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Attitude tracking control for a space moving target with high dynamic performance using hybrid actuator

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ARTICLE INFO

Article history:
Received 28 December 2017
Received in revised form 23 March 2018
Accepted 24 March 2018
Available online xxxx

ABSTRACT

Attitude tracking control for a space moving target (such as debris or malfunctioning satellite) is investigated in this paper, which is different from the traditional agile attitude maneuvering and tracking control, and is a challenging problem for attitude control system, requiring agility, large control torque output, and high dynamic accuracy, etc. The rapidly moving target and spacecraft pose several tough issues such as agile attitude tracking control and actuator configuration design. A novel attitude tracking strategy is proposed to tackle the dynamic imaging process, including three phases, earth observation, attitude adjustment and dynamic tracking phase. With the accomplishment of attitude adjustment, the spacecraft will point toward the target to start the imaging task. For the maneuvers in the attitude adjustment and tracking phases, a combined control strategy consisting of saturation controller and backstepping controller is proposed. The former one constrains the attitude angular velocity as well as the required momentum on the actuators during the initial phase, while the backstepping controller guarantees the control accuracy with high dynamic performance in the imaging phase. A hybrid momentum exchanging actuator consisting of Control Moment Gyro (CMG) and Reaction Wheel (RW) is introduced to satisfy the great control torque demand. Null motion strategy is derived for the hybrid actuator to deal with CMG singularity and RW saturation simultaneously. Numerical simulations have demonstrated the advantages of the hybrid actuator and the proposed attitude control strategy, which not only enables the spacecraft to maneuver rapidly but also guarantees the tracking accuracy.

1. Introduction

The growing demands of continuous observation or imaging rather than a static snap shot of specific earth targets, such as earthquake, flood and forest fire, etc., with High Resolution (HR) from space have forced the earth staring imaging technology, which enables the dynamic and continuous information form. This new information style is more objective and efficient for the users to benefit from. A large amount of commercial earth observation spacecraft corporations, which are competent to provide the HR images even the videos, consequently bloom and thrive throughout the world. For example, the Digital Globe's satellite constellation can capture images with 0.3 m resolution and is quite advanced for civil use.

There is no doubt that the video imaging mode of spacecraft would be more sophisticated, which, compared to the conventional earth imaging of a stationary target, is commanded to point at the target during the specific time segment. Due to the high orbital velocity and high altitude, the spacecraft attitude maintaining and adjusting becomes of great significance, and the required attitude angular velocity is around 1 deg/s. To accomplish these kinds of attitude tracking control missions with high pointing precision requirement, different models and control architectures have been proposed. Generally, two major problems should be tackled in this imaging process, attitude determination and tracking. In absence of angular velocity measurement, the attitude determination has been studied in Refs. [1] and [2]. Ref. [3] proposed an effective method to determine the desired spacecraft attitude command through the proper choice of the reference frame for the small staring satellites, and Ref. [4] covered the topic of fast prediction algorithms with attitude control. The attitude tracking problems during the imaging process also have been investigated in various papers. A quaternion dynamic output feedback for attitude tracking problem without velocity measurement was studied in Ref. [5], and high precision attitude tracking problem was discussed in Ref. [6] with an iterative learning control method to reject the effects of

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https://doi.org/10.1016/j.ast.2018.03.041
1270-9638/

Nomenclature

$\boldsymbol{A}$	CMGRW system matrix	$\boldsymbol{Q}_e$	attitude error quaternion
$\boldsymbol{a}_g$	CMG gimbal axis direction vector	$\boldsymbol{R}_{AB}$	direction cosine matrix from frame A to B
$\boldsymbol{a}_s$	CMG flywheel spin axis direction vector	S_{CMG}	CMG performance index
$\boldsymbol{a}_t$	CMG output torque axis direction vector	S_{RW}	RW performance index
$\boldsymbol{C}_s$	RW spin axis direction vector	S_{atc}	CMGRW performance index
$\boldsymbol{d}$	null motion vector	$\boldsymbol{W}_1$, $\mathbf{W}_2$	weighted matrix
$\boldsymbol{E}_n$	identity matrix of dimension n	$\boldsymbol{Y}$	the state of the CMGRW system
$\boldsymbol{J}$	Jacobian matrix	$\boldsymbol{\delta}$	CMG gimbal angle .... deg
$\boldsymbol{h}_{act}$	Momentum of the actuator	$\boldsymbol{\Omega}_{RW}$	RW angular speed .... rad/s
$\boldsymbol{I}$	moment of inertia of spacecraft	$\boldsymbol{\omega}$	spacecraft attitude angular velocity............. deg/s
$\mathbf{Q}$	$[q_0, q_1, q_2, q_3]^T = [q_0, \mathbf{q}]^T$, attitude quaternion	$\boldsymbol{\omega}_d$	desired spacecraft attitude angular velocity..... deg/s
$\mathbf{Q}_d$	desired attitude quaternion	$\boldsymbol{\omega}_e$	attitude angular velocity error.................. deg/s

the repeating disturbances on satellite. All these comprehensive works have enabled the video imaging spacecraft very advanced at present and in the future.

For the moving space targets, such as debris or malfunctioning satellites, how to observe these objects effectively to minimize the corresponding harm on spacecraft in the complex space environment? Also, for other circumstances like the space station maintenance and servicing mission, periodical supervision would serve as a greatly valued means to improve the mission efficiency. A candidate solution is to monitor these targets from a space based-platform, putting forward a new on-orbit work mode which although shares something in common with the earth staring imaging mode. Ref. [7] has investigated the orbital determination of the space-based optical space surveillance system. And, aiming to demonstrate the capability to conduct space surveillance, the Space-Based Space Surveillance and Space-Based Visible programs have been launched in America, which were expected to collect data on man-made resident space objects, from a space-based platform [8–10]. Certain missions also have been designed and planned for these kinds of spacecraft [10]. This special mission and work mode would lead to some new attitude tracking problems, which requires the spacecraft three axes to maneuver quickly rather than a single axis attitude maneuver in the earth target staring mode, and puts forward new attitude control demands, including command attitude determination, attitude tracking with high dynamic performance, and actuator configuration and steering.

The rapid attitude tracking, as considered above, can only be guaranteed by certain particular actuator, which are expected to afford large attitude control torque or to absorb considerable momentum. From the perspective of efficiency and long operating life time, Control Moment Gyroscope (CMG) transcends other actuators such as RW for its torque amplification capability and momentum storage capacity. CMG has played a significant role in the rest-to-rest attitude control of agile spacecraft and large spacecraft, like the World View series satellites and the International Space Station. Therefore, it will be adopted in this paper to afford the required torque. The major challenge in using CMG is the inherent geometric singularity, where all the units torque are coplanar, meaning no output along its normal direction [11–13]. There is no existing steering logic or strategy that can handle the elliptic and hyperbolic singularity completely. The frustrating situation in this work will be treated by introducing a kind of new hybrid momentum exchanging device, CMG and Reaction Wheel (CMGRW), which is efficient to overcome the CMG singularity and RW saturation problems by exploiting the null motion among these actuators.

Large amount of works have concentrated on the attitude tracking problem in the Earth staring work mode, which involved adaptive fault tolerant control [14], iterative learning control [6], and robust adaptive control with unknown actuator nonlinearity [15], etc. While this work would divide the entire control process into 3 different phases, earth observation, attitude adjustment, and dynamic tracking to reach the accomplishment of video image of a space target. For different stage, particular attitude control algorithms are introduced, consisting of a PID saturation controller and backsteepping controller to satisfy the requirements.

The remainder of this work is outlined as followings. Section 2 first describes the dynamic video imaging mission and establishes the orbit and attitude dynamic model of the spacecraft. Section 3 will focus on the desired attitude and angular velocity of the imaging spacecraft. Hybrid actuator configuration about CMG and RW as well as the CMG singularity problem will be discussed in section 4. Section 5 represents a novel strategy for the accomplishment of the dynamic imaging mission. The spacecraft attitude tracking control method and hybrid actuator steering strategy are designed in section 6. Numerical simulations are carried out in section 7 to demonstrate the efficiency of the proposed control method as well as the strategy. Finally, section 8 concludes the entire work of this research.

2. Mission scenario and spacecraft dynamics

The proposed dynamic video imaging mission has great potential applications for future space debris and malfunctioning satellite monitoring from space, which can provide more specific information of the target compared with the ground based observing system. The mission scenario is illustrated in the followings together with dynamic model of the spacecraft.

2.1. Mission scenario

Considering an earth observing spacecraft and a space moving target with orbit altitude difference around tens of kilometers, as illustrated in Fig. 1, the observing spacecraft is expected to perform dynamic imaging of the target during a time period when running overpass the target. The mission consequently becomes more sophisticated because of the orbit motion of the spacecraft and the target. High attitude tracking dynamic performance, what's more, must be guaranteed in order to capture clear image due to the narrow field of view of the on board camera, such as 0.1 deg.

More specific illustration is presented in Fig. 2 based on STK. The demonstration process consists of the following main steps. The spacecraft in Fig. 2(a) is performing earth observation mission; when target approaching observation window (Fig. 2(b)), the spacecraft would adjust its attitude and point at the target. During the dynamic imaging phase, the spacecraft is to track the target at any time node accurately in order to guarantee the video quality (Fig. 2(c) and (d)), where the attitude angular ve-