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A Modeling Error Compensation Approach

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ISBN 978-981-97-2846-6 ISBN 978-981-97-2847-3 (eBook)
https://doi.org/10.1007/978-981-97-2847-3

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

To our great country China and our family.

Preface

There is no doubt that our current and even future lives are highly connected to satellite. We launch satellites to establish the global positioning system to get the precise position of the unmanned vehicles and even the mankind. We launch satellites to achieve Earth observation, weather forecast, fire forecast, video broadcasting, environmental monitoring, etc. Satellite has played an important role in our daily life. To provide such services for mankind, the attitude control system should be developed for satellite. Otherwise, the payloads such as cameras, antennas, etc., will not work perfectly. In the attitude control system design, attitude controller design is one of the most important parts. Although the linear control theory-based controllers including the proportional–integral–derivative control law and its variants have been widely used in satellite attitude control engineering, they are becoming inappropriate for modern satellites demanding high control performance. That is because the dynamics of any satellite is inherently nonlinear in nature. Inspired by the superior performance ensured by nonlinear control theory, many nonlinear attitude control approaches have been proposed for satellites. However, the problem of designing an nonlinear controller to accomplish attitude maneuvers with high control performance is still open.

In addition to the nonlinear dynamics of the satellite attitude system, modeling error is another main hindrance. This inevitably acts on the satellite attitude dynamics. It mostly comes from uncertain and unmodeled inertia, unmeasurable flexible vibration and coupling between the rigid and the flexible part of the satellite, actuator fault, actuator misalignment, and the environmental disturbance torques including the gravity-gradient torque, the aerodynamic torque, the Earth magnetic torque, and the solar radiation pressure torque. Due to the current finite modeling technology, the modeling error is unknown and even time-varying. In practice, if the modeling error is not appropriatly handled and compensated, the attitude control performance will be deteriorated and even the instability of the attitude control system may be resulted. This has led to intense interest in the development of modeling error compensation control approaches, which are supposed to solve this problem.

From the standpoint of rejecting, attenuating, and compensating for modeling error, significant developments have been witnessed for the satellite attitude control system design in the past two decades. However, there is currently a lack of a unified control framework. Most of the existing methods can compensate for a single type of modeling error only. In addition, many of them do not consider physical and cost limits such as actuator constraint and unmeasurable angular velocity due to gyro failure. On the other hand, fast attitude maneuvering requirement may not be considered during critical phases of the mission in the literature during modeling error compensation. Moreover, the existing robust or adaptive attitude controllers with modeling error accommodated are characterized by severe conservativeness. This will lead to more energy consumption, and thus reduce the lifespan of a satellite. In aerospace engineering, those issues should be addressed simultaneously.

Motivated by the demand for attitude control with the above challenges solved and many existing approaches are unable to achieve this goal, this book attempts to solve the above challenge during satellite attitude control system design. This book focuses on designing advanced compensation control techniques for more types of modeling error with fast, high-accuracy, high-stability, and or velocity-free attitude maneuvering accomplished for satellite. This book first concentrates on developing nonlinear robust solutions to two or more than two types of modeling error compensation attitude control problem of satellite even in the presence of actuator constraint and fault. Its focus comes to design advanced approaches to achieve fast attitude slewing control for satellite with two or more than two types of modeling error compensated adaptively. Finally, three new observer-based approaches are synthesized to accomplish attitude control for satellite, while the modeling error is precisely and fully compensated. The corresponding controller has less and even no conservativeness. Energy is saved when they are applied to perform attitude maneuvering. More specifically, the effectiveness and the superior attitude control performance of those modeling error compensation approaches proposed in this book are verified by numerical simulation and experimental tests via several testbeds on the ground.

The book itself provides the reader with the current state of the art in the nonlinear attitude control area of rigid or flexible satellite with modeling error. Moreover, it also contains the attitude representation, model of satellite attitude system including the attitude kinematics and the attitude dynamics, some fundamental definitions, and lemmas used in nonlinear control theory. Hence, this book can be used as a reference by satellite control engineers and satellite attitude control academic researchers. The book also has readers who are interested in attitude control of other rigid bodies such as unmanned aerial or underwater vehicles. Prerequisites for understanding the book are a sound of knowledge of basic nonlinear control theory especially the Lyapunov stability analysis, rigid body attitude dynamics, basic mathematics, and fundamental physics.

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February 2024

Acknowledgements

The authors would like to dedicate their gratitude to the person who has supported us along the way. The authors would like to appreciate Prof. Bo Li from Shanghai Maritime University and his students Hui Liu, Xiangyu Zhu, Hongyue Ma, and Ziqi Yang. Without their work in helping with the preparation of the draft of this book, this book would never have been published. The authors are grateful to Prof. Dong Ye from the Harbin Institute of Technology for providing the technical materials of the testbeds in this book and for helping to carry out experimental tests by using those testbeds. Some parts of the research presented in this book are based on the academic collaborations with Prof. Shen Yin from the Norwegian University of Science and Technology, Dr. Mehdi Golestani from Southern University of Science and Technology, and Dr. Haichao Zhang from Northwestern Polytechnical University. Our gratitude also goes to them.

As a special note, the first author would like to express his sincere thanks to all the students with whom he has worked over the past ten years. He is also grateful to his friends Xing Huo, Xiaoxiang Hu, and Yaohong Qu for their encouragement and enthusiastic help. The fourth author would like to dedicate this modest work to his life, academic, and work career's advisor, Prof. Xiaoqian Chen, who is a genius scholar, hardware expert, and research leader, and most importantly, a genuine person, who left us prematurely. Undoubtedly and definitely, all the authors would be forever grateful to their families for their love, more specifically, the smile of their kids.

Most parts of this work would not have been possible without the financial support by the National Natural Science Foundation of China under Grant 11972373 and 12202065, and in part by the National Science and Technology Major Project under Grant J2019-I-0021-0020.

The last thanks go to Rammoban Krishnamurthy and Jing Dou from Springer Nature Singapore Pte Ltd. for their patience throughout this book.

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1.1 Introduction

The space and universe have always been full of attraction and mystery to the mankind. We have long had the dream and ideal of traveling to space and exploring the universe. The first satellite launched on October 4, 1957 declared that the mankind had entered the space age. The space technology has advanced by leaps and bounds. The development of space technology has shown that the mankind has made great achievements in its journey of the continuous research, exploration, and utilization of space. It brings about important impetus and significant changes in the economic and social developments of mankind. Especially, it can also "impact life on earth through the stimulation of technological development, and generation of scientific knowledge" said by Dr. Ernst Stuhlinger, the associate director for science of NASA Marshall Space Flight Center, in 1970. Of course, space technology is one of the most challenging missions and complex engineering in the world.

Satellite is the fundamental platform of any aerospace mission such as Earth observation, communication, navigation, deep space exploration, etc. For any satellite, an attitude control system (ACS) should be designed. This system is one of the most important subsystems of the satellite. It plays an important role and is an essential part in satellite design. Attitude control should be carried out to accomplish attitude stabilization or tracking maneuvers to ensure that its payloads operate normally. For example, the desired attitude trajectory should be followed to ensure that the camera fixed in the satellite can focus on the interested areas and then take images. The stabilization of attitude is one of the fundamental maneuvers and the primary attitude control tasks that any satellite needs to frequently perform during its mission. It is recognized by aerospace engineers that attitude control determines whether the space missions can be accomplished or not.

Modern space missions are becoming more and more complicated. They ask for more and better requirements for the attitude control performance. More specifically, highly accurate slewing or pointing attitude maneuvers are necessitated. Note that the dynamics of any satellite is inherently nonlinear in nature. Moreover, this

B. Xiao et al., *Advanced Attitude Control of Satellite*,
https://doi.org/10.1007/978-981-97-2847-3_1

nonlinear attitude dynamics is inevitably subject to modeling error. This modeling error will deteriorate the satellite attitude maneuvering performance. It lets the linear control theory-based control methods such as the proportional–integral-derivative (PID) attitude controller and its variants result in an unsatisfactory/inferior performance. That is because the PID controller has a weak capability of handling with such modeling error. To solve this drawback, advanced attitude control schemes are, therefore, imperative for satellites to maintain desirable stability, reliability, and enhanced performance. Inspired by the superior performance ensured by nonlinear control theory [1–3], although significant developments have been witnessed in the nonlinear controller design for satellite attitude stabilization and maneuver tracking objectives [4–7], the problem of attitude control is still open. In particular, from the standpoint of rejecting or attenuating modeling error [8–12], there is currently a lack of a unified attitude control framework.

1.2 Attitude Dynamics Modeling Error

Due to the current finite modeling technology, the mathematical model of the satellite attitude system can not be precisely established. The nonlinear attitude dynamics can not be fully described. There exists dynamics modeling error. The external disturbance torques, uncertain inertia, flexible vibration, actuator fault, and actuator misalignment are the five primary modeling error.

1.2.1 External Disturbance Torques

The gravity-gradient torque, the aerodynamic torque, the Earth magnetic torque, and the solar radiation pressure torque are the primary environmental and external disturbance. Any non-symmetrical satellite in the orbit is affected by a gravitational torque. This is due to the variation in the Earth's gravitational force over the satellite. Magnetic disturbance torques are induced by the interaction between the satellite's residual magnetic field and the geomagnetic field. The aerodynamic torque results from the satellite's motion through the tenuous upper atmosphere. The air molecule interaction with satellite body will produce such torque on the satellite. It is most effective on satellites orbiting below 400–500 km. The photons from the sun generate a force that produces a torque about the center of the mass of the satellite. This solar radiation pressure has more effect on light objects with relatively high surface. Although there are many mathematical models for those four types of external disturbance torques [13]. They can be not exactly derived. Moreover, in addition to those four torques, there are also some unexpected disturbance torques such as the collision torque due to debris or robotic manipulation. They can not be modeled.

1.2.2 Unmodeling Inertia

Once the design of the satellite is finished on the ground, its inertia matrix can be calculated and estimated by using standard equations [13]. This calculated inertia is constantly called the nominal inertia of the satellite. When the satellite is running in the space orbit, its mass properties will be uncertain. It may change due to the motion of onboard payloads such as camera and antennas, rotation of solar arrays, fuel consumption, out-gassing, etc. This leads to the actual inertia of the satellite deviating from the nominal value. Moreover, such deviated inertia is time-varying, uncertain, and unmodeled.

1.2.3 Flexible Vibration

To meet ever more demanding mission requirements, there has been a trend for developing satellites with large flexible appendages such as antennas and solar arrays. Those appendages are large, lightweight, and low-stiffness. Such a type of satellite is usually called a flexible satellite. For example, the flexible satellite ETS-VIII has two large deployable reflectors measuring 17 m $\times$ 19 m, and also a pair of large solar array panels measuring 19 m $\times$ 2 m [14]. Although the trend towards larger satellites can meet the increasing mission demands, this will inevitably increase the difficulty in their attitude control. This is because the coupling between the structural vibrations of the flexible components and the rigid-body motion can introduce dynamic perturbations to the satellite's attitude. Moreover, when performing rapid attitude maneuvering with high-pointing accuracy demanded by aerospace tasks [15–17], it induces flexible appendages to vibrate. For most flexible satellites, this coupling and the flexible vibration are not measurable. Hence, those two will act on the flexible satellite attitude dynamics as modeling error.

1.2.4 Actuator Fault

A satellite's challenging operating conditions increase the possibility of malfunctions in sensors and actuators and faults in the controllers. The analysis of recent satellite accident statistics shows that the fault of the attitude control system accounts for 32%. Moreover, in this percentage, nearly 44% of the faults are caused by actuator faults, as shown in Fig. 1.1. Once a satellite is launched, it is highly unlikely that its hardware can be repaired. Thus, the actuator fault cannot be fixed with replacement parts. When an actuator fault occurs, it will result in an error torque between the nominal torque and the actual torque generated by the satellite's attitude control actuators. This error torque is viewed as the modeling error in the attitude dynamics. It can potentially cause a host of economic, environmental, and safety problems. A recent

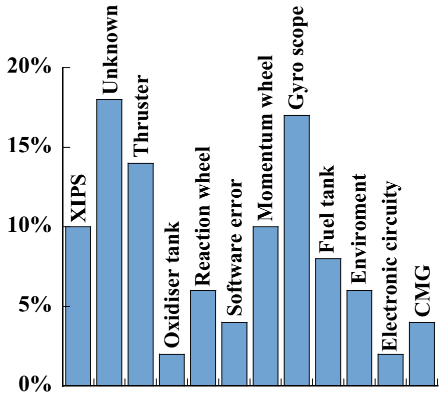

Fig. 1.1 The component fault analysis of ACS of satellite [18]

Fig. 1.2 The ChinaSat 6C satellite

accident occurred with the ChinaSat 6C satellite developed by the China Academy of Space Technology, as shown in Fig. 1.2. This satellite was launched on March 10, 2019. However, faults occurred in its thrusters on December 25, 2023. This led to more energy consumption and a reduction in its lifespan. This incident strongly motivates the development of attitude control systems that ensure an efficient and timely response to maintain stability, reliability, and required performance properties even when components fail.

1.2.5 Actuator Misalignment

Actuator misalignment is another type of modeling error in the satellite attitude system. Due to this misalignment, the actual torque acting on the three-axis of the satellite is different from the nominal torque. The extreme case of a backward actuator is especially important. In practice, whether due to finite manufacturing tolerances or warping of the satellite structure during launch, some actuator alignment error exists indeed. Moreover, the satellite's inertia properties are highly coupled to the actuator alignments. Hence, actuator misalignment may cause the onboard attitude controller to fail. This may cause mission performance to degrade and thus pose a significant risk to the successful operation of the satellite.

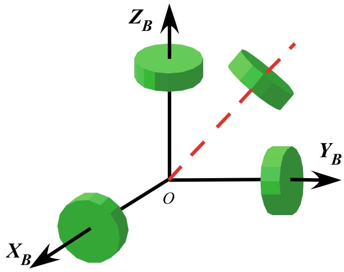

Fig. 1.3 The configuration of four reaction wheels

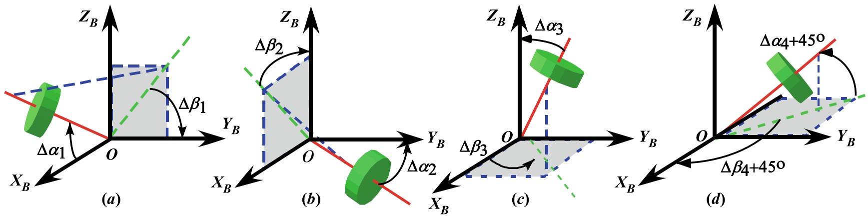

Fig. 1.4 The schematic representation of reaction wheel misalignment

Figure 1.3 shows the mechanical configuration of four reaction wheels used to activate a satellite attitude system. Three wheels are mounted orthogonally, aligned with the satellite body axes, i.e., $+X_B$, $+Y_B$, and $+Z_B$, respectively. A fourth, redundant, wheel is mounted skewed at equal angles (54.7 degrees) to each of the body axes, aligned diagonally in the $+X_B$, $+Y_B$, and $+Z_B$ quadrant. This "skew" wheel could be used to provide control power about any of the other axes if one of the orthogonal wheels was to fail. In practice, some alignment errors will exist in this reaction wheel. As an example, actuator alignment error can be mathematically modeled as shown in Fig. 1.4 for this configuration misalignment. The reaction wheel mounted on $+X_B$ axis is tilted over the nominal direction with constant angles, $\Delta\alpha_1$ and $\Delta\beta_1$; also the reaction wheels mounted on $+X_B$ and $+Y_B$ axis are tilted over the nominal direction with $\Delta\alpha_2$, $\Delta\beta_2$, $\Delta\alpha_3$, and $\Delta\beta_3$, respectively. While the "skew" wheel is titled over the nominal direction with $\Delta\alpha_4$ and $\Delta\beta_4$.

1.3 External Disturbance Attenuation Control

To attenuate the effect of the external disturbance on satellite attitude control performance, many solutions have been developed for satellite [19–22]. In the existing literature on solving the problem, there are two types of approaches. One is to view disturbance torque and uncertain inertia as lumped disturbances/uncertainties, and then design a robust attitude controller [23]. Applying such a robust controller, robustness to disturbance and uncertain inertia is guaranteed [24, 25]. Desired attitude control performance is resulted despite external disturbances, system uncertainties, and even flexible vibrations. The other type to achieve disturbance/uncertainties rejection control is the disturbance observer-based (DOB) control design [26, 27]. For this type, an observer is first designed to estimate disturbance/uncertainties, and the controller is developed by using the observed value to achieve the control objectives with the disturbance accommodated.

1.3.1 Robust Attenuation Control

Robust control of external disturbance is widely seen in the literature [28–30]. For instance, the $\mathcal{H}_\infty$ control theory was applied to achieve robust control of external disturbance [31, 32]. In [33], another robust controller was reported to handle external disturbance for the rigid bodies subject to actuator faults and angular velocity constraints. This method was further applied in [34] for satellite attitude tracking with the prescribed performance ensured despite disturbance. In [35], a backstepping-based attitude stabilization controller was designed with external disturbances and constraints in input and measurement solved. The problem of robust disturbance control was also studied in [36]. Only a class of external disturbances with known dynamics was addressed. In [37], the attitude stabilization problem of rigid bodies with external disturbance was solved in the event-triggered framework.

In [38], an adaptive robust tracking controller was presented for robot manipulators. The tracking error was governed to be finite-time stable. In [39], robust cooperative control design of multiple surface vessels was studied, while the vessels were subject to unknown ocean currents and unmodelling dynamics. In [40], the problem of designing a robust tracking controller for rigid body with uncertainty was studied, and it was further investigated in [41] and [42]. The proposed schemes were verified on quadrotors. For surface vessels subject to disturbance uncertainty, a backstepping-based robust trajectory tracking controller was reported in [43]. In [44], a novel controller was developed for aerial robots to achieve attitude trajectory tracking with robustness guaranteed. The proposed law governed the tracking error converging into a small ball, and such error is robust to unknown dynamics. Using the technique of uncertainty and disturbance estimator, a robust tracking control strategy was synthesized for non-affine systems.

In the robust attitude control design, disturbance and uncertainties will not be rejected, and robustness to them is achieved with acceptable attitude control performance. In contrast, another approach to achieve attitude control with good accuracy is to reject disturbance/uncertainties [45–48]. For this type of approach, the magnitude or its upper bound of disturbance torque and uncertainties will be estimated, and then a controller will be designed to compensate for it. To achieve this goal, the adaptive control technique is one widely applied approach [49, 50]. In [51], robust trajectory tracking control was guaranteed for a delta robot. Disturbance rejection was achieved by the adaptive control technique. In [52], an adaptive estimation law was firstly designed to estimate the parameters of uncertain inertia. By using the estimated information, a nonlinear controller was proposed for the attitude tracking maneuver. In [53], the Chebyshev neural network was adopted to approximate the uncertain dynamics introduced by disturbance and uncertain parameters. Using the approximated value, a terminal sliding mode attitude controller was proposed. In addition to those adaptive controllers, some investigations on attitude control by using adaptive control were also available in [54, 55].

Of particular interest, taking the sliding mode control theory's (SMC) advantages including rapid response and insensitiveness to uncertain parameters or disturbances, this technique has become one of the widely applied tool to design robust attitude controller [56, 57]. In [58], a high-order sliding mode controller was developed. Attitude tracking with high-pointing accuracy was achieved. The proposed controller guaranteed that the system output was robust to disturbance and uncertain inertia. In [59], the problem of attitude tracking control despite disturbance and uncertain inertia was addressed by presenting a sliding mode controller. This problem was also investigated in [60] for satellite attitude stabilization maneuver with actuator output torque constrained. The rejection of disturbance was achieved via the SMC [61].

1.3.2 Observer-Based Attenuation Control

The disturbance robust control of satellite is characterized that the developed robust controllers are conservative. In practice, this conservativeness is not desirable for rigid bodies. Motivated by avoiding this drawback, the disturbance-observer-based (DOB) control is a common solution with the disturbance rejection ensured [62–66]. In this solution, a disturbance observer (DO) is preliminarily designed to estimate the external disturbance. Then, a control law is designed by using the estimation of the disturbance to stabilize the closed-loop attitude system [67–70]. A recent review on observer-based uncertainty or disturbance attenuation control design was given in [71]. More specifically, observer-based PID tracking control design was witnessed for uncertain systems in [72, 73]. In [74], a DOB anti-windup controller was presented for hypersonic vehicles. Integrating the DO with the adaptive control theory, a neural-network-based controller was developed for robots with variable stiffness joints and uncertainties [75]. For a class of uncertain stochastic systems, a DOB $\mathcal{H}_\infty$ control law was designed in [76]. Although the disturbances acting on the system were accommodated, the disturbances were required to satisfy an exogenous model. In [77], to handle the external disturbances and uncertainties in the hybrid active-passive heave system, a robust prediction control approach was presented via the DOB technique.

The development of DO plays an important role in the DOB rejection control. To ensure perfect estimation for disturbance, a number of investigations on DO design have been reported. In [78, 79], a high-gain DO was seen to estimate the external disturbance or the uncertainties. However, the high gains would amplify the effect of sensor noise on the system performance. Due to the robustness property of sliding mode control, sliding mode observer (SMO) [80–82] or high-order sliding mode observer (HOSMO) [83–85] are widely applied in DOB control design with external disturbance compensated.

The extended-state-observer (ESO) is another widely applied technique to accomplish the design of DO [86–88]. For example, the estimation of the mismatched uncertainty was studied in [89]. An ESO was presented in [90] for the quadrotor to estimate the external disturbance due to unknown gust wind. In [91], the trajectory tracking control problem of underwater robots despite external disturbance and uncertainties was studied by including an ESO. In [92], the problem of robust load frequency control of power systems was studied via sliding mode control and ESO. For a class of multi-input-multi-output systems, a generalized ESO was presented in [93]. Moreover, the adaptive ESO (AESO) was another solution to the problem of disturbance or uncertainty estimation [94].

The most existing DO design requires the external disturbance to satisfy some strict conditions. For instance, most ESO are only feasible for the unknown constant disturbance or the disturbance with slow variation [95]. More specifically, because the external disturbance is treated as an extended state in ESO, the external disturbance should be differentiable. On the other hand, it usually requires the SMO or HOSMO to be upper bounded by a known value. In practice, however, the external disturbance may not satisfy these assumptions. The class of the external disturbance handled by the existing DO is limited. Hence, it is of interest to determine observers that can release these constraints or assumptions. Although this is achieved in [95], its result is applicable to linear systems only.

To solve the above drawback [96], viewing disturbance as an unknown input, and then applying the theoretical framework of unknown-input-observer (UIO) [97] is becoming an effective way to estimate disturbances. In [98], the tracking control problem of the linear parameter-varying system was solved by using an unknown input observer. For linear/nonlinear systems, the problem of high-performance control design by using UIO to estimate system uncertainties and disturbances has been extensively investigated [99]. An output feedback bilateral teleoperation approach was designed for robot manipulators [100]. In this approach, UIO was applied to estimate external forces. On the other hand, the problem of observer-based disturbance rejection approach design has also attracted considerable attention in the field of satellite/unmanned aerial vehicle attitude control design in recent years. The result of applying this approach to achieve attitude control can be referred to [101]. In [102], a disturbance observer-based SMC approach was proposed for quadrotor vehicles. A sliding mode observer was presented to estimate external disturbances. The problem of designing observer-based disturbance control for satellite attitude system design was solved in [103].