Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 55 (2015) 343–353

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Optimal reorientation of asymmetric underactuated spacecraft using differential flatness and receding horizon control

Wei-wei Cai *, Le-ping Yang, Yan-wei Zhu

College of Aerospace Science and Engineering, National University of Defense Technology, PR China

Received 24 June 2014; received in revised form 12 October 2014; accepted 14 October 2014
Available online 22 October 2014

Abstract

This paper presents a novel method integrating nominal trajectory optimization and tracking for the reorientation control of an underactuated spacecraft with only two available control torque inputs. By employing a pseudo input along the uncontrolled axis, the flatness property of a general underactuated spacecraft is extended explicitly, by which the reorientation trajectory optimization problem is formulated into the flat output space with all the differential constraints eliminated. Ultimately, the flat output optimization problem is transformed into a nonlinear programming problem via the Chebyshev pseudospectral method, which is improved by the conformal map and barycentric rational interpolation techniques to overcome the side effects of the differential matrix's ill-conditions on numerical accuracy. Treating the trajectory tracking control as a state regulation problem, we develop a robust closed-loop tracking control law using the receding-horizon control method, and compute the feedback control at each control cycle rapidly via the differential transformation method. Numerical simulation results show that the proposed control scheme is feasible and effective for the reorientation maneuver.

Keywords: Differential flatness; Mapped Chebyshev pseudospectral method; Differential transformation; Receding-horizon control; Underactuated spacecraft

1. Introduction

Recent advantages in satellite technology have greatly promoted the attitude-control capabilities for small spacecraft, including higher agility, higher-precision pointing and/or slewing. Most of the existing attitude control schemes are developed for the actively controlled spacecraft that is equipped with sufficient actuators equal to, or more than, the number of degrees of freedom to be controlled (Alkhodari and Varatharajoo, 2009; Weiss et al., 2013; Wu et al., 2011). However, if actuators in one or two dimensions fail, the spacecraft, which is called underactuated, will be prevented from performing arbitrary maneuvers. In this case, developing suitable control strategies for the underactuated spacecraft is a cost-reducing alternative, compared with equipping the spacecraft with some redundant actuators, to improve the system's reliability.

In the field of underactuated spacecraft control, many researches focusing on the controllability and stabilization problem have been carried out. Godard and Kumar (2011) investigated a robust sliding mode control scheme to stabilize the attitude of the spacecraft subject to actuator failures, external disturbances and physical parameter uncertainties. Based on the sequential Euler angle rotation strategy, Kim and Turner (2014) developed the necessary

* Corresponding author at: College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, PR China.

E-mail addresses: tsaiweiwei@hotmail.com (W.-w. Cai), ylp_1964@163.com (L.-p. Yang), zywnudt@163.com (Y.-w. Zhu).

http://dx.doi.org/10.1016/j.asr.2014.10.014

conditions for coupling sub-maneuvers and addressed the near-minimum-time control problem of asymmetric underactuated spacecraft with bounded input magnitudes. For an axisymmetric spacecraft with only two control torques, the attitude stabilization and command tracking problems are addressed using a computationally efficient $\mathcal{H}\infty$ control design procedure (Zheng and Wu, 2009). Making use of the generalized dynamic inverse method and a novel saturated function, a full-stated feedback control law is proposed for an underactuated spacecraft with bounded wheel speeds (Gui et al., 2013). Note that due to the inherent nonholonomic constraints, some trajectories in the configuration space are just infeasible, or cannot be steered, for an underactuated spacecraft, leaving it a challenge to reorientation controller design. It has been demonstrated that it is efficient to address the reorientation control problem for an underactuated spacecraft in two steps: nominal reorientation generation and trajectory tracking. Considering the obstacles along the angular path and constraints on admissible rotation axes, an attitude path planning strategy for the single-axis pointing of an underactuated spacecraft is studied (Angelis et al., in press). Taking the underactuated spacecraft and flywheels as a whole system, Zhang et al. (2014) planned the attitude trajectory which minimizes the angular velocity change of flywheels by Gauss pseudospectral method. Given a rigid spacecraft with only two control torques due to actuator failures, the reorientation trajectory with minimum control efforts are generated by using the sequential control concept, which aims to avoid the axis where the actuator failure has occurred (Kim et al., 2013a,b). Recently, Kim et al. (in press) has suggested a novel Davidenko-like homotopy algorithm to achieve the optimal reorientation trajectory of an underactuated spacecraft by starting from the associated trajectory where all three actuators are available. Aguilar (2005) investigated an asymptotic trajectory tracking control law to steer the spacecraft maneuver along a given attitude trajectory. Based on the latest development in nonlinear system and optimal control theories, this paper aims to develop a novel optimal attitude maneuver controller for an asymmetric spacecraft with only two control torque inputs available.

The nominal maneuver trajectory for an underactuated spacecraft is often designed by formulating a constrained nonlinear optimal control problem. Since the system is strongly coupled and highly nonlinear, the analytical solutions are seldom available or even possible, hence the superiority of numerical methods. However, the solution efficiency of numerical methods is often compromised by computational efficiency, which is mainly induced by the treatment of differential constraints. In recent years, the differential flatness based method has emerged as one of the promising numerical techniques for aerospace applications (Chamseddine et al., 2012; Morio et al., 2009). Based on the system's flatness property, the states and inputs are formulated as functions of the flat output and its derivatives, thus transforming the original trajectory optimization problem into the flat output space, which means that all the differential constraints are eliminated. Tsiotras (2000) applied the differential flat theory to the problem of feasible trajectory generation for a spacecraft with two control torques, and the resulted trajectories could be used for closed-loop tracking controller design. In addition, the flatness of a general underactuated spacecraft was discussed in (Zhuang et al., 2012), and then the continuous flat system was discretized by a fixed count of control steps with the sampling periods as decision variables. Though the design procedure has been greatly simplified by using the differential flat theory, the resulted trajectory may only be feasible, not optimal. In this paper, we mainly focus on the reorientation trajectory optimization and tracking problem using differential flatness and receding horizon control techniques.

The computational framework facilitated by the pseudospectral (PS) methods applies quite naturally and easily to the flat output optimization problem. Note that the approximation accuracy of the high order derivatives should be considered since they are required in the framework of flatness based trajectory optimization. The PS method employs globally orthogonal polynomial approximations for the flat output with its values at suitably chosen discretization points as the expansion coefficients. Compared with other discretizing schemes, the PS approximations offer a higher degree of accuracy with much fewer nodes. And the differentiation matrix based computation approach for the high order derivatives of flat output at the selected nodes is more accurate and effective. Among various PS methods, the Chebyshev PS method (CPM) is somewhat more attractive since the Chebyshev expansion is very close to the best polynomial approximation of a given function in the infinity norm (Trefethen, 2000). Moreover, the Chebyshev–Gauss–Lobatto (CGL) nodes and Chebyshev differentiation matrix can be evaluated in closed form, providing prominent computational advantages. Thus the CPM is selected to transform the flat outputs optimization problem here. However, a direct application of the CPM may result in great degradation of the accuracy for high order derivatives of flat output due to the ill-condition of the Chebyshev differentiation matrix (Mead and Renaut, 2002). A mapped Chebyshev pseudospectral method (MCPM) based on the conformal map and barycentric rational interpolation techniques is proposed in this paper to improve the ill condition so as to enhance the numerical computational performance.

In practice, an underactuated spacecraft would deviate from the nominal trajectory due to inevitable external disturbances and/or model uncertainties, calling for the closed-loop trajectory tracking control. The receding horizon control, with which closed-loop stability can always be achieved, has been used as an efficient tracking method for various systems (Lu, 1999; Peng et al., 2013). The implementation of this tracking control law requires on-line solution to the resulted two-point boundary value problem (TPBVP) over a shorter moving horizon. However, the