Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 50-1 (2017) 15990–15995

Altitude Control for an Indoor Blimp Robot

Yue Wang *,** Gang Zheng *,** Denis Efimov *,** Wilfrid Perruquetti *,**

* CRIStAL (CNRS UMR 9189), Ecole Centrale de Lille, 59650 Villeneuve d'Ascq, France
** Non-A team of INRIA-LNE, Parc Scientifique de la Haute Borne, 40 avenue Halley, Building A Park Plaza, 59650 Villeneuve d'Ascq, France, (e-mail: Yue.Wang, Gang.Zheng, Denis.Efimov, Wilfrid.Perruquetti@inria.fr)

Abstract: This paper presents design of altitude controller for an indoor blimp robot and its realization. Due to hardware restrictions, the altitude control behavior of blimp is modeled as a switched system with time-varying delay. HOSM differentiator is used as an observer for vertical velocity, it is also used in order to estimate the switching signal. Then a predictor-based controller is conceived, its gain is determined by common Lyapunov function method to ensure the global uniform exponential stability of switched system. Control scheme is implemented by Matlab Simulink, finally, the performance of blimp altitude controller is verified in experiments.

Keywords: Flying robots, Output feedback control, Control of switched system.

1. INTRODUCTION

Robotics is a quickly developing area of science and technology nowadays. Frequently robots are developed for replacing humans in dangerous operating conditions or for optimization of manufacturing expenses. According to their operating environment, robots can be classified into two types: indoor or outdoor, since depending on that they have different restrictions on dimensions, noise level, actuators and sensors used. Among the flying robots it is worth to mention airships or blimps which are Lighter-Than-Air (LTA) aircrafts, for their long endurance in air, high payload-to-weight ratio, and low noise level features, compare with fixed-wing aircrafts and rotor-wing aircrafts [Li et al. (2011)].

In the present work a small blimp robot for indoor operation is considered. This robot has to possess a good autonomy operation time and demonstrate a low noise production level. The blimp can be used to do indoor long-term monitoring, or unknown dangerous environment exploring etc. In order to accomplish those complex goals, it has to be well controlled under different scenarios, and stabilizing the blimp at a desired altitude is the basic requirement. Thus, the problem of altitude stabilization is considered in this work. To this end, based on real data obtained for the blimp platform available in our laboratory, a switched time-delay model of altitude dynamics is identified. Next, predictor based control is designed. The obtained solutions are experimentally verified.

This paper is organized as follows. In next section, some related works are introduced and discussed. Structure of our blimp system is presented in section 3, the altitude model and its parameter identification are also discussed in this section. In section 4, a controller design based on predictor is illustrated, moreover, simulations are made to test its feasibility. Afterwards, we focus on the real blimp, use a motion capture system to enhance the control scheme, experiment results are presented in section 5. Finally, conclusion comes in section 6.

2. RELATED WORKS

Researchers have put increasing attention on autonomous blimp robots over the last few years, they use airships as experiment platforms to study information acquisition, robot control and navigation algorithms.

Many of these blimps are large scale, which can only be tested outdoor. They normally have a payload of several kilograms, which allow them to carry plenty of high precision sensors to do experiments. For instance, Hygounenc et al. (2004) used blimp in their terrain mapping research, achieved positioning of blimp in the three-dimensional space with a centimeter accuracy. Kantor et al. (2001) discussed the use of solar energy as a renewable power source for airships, which they used for environmental data sampling and monitoring. Rao et al. (2005) proposed a fuzzy logic controller based on the vehicle dynamics for heading angle and altitude control, their robot realized 3D path tracking with acceptable error.

Furthermore, other researchers made various studies of blimps in indoor environments, such as localization of robot, obstacle avoidance algorithm, trajectory planning and path tracking control etc. Wyeth and Barron (1998) used landmark navigation system to navigate their blimp. Fukao et al. (2003) installed a camera on airship for surveillance system and illustrated a tracking control based on image processing for an indoor blimp. Green et al. (2005) also used camera on blimp to realize obstacle avoidance

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2017.08.1909

function. Zufferey et al. (2006) used neuronal controllers in simulation to map visual input into motor commands to accelerate the movement of flying robot while avoiding collisions. Ko et al. (2007) combined their Gaussian Processes enhanced model to reinforcement learning and designed a controller for blimp yaw and yaw rate control. Rottmann et al. (2007) also used reinforcement learning to design a controller which can be used to control blimp altitude without knowledge of system dynamics or other environment parameters.

As we can see from the related works, some of them did not propose models for indoor blimp robot, while the others built complex models, which need lots of experiment data to identify the parameters but there are still disturbances from the environment which cannot be modeled. Since an indoor blimp robot is considered in this work, then it has to be sufficiently small, and its payload is limited. This limits possible quantity of sensors mounted on the robot and computational complexity of the control and estimation algorithms. That is why we intend to use a simple model for blimp altitude control task, and design a controller which can estimate the errors in real-time (error estimation is not discussed in this paper), so that the accuracy of control is assured while the complexity is reduced to a minimum. Our developed modeling, estimation and control algorithms are based on real data measurements and experimental validation performed on real platform, which is described in the next section.

3. BLIMP SYSTEM

We will consider a blimp robot for indoor operation, with a nylon balloon of 132cm length and 94cm of maximum diameter. Helium is used to inflate the balloon so it has a payload of about 250 grams. Therefore only low weight sensors and actuators can be integrated in an embedded micro-system, which means the measurement of on-board sensors can not be very accurate.

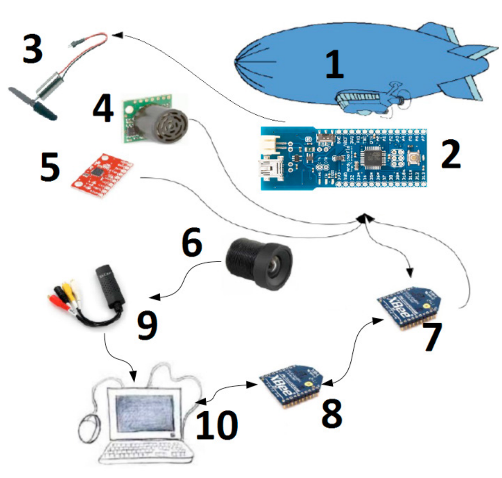

Fig. 1. Structure of the blimp system
1.Balloon 2.Arduino FIO 3.Motor 4.Ultrasonic sensor 5.IMU 6.Camera 7&8.XBee Unit 9.Camera Receiver 10.PC

Fig. 1 shows the structure of our first prototype. Ultrasonic sensors and Inertial Measurement Unit (IMU) are installed as on-board sensors. The micro-controller used is Arduino FIO, which controls three mini motors, two work in the horizontal plane, one works in vertical direction. The wireless communication between control board on blimp and ground PC is realized by a pair of XBee modules. Moreover, a wireless camera is mounted to capture visual information in blimp forward direction.

3.1 Altitude control model

Following investigation of Hygounenc et al. (2004) that the state parameters of airship dynamics in lateral and longitudinal motions are weakly dependent. For blimp dynamics in longitudinal plane, it is imperative to stabilize the airship at a desired altitude since it is the fundamental demand of blimps to perform complex tasks. In fact, altitude control is already a complex task as a blimp is really sensitive to environment changes and its behavior is easily influenced by many factors like the payload change, battery level, air flow disturbances, temperature etc.

First, in this work we intend to model the altitude control behavior of blimp and identify the parameters. To this end, the dynamical equation in vertical axis is considered. The blimp is subjected to its gravity, buoyancy, the propulsive force by its vertical motor, and the air resistance when it moves. So for the dynamical equation along vertical axis, based on Newtonian principles, there is:

$$m\ddot{z} = F_p + F_b - G - F_r \tag{1}$$

where z is the altitude of blimp to the reference plane, F_p, F_b, G, F_r represent propulsive force, buoyancy, gravity, and air resistance respectively.

The equation is simplified with the following assumptions:

- the buoyancy and gravity of blimp do not change wherever it is in the testing environment;
- the buoyancy and gravity of blimp are approximately equal;
- the air resistance is proportional to blimp velocity (the blimp has low speed);
- the propulsive force is proportional to square of motor rotation speed, which is modeled as input;
- the delay between emission of control signal to the rotation speed change of the motor is denoted as τ.

So equation (1) is simplified as:

$$\ddot{z}(t) = a\dot{z}(t) + bu(t-\tau) + c \tag{2}$$

where c represents the resultant of buoyancy and gravity of blimp, a, b, and τ are the parameters which have to be estimated to validate the model.

3.2 Parameter identification

In order to identify the model parameters, the input u for vertical motor is set as a step signal, and blimp altitude is measured using ultrasonic sensor with a rate of 10Hz. In our tests there is a significant time-varying delay in blimp control loop, so firstly the delay has to be manually measured in different tests.

Fig. 2 shows one test result, the delay τ can be measured from the figure as 0.8s. After the delay τ is measured, the

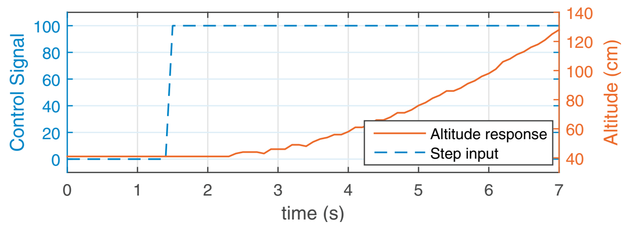

Fig. 2. Blimp response to step input for vertical motor Note: Control signal can be set to an integer from [-255,255]

parameters a, b can be identified. Using Laplace transform for the differential equation (2), we get:

$$\begin{aligned} &s^2Z(s) - sz(0) - \dot{z}(0) \\ =&a(sZ(s) - z(0)) + bU(s)e^{-\tau s} + cs^{-1} \end{aligned} \tag{3}$$

The Laplace transformation of the step input:

$$U(s) = \frac{N}{s} \tag{4}$$

where N is the step input gain, in this test $N = 100$. Assume at the beginning, blimp is static, i.e. $\dot{z}(0) = 0$, $c = 0$, the output is:

$$Z(s) = \frac{Nb}{s^2(s-a)}e^{-\tau s} + \frac{z(0)}{s} \tag{5}$$

Using inverse Laplace transform we get:

$$z(t) = z(0) + N(\frac{b}{a^2}e^{a(t-\tau)} - \frac{b}{a^2} - \frac{b}{a}(t-\tau)) \tag{6}$$

Then the Levenberg-Marquardt nonlinear least squares algorithm is used to estimate parameters in the given function [Seber and Wild (2003)].

It is worth to mention that the motor rotation speed is not the same in practice when it rotates in forward/backward direction with same input value due to motor defect. Besides, the air resistance coefficient differs when the blimp moves upward and downward on account of the installation of control board at bottom of balloon.

Therefore step input tests with positive and negative final value are made to separately identify parameters a and b, they have to be switched according to blimp state (direction of movement) and motor command. See Table 1 for the parameter identification result. Note that a is related to the air resistant coefficient, and b is related to the motor rotation speed.

Table 1. parameter identification result

case	$\dot{z} \geq 0$	$\dot{z} < 0$
$u \geq 0$	$a = -0.28412$	$a = -0.34316$
	$b = 0.11214$	$b = 0.11214$
$u < 0$	$a = -0.28412$	$a = -0.34316$
	$b = 0.06149$	$b = 0.06149$

3.3 System description

In general, the blimp altitude control system studied in this paper is a *switched system with time-varying delay* [Sun et al. (2008)]. Blimp altitude z and velocity in vertical axis $\dot{z}$ are chosen as the state vector $X = \begin{bmatrix} z \\ \dot{z} \end{bmatrix}$, the system can be written in state equation form:

$$\begin{cases} \dot{X}(t) = A_\sigma X(t) + B_\sigma u(t - \tau(t)) \\ Y(t) = CX(t) \\ \qquad \sigma \in \mathcal{P} = \{1, 2, 3, 4\} \end{cases} \tag{7}$$

where $A_\sigma = \begin{bmatrix} 0 & 1 \\ 0 & a_\sigma \end{bmatrix}$, $B_\sigma = \begin{bmatrix} 0 \\ b_\sigma \end{bmatrix}$, $C = [1 \ 0]$, switching signal

$$\sigma = \begin{cases} 1, \ u \geq 0 \text{ and } \dot{z} \geq 0 \\ 2, \ u \geq 0 \text{ and } \dot{z} < 0 \\ 3, \ u < 0 \text{ and } \dot{z} \geq 0 \\ 4, \ u < 0 \text{ and } \dot{z} < 0 \end{cases} \tag{8}$$

From the results in section 3.2, there is:

$$\begin{aligned} a_1 = a_3 &= -0.28412 \\ a_2 = a_4 &= -0.34316 \\ b_1 = b_2 &= 0.11214 \\ b_3 = b_4 &= 0.06149 \end{aligned} \tag{9}$$

4. ALTITUDE CONTROLLER DESIGN AND SIMULATION

In order to solve the altitude stabilization problem for the system (7) an output feedback should be designed. For this purpose, in this work the following steps are proposed:

1) Design an observer which can estimate state and switching signal of time-delay switched system (7).
2) Design a controller which stabilizes the system in the nominal delay-free case.
3) Modify or develop the control algorithm to compensate the delay influence.

4.1 Observer design

As the sensors in system can only measure blimp altitude, in order to use state feedback to design the closed-loop system, both components of the state (z and $\dot{z}$) have to be known. Moreover, the switching signal σ has to be also estimated to give commutation information about the system. As σ is determined by state $\dot{z}$ and command u (see equation (8)), so $\dot{z}$ has to be calculated.

For this purpose three different differentiators are considered: High-Gain, HOSM (High-order sliding mode) and HOMD (Homogeneous finite-time). They can be written in a similar formulation according to Perruquetti et al. (2008):

$$\begin{aligned} \dot{x}_1 &= -k_1 \lceil x_1 - y \rfloor^{\alpha} + x_2 \\ \dot{x}_2 &= -k_2 \lceil x_1 - y \rfloor^{2\alpha - 1} + x_3 \\ \dot{x}_3 &= -k_3 \lceil x_1 - y \rfloor^{3\alpha - 2} \end{aligned} \tag{10}$$

where for any real number $x \in \mathbb{R}$, $\lceil x \rfloor^{\alpha} = |x|^{\alpha} \operatorname{sign}(x)$, y represents the measurement, x_1, x_2, x_3 respectively represent the zero, first, and second order derivative estimation. So this differentiator can be considered as a state observer for the system:

- For High-Gain differentiator $\alpha = 1$;
- For HOMD differentiator $\alpha \in (\frac{2}{3}, 1)$;
- For HOSM differentiator $\alpha = \frac{2}{3}$.

These three differentiators give similar result for $\dot{z}$ estimation, but HOMD and HOSM have less computational complexity, so HOSM is used to estimate $\dot{z}$ [Levant (2003)]. Then the value of $\hat{\sigma}$ can be evaluated by the sign of u and $\dot{z}$ using criteria:

$$\hat{X} = [\, \hat{x}_1 \;\; \hat{x}_2 \,]^{\mathrm{T}}$$
$$\hat{\sigma} = \begin{cases} 1, \; u \geq 0 \text{ and } \hat{x}_2 \geq 0 \\ 2, \; u \geq 0 \text{ and } \hat{x}_2 < 0 \\ 3, \; u < 0 \text{ and } \hat{x}_2 \geq 0 \\ 4, \; u < 0 \text{ and } \hat{x}_2 < 0 \end{cases} \tag{11}$$

4.2 Predictor-based controller design

In this section, for brevity of presentation we will assume that the time delay in (7) is fixed and known, thus $\tau(t) = \tau$. Considering the system is time-delayed, a predictor based controller is designed. It has two parts:

1) Predict state at time $t+\tau$ using Smith (1959) predictor:
$$\hat{X}(t+\tau) = e^{A_{\hat{\sigma}}\tau}\hat{X}(t) + \int_{-\tau}^{0} e^{-A_{\hat{\sigma}}s} B_{\hat{\sigma}} u(t+s) \mathrm{d}s \tag{12}$$
where $\hat{\sigma}$ is estimated according to (11).
2) Assign the controller output based on predictor result and desired state X_{set}:
$$u(t) = K_{\hat{\sigma}}(X_{set} - \hat{X}(t+\tau)). \tag{13}$$

The gain of controller $K_{\hat{\sigma}}$ should be set to make switched system globally uniformly exponentially stable. According to Liberzon and Morse (1999), if all the systems in switched system family (7) share a common Lyapunov function, then the global stability is ensured independently on switching signal. Therefore, it is necessary to find conditions, under which there are gain matrices $K_{\hat{\sigma}}$ guaranteeing existence of a common Lyapunov function.

Assume the gains of controller of switched system are chosen to be the same for all σ, i.e. $K_{\hat{\sigma}} = K$, to simplify calculation. The purpose is to find a common Lyapunov function for the four switched systems. Choose a quadratic form Lyapunov function $V(X) = X^{\mathrm{T}}PX$, with $P = P^{\mathrm{T}} \succ 0$, then for closed-loop system:

$$\dot{V}(X) = X^{\mathrm{T}}[(A_\sigma - B_\sigma K)^{\mathrm{T}}P + P(A_\sigma - B_\sigma K)]X \tag{14}$$

Using the second Lyapunov function method we obtain:

$$\begin{cases} P \succ 0 \\ (A_\sigma - B_\sigma K)^{\mathrm{T}}P + P(A_\sigma - B_\sigma K) \prec 0, \forall \sigma \in \mathcal{P} \end{cases} \tag{15}$$

Transform (15) to:

$$\begin{cases} P^{-1} \succ 0 \\ P^{-1}(A_\sigma - B_\sigma K)^{\mathrm{T}} + (A_\sigma - B_\sigma K)P^{-1} \prec 0, \forall \sigma \in \mathcal{P} \end{cases} \tag{16}$$

Let $W = KP^{-1}$:

$$\begin{cases} P^{-1} \succ 0 \\ P^{-1}A_\sigma^{\mathrm{T}} - W^{\mathrm{T}}B_\sigma^{\mathrm{T}} + A_\sigma P^{-1} - B_\sigma W \prec 0, \forall \sigma \in \mathcal{P} \end{cases} \tag{17}$$

where decision variables are P^{-1} and W. If there exists solution for LMI (17), then it proves that the switched system (7) has a common Lyapunov function, and the switched system (7) is globally uniformly exponentially stable.

A feasible solution of P and K can be solved by YALMIP toolbox of Matlab [Löfberg (2004)]:

$$\begin{cases} P = \begin{bmatrix} 0.3082 & 0.5851 \\ 0.5851 & 2.4166 \end{bmatrix} \\ K = \begin{bmatrix} 0.3818 & 1.1444 \end{bmatrix} \end{cases} \tag{18}$$

4.3 Simulation of altitude control system

Before tests on real blimp, some simulations are done to verify the effectiveness of controller. To realize the blimp altitude real-time control, Matlab Simulink is used and Fig. 3 shows the designed Simulink block diagram.

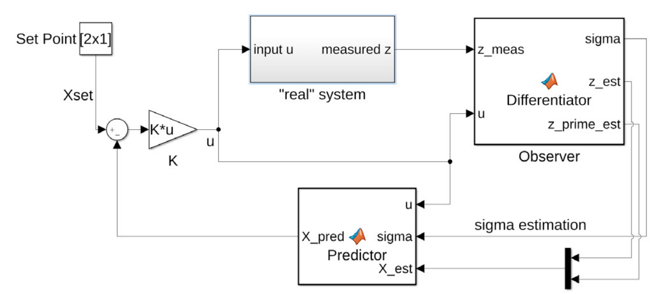

Fig. 3. Simulink block diagram of predictor-based altitude controller

Regarding the simulation program, the following points should be noticed:

- The parameters of the "real" system block is set to some random values which are not too far from identified results in experiments. Let $a_{r1} = a_{r3} = -0.2$, $a_{r2} = a_{r4} = -0.4$, $b_{r1} = b_{r2} = 0.12$, $b_{r3} = b_{r4} = 0.05$, and delay $\tau_{real} = 1$s.
- The observer block is in fact a differentiator used to estimate $\hat{X}$ and it gives switching signal estimation $\hat{\sigma}$ as described in section 4.1.
- Predictor uses $\hat{\sigma}$ to switch matrix $A_{\hat{\sigma}}$ and $B_{\hat{\sigma}}$ in prediction. To simplify the calculation, delay τ used in "Predictor" block is set as a fixed value 0.7s, which can reasonably represent the variable delay of communication measured from 0.5s to 1s.

Fig. 4 shows one result of the predictor-based altitude controller simulation, the initial state of blimp is set as altitude 50cm, velocity in axis z 0cm/s, the desired state is set to be at altitude 100cm, velocity in axis z 0cm/s.

As shown in the figure, there is no overshoot of altitude in the control process, and it reaches the set point in 25s. Moreover the observer can perfectly estimate the real state in less than 3s.

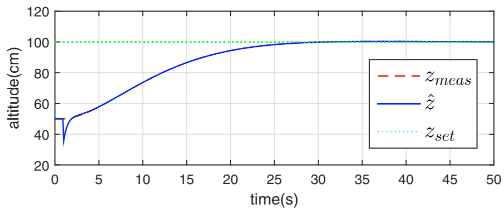

Fig. 4. Predictor-based altitude controller simulation

Nevertheless the impulse of observer output at the beginning will cause controller output sudden change. In order to avoid the damage of motor, the change rate of controller output is limited in program. The command signal of controller is shown in Fig. 5.

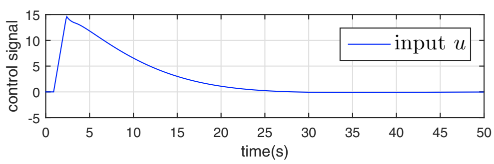

Fig. 5. Motor command signal in simulation

The simulation result shows that the designed predictor-based altitude controller can fulfill its mission, realize a smooth control of blimp altitude without overshoot or bias.

5. IMPLEMENTATION ON REAL BLIMP

As it has been indicated in section 3.2, there is a time-varying delay between control signal and blimp reaction which is measured as $0.5s - 1s$, it is due to the process time of ultrasonic sensor in the altitude measurement task, the response time of motor, and wireless communication delay between PC and blimp control board. In consequence, an ameliorated system is considered to improve the performance of blimp altitude control.

5.1 OptiTrack-Enhanced control system

The high precision position and pose capturing system OptiTrack is considered to enhance the blimp system. It uses infrared to capture the markers mounted on blimp control board, and solves the blimp position with a precision of 1mm. The corresponding control system scheme is shown in Fig. 6.

According to this scheme, first, OptiTrack captures and tracks the blimp, then it reconstructs the position and pose of blimp (cameras are calibrated and reference frame is set beforehand in software) and sends message to PC where the controller is implemented in Simulink. The differentiator in observer calculates $\dot{z}$ and observer gives estimation of switching signal $\hat{\sigma}$. Next, predictor estimates the state of blimp at moment $t + \tau$. Then controller solves command for motor based on predicted state as shown in equation (13), the delay is compensated, so the control command can be derived with a higher precision and sent to blimp control board. The control board only receives command, and ultrasonic sensor is no longer used to measure blimp altitude, thus delay in control loop is reduced to $0.2s - 0.4s$.

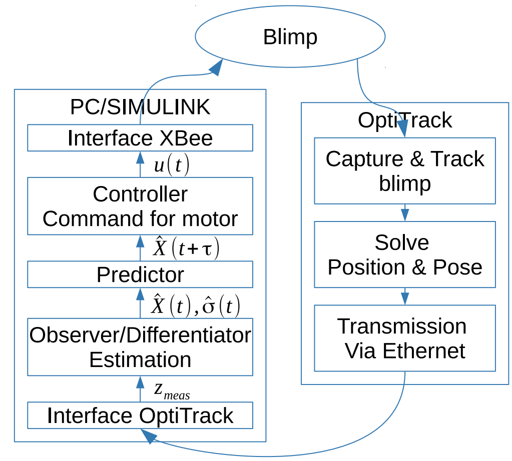

Fig. 6. Scheme of Optitrack-Enhanced blimp control system

The simulation shows satisfying result as shown in Fig. 4, the Simulink program can be easily implemented with the blimp robot by changing the "real" system block in Fig. 3 to a block representing the real blimp. In fact this block serves as the communication interface between OptiTrack, XBee, and Simulink.

5.2 Results

Experiments are made in a normal office room whose height is 3m. Five infrared cameras are installed on ground and form a circle, point their optic axis inclined upward to the vertical axis which passes the center of circle. The blimp floats inside the circle formed by camera system, when it moves to reach desired altitude, it does not leave the view of cameras.

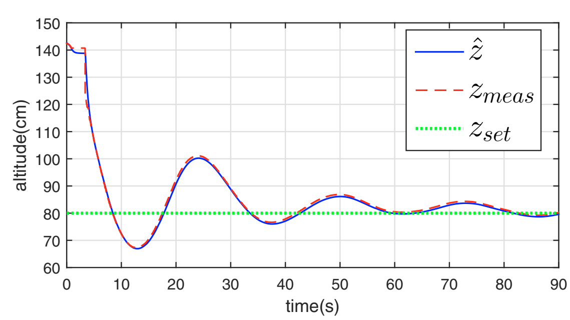

Fig. 7. Real blimp altitude control result
(Robot initialized over desired altitude)

Whether initialized from a altitude over the desired altitude (Fig. 7) or below the desired altitude (Fig. 8), the blimp reaches the desired altitude with a error less than ± 10cm within 30s.

However, as shown in figures, overshoot and oscillation appear in blimp altitude control process. They are due to the slight difference between buoyancy and gravity, error between nominal model and real blimp system, time-varying delay in control loop, and other environment disturbances.

Experiments on real blimp prove that our predictor-based controller can stabilize the blimp at desired altitude with acceptable precision and settling time.

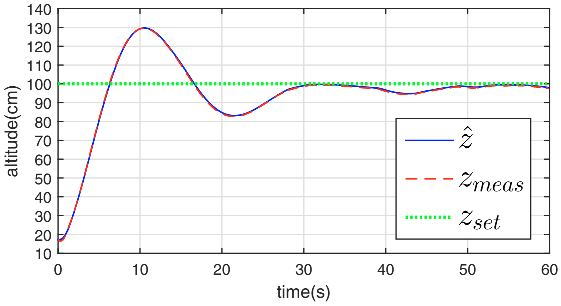

Fig. 8. Real blimp altitude control result (Robot initialized below desired altitude)

6. CONCLUSION AND FUTURE WORK

In this paper, we presented our work on the study of indoor small blimp robot altitude control. The work started from the modeling of indoor blimp robot, presenting an efficient way to identify model parameters. The model is identified as a switched system with time-varying delay. Next, HOSM differentiator is used to evaluate blimp vertical velocity in order to estimate switching signal for observer design. Then, a predictor-based controller is designed for altitude stabilizing task, it is implemented in Matlab Simulink program and gives good simulation results. When it comes to realization on real blimp, the high precision motion capture system is combined into the blimp system to reduce delay and improve measurement accuracy. Finally, we got a satisfying result in real tests, and verified the performance of our controller in blimp altitude stabilizing task.

Despite these encouraging results, there is still potential to ameliorate the performance of blimp. For instance, the estimation of disturbances come from environment and inside system are not discussed in this paper, we are working on it to improve controller performance and robustness. In the future, we will continue the study on blimp robot, develop applications like long-term monitoring, or unknown environment exploring etc. To achieve that, we have to make the blimp system more autonomous, realize accurate position and pose estimation with information only comes from inside the system, and make the blimp more robust to disturbances.

ACKNOWLEDGEMENTS

The PhD student is sponsored by China Scholarship Council (CSC). This work is also supported in part by ANR Finite4SoS (ANR 15 CE23 0007), by the Government of Russian Federation (Grant 074-U01) and the Ministry of Education and Science of Russian Federation (Project 14.Z50.31.0031). Thanks to our team engineer Mr. Xin Jin for his work on the development of blimp first prototype. Thanks to Paul Lesur for his work on the communication interface between Simulink and OptiTrack and his help during tests.

REFERENCES

Fukao, T., Fujitani, K., and Kanade, T. (2003). Image-based tracking control of a blimp. In *Decision and Control, 2003. Proceedings. 42nd IEEE Conference on*, volume 5, 5414–5419 Vol.5. doi: 10.1109/CDC.2003.1272498.

Green, W.E., Sevcik, K.W., and Oh, P.Y. (2005). A competition to identify key challenges for unmanned aerial robots in near-earth environments. In *ICAR '05. Proceedings., 12th International Conference on Advanced Robotics, 2005.*, 309–315. doi: 10.1109/ICAR.2005.1507429.

Hygounenc, E., Jung, I.K., Soueres, P., and Lacroix, S. (2004). The autonomous blimp project of laas-cnrs: Achievements in flight control and terrain mapping. *The International Journal of Robotics Research*, 23(4-5), 473–511.

Kantor, G., Wettergreen, D., Ostrowski, J.P., and Singh, S. (2001). Collection of environmental data from an airship platform. In *Intelligent Systems and Advanced Manufacturing*, 76–83. International Society for Optics and Photonics.

Ko, J., Klein, D.J., Fox, D., and Haehnel, D. (2007). Gaussian processes and reinforcement learning for identification and control of an autonomous blimp. In *Proceedings 2007 IEEE International Conference on Robotics and Automation*, 742–747. doi: 10.1109/ROBOT.2007.363075.

Levant, A. (2003). Higher-order sliding modes, differentiation and output-feedback control. *International journal of Control*, 76(9-10), 924–941.

Li, Y., Nahon, M., and Sharf, I. (2011). Airship dynamics modeling: A literature review. *Progress in Aerospace Sciences*, 47(3), 217–239.

Liberzon, D. and Morse, A.S. (1999). Basic problems in stability and design of switched systems. *IEEE Control systems*, 19(5), 59–70.

Löfberg, J. (2004). In *In Proceedings of the CACSD Conference*. Taipei, Taiwan.

Perruquetti, W., Floquet, T., and Moulay, E. (2008). Finite-time observers: application to secure communication. *IEEE Transactions on Automatic Control*, 53(1), 356–360.

Rao, J., Gong, Z., Luo, J., and Xie, S. (2005). A flight control and navigation system of a small size unmanned airship. In *IEEE International Conference Mechatronics and Automation, 2005*, volume 3, 1491–1496 Vol. 3. doi: 10.1109/ICMA.2005.1626776.

Rottmann, A., Zitterell, T., Burgard, W., Reindl, L., and Scholl, C. (2007). Towards an experimental autonomous blimp platform. In *the European Conf. on Mobile Robots (ECMR)*. Citeseer.

Seber, G.A.F. and Wild, C.J. (2003). *Nonlinear Regression*. Wiley-Interscience.

Smith, O.J. (1959). A controller to overcome dead time. *iSA journal*, 6(2), 28–33.

Sun, X.M., Wang, W., Liu, G.P., and Zhao, J. (2008). Stability analysis for linear switched systems with time-varying delay. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, 38(2), 528–533. doi:10.1109/TSMCB.2007.912078.

Wyeth, G. and Barron, I. (1998). An autonomous blimp. In *Field and Service Robotics*, 464–470. Springer.

Zufferey, J.C., Guanella, A., Beyeler, A., and Floreano, D. (2006). Flying over the reality gap: From simulated to real indoor airships. *Autonomous Robots*, 21(3), 243–254.