2009

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Publication Details

Liu, Y., Pan, Z., Stirling, D. A. & Naghdy, F. 2009, 'Control of autonomous airship', Proceedings of the 2009 IEEE International Conference on Robotics and Biomimetics, IEEE, Guilin, China, pp. 2457-2462.

Proceedings of the 2009 IEEE
International Conference on Robotics and Biomimetics
December 19 -23, 2009, Guilin, China

Control of Autonomous Airship

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***Abstract*— Scientific research and development on the control of autonomous airship have shown a significant growth in recent years. New applications appear in the areas such as freight carrier, advertising, monitoring, surveillance, transportation, military and scientific research. The control of Autonomous airship is a very important problem for the aerial robots research. In this paper, the previous research on the control of autonomous blimp is reviewed, Several popular control methods are categorized and discussed in detail. Then an intelligent navigation control method, reinforcement learning control, is introduced in the autonomous blimp which was used for 2007 UAV Outback Challenge. The future work on intelligent airship control is also outlined.**

I. INTRODUCTION

An autonomous airship is an unmanned aerial robotic platform possessing six or more variable-function control inputs. These inputs are actuated in many combinations seeking to attain, a mission prescribed, series of task goals, some or all of which may be challenged by significant stochastic environmental disturbances.Blimp is a special type of airship without grid structure on the body. Most existing airships are manually operated by a pilot directly or through radio control. One of the most famous examples is the Goodyear Blimp used for commercial advertising. With the fast development of microcontroller and electronic technologies, autonomous airships have recently attracted great research interest as a platform to reach dangerous or difficulty-to-access environment in applications such as disaster exploration and rescue, security surveillance in public events and climate monitoring, etc.

The purpose of this review paper is to show a compendium of recent approach to airship autonomous control in the context of the aerial robotic research in order to highlight the potential advantages of intelligent control methods. It is an efficient way to analyze and improve the autonomous control in the aerial robots research.

The paper is organized as follows. Firstly, a description of potential applications and needs of autonomous airship are presented. Section II outlines the basic configuration for control tasks in autonomous airship application. Section III describes in the control methods used for autonomous airship. Section IV provides the more detail on intelligent control of blimp navigation, and section V concludes this paper and points out the future work.

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A. Potential applications of autonomous airship

The autonomously control of the airship is a challenging job, especially in the outdoor environment under the various disturbance and uncertainties. Autonomous airship was developed with different control methods in various environments. The potential applications of autonomous airship are categorized in Table I.

TABLE I
POTENTIAL APPLICATION OF AUTONOMOUS AIRSHIP

Industrial Areas	Application Example
Environment	. Greenhouse gas emission detecting and climate change monitoring.
Disaster Rescue	. Monitoring and rescue services in inaccessible environment.
Infrastructure	. Working platform for spiderman.
Astro Exploration	. Monitoring and service for planet exploration.
Transportation	. Big carriages and low costs for the long distance transports.
Telecommunication	. Relaying the communication signals in remote areas.
Military Operation	. Monitoring and weapon platform in tactics tasks.
Security	. Mobile monitoring guard and anti-terror attack.
Science and Research	. Astro and environmental research.

B. Needs for autonomous airship

The history of airship starts in 1852 when Henri Giffard built the first powered airship. A non-rigid airship, or blimp, differs from a rigid airship(Zeppelin airship) in that it does not have a rigid structure that holds the airbag in shape.Autonomous airship has many benefits compared to other Unmanned Aerial Vehicles(UAVs), such as winged planes and helicopters. It does not require any motor action to maintain a certain altitude and position in the space as it relies on low density gas inside the envelope to balance its own weight. With this feature, airship could conduct a continuous aerial operation with very low energy consumption. Advantages of airship made over the last two decades in upgrading the first human practical air vehicle, have been rather overshadowed by space programs, satellites orbiting the earth, jet mass transport, and supersonic aircrafts. More recently they have received special attention for environmental applications such as research in bio-diversity, ecology, climatology, and agriculture

From the beginning of this century, researchers at university and corporations have been working on principles and designs of autonomous airships. The research and development is mainly done in U.S., Japan, and European countries. The Jet Propulsion Laboratory of NASA is the main contributor for this research in America. Their research destination is to develop the blimp planet rover to account for astro-exploration. Japanese researchers focus on the development of new advanced control technology and new electronic devices of airships. European countries mainly research the stability and reliability of autonomous airship control. The existing researches of autonomous airships are summarized in Table II.

II. Basic configuration of control tasks for autonomous airship

Many different control tasks could be considered for an autonomous airship to achieve a successful flight test. Motion control, obstacle avoidance control, navigation control, and anti-disturbance control are the most commonly available choices. Due to the special requirement of automatic flight in complex outdoor environment, motion control and navigation control are of most practical consideration.

A. Motion control

Motion control task is the most developed and discussed issue in practical applications. It is used to autonomously and efficiently control certain flight motions, such as hovering motions, taking off motions, landing motions, and so on. To consider the motion control tasks, acquiring and analysis of blimp dynamic models are usually the key research problem, which is involved in analyzing dynamic models of the airship.

Sergio B.[1] fully discussed the problem of building up the general dynamic model of airship. In this research, they presented a comprehensive description of the physical principles of airship operation, along with their dynamic model in a form suitable for controller design and computer simulation. Airship response modes are discussed according to their airship dynamic model, and the challenges during motion control challenges are pointed out at the same time.

From this paper, the general dynamic model equation can be stated as in equation:

$$M\dot{x} = F_d(x) + A(x) + G(\lambda_{13}, \lambda_{23}, \lambda_{33}) + P \qquad (1)$$

where each of the components is described in the below.

- Velocity vector $\dot{x}$ is the 6×1 velocity vector contains the three linear velocities and three rotational velocities.
- The 6×6 matrix M incorporates the masses and inertial of the airship.
- F_d is the dynamic force vector which contains the Coriolis and centrifugal terms of the dynamic model.
- A is the aerodynamic forces vector which contains the aerodynamic terms of the model.
- G is the gravity and buoyancy vector.
- P is the propulsion vector which contains the terms associated with the propulsive forces and moments.

Equation(1) is analyzed via the airship body axes coordinate system which is shown in Fig.1 as follow.

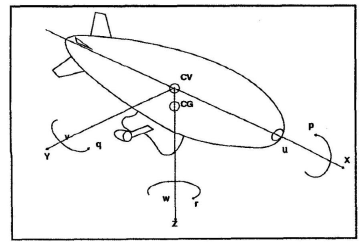

Fig. 1. Airship body axes coordinate system showing the Center of Volume, Center of Gravity and linear (u, v, w) as well as angular (p, q, r) velocities around the X, Y, and Z axes respectively [1].

Based on this airship dynamic model research, Jose R. Azinheira has done a specific research on hovering control of the airship. He used the visual servo control[2] and backstepping control technology[9] to realize the hovering tasks in the outdoor environment.

Jongwoo Kim[3] presented the randomized motion planning algorithms on the blimp control and considered the problem of motion planning for systems with both kinematic and dynamic constraints. Toshihiko Takaya[7] developed a PID controller to control the landing orbit motion for an indoor blimp robot. Fig.2 shows the physical structure of this indoor blimp robot and the control procedure of the landing orbit motion. In their research, the dynamic model of the blimp for the landing motion was discussed and modified.

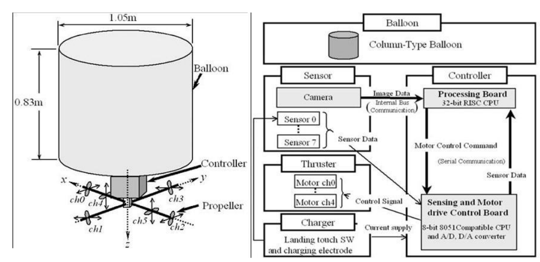

Fig. 2. Physical structure of this indoor blimp robot and the control procedure of the landing orbit motion [7].

B. Navigation control

Navigation is the crucial control task for an autonomous airship. To realize the autonomous control, acquiring the position information of the destinations and tracking the airship flights are the heart of this task. Plenty of researches were found on these two crucial points.

De Coelho[10] developed a computer vision-based navigation system for autonomous blimps in 1998. The blimp developed in his research is capable of autonomously following a trajectory based on the visual information imaged by on-board cameras. The computer vision system used in this project helps the blimp to estimate the position and orientation information from images of visual beacons - objects with known geometrical properties are recognizable by the system.

Hongzhang[11] described an indoor vision-guided blimp control system. In this research, a methodology is developed

TABLE II
SUMMARY OF EXISTING RESEARCH OF AUTONOMOUS AIRSHIP

Name/Maker	Time	Experimental Airship	Main Research Achievements	Reference
Autonomous Institute of CTI Campinas, Brazil	1998-2003	AURORA Airship	. Environmental monitoring missions. . Airship dynamic model. . Optimal visual servoed guidance. . Internet-based solution in airship control.	[23],[1],[12],[24]
University of Pennsylvania USA	1998-2003	GRASP Blimp	. Computer vision-based navigation. . Motion Planning.	[10],[11],[25],[3]
LAAS/CNRS France	2002-2003	Robot Karma	. Backstepping control methods. . Terrain mapping.	[17],[26],[27],[28]
Kyoto University Japan	2003-2005	Indoor Blimp	. Image-based tracking control. . Inverse optimal tracking control.	[14], [29],[19]
Technical University of Lisbon,Portugal	2005-2008	AURORA Airship	. Robust control. . Hovering motion control.	[20], [9]
Evry Val d'Essonne University, France	2005-2006	LSC Airship	. Characterization of non trim trajectories. . Calculation of the trim trajectories.	[30], [8]
Hokkaido University Japan	2006	Balloon Robot	. Motion control.	[7], [31]
University of Tokyo	2006-2007	Indoor Blimp	. Model predictive control.	[21],[32], [33]
NASA JPL USA	2003-2008	Planet Blimp	. Optimal aerobot trajectory planning. . Human robot Lunar exploration.	[4], [34]

for incorporating the physical parameters of a mechanical system into the image plane for performing visual servoing. It is noted that under suitable conditions, namely the existence of a diffeomorphism between image features and robot pose, many tools from mechanical system control theory can be used directly when applied in the image plane.This image navigating idea was improved by Jonathan Ko[15]. He predicted the next possible movement positions for the autonomous airship based on the image monitoring system.

In 2002 and 2003, Silveira, G. F.[12] and Yasunori Kawai[13] adopted vision analysis in their airship research to acquire the position information and provide flying motion instructions from the image processing.

Fig.3 shows the main structure of this blimp control system.

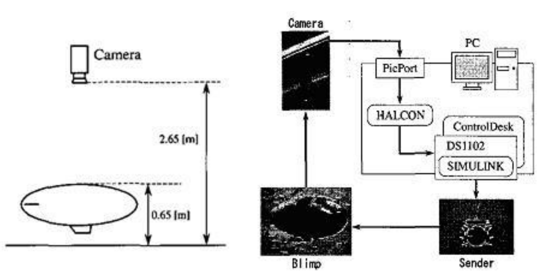

Fig. 3. Unmanned blimp control system built by Yasunori Kawai [13].

With a similar idea, Takanori Fukao[14] implemented the image-based tracking control algorithm to account for the navigation task in his research.

In 2007, Niko Suinderhauf[16] and his research group used the Simultaneous Localization And Mapping (SLAM) technology to deal with the navigation tasks for the autonomous airship. In this research, the simultaneous location information was collected by the visual system on board and then was transferred to the airship control system. Fig.4 shows their airship control system.

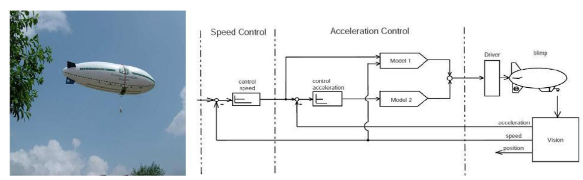

Fig. 4. Airship navigation system used the SLAM [16].

III. CONTROL METHODS IMPLEMENTED ON AUTONOMOUS AIRSHIP

Compared to the manned or semi-manned airship, autonomous airship control involves providing independent and accurate flight operations with little human intervention. The control methods implemented on autonomous airship lie in two categories, traditional control methods and advanced control methods. The traditional control methods achieve autonomous control goals via classical control algorithms, such as the PID control theorem. These control methods have the advantages of being easily implemented and providing reliable control performance, while the weaknesses include the costs of computation to model the system and tuning the control parameters. Advanced control methods are becoming more popular for blimp autonomous control, as these control methods are mainly developed to improve the control performance of autonomous airship in a complex and unstable flight environment.

A. *Traditional control methods*

Main challenges of traditional control methods are to acquire the dynamic model of the airship precisely in a changing environment and to responsibly modify the PID parameters under this condition. For a specific control application, PID control can combine with other advanced technology to realize airship autonomous control. Jose R. Azinheira[2] presented a PD control problems of automatic hovering of an outdoor autonomous airship using image-based visual servoing. The hovering controller was designed using a full dynamic model of the airship, in a PD error feedback scheme, taking the visual signals extracted from an on-board camera as output. This PD control approach was validated in simulation by using an accurate airship model.

In [7], Toshihiko Takaya and his group implemented a PID control on blimp landing control. They developed a method of landing with orbital control of the charge point that gives autonomy to a blimp robot. This landing motion is used to provide an autonomous battery charge that allows blimp autonomous operation for a long time. The performance of PID control in this application is good enough for the blimp to achieve certain space orbit points. From this application, it is easy to see that PID control can be efficiently used in an indoor environment.

B. Advanced control methods

Most of these applications are faced with highly nonlinear and time-varying control systems, in which it is difficulty to obtain an accurate dynamic model of the blimp and environment. Several advanced control methods have been developed, such as back stepping control, robust control, model-prediction control, and other intelligent control methods.

Alexandra Moutinho[20](2005) used the dynamic inversion to realize robust control method in their autonomous airship of the AURORA project. A Dynamic Inversion controller was implemented with desired dynamics given by a linear optimal compensator. The stability analysis of the nonlinear system is done applying Lyapunov's stability theory. Robustness tests were performed in this research in order to verify the nonlinear controller performance in the face of disturbances and model parameters errors. The results obtained illustrate the overall system robustness, and point at the most sensitive model parameters of the AURORA airship, for which a more careful identification and determination should be carried. Fig.5 shows the AURORA airship and its robust control system structure.

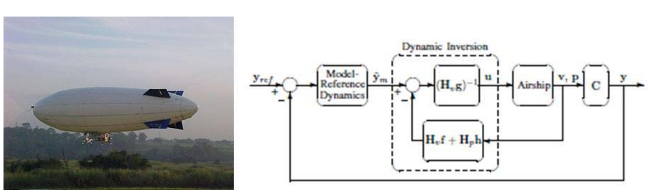

Fig. 5. AURORA airship and its robust control system structure [19].

Takanori Fukao[19] implemented inverse optimal tracking control to improve the robustness of an autonomous airship control system. These robust control methods provided the higher flight stability to the airship.In all of these advanced control methods, the backstepping control and model-prediction control are two efficient and well discussed control algorithms.

1) Backstepping control: Lotfi Beji[18] (2002) and his group research the control strategy combined averaging and backstepping approach to design a time-varying stabilization of the position and orientation of an under-actuated autonomous airship. In their research, the stabilization problem was addressed through a detailed analysis of the blimp dynamic model. The stabilizing feedback law was proved and the averaging and backstepping approach were implemented. At the same time, Emannuel Hygounenc[17] ran the LAAS-CNRS project of autonomous blimp robot development. In this research, they deal with autonomous airship control in the case of very low perturbations. For each phase a reduced model is determined and a controller is designed on the basis of backtepping techniques. This approach allowed one to consider the kinematic and dynamic requirements separately. Fig.6 shows their autonomous airship (Robot Karma) which had been developed in LAAS-CNRS project 2002-2003.

Fig. 6. Robot Karma in LAAS-CNRS project 2002-2003 [18].

In 2008, Jos Raul Azinheira[9] used backstepping control methods to control the hovering motion in his autonomous blimp research, which showed good performance in motion control tasks.

2) Model-predictive control: Model-predictive control has been combined with dynamic model analysis for airship control problems. Hiroaki Fukushimal[21] and his group developed an autonomous blimp control system via model-predictive control in 2006. They investigated the applicability of model predictive control to mechanical systems based on experimental examples of multi-vehicle formation and autonomous blimp control.

In 2007, Jonathan Ko [15] presented a new type of model-predictive control which was related to the Gaussian Processing and Reinforcement learning technology. In his autonomous blimp application, whole movements of the autonomous blimp were monitored by a visual measurement system in the laboratory. Based on this movement information, the research was able to identify the airship dynamic model in the flight and then predict the next the most probable position to guide airship to the goal position. His research obtained better performance for an autonomous airship control system. fig.7 shows the experimental environment and the actuators of this airship control system.

IV. Reinforcement learning control of autonomous blimp navigation

Intelligent control, as a certain new trail, is also transferred to the autonomous airship control applications from the

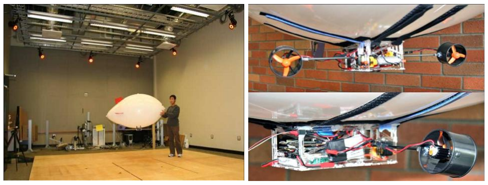

Fig. 7. The left image shows the blimp used in test environment equipped with a motion capture system. It has a customized gondola (right images) that includes an X Scale based computer with sensors, two ducted fans that can be rotated by 360 degrees, and a webcam [15].

modern robotics researches[22]. Reinforcement learning is one certain intelligent learning technology, which can help facilitate an easier design process for autonomous control system, and reduces human intervention as much as possible in airship flights. The blimp controlled by a reinforcement learning algorithm is used as the testing platform for "2007 UAV Outback Challenge" organized by Australian Research Center for Aerospace Automation (ARCAA).The destination of this blimp control system is to achieve autonomous navigation without a blimp model.

The autonomous control system for the blimp navigation contains two major parts. The first part is the on-board controller attached on the gondola of the blimp. An AVR microcontroller is used as the main control unit (MCU). Other peripheral equipment includes a wireless sensor connection, a servo to control the pitch and thrust of the blimp, three DC motors, and several sensors. All of these devices are working for collecting and sending data to the MCU, and executing the commands from the microcontroller. Fig.8 shows the whole structure of the blimp control system. From this figure, it is easy to see that main design of this control system is the machine learning parts which can help blimp have the learning ability like the human being.

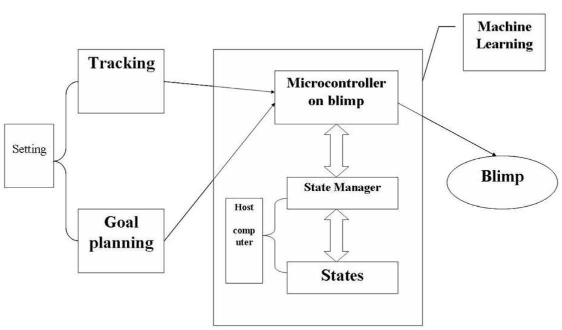

Fig. 8. Learning control system of the autonomous blimp.

Hardware structure of this control system in practical has been developed according to above control structure block diagram. The components of each part were chosen according to the consideration of capability, reliability, and economy. Fig.9 provides detail of the hardware design on this autonomous blimp control system. It can be obviously found that whole system is divided by two main executive parts, which are both ground station and onboard unit. On the onboard unit, one effective microcontroller is designed to manage the communication with the ground station via Zigbee devices, and control over all actuators on the blimp, such as GPS, measurement sensors, DC motor for propellers and power for this onboard system.The small size electrical circuit board is developed, and tests all onboard components separately.

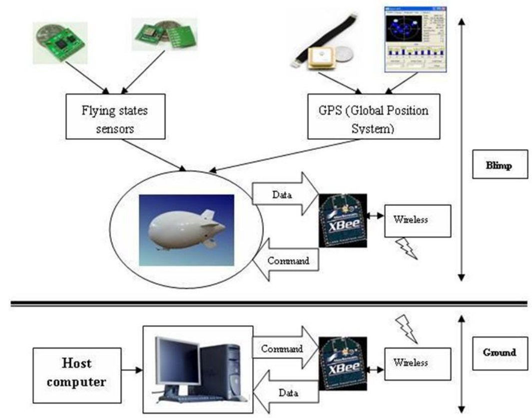

Fig. 9. Hardware for autonomous control system.

V. CONCLUSION AND FUTURE WORK

After more than one decade of research efforts by many researchers from different countries, autonomous airships are increasingly treated as a high level automation platform for various applications. Newer technologies, such as new materials, high speed computation, more accurate sensing technology, and more advanced control methods, drive the autonomous airship to be as independent and reliable as possible. Currently the development of intelligent control for autonomous airship is still at laboratory stage. Several technical requirements, such as a more precise dynamic model, microcontroller with higher performance computation, and accurate sensing, still not satisfied. With the technological progress in these areas, commercial smart control airship will appear in the near future.

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