x\end{bmatrix} \tag{4}$$

4.3 Longitudinal Mode

The perturbed state variables for the longitudinal mode are $x(t) = [x(t)\ \ v_x(t)]^T$. The mode is described by the state space model in equation (5)

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}-M^{-1}D & -M^{-1}G\\ J & 0\end{bmatrix}\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} + \begin{bmatrix}M^{-1}B\\ 0\end{bmatrix}u$$
$$y = \begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}x\\ v_x\end{bmatrix} \tag{5}$$

5. CONTROLLER DESIGN

This section deals with controllers which are designed for the wall following control of the blimp. Our strategy uses experimentally tuned PD-controllers for each controllable degree of freedom.

5.1 Lateral Mode Controller

The designed controllers for the lateral mode are as follows.

$$T_l(t) = k_p e_d(t) + k_d \frac{d}{dt} e_d(t) + k'_p e_a(t) + k'_d \frac{d}{dt} e_a(t)$$
$$T_r(t) = k_p e_d(t) + k_d \frac{d}{dt} e_d(t) - k'_p e_a(t) - k'_d \frac{d}{dt} e_a(t)$$

The steady state error of yaw angle ($e_d(t)$) and position ($e_a(t)$) are calculated with sensor S1, sensor S2 as shown in Fig. 1. k_p , k_d are the PD gains to control the distance between the blimp and the wall. And k'_p , k'_d are the PD gains to control the pose of the blimp. The output $T_l(t)$, $T_r(t)$ are determined by the PD controller. Where, $T_l(t)$ is the thrust of the motor M1 and $T_r(t)$ is the thrust of the motor M2.

5.2 Altitude Mode Controller

The designed controllers for the altitude mode are as follows.

$$T_l(t) = \tilde{k}_p \tilde{e}_d(t) + \tilde{k}_d \frac{d}{dt}\tilde{e}_d(t) + \tilde{k}'_p \tilde{e}_a(t) + \tilde{k}'_d \frac{d}{dt}\tilde{e}_a(t)$$

$$T_r(t) = \tilde{k}_p \tilde{e}_d(t) + \tilde{k}_d \frac{d}{dt}\tilde{e}_d(t) - \tilde{k}'_p \tilde{e}_a(t) - \tilde{k}'_d \frac{d}{dt}\tilde{e}_a(t)$$

The steady state error of roll angle ($\tilde{e}_a(t)$) and position ($\tilde{e}_d(t)$) are calculated with sensor S3, sensor S4 as shown in Fig. 1. $\tilde{k}_p, \tilde{k}_d$ are the PD gains to control the altitude of blimp. And $\tilde{k}'_p$, $\tilde{k}'_d$ are the PD gains to control the pose of the blimp. The output $T_l(t)$, $T_r(t)$ are determined by the PD controller. Where, $T_l(t)$ is the thrust of the motor M3 and $T_r(t)$ is the thrust of the motor M4.

5.3 Longitudinal Mode Controller

The designed controller for the longitudinal mode is as follow.

$$T(t) = \hat{k}_p \hat{e}(t) + \hat{k}_d \frac{d}{dt}\hat{e}(t)$$

The steady state error of position ($\hat{e}(t)$) are calculated with sensor S5, sensor S6 as shown in Fig. 2. $\hat{k}_p$, $\hat{k}_d$ are the PD gains to control the longitudinal mode of blimp. The output, $T(t)$ are determined by the PD controller. Where, $T(t)$ is the output of motor M5 and motor M6.

The longitudinal mode controller is designed to make a round trip through constant distance. However, the range of ultra sonic sensor is 2.5 meter. So if the blimp becomes out of the sensor's range, it is programmed so that flies with constant velocity toward the longitudinal direction until it reaches within the sensor's range. Then the longitudinal controller on the blimp corrects course of the blimp to fly the predetermined trajectory of the blimp. By repeating these procedures, the blimp follows the wall with stable behavior.

6. EXPERIMENTS

We conducted experiments that the blimp flies and returns constant distance as shown in Figure 3. And the arbitrary disturbances are applied to the blimp to test performance of the designed controller. The conditions of experiments are as follows:

Table 1 The Conditions of Experiments.

The altitude	85 (cm)
Distance between the wall and the blimp	95 (cm)
The flying distance	10 (m)

The altitude of the blimp is 85 (cm), the distance between the wall and the blimp is 95 (cm), and the flying distance is 10(m) as shown in Table 1.

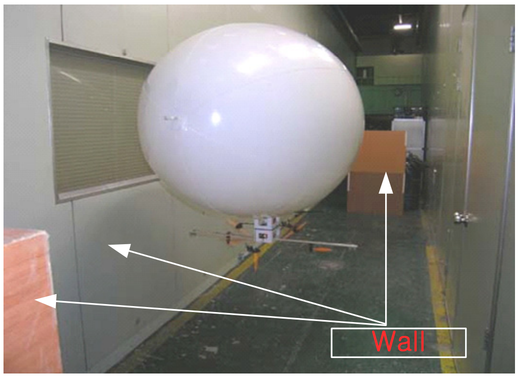
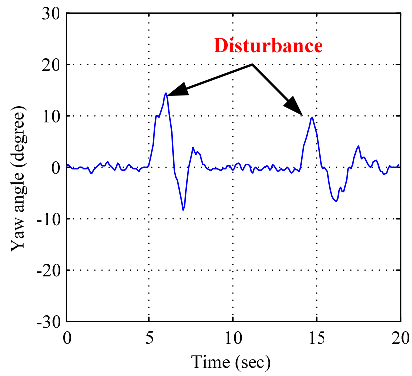
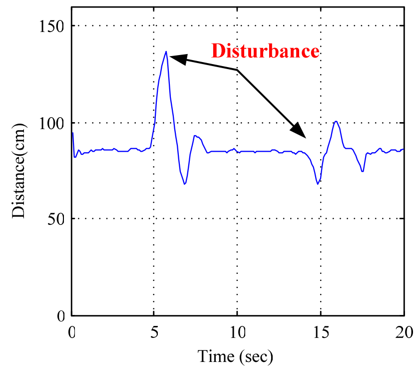


Fig. 3 Experimental setup

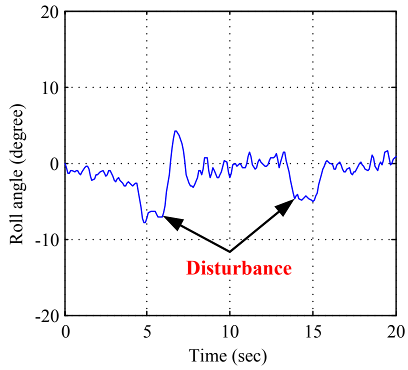
Fig. 4(a) presents the steady state error of yaw angle during the wall following. Fig. 4(b) shows the distance between the wall and the blimp. Fig. 4(c) is the steady state error of roll angle during the wall following. Fig. 4(d) expresses the altitude of blimp. Fig. 4(e) presents the longitudinal distance when it flies toward and backward. The disturbances are applied to the blimp two times; 5(sec) and 14(sec). The experiment results show that the position and pose of the blimp could be stabilized within 4(sec) in spite of the disturbances during the wall following as shown in Figure 4.



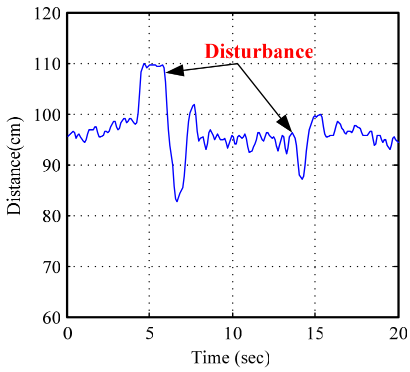
(a) The lateral mode control (yaw angle error)



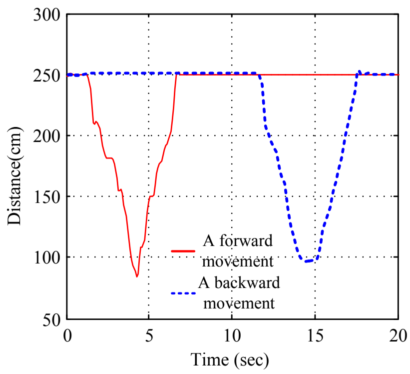
(b) The lateral mode control (distance from the wall)



(c) The altitude mode control (roll angle error)



(d) The altitude mode control (the altitude)



(e) The longitudinal mode control

Fig. 4 Experimental results

7. CONCLUSIONS

In this paper, the wall following control of the blimp is presented. We developed the new blimp which has no rudders and elevators. The proposed blimp was designed to have simple structure and consisted of the small low-cost ultra sonic sensors and motors. However, the response of the proposed blimp has faster than general blimps which are controlled by rudders and elevators.

The controller was designed to control the blimp autonomously and it could maintain the stable pose and position of the blimp in spite of arbitrary disturbance during the wall following.

The effectiveness of the controller was verified by experiments that the blimp could return the original pose and position within a short period despite of the arbitrary disturbance.

If our blimp with the advertisements flies in crowded places, it makes people to concentrate on the advertisements. Therefore, our blimp would be useful to transfer the information in public places and its applications could be extended in the field of advertisement.

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