Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 57 (2016) 1901–1913

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Modeling and path-following control of a vector-driven stratospheric satellite

Zewei Zheng [a,c], Tian Chen [b,*], Ming Xu [a,c], Ming Zhu [b]

[a] The Seventh Research Division, Beihang University, Beijing 100191, PR China
[b] School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, PR China
[c] Science and Technology on Aircraft Control Laboratory, Beihang University, Beijing 100191, PR China

Received 24 April 2015; received in revised form 1 December 2015; accepted 3 February 2016
Available online 10 February 2016

Abstract

The stratospheric satellite driven by steady prevailing winds in the stratosphere must be controlled in its longitudinal excursion to keep a latitudinal orbital flight. In a reliable and high-precision control system, an available system model must come first. In this paper, we study the 6 degree-of-freedom (DOF) modeling and path-following problem of a novel stratospheric satellite which consists of a high-altitude helium balloon, a truss and two vector-motor-driven propellers. To keep a latitudinal flight orbit, an algorithm for accurate latitudinal path following is proposed based on the theories of vector field and sliding mode control. Moreover, a forward velocity controller is added to the control algorithm to maintain a constant velocity. Finally, a series of open-loop control simulations are completed to verify the effectiveness of the model in the performance of the stratospheric satellite dynamics, and path-following control simulation results demonstrate the effectiveness of the proposed control algorithm.

Keywords: Stratospheric satellite; Modeling; Path-following control; Vector field

1. Introduction

Near space is quantitatively defined as the range of earth altitudes from 20 km to 100 km, below which aerial aircraft is able to produce sufficient lift for steady flight, above which the atmosphere is rarefied enough for satellites to orbit with meaningful lifetimes (Young, 2009), and in which the space from 20 km to 50 km belongs to the stratospheric space. In the development of technologies in energy and material, the research of near space platforms comes to the front in recent years, which involves the hypersonic flight vehicle, the solar powered aircraft, the stratospheric airship and the stratospheric balloon. Compared to its counterparts, the stratospheric balloon has remarkable advantages in cost-efficiency, deployment and retrievement (Henry, 2001). Stratospheric balloon systems being developed include stratospheric satellites and free-floating balloons, which are classified by controllability. Project Loon launched by Google last year, which is aimed to provide WiFi service in remote areas of the world, is developing a kind of free-floating balloons in the stratosphere. The balloons are driven by the steady prevailing winds without control.

The stratospheric satellite (Supeng et al., 2011) is proposed on the basis of the stratospheric balloon, whose longitudinal excursion can be adjusted by the additional driver to keep a latitudinal orbital flight as a satellite. NASA has been developing super-pressure, very long-life balloon technology in their Ultra-Long Duration Balloon Project for

---

* Corresponding author. Tel./fax: +86 010 82319852.
E-mail addresses: zeweizheng@buaa.edu.cn (Z. Zheng), chentianbuaa@gmail.com (T. Chen), mingxu_xjl@163.com (M. Xu), zhuming@buaa.edu.cn (M. Zhu).

http://dx.doi.org/10.1016/j.asr.2016.02.004
0273-1177/

years to fly multi-ton sensors and telescopes into the stratospheric space for studying space science phenomena that cannot be studied well, if at all, from the surface (Stuchlik and Tillery, 1991). It is not until a stratospheric satellite was developed by the Global Aerospace Corporation of NASA, successive experiments were carried out at Antarctica (Cathey, 2013; Smith and Cathey, 2005). The satellite consists of a super-pressure helium balloon, a load cabin, a tether and a stratosail, where the balloon works in latitudinal orbits by prevailing winds in the altitude of 35 km and the stratosail suspended by a 15-km-long tether in the altitude of 20 km. Utilizing the relative wind speed, the stratosail is manipulated by the rudder to generate aerodynamic forces which can be translated by the tether to control the longitudinal excursion.

Relied on the relative winds, it is clear that low efficiency of the stratosail can reduce the time–cost in the excursion adjusting, especially the adjusting will be unavailable as the relative low wind speed (Nock et al., 2007). However, the business level application of stratospheric balloon systems requires cooperation of several balloons or satellites, which requires more rapidly dynamic response. With the development of the high-altitude propeller and the utilization of the solar energy, the propeller-driven control technology comes true (Han et al., 2015). To enhance the maneuverability during the latitudinal-orbit flight in the prevailing winds, we propose a novel stratospheric satellite to adjust the excursion by two propellers driven by vector motors, which are fixed on a framework fastened on a helium balloon. The propeller-driven stratospheric satellite travels by the prevailing winds, while the longitudinal excursion can be controlled by the propellers timely and effectively.

To control the novel stratospheric satellite effectively, a reliable mathematical model should be presented first. Different with the general vehicles such as aircraft and robot, the additional fluid inertia force and the elastic deformation of balloon should be taken consideration due to the huge flexible structure during modeling (Mueller and Paluzaek, 2004). Apart from the traditional modeling methods based on the Newton–Euler equations (Schmidt, 2007), some new methods based on semidirect product reduction theory (Azouz et al., 2002) and Updated Lagrangian model (Azinheira et al., 2002) are presented. Bijker and Steyn (2008) model the airship through traditional methods, and estimate the model parameters with a Kalman filter. Li et al. (2008) integrated the flight dynamics, structural dynamics, aerostatics, aerodynamics of flexible airships, and proposed a dynamics modeling approach.

After modelling the stratospheric satellite by Newton–Euler equations, controller design comes next. One of the major control technologies playing key roles in developing stratospheric satellite is a latitudinal orbit keeping, which could be realized by trajectory tracking and path following algorithm. For trajectory tracking control, the backstepping technique has been applied to control an unmanned airship (Lee et al., 2007), which drives the position of the airship to approach a desired time-varying trajectory (Zhu et al., 2014). Unlike the trajectory tracking control, the vehicle is required to reach and follow a path that is specified without temporal constraint in path following control research. Considering their low-manoeuvrability character, it is more suitable to study the path following control problem for stratospheric satellites (Zheng et al., 2013; Azinheira et al., 2000). The objective of path following control is chiefly concerned with providing a stable motion along a given path without strict temporal specifications (Xiang et al., 2009). Given a path, the initial location of the aerial vehicle, and its heading angle, the path-following problem is to determine the commanded heading angle that accurately tracks the path (Sujit et al., 2014). Typically, most missions are either straight-line paths or circular-arc paths (Zheng and Huo, 2013). Some strategies for the path-following problem have been proposed in the literatures of path-following, such as pure pursuit (Conte et al., 2004), line-of-sight (LOS) (Rysdyk, 2006), variants of pursuit and LOS guidance laws (Park et al., 2007) and vector field guidance laws (Nock et al., 2007). The vector field approach is a well-known method for guidance problems. It has been applied to different types of vehicles, such as wheeled, underwater, and aerial vehicles (Lim et al., 2014). This method is popular due to its simplicity and robustness to actuator errors and external disturbances like wind.

Not only the geometric but also the control theoretic solution strategies have been presented in recent years, such as linear quadratic regulator, sliding mode control, model predictive control, back-stepping control, gain scheduling theory, adaptive control, dynamic programming and trajectory linearisation control theory (Sujit et al., 2014). For the complicated atmospheric environment in the stratosphere and the complexity of the stratosphere satellite dynamic model, external disturbances and model uncertainties should be taken into consideration when we design path-following controller. Sliding mode control is one of the most important approaches to handling systems with large uncertainties, nonlinearities, and bounded external disturbances (Zhihong et al., 1994). It has been used in the development of stratospheric aircraft control system in recent years (Yang et al., 2014; Yang and Yan, 2015; Yang et al., 2013, 2012). Chen et al. (2013) presented a composite control structure for the stratospheric airship to realize accurate position control and to decrease energy consumption, which took the control allocation problem into consideration.

In this paper, we study a 6-DOF model for the control system of the novel stratospheric satellite, which is built on the Newton–Euler formulation. The same as stratospheric airship, the stratospheric satellite is effected by the additional initial force and the additional initial moment due to its huge volume. Open-loop control simulations testify the correctness of the model, which is applied in the design of path-following controllers for the stratospheric satellite. To realize latitudinal orbit keeping, the