Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 61 (2018) 2328–2343

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

# Thrusting maneuver control of a small spacecraft via only gimbaled-thruster scheme

Mansour Kabganian [a], Hamed Kouhi [a], Morteza Shahravi [b], Farhad Fani Saberi [c,*]

[a] Department of Mechanical Engineering, Amirkabir University of Technology, 424 Hafez Ave, Tehran 15875-4413, Iran
[b] Space Research Institute, Tehran 15875-1774, Iran
[c] Space Science and Technology Institute, Amirkabir University of Technology, 424 Hafez Ave, Tehran 15875-4413, Iran

Received 22 April 2017; received in revised form 8 February 2018; accepted 13 February 2018
Available online 21 February 2018

---

## Abstract

The thrust vector control (TVC) scheme is a powerful method in spacecraft attitude control. Since the control of a small spacecraft is being studied here, a solid rocket motor (SRM) should be used instead of a liquid propellant motor. Among the TVC methods, gimbaled-TVC as an efficient method is employed in this paper. The spacecraft structure is composed of a body and a gimbaled-SRM where common attitude control systems such as reaction control system (RCS) and spin-stabilization are not presented. A nonlinear two-body model is considered for the characterization of the gimbaled-thruster spacecraft where, the only control input is provided by a gimbal actuator. The attitude of the spacecraft is affected by a large exogenous disturbance torque which is generated by a thrust vector misalignment from the center of mass (C.M). A linear control law is designed to stabilize the spacecraft attitude while rejecting the mentioned disturbance torque. A semi-analytical formulation of the region of attraction (RoA) is developed to ensure the local stability and fast convergence of the nonlinear closed-loop system. Simulation results of the 3D maneuvers are included to show the applicability of this method for use in a small spacecraft.

*Keywords:* Orbital maneuver; Small spacecraft; Gimbaled-SRM; Two-body dynamics; Thrust vector misalignment; Region of attraction

---

## 1. Introduction

Attitude control of a spacecraft during an impulsive thrusting maneuver is a difficult control problem. An impulsive orbital maneuver (e.g., retrofiring before an atmospheric re-entry) is used to create a velocity increment $\Delta \boldsymbol{v}$ by using a large thrust force in a short time. During the burning of a spacecraft (launch vehicle) rocket, thrust vector misalignment from the C.M, always exists and is inevitable (Orr and Shtessel, 2012). This misalignment produces a large disturbance torque that results in attitude instability and also thrust vector deviation from the desired inertial direction. It is obvious that a powerful attitude control system is needed to compensate the large exogenous disturbance torques. Since the spacecraft attitude during the motor burning is naturally unstable, the generated $\Delta \boldsymbol{v}$ does not meet the desired value. The destructive effects of thrust vector offset on orbit transfers, has been addressed in review study (Souza et al., 1998).

The conventional control methods are explained in the NASA report (Noll, 1971); (1) spin-stabilization for a small spacecraft, (2) RCSs, and (3) combination of the RCS and TVC (for large spacecraft such as Apollo and Viking). In addition to the methods presented in Noll (1971), the idea of the combination of the 1 degree of freedom (DoF)

---

* Corresponding author.
*E-mail addresses:* kabgan@aut.ac.ir (M. Kabganian), h_kouhi@aut.ac.ir (H. Kouhi), shahravim@yahoo.com (M. Shahravi), f.sabery@aut.ac.ir (F. Fani Saberi).

https://doi.org/10.1016/j.asr.2018.02.011

gimbaled-TVC and spin-stabilization can be found in (Kouhi et al., 2017c). Furthermore, a new control system with many advantages are introduced and studied in (Kouhi et al., 2017b) where, the combination of the spin-stabilization, 1DoF gimbaled-thruster and two reaction wheels are employed.

Spin-stabilization is a simple structural method for use in orbital maneuvers of small spacecraft (Oldenburg and Tragesser, 2002; Thienel and Markley, 2011; Hu and Gong, 2016). But it has some deficiencies and requirements such as: (1) for an only spin-stabilized spacecraft, only the spin about the axis of maximum moment of inertia remains stable. (2) For many spin-stabilized spacecraft, nutational or coning instability has been observed (see Meyer, 1996; Janssens and Van Der Ha, 2014; Martin and Longuski, 2015) thus, an active nutation controller is also needed. (3) Some thrusters (usually solid propellant (Schonenborg, 2004)) are needed for spin-up and spin-down, it is clear that the more the rotational kinetic energy (due to spin) the larger and heavier the thrust system. (4) In some works such as (Cloutier, 1969, 1976; Meehan and Asokanthan, 1998) the resonance in spin-stabilized spacecraft with flexible (movable) devices is addressed. (5) For an only spin-stabilized spacecraft, spin-axis stabilization (thrust vector stabilization) with respect to the desired inertial direction is not possible. In Tsiotras and Longuski (1994), Childs (1970), Childs et al. (1969), Gui and Vukovich (2015) it is shown for the spin-axis stabilization, an active control system with extra actuators (such as RCSs) is needed. Moreover, in Kouhi et al. (2017b) the spin-stabilized spacecraft is equipped with the gimbaled–thruster and two reaction wheels for doing the aforementioned task. (6) Spin-stabilization may not be a good choice for spacecraft with solar panel, directional antenna and optical sensors (which are sensitive to angular motion), especially for a long time mission.

RCSs as powerful control systems can provide a high level active control torque in order to reject exogenous disturbances and perform fast attitude maneuvers. Although they have many advantages, their deficiencies especially for use in small spacecraft are not negligible, which are: (1) they include several equipment that leads to a complex and high cost spacecraft. (2) Because use of liquid propellants, fuel sloshing happens by rotational and lateral motions of propellant tanks; attitude control of spacecraft is very difficult in presence of fuel sloshing. There are several works such as (Reyhanoglu and Hervas, 2012; Bandyopadhyay et al., 2009; Peterson et al., 1989; Shekhawat et al., 2006) about the interaction of spacecraft dynamics and slosh dynamics and their control. In Hervas and Reyhanoglu (2014), Kishore et al. (2013) and Reyhanoglu and Hervas (2012) the TVC for the rocket engine is addressed considering the fuel slosh dynamics where many external torques have been used in the control system. (3) For using RCSs, nonlinear complex control logic are needed (Hall et al., 2016). Although for upper stage vehicles and large spacecraft RCSs can be combined with TVC (see Yeh, 2013; Widnall, 1970; Wang et al., 2016; Orr and Shtessel, 2012; Reyhanoglu and Hervas, 2012), RCSs are not suitable for small spacecraft mission.

TVC method is a powerful and efficient technique in control of spacecraft and launchers which is actuated by a servo (hydraulic) actuator without fuel consumption. Although during an impulsive maneuver a high level disturbance torque is created, TVC can generate an active control torque larger than the disturbance level. When the exogenous disturbance level is so larger than the attitude control capacity, a fixed thrust system is not efficient (Apollo, Cassini (Rizvi and Weitl, 2013; Reed, 2014) and launchers). The TVC can be applicable to eliminate the disturbance caused by thrust misalignments (Felicetti et al., 2014).

In comparison with the gimbaled-thruster, the other TVC methods such as moving plate (Kong et al., 2016) are accompanied by a highly nonlinear behavior. Gimbal type TVC, can be also employed for solar-sail spacecraft (Sperber et al., 2016). The gimbaled-thruster can be very useful to save weight, simplify attitude control system and reduce the requirements of the C.M positioning accuracy (Noll, 1971; Kouhi et al., 2017c; Wang et al., 2016). In Saberi and Zandieh (2015) some RCSs are gimbaled to a satellite body to enhance the reliability and efficiency of the 3-axis attitude control system, but in our work a gimbaled-SRM is employed for both attitude and orbit control in an impulsive orbital maneuver.

In large and massive spacecraft and rockets, TVC method can be utilized alone because the mass properties of the liquid propellant rocket are negligible in comparison with the body's or the dynamical interaction between the gimbaled-engine and body is very small (see Reyhanoglu and Hervas, 2012; Orr and Shtessel, 2012; Hervas and Reyhanoglu, 2014). I many large spacecraft, TVC was used together with RCSs (Orr and Shtessel, 2012; Reyhanoglu and Hervas, 2012; Yeh, 2013; Widnall, 1970) and exact landing capability of Falcon-9 rocket is provided with only TVC (SpaceX project). But for a small spacecraft with a SRM, the mentioned interaction cannot be neglected that leads to a nonlinear two-body dynamics (see Kouhi et al., 2017b, 2017c; Saberi et al., 2017; Wang et al., 2016).

Although the attitude control during an impulsive thrusting maneuver has received a large attention, the issue of small spacecraft attitude control with only a gimbaled-SRM is not concerned. The purpose is to suggest a simple, light and reliable control system without fuel consumption. The proposed methodology is based on only TVC (gimbaled-SRM) method without utilizing RCSs or spin-stabilization. The difficulty of the present control problem is that, for the two-body nonlinear plant, both attitude and thrust vector stabilization must be performed using only a gimbal actuator while rejecting the high level exogenous disturbance torque. According to the previous literatures, the aforementioned performances need some thrusters (RCSs) and fuel consumption which are not efficient for a small spacecraft. In contrast to (Wang et al., 2016), the