UNIVERSITI PUTRA MALAYSIA

SLIDING MODE CONTROL TECHNIQUES FOR COMBINED ENERGY AND ATTITUDE CONTROL SYSTEM

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By

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Attitude control and power storage subsystems are two of the essential utilities provided on a satellite. As they compromise a significant fraction of a satellite's weight, a synergism concept that integrates these two into one subsystem can reduce the mass and volume of a satellite. The reduction will decrease the total cost of development and deployment of a satellite. A combined energy and attitude control system (CEACS) is an optimization concept that utilizes flywheels as a means of power storage and simultaneously as attitude actuators. A series of work on CEACS have proposed solutions for the satellite's attitude control problems. However, the analysis disregarded the high non-linearity involved in the satellite's attitude control itself. In addition, the proposed controllers' feasibility in presence of unknown disturbances and uncertainties were not examined. This thesis addresses a more complex attitude-tracking problem. This work proposes the use of the sliding mode control technique for the attitude-tracking problem of CEACS. Furthermore, an enhanced sliding mode control (SMC) technique is introduced to achieve robustness against uncertainties and external disturbances. Integral Augmented Sliding Mode Control with Boundary Layer (ISMC-BL), a locally asymptotically stable controller, is developed to provide a robust and accurate solution for the CEACS's attitude-tracking problem. The controller alleviates the chattering phenomenon influence on the attitude tracking performance that is associated with the conventional sliding mode using a boundary layer technique. Simultaneously, it reduces the steady-state error using an integral action. The numerical evaluation of the proposed controller demonstrates an enhanced attitude control accuracy in the presence of the system's uncertainties and external disturbances. However, ISMC-BL suffers from overshoots in its transient response. In addition, the model focuses only on mission with small attitude orientations involved. Therefore, this thesis proposes a Nonsingular Terminal Sliding Mode (NTSM) control scheme for a global attitude-tracking mission of a CEACS. The nonlinear system herein is subjected to unknown but bounded disturbances and uncertainties. The Lyapunov stability theorem is used to prove the finite-time convergence in both reaching and sliding phase. The proposed method avoids the inherited singularity of conventional terminal sliding mode. The numerical analysis provides proofs of the controller's robustness in rejecting the unknown disturbances and keeping the attitude errors as small as possible under the influence of uncertainties. The results provided by NTSM control method demonstrate the superiority of this sliding mode scheme compared to the previous proposed techniques for the CEACS's attitude control.

Abstrak tesis yang dikemukakan kepada Senate Universiti Putra Malaysia sebagai keperluan untuk ijazah Master Sains

GELONGSOR KAWALAN MODE TEKNIK UNTUK TENAGA DAN GABUNGAN SISTEM KAWALAN SIKAP

Oleh

SAMIRA ESHGHI KHOUZANI

February 2015

Pengerusi: Profesor Renuganth Varatharajoo, PhD

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Kawalan atitud dan penyimpanan kuasa subsistem adalah dua daripada utiliti yang disediakan dalam satelit. Oleh kerana subsistem ini berkompromi sebahagian besar jisim satelit, satu konsep sinergisma yang mengintegrasikan kedua-dua subsistem menjadi satu subsistem boleh mengurangkan jisim dan isipadu kapal angkasa. Pengurangan ini akan juga mengurangkan jumlah kos pembangunan dan penggunaan satelit. Penggabungan sistem tenaga dan atitud kawalan (CEACS) adalah satu konsep yang menggunakan pengoptimuman roda tenaga sebagai satu cara penyimpanan kuasa dan pada masa yang sama sebagai penggerak atitud. Satu siri kerja pada CEACS telah mencadangkan penyelesaian masalah kawalan atitud sistem. Walau bagaimanapun, analisis sebelum ini tidak mengambil kira ketodaklinearan kawalan atitud satelit. Di samping itu, prestasi kawalan atitud yang dicadangkan dalam kehadiran gangguan yang tidak diketahui dan ketidaktentuan orbit tidak diperiksa. Tesis ini menangani masalah atitud yang lebih kompleks : masalah atitud berkembar. Tesis ini mencadangkan penggunaan mod kawalan teknik gelangsor untuk kawalan atitud CEACS. Tambahan pula, satu teknik baharu mod kawalan teknik gelongsor (SMC) diperkenalkan untuk mencapai keteguhan terhadap ketidakpastian dan gangguan luaran. Mod kawalan teknik gelongsor integral tingkatan dengan lapisan sempadan (ISMC - BL), suatu kawalan asimptot stabil yang bertujuan untuk menyediakan satu kawalan atitud yang mantap dan tepat untuk CEACS. Kawalan ini boleh mengurangkan masalah gelugutan fenomena yang berkaitan dengan mod gelongsor menggunakan teknik lapisan sempadan. Penilaian berangka kawalan yang dicadangkan menunjukkan peningkatan ketepatan kawalan atitud dalam menghadapi ketidaktentuan sistem dan gangguan luar. ISMC - BL mengalami lonjakkan atitud. Di samping itu, model itu hanya sesuai untuk misi dengan orientasi atitud yang kecil. Oleh itu, tesis ini mencadangkan satu skim mod gelongsor kawalan terminal tidak unik (NTSM) untuk kawalan atitud bagi kawalan global CEACS. Katidak stabilan system adalah tertakluk kepada gangguan dan ketidaktentuan orbit. Teorem Lyapunov digunakan untuk membuktikan penumpuan terhingga masa dalam mencapai gelongsor fasa. Kaedah yang dicadangkan mengelakkan kelemahan yang diwarisi mod kawalan gelongsor terminal konvensional. Analisis berangka menunjukkan bukti kemampuan kawalan dalam menangani gangguan yang tidak diketahui dan memastikan atitud sekecil mungkin di bawah pengaruh ketidakpastian. Perestasi kaedah kawalan NTSM menunjukkan keunggulan skim mod gelongsor berbanding dengan teknik sebelum ini yang dicadangkan untuk kawalan atitud CEACS .

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Words cannot describe my gratitude and appreciation towards my husband. His support and kindness are not comparable to any other motivation.

I certify that a Thesis Examination Committee has met on 4 December 2015 to conduct the final examination of Samira Eshghi Khouzani on her thesis entitled "Sliding Mode Control Techniques of Combined Energy And Attitude Control System" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The committee recommends that the student be awarded the Master of Science.

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LIST OF ABBREVIATIONS

ACESE	Attitude Control and Energy Storage Experiment
AFC	Active Force Control
CEACS	Combined Energy and Attitude Control System
CNF	Composite Nonlinear Feedback
CNN	Chebyshev Neural networks
DCM	Direct Cosine Matrix
GPS	Global Positioning System
IPACS	Integrated Power and Attitude Control System
ISMC-BL	Integral Augmented Sliding Mode Control with Boundary- : Layer
LEO	Lower Earth Orbit
LSM	Linear Sliding Mode
NTSM	Non-Singular Terminal Sliding Mode
PD	Proportional-Derivative
PID	Proportional–Integral–Derivative
SMC	Sliding Mode Control
SMC-BL	Sliding Mode Control with Boundary-Layer
SMRSMC	Smoothing Model-Reference Sliding Mode Control
TSM	Terminal Sliding Mode

LIST OF NOMENCLATURES

ΔJ : Uncertainty of moment of inertia tensor

η : Positive constant for sliding condition

θ : Pitch attitude [radian or degree]

λ : Minus slope of the sliding surface

$\lambda_{\min}(.)$: Minimum eigenvalue of a constant

ρ : Reaching phase constant

τ_c : Control torque [N.m]

τ_d : Disturbances Torque [N.m]

τ_{eq} : Equivalent control torque [N.m]

τ_{sw} : Switching control torque [N.m]

τ_w : Speed loop response time [seconds]

Φ : Euler angle of rotation

ϕ : Roll attitude [rad or degree]

φ : Boundary layer

Ω_c : Control speed [rad/s]

Ω_W : Flywheel speed [rad/s]

ψ : Yaw attitude [rad or degree]

$\omega_x, \omega_y, \omega_z$: Satellite's body angular rate [rad/s]

$\dot{\omega}_x, \dot{\omega}_y, \dot{\omega}_z$: Satellite's body angular acceleration [rad^2/s^2]

$\omega_{d,x}, \omega_{d,y}, \omega_{d,z}$: Desired angular velocity [rad/s]

$\dot{\omega}_{d,x}, \dot{\omega}_{d,y}, \dot{\omega}_{d,z}$: Desired angular acceleration [rad^2/s^2]

$\omega_{e,x}, \omega_{e,y}, \omega_{e,z}$: Angular velocity error [rad/s]

$C(q_e)$: Transformation Matrix

$\mathbf{e}$: Euler axis of rotation

h_w : Angular momentum vector of a flywheel [kgm^{2}s^{-1}]

J_o : Satellite's nominal moment of inertia tensor [kgm^2]

J_m : Switching control gain margin

K : Time constant of a flywheel

k_{int} : Integral augmentation gain

k_m : Motor/generator torque constant of a flywheel

K_W : Proportional speed loop gain of a flywheel

L : Upper bound of uncertainty function

$L^u(\Delta J)$: Uncertainty function

p/q : Fractional power

q : Quaternion

q_d : Desired quaternion trajectories

q_e : Quaternion tracking error

$s(\bar{q}_e, t)$: Sliding mode surface

$T^{S/W}$: Projection matrix from the satellite's coordinate frame to a flywheels' coordinate frame

$T^{W/S}$	: Projection matrix from a flywheel's coordinate frame to the satellite's coordinate frame
T_W	: Torque induced by a flywheel [N.m]
t_{reach}	: Reaching time [seconds]
$V(t)$	: Lyapunov function candidate
X_B, Y_B, Z_B	: Satellite's body coordinate system
X_D, Y_D, Z_D	: Desired coordinate system
X_{IE}, Y_{IE}, Z_{IE}	: Inertial Earth (IE) coordinate system
X_R, Y_R, Z_R	: Relative coordinate system
$(\cdot)^{p/q}$	: Notation of fractional power for a vector
$(\cdot)^{\times}$	: Cross-product operator

CHAPTER 1

INTRODUCTION

1.1 General Overview

Satellites are substantial components of space exploration for understanding the outer space and addressing issues such as climate change, natural hazards and resources availability. This structure plays an important role in numerous technical fields such as long distance communications systems, weather forecasting, GPS (Global Positioning System) systems, remote sensing, satellite television, and many more applications.

Starting from the early days of space era, the satellites with bulky structures were designed for expensive and complex space project. However, the high costs, complexity and long development; and deployment schedules associated with the usual larger satellites have urged the scientists to plan and execute space missions differently.

A very substantial fraction of the costs involved in a satellite mission is devoted to deployment. The cost of launching a satellite depends on the volume and weight of the structure. Therefore, small satellites with smaller structures and lighter weights such as microsatellites and nanosatellites are great alternatives to have quicker and cheaper missions and more frequent research opportunities. Moreover, the new programs have prompted universities from all around the world to get more involved in space researches with no fear of modest budgets and little experience in space technology (Bearden, 2001; Curto & Hornstein, 2005; Sandau, 2010).

Despites of all advantages introduced by small satellite programs, the typical complexity in the subsystems' design and onboard instrumentation of a satellite compounded by the limitation of the mass and volume constitute a challenge to the development process. In addition, the increasing mission's requirements call for an extreme optimization in the design process.

Synergism of different subsystems of a satellite is an optimization approach to tackle the expanding demands and costs for space missions. Integration of two or more subsystems reduces the total size and weight of the structure and allows a greater fraction of the satellite's mass to be devoted to payloads. In addition, it could provide a better overall performance, e.g., reliability and mass/cost saving.

Synergism for a satellite's attitude control system, as one of the most crucial and costly subsystems on-board, is very convenient. The implementation of mechanical flywheels for controlling the orientation of a satellite and for simultaneous energy storage is; therefore, an attractive synergism concept.

Possessing a great deal of rotational kinetic energy, flywheels can provide electrical energy in collaboration with a motor/generator unit integrated onboard. The promising characteristics of flywheels such as high depth-of-discharge, long life cycle and temperature independence make these actuators and power storage systems greatly competent (Ginter et al., 1998). This on-board combined subsystem decreases the mass/volume budgets of a platform allowing the payload mass increment. The concept of simultaneous application of flywheels for energy storage and attitude control was investigated for International Space Station (Roithmayr, 1999). In addition, this concept was adopted for larger satellites in several studies (Richie et al., 2001; Tsiotras et al., 2001; Yoon & Tsiotras, 2002). Although the previous researches highlighted some enhanced performance and numerous advantages for this combined system, the implementations were limited to massive platforms.

Combined Energy and Attitude Control System (CEACS) adopts the above-mentioned synergism concept for small satellites. A double counter rotating flywheel assembly that serves simultaneously for the satellite energy and attitude management is the main building block of this system. Typically, CEACS consists of high speed composite rotors, magnetic bearings, motors/generators, and control electronics for the energy/attitude management (Varatharajoo & Fasoulas, 2002).

The linear control of CEACS has been examined in several studies using classic control techniques such as PD, PID, PID-Active Force Control (AFC) (Renuganth Varatharajoo, 2011; Varatharajoo, 2006a; Varatharajoo & Abdullah, 2004). However, linear feedback control techniques applied in the aforementioned studies disregarded the highly nonlinear parameters in mathematical model of the satellite's motion. The initial assumptions and simplifications associated with the linearization affected the precision of the results adversely.

In addition, it is of particular importance to address the uncertainties of the existing system to achieve a realistic view of the system's feasibilities in terms of control characteristics. The variation of external or internal parameters such as disturbances and inertia influence the system's model with uncertainties. The failure to address these uncertainties can degrade the system's performance or even cause instability.

The influence of uncertainties on the attitude performance of CEACS was examined using optimal controls such as H_2 and H_∞. However, the pointing accuracy degraded significantly for a system subjected to internal uncertainties (Ban & Varatharajoo, 2013; Ban et al., 2012). Therefore, it is of great interest to use an attitude control technique for CEACS that is robust to external disturbances and uncertainties.

In addition, the capabilities of CEACS have only been examined for attitude pointing missions. It is of great interest to investigate the feasibility of the system in more complex missions such as attitude-tracking.

One of the well-known approaches that deal with model uncertainty in complex nonlinear dynamic systems is sliding mode control (SMC). The most promising feature of the SMC is its invariance to parametric uncertainties and external disturbances. For aforesaid properties along fast dynamic response and good transient performance, SMC has been applied to a wide variety of applications including satellite control, robot manipulators, underwater vehicles, automotive transmissions and engines, high-performance electric motors and power systems (Kaynak et al., 2001; Slotine & Li, 1991; Vecchio et al., 2009) .

The limitations of classical control techniques have inspired many researchers to adopt this robust control scheme for satellite's attitude control specifically for attitude-tracking missions (Lo & Chen, 1995; McDuffie & Shtessel, 1997; Yongqiang et al., 2008).

However, in practical applications including control of a satellite's attitude, the system state trajectory does not slide along the sliding surface smoothly but with a high-frequency oscillation known as chattering phenomenon. This oscillation, highly undesirable, is the major drawback of pure SMC (Kaynak et al., 2001; Vecchio et al., 2009). Therefore, a variety of strategies has been proposed to solve the chattering problem. Sliding mode control with boundary layer (SMC-BL) is a convenient solution with easy implementation and relatively good results (Utkin & Lee, 2006). However, an effective alleviation of chattering subjects the system to a high steady-state error (Slotine & Li, 1991). The well-known properties of integral controls in reducing the steady-state error can be used to conquer the disadvantages of SMC-BL. However, the inherited overshoot characteristic of integral control actions hinders the performance of the controller. Consequently, more advanced types of sliding mode technique are recommended to achieve a desirable performance.

Hence, designing an efficient sliding mode controller for the attitude-tracking problem of CEACS that is invariant to external disturbances and uncertainties of the system is the primary motivation herein. In addition, this work intends to provide solutions to overcome the chattering phenomenon and to reduce its influence on the attitude tracking performance of CEACS. Furthermore, it aims to improve the steady-state error as well. Furthermore, finite-time sliding mode control techniques such as terminal sliding mode control (TSM) and non-singular terminal sliding mode control (NTSM) are also introduced to improve the transient response and to overcome the typical challenges of linear sliding mode controls.

1.2 Problem Statement

The attitude control of a satellite featuring CEACS has been addressed in a series of work initiated by Varatharajoo (Varatharajoo & Fasoulas, 2002). Several linear control techniques and two optimal control methods were proposed to investigate the feasibility of CEACS in attitude pointing missions in terms of control performance; however, the mathematical model of the satellite's motion was linearized and the nonlinear parameters involved were not addressed. In addition, the feasibility of CEACS in more complex missions such as attitude tracking has not been studied.

To examine the efficiency of each controller, an ideal and a non-ideal cases were introduced. The former considered an ideal case where all parameters were known while the later involved with some errors in the flywheel's inertia and the motor/generator gain constant. The values of the errors were considered to be known and relatively small.

Table 1.1 illustrates the pitch accuracy of several control techniques for both ideal and non-ideal cases.

Table 1.1: Pitch Accuracies of Control Techniques Applied to CEACS

Control Technique		**Pitch Accuracy (Degree)**	
		Ideal	**Non-ideal**
PD Controller (Varatharajoo, 2006a)	Nanosatellite	0.148	0.2
	Microsatellite	0.104	0.3
	Enhanced Microsatellite	0.102	0.28
AFC-PD Controller (Varatharajoo et al., 2011)		0.0039	0.01
H_2 Controller (Ban et al., 2012)		0.00541	0.01251
H_∞ Controller (Ban & Varatharajoo, 2013)		0.0185	0.043

It is apparent that the controllers were susceptible to errors and the pitch accuracy degraded significantly for the non-ideal cases. In addition, the errors were considered to be exactly known, in contrast to real applications where the system is subjected to unknown but bounded uncertainties.

While the existence of some errors in the flywheel's inertia was acknowledged in previous works, the uncertainty of this model parameter was not investigated. The value of the inertia matrix changes during the operation due to the possible motion of the payloads onboard, rotation of the solar panel arrays and fuel consumption (Cai et al., 2008). The limitation of the existing technology does not allow a precise calibration of model errors, therefore, the exact value of the inertia matrix is uncertain over the course of the mission (Cao et al., 2013). However, the variation can be considered as bounded in practice (Jin et al., 2008).

In addition, the determination of the external disturbances including aerodynamics, solar radiation pressure, gravity gradient and Earth's magnetic field, which continuously act upon the satellite's body during the mission, requires exact information of the inertia matrix. For a satellite with an uncertain inertia matrix, the values of the external disturbances are not exactly known, but can be considered to be bounded (Du et al., 2011; Li et al., 2009). However, none of the preceding researches on attitude control of CEACS considered the uncertainty of the external disturbances. The failure to address these bounded uncertainties results in poor control performance and a slow convergence rate.

Therefore, robust control strategies are required to make the system insensitive to disturbances and unknown but bounded uncertainties. Although sliding mode control (SMC) has proven its capability in that regard, it suffers from certain drawbacks. The conventional SMC suffers from a phenomenon called chattering that may cause instability in the system. In particular, this phenomenon degrades the attitude tracking accuracy of the system. The chattering influence on the attitude tracking performance can be effectively alleviated with boundary layer techniques but the steady-state error increases as a result (Utkin & Lee, 2006). The introduction of integral actions can enhance the error but an undesirable overshoot may occur before the system stabilizes (Utkin & Shi, 1996).

Further, most of the SMC techniques provide asymptotic stability with exponential convergence rate. As a result, the system tracking errors cannot converge to the equilibrium in a finite time. Control strategies with finite time convergence can stabilize the system with faster convergence rates and higher accuracies. Moreover, the systems under their influence demonstrate better disturbance rejection properties and better robustness against uncertainties (Bhat & Bernstein, 2000; Du & Li, 2012; Li et al., 2011). Terminal sliding mode control (TSMC) is well-known for its finite time convergence properties. However, it suffers from a singularity problem and it has relatively a slow convergence rate which could be critical for many applications. Non-singular TSMC (NTSMC) proposed by Feng, Yu, & Man (2002) is an adequate solution to eliminate the singularity problem of the original TSMC (Zou et al., 2011).

Consequently, the application of a finite time control strategy such as NTSMC is recommended to achieve the desirable performance in finite time and at the same time address the disturbances and unknown but bounded uncertainties (Song et al., 2014).

1.3 Research Objective

This thesis aims to propose suitable sliding mode control strategies for the attitude-tracking control problem of a satellite featuring CEACS. The specific objectives of this research are:

- To design robust sliding mode control techniques which are invariant to disturbances and uncertainties for the attitude-tracking control of CEACS.

- To enhance the performance of linear sliding mode controller by alleviating the influence of chattering on the attitude tracking accuracy, and by decreasing the steady-state error using boundary layer and integral augmentation techniques.

- To utilize finite-time sliding mode control technique as a global solution to the attitude-tracking problem of CEACS to achieve a finite-time convergence of the satellite's trajectories.

1.4 Scope of Study

The primary focus of this research is to design a sliding mode controller that is invariant to uncertainties and disturbances for the attitude-tracking control of a Low Earth Orbit (LEO) small satellite utilizing CEACS.

The satellite is assumed to be a rigid body that rotates under the influence of a body-fixed flywheel set. The methodological framework of the system's analysis consists of the detail mathematical model of the satellite's motion and the tracking error dynamics. Two attitude tracking error dynamics are defined for two different types of missions, the first one is developed for missions during which the Euler anglers are relatively small and less precise attitude-tracking is required, and the other one considers all possible orientations. The former is suitable when less precise attitude-tracking is required, and the later supports missions with high tracking accuracy requirements.

Two uncertain parameters namely the uncertainty of the inertia matrix and the external disturbances are considered in this work. Further, their influences on the tracking error dynamics are mathematically formulated.

Several techniques including the boundary layer and integral augmentation options are used to enhance the performance of the conventional sliding mode controller. Finite time sliding mode techniques provide a further enhanced performance for attitude-tracking problem of CEACS. The linear SMC technique is provided for missions during which the Euler anglers are relatively small. This technique is suitable for missions that require less precise attitude-tracking. A global solution is provided using finite-time SMC. The computational method is relatively intense; however, it is an adequate solution for a very precise attitude-tracking. The Lyapunov stability theorems are used to verify the stability of the proposed controllers and their robustness against uncertainties and disturbances. The study is conducted using mathematical modeling of the system and the controllers, and numerical analysis is performed using Matlab®-Simulink™.

A small satellite utilizing CEACS is the main benchmark with different controllers for each numerical in-orbit evaluation. Each controller is tested under both the nominal and the uncertain cases. The nominal case considers the disturbances rejection performance of controller when the system's parameters are exactly known. In particular, the satellite's inertia matrix is known and its value is constant for the duration of the mission. Consequently, the disturbance accommodation term of the control law is known and it is defined based on a worst-case estimate of the disturbance torque.

The uncertain case highlights the controller's invariance to uncertainties. The inertia matrix of the satellite, and the external disturbances are considered to be uncertain but upper-bounded. The inertia matrix changes within a certain limit but its variation is assumed to be time-invariant. In the uncertain case, a 10% of variation is considered for the inertia matrix of the satellite. The upper-bounds on the inertia and disturbances uncertainties are later used for the computation of the control gains. In addition, the stability analyses provide the sufficient and necessary conditions for the computation of the control gains.

Further, a comparison is made between the conventional sliding mode and the modified linear SMC technique. The performance of finite-time SMC is also compared with the linear SMC to emphasize its superior characteristics. A final comparison between all techniques accentuates the best controller.

1.5 Thesis Outline

This thesis consists of five chapters. The outlines are as follows:

Chapter 1 provides a general overview about satellite synergism and combined energy and attitude control system (CEACS). A brief description about sliding mode control (SMC) highlights the advantages and disadvantages of this control technique. The problem statement, research objectives and the scope of study are also included in this chapter.

Chapter 2 reviews the literature on CEACS and the sliding mode techniques. It covers the examination of CEACS in terms of attitude control characteristics conducted by other researchers. In addition, the development of linear and finite-time SMC; and their advantages and disadvantages are covered.

Chapter 3 provides a detail description of underpinning fundamentals of the satellite's motion in space. The architecture of CEACS is described in addition to a description of external disturbances and system's uncertainties. The control methods are developed and the stability analysis are provided in this chapter.

Chapter 4 is devoted to the numerical study of the system controlled by the proposed controllers. The attitude performance of CEACS is presented for nominal and uncertain cases. The relevant discussions explore the feasibility of each controller in attitude-tracking control of CEACS. Chapter 5 concludes this study and provides suggestions for future researches.

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