OPTIMIAL CONTROL OF THE ATTITUDE MANEUVERING FOR RAZAKSAT® CLASS SATELLITE BASED ON RIGID AND FLEXIBLE MODEL

by

TEOH VIL CHERD

(1140610711)

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School of Mechatronic Engineering
UNIVERSITI MALAYSIA PERLIS

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LIST OF ABBREVIATION

ADCS	Attitude Determination and Control System
ANSYS	Analysis System
AOCS	Attitude and Orbit Control System
APDL	ANSYS Parametric Design Language
DAE	Differential Algebraic Equation
DM	Dynamic Model
DOF	Degree of Freedom
EMR	Effective Mass Representation
EOM	Equation of Motion
EQF	Eigen-axis Quaternion Feedback
ERT	Euler Rotation Theorem
FE	Finite Element
FEM	Finite Element Method
FFR	Floating Frame Reference
GPOPS	General Purpose Optimal Control Software
IFE	Incremental Finite Element
LDV	Large Deformation Vector
LTED	Linear Theory of Elasto-dynamics
MED	Momentum Exchange Device
PMP	Pontryagin Maximum Principles
PZT	Lead Zirconate Titanate
RMSE	Root Mean Square Error
RW	Reaction Wheel

LIST OF SYMBOLS

γ_i	Angle of Rotation of q_i-r_i Plane
α_i	Angle of Rotation of X-Y Plane
α_{RW}	Angle of $\hat{W}_1$, $\hat{W}_2$ Plane Rotation
β_{RW}	Angle of $\hat{W}_1$, $\hat{W}_3$ Plane Rotation
h	Angular momentum
$h_{r,j}$	Angular Momentum of RW
$\boldsymbol{h}_{out}$	Angular Momentum With Reference To The Satellite Body
Ω_j	Angular Velocity of RW
C	Arbitrary Constant
$\hat{w}_1, \hat{w}_2, \hat{w}_3$	Body Frame of Coordinate System of RW
β	Cant Angle
x_i, y_i, z_i	Component of Vector Position of The Panel
$\beta_{2,i}$	Constants With the Unit S
$\beta_{1,i}$	Constants With the Unit S-1
$u(t)$	Control Function
J	Cost Function
λ	Co-State
I_i	Cross Sectional Moment of Inertia
ζ_i	Damping Ratio
$\boldsymbol{\mu}$	Deflection of the Flexible Panels
C_c	Derivative Gain
η_i	Energy Dissipation Per Stress Cycle
t_f	Final Time
$E_i I_i$	Flexural Rigidity
ε_i	Generalized
A_j	Generalized Coordinate of the System
$\boldsymbol{Q}$	Generalized Forces
X, Y and Z	Global Coordinate System
H	Hamiltonian
h_i	Height of Panel

$\hat{C}_1, \hat{C}_2, \hat{C}_3$	Inertia Frame of Coordinate System of RW
t_0	Initial Time
T_{di}	Kinetic Energy Due To Flexible Motion
T_i	Kinetic Energy Due To Rotation
T_R	Kinetic Energy of The Rigid Body
L	Lagrangian
L_i	Length of Panel
p_i, q_i, r_i	Local Coordinate System of Flexible Panel
a_i, b_i, c_i	Magnitude of OPi Vector
μ_i	Magnitude of The Deflection
$M, M_{k,i}$	Mass Matrix
ρ_i	Mass Per Unit Volume of Flexible Panel
$\boldsymbol{W_i}$	Matrix of The Velocity of Unit Mass of The Flexible Panel
N	Moment
I_x, I_y, I_z	Moment of Inertia of The Satellite Body
$\omega_{n,i}$	Natural Frequency of i-th Panel
n	Number of Panel
m	Number Or Modes
u^*	Optimal Control
R_i	Position Vector (Local Coordinate)
V_i	Potential Energy Is Associated Strain Energy
k_c	Proportional Gain
$\boldsymbol{q}, \boldsymbol{q}_{123}, q_4$	Quaternion
$\dot{\boldsymbol{\theta}}_s$	Rate of Angular Rotation of The Satellite
$\tau_{r,i}$	RE Generated Torque
$\dot{\theta}_X, \dot{\theta}_Y, \dot{\theta}_Z$	Satellite Angular Velocity
$\theta_X, \theta_Y, \theta_Z$	Satellite Attitude Rotation
$\O_{i,j}$	Shape Function
$K, K_i, K_{k,i}$	Stiffness Matrix
σ_i	Stress In The System
$S(t)$	Switching Function
$\mathbf{I_s}$	The Total Moment of Inertia
τ_{req}	Torque Required

$\tau_{X}, \tau_{Y}, \tau_{Z}$	Torques
T	Total Kinetic Energy
$^{B}\boldsymbol{G}^{A}$	Transformation Matrix of Qi-Ri Plane
$^{O}\boldsymbol{F}^{P}$	Transformation Matrix of X-Y Plane
$^{C}\boldsymbol{R}^{w}$	Transformation Matrix That Relates The Wheel Frame To The Satellite Body Frame
I, j, k	Unit Vector Notation
$\overline{OP_i}$	Vector of Pi from O
w_i	Width of Panel
E_i	Young Modulus

Kawalan optimum pemutaran sikap untuk satelit kelas RazakSAT® berdasarkan model tegar dan fleksibel.

ABSTRAK

Peningkatan keperluan terhadap prestasi satelit telah menyebabkan penggunaan tenaga yang semakin meningkat. RazakSAT-2 adalah program satelit baru yang akan dilengkapi dengan panel suria yang lebih besar untuk menghasilkan tenaga yang mencukupi bagi tujuan tersebut. Ini akan menyebabkan fleksibiliti menjadi menonjol dalam sistem satelit. Operasi satelit adalah sangat sensitif terhadap gangguan gerakan kenyal dan had masa. Oleh itu, pemahaman terhadap kelakuan sistem adalah penting untuk mendapat penyelesaian kepada situasi masa operasi yang terhad dan masalah fleksibiliti. Kaedah Bingkai Rujukan Terapung telah digunakan untuk menperoleh model matematik sistem satelit yang terdiri daripada tiga panel solar. Di samping itu, model dinamik untuk sistem empat roda reaksi dan kawalan maklum balas Quaternion paksi Eigen juga diperolehi. Seterusnya, simulasi model dijalankan dengan perisian MATLAB dan ANSYS untuk tujuan pengesahan model. Melalui simulasi tersebut, peratusan ralat min persegi yang diperoleh adalah rendah iaitu di antara kadar peratusan 2.015% hingga 4.841%. Ini bermaksud model yang diperoleh itu adalah mencukupi untuk menggambarkan dinamik sistem satelit tersebut. Dengan menggunakan model dinamik tersebut, kawalan optimum digunakan untuk meminimumkan masa bagi mencapai orientasi yang dikehendaki. Di samping itu, kaedah tersebut juga dapat meminimumkan amplitud kenyal panel suria. Perisian GPOPS telah digunakan untuk tujuan tersebut. untuk mengarahkan satelit ke arah yang diingini sambil meminimumkan amplitud kenyal panel suria. Kawalan optimum telah menunjukkan pengurangan masa manuver sebanyak 3.49% hingga 25.11% untuk perbandingan antara maneuver Axis Eigen dengan pengawal konvensional maklum balas Quaternion paksi Eigen. Fenomena ini disumbangkan oleh dua factor utama, iaitu, kawalan optimum dapat menggunakan sepenuhnya keupayaan roda reaksi manakala pengawal maklum balas Quaternion paksi Eigen dipengaruhi oleh batasan pseudo-inverse. Ini menyebabkan peningkatan prestasi roda reaksi maksimum sebanyak 35%. Kedua, penggunaan kawalan optimum membolehkan trajektori untuk menyimpang dari paksi Eigen kepada paksi yang mempunyai kelisan yang lebih tinggi bagi mencapai manuver yang lebih pantas. Dari segi prestasi penggunaan model tegar dan fleksibel dalam kawalan optimum, ia telah menunjukkan bahawa pergerakkan fleksibel dapat dihapuskan pada kadar 10.53% lebih cepat untuk model fleksibel. Faktor utama yang mempengaruhi masa manuver adalah frekuensi semula jadi sistem satelit. Kesan frekuensi semula jadi terhadap kawalan optimum diperhatikan menunjukan bahawa masa manuver meningkat apabila frekuensi semula jadi berkurangan. Untuk kerja-kerja masa depan, parameter tambahan seperti kesan pengikatan, gangguan luaran dan pengagihan jisim ketidakseimbangan pada badan satelit yang tegar dan fleksibel akibat pemesongan perlu dikaji. Ini boleh menyumbang kepada model fleksibel yang lebih baik dan meningkatkan ketetapan model.

Optimal control of attitude maneuvering for RazakSAT® class satellite based on rigid and flexible model.

ABSTRACT

The increase in demand for performance for satellite capabilities has pushed the design of the system to be more and more power consuming. This is the case for RazakSAT-2, which is a new satellite program that will be equipped with bigger solar panel to generate sufficient power. Thus, this translates to a higher flexibility in the satellite. Satellite mission is known to be highly sensitive to the flexible motions and it is time constrained. Hence, understanding the behavior of the system is required to solve the time constrain flexibility problem. The Floating Reference Frame is applied to obtain the mathematical model of the system which consists of three solar panels. In addition, the model for the actuator is also developed for a four-reaction-wheel system and the Eigen-axis Quaternion Feedback control is also derived. The obtained model is simulated using the MATLAB and ANSYS software for verification of the model. The obtained Percentage Root Mean Square Error falls between 2.015% to 4.841% which is low. Hence, this signifies that the model is sufficient to describe the dynamic of the system. From the model, the control of the minimum time optimal control is developed to minimize the time to achieve desired orientation while minimizing the amplitude of the flexible solar panel. GPOPS toolbox is applied to obtain the optimal control solution. The optimal control is shown to decrease the maneuver time by 3.49% to 25.11% depending on the Eigen Axis of the rotation compared to the conventional Eigen-axis Quaternion Feedback controller. This phenomenon is contributed by two factors. Firstly, the optimal control is able to fully utilize the all the capacity of the reaction wheel while the Eigen-axis Quaternion Feedback controller is plagued by the pseudo-inverse limitation which allows a maximum 35% increases in performance. Secondly, the application of optimal control allows the trajectory to deviate from the effective Eigen axis to achieve faster maneuver by utilizing the torque that is unavailable to the effective Eigen axis maneuver. In terms of the performance of the rigid and flexible model in the optimal control, it shown that the flexible motion converges at 10.53% faster for the flexible model. The primary factor that affects the maneuver time is the natural frequency of the system. The effect of the natural frequency is observed in this section and is shown that maneuver times increase when the natural frequency decreases. For future works, additional parameters such as the stiffening effect, external disturbances and the imbalance mass distribution on the rigid and flexible due to the deflection are studied. This can contribute to a more refined flexible model that would further increase the accuracy of the model.

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter presents an introduction of the thesis that includes the research background, problem statement, objectives, scopes and the thesis organization. An overview flow chart of the research is illustrated in Section 1.7 of this chapter.

1.2 Research Background

RazakSAT, as shown in Figure 1.1 is launched into low Earth orbit on 14 July 2009. It is placed into a near-equatorial orbit that presents many imaging opportunities for the equatorial region. It weighs over three times as much as TiungSAT-1 and carries a high resolution Earth observation camera. The satellite is intended to provide greatly increased coverage of Malaysia, compared to most of the other earth observation satellites. RazakSAT 2 Satellite Program is a continuation of the strategic satellite technology development of RazakSAT. The program aims to strengthen the satellite technology of Malaysia in the aspect of infrastructure, human capital and industry's capabilities enhancement. The ever increasing demand for the complexity and advancement of space missions leads the satellite to be designed with deployable appendages such as solar panels, booms or antennas that are flexible in the nature. In 1958, the first spacecraft was launched by the United States which incorporated solar panels appendages was the Vanguard 1 satellite. The spacecraft design was largely influenced by Dr. Hans Ziegler who is regarded as a pioneer to the spacecraft solar power (Perlin, 2004).

Solar panel designed on the satellite supplies power for two primary purposes, namely the power to operate the sensors, active heating, cooling and telemetry while the power for the satellite propulsion is the electric propulsion, or sometimes it is also called the solar-electric propulsion (Doody, Stephan, & Fisher, 2015). Hence, the solar panel requires a large surface area that allows it to be pointed towards and exposed to the sun as the satellite moves to collect the sunlight and turn it into power for the system. Generally, satellite is built so that the solar panel is pivoted on the satellite body as it moves. Thus, the panel can be shifted to remain in the direct path of the sun light regardless of what the attitude of the satellite is pointed even if the rest of the body of the satellite moves around. The larger surface area of the solar panel, the more electricity can be converted from light energy from the Sun. Since satellite is designed to be compact and small, this has posed a limitation on the amount of power that can be generated (Doody, 2015).

Attitude maneuvering is the most fundamental function of satellite that is essential to complete mission requirements. The attitude maneuvering of the satellite is usually done by rotating around the three primary axes, namely the roll, pitch and yaw axis. In the rotational maneuvers of satellite system with large flexible panel, elastic deformations in the flexible appendages are often present (Elmadany et al., 2013). The solar panel is an essential satellite element as well as the potential sources of vibratory motion. In space operation, problems with minuet vibrations are particularly acute where precision is a critical aspect of completing any space mission due to the fact that satellite missions usually focus their attention on small objects at very great distances away so that any minor local disturbances can greatly become accentuated. The flexibility will become prominent when the size of the panel increases, the lower Young's Modulus material is used for the structure of the appendages and the larger angle of rotation. Nevertheless, the weight of the satellite is a critical issue that must be kept to a minimum while an increase in the strength of high-performance materials does not match in terms of their stiffness where it has evolved to be lighter, flexible and vibration-prone.

Figure 1.1: RazakSAT Satellite (ATSB, 2016)

The structure of the satellite attitude maneuvering system consists of two important sections, namely the attitude control and the satellite dynamics. The attitude control confines the controller and the actuator which provide the torque into the satellite system to obtain the desired angle of rotation. The satellite dynamics describes the response of the satellite system to the given input provided by the actuator. Generally in a satellite system, control engineers typically employ different types of actuators to perform spacecraft attitude control. Satellite applies the gravity gradient stabilization or magnetic control technique to control the satellite's attitude because they are simple and cost less. However, these methods are only able to achieve low accuracies and limited control torques because they are dependent on the gravitational field and the geomagnetic field condition. Hence, Momentum Exchange Device (MED) becomes preferable to cope with these limitations. One of the most common MED is the Reaction Wheel (RW), which generates a reactionary body torque and momentum by counter-rotating a small rotor. RWs are simple to control and have a high momentum capacity, which translates to high angular velocity rates for the satellite. It is common for a satellite to be designed with three or more RWs (S. Nudehi et al., 2008). The RWs are prevalent, cost less, are mechanically simpler, weigh less, and are easier to control compared to other types of actuator (Crews, 2013). An example of a four RWs system is shown in Figure 1.2.

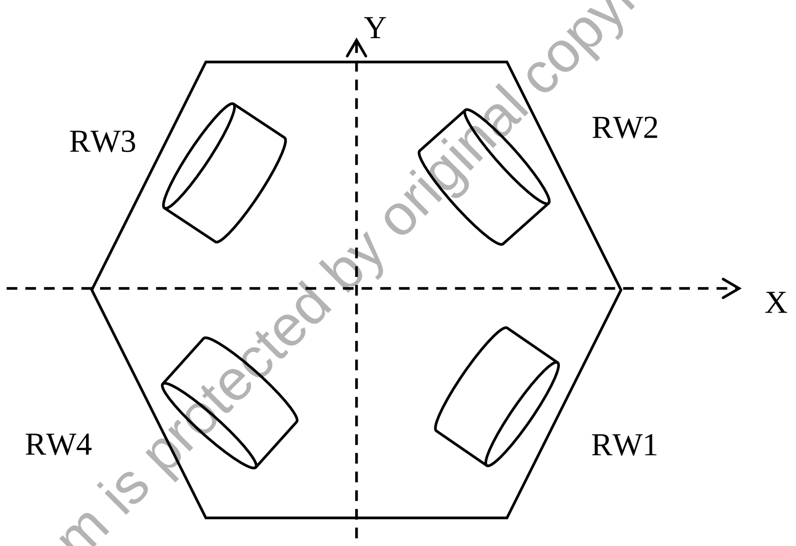

Figure 1.2: Configuration of RWs

Satellites are sometimes required to reorient or reposition as soon as possible with the condition that the structural vibrations are minimal. Achieving such control task for the systems becomes difficult when many structural flexible modes exist in the satellite. Vibration control can be classified as passive control where devices lack feedback capability. The active control involves the real-time recording instrumentation integrated with input processing equipment and actuators within the structure. Hybrid control devices have combined features of active and passive control systems (Chu et al., 2005). However, due to the constrain of power supply, active and hybrid control is not ideal in satellite mission. Hence, a time optimal control is applied to achieve the desired output where optimal control function for the atttiude change torque is applied in the satellite system. The time optimal solutions are usually obtained using numerical methods that are generally computationally extensive where time-optimality Pontryagin Minimum Principle (PMP) is applied (Wie, 2008). The Minimum Principle is a set of necessary conditions for optimality formulated in 1956 by Lev Pontryagin (Naidu et al., 2002). PMP provides necessary conditions for obtaining the time-optimal control solutions. In the case of the satellite attitude maneuvering for a rest-to-rest rotation, bang-bang control is applied for the PMP because of its simplicity which only consists of switching the excitation between the two boundary values to achieve the desired attitude change. The time-optimality for a bang-bang control only depends on the times when the switches take place while maintaining the load constant between the positive and negative value (Clarke, 2013).

The solution to the optimal control is observed via virtual and physical experimental simulation. Physical experiment involves the scaled or exact reproduction of the processes in the laboratory that the material is subjected to the actual in space. However, the cost of physical simulator is high due to the requirement to emulate the space environment which is near vacuum and no gravitational field. Alternatively, a virtual simulation is able to model a real-life situation in a computer so that it can be studied to observe how the system works by changing variables in the simulation and the predictions may be made about the behavior of the system. Virtual simulation is selected for observing the response of the satellite system. It is defined as the imitation of the response or operation (Banks, 2005). In order to simulate the satellite system, the dynamic model must be obtained which is the representation of the key characteristics or behaviors of the physical or abstract system. The developed dynamic model represents the satellite system itself while the simulation is the representation of the operation of the satellite system. Simulation can be used to illustrate the effects of desired alternative conditions and courses of action of the dynamic motion. In addition to that, simulation is ideal because the actual operational environment of the satellite is difficult to engage because it is not easily accessible or it may simply not exist (Sokolowski et al., 2008).

1.3 Problem Statement

The current RazakSAT Satellite System applies a rigid model which is shown in Figure 1.3. A rigid model is a simple assumption that idealizes the behavior of the structure as a non-deformable block of body. This has provided simplified solution to the attitude rotation and much of the satellite relies on this rigid body assumptions. However, a rigid body never exists in the physical world, and it is essentially just idealized assumption (Hughes, P.C., 2012). The model has a very little physical representation of the real behavior of the satellite structure. In the form of multi-body satellite where flexible deformable bodies make up a significant part of the system, then flexibility must be considered into the dynamic model (Azadi et al., 2015). An ill-defined dynamic model inherits inaccuracy and unpredictability to the attitude maneuvering of the satellite system. This threatens a critical operation such as satellite imaging which is highly sensitive to the vibration and leads to a decline in imaging quality of space camera in satellite remote sensing imaging (Haghshenas, 2015). In order to cater to these problems, understanding the dynamics of the structure is the primary step to describe the system.

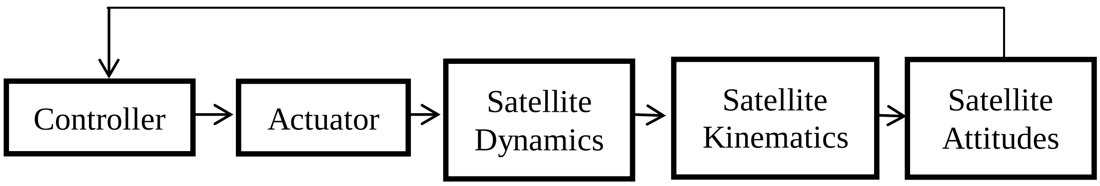

Figure 1.3: Block diagram of rigid satellite dynamic

An Eigen-axis Quaternion Feedback (EQF) controller is developed for satellite Eigen-axis rotational maneuver. The controller basically consists of a linear feedback of error and body rates with the natural gyroscopic coupling torque. It works by continuously taking measurements using a sensor and making calculated adjustments to rotate the satellite attitude to the desired state. Through the EQF controller, the attitude maneuvering is able to perform a multiple-axis rotation with a single axis of rotation via the Eigen-axis. This is an advantage to the attitude maneuvering provided that the controller is able to access to the full capacity of the actuator. However, for the satellite system in order to provide for redundancy, the RW assembly includes at least one additional RW. This configuration of the RW is applied in RazakSAT satellite (Lee, H. et al., 2002). The four RWs are configured in the pyramidal form. The use of four or more wheels presents a control allocation problem. This is caused when torque or momentum required in the body frame must be produced by the redundant set as well. A common method of torque and momentum allocation is to use the Moore-Penrose pseudo-inverse, which provides a least squares solution. According to this approach, the full magnitude of the torque capacity generation of RW may not be available in every direction. The pseudo-inverse does not take physical wheel limitations into account and