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Hybrid-triggered orbit-attitude coupled station keeping control of a spacecraft with pure thrusters

Hongyi Xie[1,a *] and Franco Bernelli-Zazzera[1,b]

[1]Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa, 34, 20156, Milano, Italy

[a]hongyi.xie@polimi.it, [b]franco.bernelli@polimi.it

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Abstract. This paper introduces a specialized attitude-orbit control system designed for three-axis stabilized micro-spacecraft facing the challenge of maintaining orbit radius near small asteroids. Utilizing a fixed main thruster and inclined small thrusters, the system addresses intense orbit-attitude coupling. An intermittent hybrid-triggered control method optimizes main thruster alignment with the asteroid's center of gravity and maintains the spacecraft's orbit within a specified range. The system responds to attitude deviations by activating only the inclined thrusters and triggers overall control for specified orbital conditions, ensuring spacecraft safety. Simulation results confirm the efficacy of the proposed control system.

Introduction

Small spacecraft, like CubeSats, offer cost-effective, rapid, and versatile solutions for deep space exploration. Their small size allows for faster development, technology testing, and collaboration [1]. With lower costs, multiple spacecraft can be deployed, mitigating risks and increasing mission success. Additionally, small spacecraft contribute to educational opportunities and are suitable for interplanetary exploration, enabling missions to asteroids, moons, and planets [2]. However, the actuators in small spacecraft are simpler compared to their larger counterparts. The maximum output of reaction wheels in a 50kg micro spacecraft is always limited to no more than 0.02 Nm [3]. An attitude control system with a reaction wheel might be impractical for a lightweight Cube spacecraft, weighing only 1kg. Consequently, inclined thrusters are consistently incorporated into these kinds of spacecraft to generate sufficient attitude control torques as needed. A classical layout of a small spacecraft with inclined thrusters is given as follows:

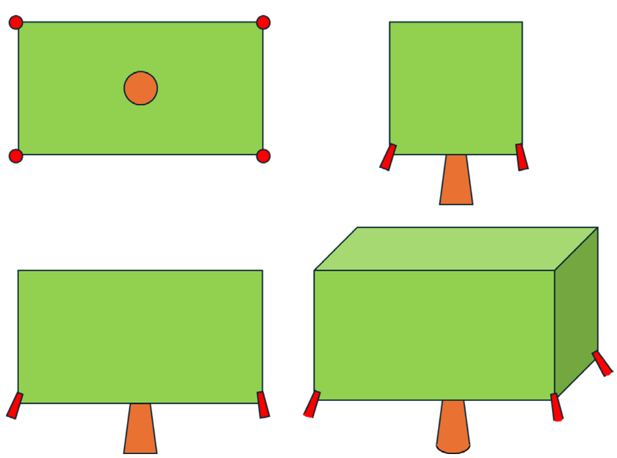

Fig.1. Three view drawing of a small spacecraft with a classical layout of 4+1 thrusters

Fig. 1 illustrates a classical layout of thrusters on a small spacecraft. There are 4 inclined thrusters and 1 main thruster fixed on the same side of this spacecraft, where the main thruster is fixed on the center of this surface with its direction orthogonal to this surface of the spacecraft. Compared with the main one, the four inclined thrusters can provide smaller thrusts, with their direction a little deviating from the axis direction of the main thruster at the same small angle. Note that the directions of the 4 main thrusters are very close to that of the main thruster. Therefore, this spacecraft can provide a high control torque in two directions of attitude control, for example roll and pitch, while the maximum theoretical control torque that could be given by this spacecraft is much smaller along the yaw axis. This layout is associated very well with the mission of an orbital station keeping in the vicinity of an asteroid, with a high requirement for control torques in roll and pitch owing to the non-spherical gravity and the gravity gradient and a very low need for control torques in yaw if the inertia matrix of the spacecraft is selected properly [4]. Consequently, integrated orbit and attitude control of a small spacecraft in the vicinity of an asteroid is possible by using this layout with a reasonable design of the control system.

The spacecraft's orbital thruster can operate continuously [5] or intermittently [6]. Continuous thrust may requires a complex inner structure, making intermittent thrusters a cost-effective and more robust choice for small spacecraft. Stabilizing a spacecraft within a narrow range around the center of a celestial body poses challenges, particularly with intermittent thrusters. An intermittent event-triggered control scheme effectively confines the spacecraft within a safety zone, limiting orbital radius and velocity direction. This approach has proven successful in pure orbital control [7] and orbital control considering orbit-attitude coupled dynamics [8] near asteroids. However, dealing with the manipulation of spacecraft attitude using only inclined thrusters requires a different approach. A hybrid-triggered control scheme [9] becomes valuable for executing necessary control orders when the spacecraft's attitude deviates too far or is at risk of leaving the designated mission area.

Therefore, this paper introduces a hybrid-triggered control scheme to effectively confine the orbital radius of a small spacecraft within a defined area. This hybrid-triggered approach integrates an improved version of the intermittent event-triggered orbit control scheme from [8] and another intermittent event-triggered scheme focusing on the spacecraft's attitude states. Each subsection's triggering initiates a new activation moment, employing thrusters to alter the spacecraft's motion states. However, the control response varies significantly depending on the triggering conditions. If the hybrid scheme is triggered by a substantial attitude error, specific inclined thrusters engage to reduce the error. By contrast, if triggered by jeopardized orbital states, the inclined thrusters address pitch and roll attitude errors initially. Afterward, the inclined thrusters deactivate, and the main thruster takes over to safely return the spacecraft to its orbital station.

Problem Formulation

The spacecraft's dynamics model aligns closely with our prior research [8], incorporating considerations for the non-spherical gravity of the asteroid, the significant impact of the gravity gradient around it, and the effects of solar radiation pressure (SRP). However, due to the spacecraft's layout illustrated in Fig. 1, it lacks the ability to generate thrust directed downward, hindering the reduction of its orbital radius. This limitation stems from the necessity of a 180-degree attitude maneuver in either the roll or pitch channel for initiating downward thrust. Executing such a maneuver incurs high energy costs with inclined thrusters. The hybrid-triggered mechanism is designed to activate before the completion of such a maneuver, utilizing the asteroid's gravity for this purpose. Accordingly, the "mid-line" orbital radius, denoted as r_0, is set below the average of the upper and lower limits, ensuring the avoidance of triggering by the orbital subsection in the range $\|\boldsymbol{r}\| \in (r_0, r_{max})$. Here, $\|\boldsymbol{r}\|$ represents the distance from the spacecraft's center to the asteroid's center, and r_{max} corresponds to the upper limit of the safety area's orbital radius. Besides, the layout of the spacecraft and also the special settings about the inclined thrusters are presented in the following figure:

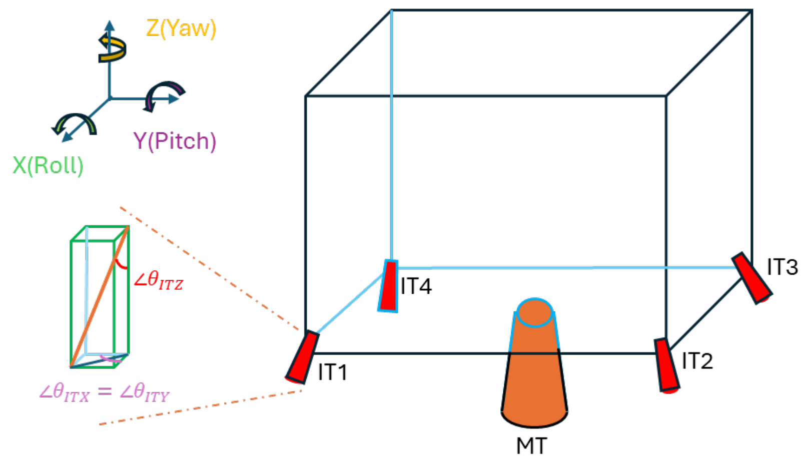

Fig.2. The spacecraft's layout with 4 inclined thrusters and corresponding definitions

The thrust generated by inclined thrusters 1, 2, 3, or 4 is consistently set to a fixed value denoted as F_I, and the inclined angles are uniformly defined with varying orientations, as illustrated in Fig. 2. Achieving 3-axis attitude control involves activating different combinations of inclined thrusters. For instance, rolling about the X-axis is attainable by simultaneously activating IT2 and IT3 or by concurrently engaging IT1 and IT4 for a roll motion in the opposite direction. Pitching about the Y-axis can be realized by activating IT1 and IT2 together or by concurrently opening IT3 and IT4 for pitch motion in the opposite direction. Similarly, yawing about the Z-axis is achievable by simultaneously activating IT1 and IT3 or by concurrently opening IT2 and IT4 for yaw motion in the opposite direction, provided that the thrust direction of IT1 and IT3 or IT2 and IT4 is not on the same plane.

Methodology

The hybrid-triggered mechanism is divided into two subsections. The first subsection is about the attitude control.

$$t_{k1} = \min\{\theta_b \geq b_w\}, k = 1,2, \dots \tag{1}$$

where θ_b denotes the angle between the aimed body-fixed coordinated label system of the spacecraft and the real-time body-fixed coordinated label system of the spacecraft. b_w is the upper limit of the allowed angle of this deviation. Once after this mechanism is triggered, any necessary thruster will be opened to recover the aimed attitude orientation on an almost optimal way. The second subsection is about the orbit control, which is an enhanced version of that in [8]. This subsection is given as follows:

$$t_{k2} = \min\left\{\frac{r_0 - \|\boldsymbol{r}\|}{\|\boldsymbol{r}\|}\boldsymbol{r}\cdot\boldsymbol{v} + \boldsymbol{\alpha} \leq 0\right\}, k = 1,2, \dots \tag{2}$$

where $\boldsymbol{v}$ is the orbital velocity of the spacecraft, and $\boldsymbol{\alpha}$ is a special designed variable to make the triggering condition properly. Similarly, once after this mechanism is triggered, any necessary thruster will be activated to recover the aimed attitude orientation, and then generate enough upwards thrusts to increase the orbital altitude of the spacecraft in an almost optimal way. Combing (1) with (2) yields the hybrid-triggered mechanism as follows:

$$t_k = \min\left\{\theta_b \geq b_w \; or \; \frac{r_0 - \|\boldsymbol{r}\|}{\|\boldsymbol{r}\|}\boldsymbol{r}\cdot\boldsymbol{v} + \boldsymbol{\alpha} \leq 0\right\}, k = 1,2, \dots \tag{3}$$

Expected Results

Expected results involve effectively constraining the spacecraft's orbital position within the predetermined range. The hybrid-triggered mechanism further limits the spacecraft's attitude deviation within a specified range set by the corresponding subsection. Achieving both orbital and attitude maneuvers requires fewer triggering orders, resulting in a decreased overall thrust requirement from the thrusters. This approach ensures a cost-effective control subsystem for the spacecraft, contributing to an economical solution for the entire system.

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