UNIVERSITI PUTRA MALAYSIA

ENHANCED ATTITUDE CONTROL STRUCTURE FOR SMALL SATELLITES WITH REACTION WHEELS

ZULIANA BINTI ISMAIL

ENHANCED ATTITUDE CONTROL STRUCTURE FOR SMALL SATELLITES WITH REACTION WHEELS

By

ZULIANA BINTI ISMAIL

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

August 2019

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

ENHANCED ATTITUDE CONTROL STRUCTURE FOR SMALL SATELLITES WITH REACTION WHEELS

By

ZULIANA BINTI ISMAIL

August 2019

Chair : Y.Bhg. Prof. Dato' Renuganth Varatharajoo, PhD, Ir
Faculty : Engineering

Attitude accuracies of a three-axis satellite are highly influenced by space environment disturbances and uncertainties. Similar to actuators, an attitude controller also plays an important role and must be robust enough to cope with any disturbances and uncertainties. Various controllers have been used for satellite attitude controls either linear or nonlinear control theories. This thesis presents an enhanced attitude control structure for a small satellite with reaction wheels (RWs) and the wheel angular momentum unloading control using magnetic torquers (MTQs). In order to improve the attitude control performances, a proportional derivative-active force control (PD-AFC), and a Fuzzy PD-AFC are developed. For the momentum unloading control, a Fuzzy-proportional integral (Fuzzy-PI) is developed to remove the excess wheel momentum. Using the PD-AFC and Fuzzy PD-AFC, the actual disturbances torques are considered totally rejected by the system without having to have any direct prior knowledge on the actual disturbances itself. These days, however, satellites have become increasingly more complex, with many additional components, such as antennas, cameras, solar panels and mechanical manipulators. These components introduce flexible mode which results in a satellite dynamic system becoming highly nonlinear. Therefore, a robust nonlinear controller such as sliding mode control (SMC) is highly desirable. Besides, a number of studies have shown that, fractional order controller (FOC) could enhance the control system performance due to its extra degrees of freedom. In this thesis, a fractional order sliding mode control (FOSMC) is developed. In fact, this current work will be one of the maiden works on FOSMC for small satellites. All the proposed controllers were also tested for a satellite with only two functional RWs, in which the control allocation technique is proposed to solve the underactuated satellite attitude control problem. All the relevant attitude control architectures are developed together with their governing equations. Eventually, all control algorithms are numerically treated and analysed. The research results obtained proved that the PD-AFC, Fuzzy PD-AFC and FOSMC to be successful in achieving the overall stability attitude control system in the presence of external disturbances and

uncertainties, i.e., PD-AFC ($\pm 0.0040° - 0.0055°$); Fuzzy PD-AFC ($\pm 0.0010° - 0.0015°$); FOSMC (± 0.00020), and with the Fuzzy-PI for momentum unloading control whereby, the wheel momentum can be well maintained. Finally, the research for underactuated satellite attitude control performances using two RWs have been also successfully demonstrated and the research results proved that the control allocation technique provides a good performance in controlling the satellite attitude.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah ijazah Doktor Falsafah

STRUKTUR KAWALAN ATITUD DIPERTINGKATKAN UNTUK SATELIT KECIL DENGAN EMPAT RODA REAKSI

Oleh

ZULIANA BINTI ISMAIL

Ogos 2019

Pengerusi : Y.Bhg. Prof. Dato' Renuganth Varatharajoo, PhD, Ir
Fakulti : Kejuruteraan

Ketepatan attitud satelit tiga paksi sangat dipengaruhi oleh gangguan persekitaran angkasa dan ketidakpastian. Sama seperti penggerak, pengawal attitud juga memainkan peranan penting dan mesti cukup mantap untuk mengatasi sebarang gangguan dan ketidakpastian. Pelbagai pengawal telah digunakan untuk mengawal attitud satelit sama ada teori kawalan linear atau tidak linear. Tesis ini membentangkan struktur kawalan attitud yang dipertingkatkan untuk satelit kecil dengan roda reaksi dan kawalan momentum roda reaksi menggunakan tork magnet. Untuk meningkatkan prestasi attitud, PD-AFC dan Fuzzy PD-AFC direka bentuk. Untuk kawalan momentum roda reaksi, Fuzzy-PI direka untuk mengurangkan momentum yang berlebihan. Menggunakan PD-AFC dan Fuzzy PD-AFC, tork gangguan boleh dibatalkan oleh sistem tanpa memerlukan pengetahuan terlebih dahulu mengenai gangguan sebenar tersebut. Kini, sistem satelit semakin kompleks, dengan banyak komponen tambahan, seperti antena, kamera, panel solar dan manipulator mekanik. Komponen ini memperkenalkan mod fleksibel yang mengakibatkan sistem dinamik satelit menjadi sangat tidak linear. Oleh itu, pengawal bukan linear yang mantap seperti pengawal mod gelongsor SMC amat sesuai. Selain itu, beberapa kajian telah menunjukkan bahawa, fractional order control (FOC) dapat meningkatkan prestasi sistem kawalan. Dalam tesis ini, gabungan FOC dan SMC (FOSMC) direka. Malah, kajian ini akan menjadi salah satu kajian sulung untuk FOSMC diaplikasikan di satelit-satelit kecil. Semua pengawal yang dicadangkan juga telah diuji untuk satelit yang hanya ada dua roda reaksi yang berfungsi, di mana teknik peruntukan kawalan dicadangkan untuk menyelesaikan masalah pengendalian attitude satelit yang kegagalan roda reaksi. Kesemua arkitektur kawalan atitud yang relevan dibangunkan bersama dengan persamaan asas. Seterusnya, semua algoritma kawalan diuji secara berangka dan keputusan dianalisisa. Keputusan kajian yang diperoleh membuktikan bahawa PD-AFC, Fuzzy PD-AFC dan FOSMC berjaya mencapai kestabilan keseluruhan walaupun adanya gangguan luar dan ketidakpastian sebagai contoh; PD-AFC (±0.0040°-0.0055°); Fuzzy PD-AFC (±0.0010°-0.0015°); FOSMC (±0.00020), dan dengan Fuzzy-PI untuk kawalan momentum, momentum roda reaksi dapat

dikawal dengan baik. Akhir sekali, kajian yang hanya ada dua roda reaksi yang berfungsi telah berjaya ditunjukkan dan keputusan kajian membuktikan bahawa teknik peruntukan kawalan memberi prestasi yang baik dalam mengawal attitude satelit.

ACKNOWLEDGEMENTS

All praises are due to Allah S.W.T, for all his blessings for giving me patience and good health throughout the duration of this PhD research. May Allah's peace and blessings be upon His final prophet and messenger, Muhammad S.A.W, his family and his companions.

First and foremost, I wish to express my special appreciation and thanks to Y.Bhg. Prof. Dato' Dr.-Ing. Ir. Renuganth Varatharajoo, Chairman of the Supervisory Committee for his dedications and overwhelming guidance throughout the completion of the research. I am also very thankful to the members of the Supervisory Committee: Associate Professor Lt. Kol (R) Mohd Ramly bin Mohd Ajir and Associate Professor Dr. Azmin Shakrine Bin Mohd Rafie for all the valuable contributions and assistances in this research.

Thanks to Dr Chak Yew-Chung, Miss Nurhana M. Rouyan, Mrs Samira Esghi Khouzani, Dr Aaron Aw Teik Hong and Mr Effendi for their helps, supports and suggestions throughout my work. Special thanks to my dearest husband, my daughters and my son for their constant support. Finally, my deepest gratitude goes to my lovely parents and siblings for continuously supporting me during my study life.

Last but not least, I gratefully acknowledge financial support provided by MyBrain MyPhD Scholarship and UPM SGRA scheme.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Renuganth Varatharajoo, PhD
Professor, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Azmin Shakrine Bin Mohd Rafie, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohd Ramly bin Mohd Ajir, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ________________________ Date: __________________

Name and Matric No.: Zuliana Binti Ismail, GS34243

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature:	
Name of Chairman of Supervisory Committee:	Prof. Dato' Dr.-Ing. Ir. Renuganth Varatharajoo

Signature:	
Name of Member of Supervisory Committee:	Assoc. Prof. Dr. Azmin Shakrine bin Mohd. Rafie

Signature:	
Name of Member of Supervisory Committee:	Assoc. Prof., Lt. Col. (R) Mohd. Ramly bin Mohd. Ajir

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AFC	Active Force Control
ACS	Attitude Control System
ADCS	Attitude Determination and Control Subsystem
CEACS	Combined Energy and Attitude Control System
CMG	Control Moment Gyros
CLF	Control Lyapunov Function
DCM	Direct Cosine Matrix
DOBC	Disturbance Observer Based Control
FIS	Fuzzy Inference System
FOC	Fractional Order Control
FOSMC	Fractional Order Sliding Mode Control
GPS	Global Positioning System
LEO	Lower Earth Orbit
MF	Membership Function
MTQ	Magnetic Torquer
PD	Proportional-Derivative
PI	Proportional-Integral
PID	Proportional–Integral–Derivative
RW	Reaction Wheel
SMC	Sliding Mode Control
IAA	International Academy of Astronautics
LQR	Linear Quadratic Regulator
MIMO	Multi Input, Multi Output
NASA	National Aeronautics and Space Administration

LIST OF SYMBOLS

a	Semi-major axis $[m]$
ζ	Damping Ratio for the attitude control loop
$\mu_{\oplus}$	Earth gravitational constant, $\mu_{\oplus} = 3.986 \times 10^{14} m^3/s^2$
μ_f	Magnetic field's dipole strength. $\mu_f = 7.9 \times 10^{15} Tesla \cdot m^3$
ω	Argument of perigee
ω_o	Orbital frequency [rad/s]
ω_{Earth}	Earth's rotation frequency, $\omega_{Earth} = 7.29211515 \times 10^{-5} ra\,d/s$
ω_n	Natural Frequency for the attitude control loop [rad/s]
$\omega_x, \omega_y, \omega_z$	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]
$C(\boldsymbol{q})$	Transformation Matrix
ϕ	Roll attitude [rad or degree]
θ	Pitch attitude [rad or degree]
ψ	Yaw attitude [rad or degree]
Φ	Euler angle of rotation
Ω	Right ascension of ascending node
v	True anomaly
$[\boldsymbol{R}_{rw}]$	Reaction wheel allocation matrix
B^2	Magnitude of the Earth's magnetic field vector [Tesla]
$\boldsymbol{B}$	Earth's magnetic field vector in the Body coordinate system [Tesla]
B_0	Average magnetic field intensity in low earth orbit, $B_0 = 2.5 \times 10^{-5} Tesla$
C_s	Solar radiation constant, Cs =1358 W/m^2
c	Speed of light, $c = 3 \times 10^8$ m/s
e	Euler axis of rotation
h	Satellite's Altitude
$\boldsymbol{h}_w$	RW momentum of a satellite [kgm^2s^{-1}]
i	Satellite orbit inclination with respect to the equatorial plane
$\boldsymbol{J}$	Satellite moments of inertia [kgm^2]
$\Delta\boldsymbol{J}$	Uncertainty of moment of inertia tensor
$\boldsymbol{K}_p$	Proportional attitude control gain
$\boldsymbol{K}_i$	Integral attitude control gain
$\boldsymbol{K}_d$	Derivative attitude control gain
$\boldsymbol{m}$	Magnetic dipole moments of the magnetic torquers [Am^2]
M_E	Geomagnetic strength of dipole, $7.9 \times 10^{15} Wb \cdot m^{-1}$
$\boldsymbol{q}_e$	Error of quaternion
q_r	Solar reflectance factor
R_E	Radius of the Earth, $R_E = 6378 km$
s	Sliding mode surface
T_o	Period of orbit
$\boldsymbol{T}_w$	Applied torque vector by reaction wheels [Nm]
$\boldsymbol{T}_m$	Magnetic torque vector induced by magnetic torquers [Nm]
$\boldsymbol{T}_d$	External disturbance torque vector [Nm]
$\boldsymbol{T}_{pd}$	PD control torque [Nm]
$\boldsymbol{T}_{pdafc}$	PD-AFC control torque [Nm]

$\boldsymbol{T}_{f}$	Fuzzy control torque [Nm]
$\boldsymbol{T}_{fpdafc}$	Fuzzy PD-AFC control torque [Nm]
$\boldsymbol{T}_{smc}$	Sliding mode control torque [Nm]
$\boldsymbol{T}_{eq}$	Equivalent control torque [Nm]
$\boldsymbol{T}_{sw}$	Switching control torque [Nm]
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
$(\cdot)^{\times}$	Cross-product operator
η	Positive constant for sliding condition
λ	Minus slope of the sliding surface
Φ	Euler angle of rotation
b	Boundary layer

CHAPTER 1

INTRODUCTION

1.1 General Overview

A satellite is a space vehicle launched by a rocket and placed in an orbit around the Earth. It is designed for various applications such as Earth observation, weather forecasting, communications, scientific exploration, defence purposes, and also for university experiments. In recent years, the development of small satellites has gained more attention than that of the larger satellite because it can be developed to actualise advanced space missions at low cost in short amount of time, with less complexity and the ability to provide valuable scientific returns (Inamori, 2012).

According to International Academy of Astronautics (IAA), small satellites can be categorised into four groups based on their weight which are minisatellite (less than 1000 kg), microsatellite (less than 100kg), nanosatellite (less than 10 kg), and picosatellite (less than 1 kg) (Ram S & Joseph N, 2014). The progressive development of Micro-Electro-Mechanical Sensors (MEMS) and Commercial Off-the-Shelf Components (COTS) contributed to the emerging of small satellites space mission in the recent years.

The Attitude Determination and Control System (ADCS) is one of the satellite subsystems which is the primary field area covered in this research. Most of the satellite components can be miniaturised to reduce the cost and at the same time able to retain their high performance (Nicolai et al., 2014). Nevertheless, all must-have seven subsystems in any satellites are summarised in Table 1.1.

Table 1.1: The function of each satellite subsystems (Larson & Wertz, 2005)

Satellite Subsystems	Functions
Attitude Determination and Control System (ADCS)	Determines and controls the satellite angular orientation throughout the mission.
Telemetry, Tracking and Command (TTC)	Provides satellite housekeeping data to the ground station.
Command and Data Handling (CDH)	Distributes commands received from the ground station to the satellite.
Power	Provides and manages power to the satellite.
Structures and Mechanism	Provides an interface for all subsystems
Guidance and Navigation:	Determines the satellite's state vector and its orbital elements.
Thermal	Provides acceptable temperature ranges for all the satellite's component.

The ADCS can be categorised into two separate subsystems, namely the Attitude Control System (ACS) (i.e. the control actuators) and the Attitude Determination

System (ADS) (i.e., the attitude and angular velocity sensors). The commonly used attitude sensors include Sun sensors, Earth sensors, magnetometers, star trackers, Global positioning systems (GPS), and gyroscopes, where the details are described in (Larson & Wertz, 2005). However, the primary focus of this thesis is only on ACS studies. ACS is a substantial subsystem of a satellite in controlling and maintaining the high accuracy autonomous attitude pointing and rapid slewing capabilities in the presence of environmental and systematic errors.

Upon separating from the launch vehicle, the satellite will tumble to an undefined angular rate. As shown in Figure 1.1, this first phase is called as the detumbling mode where the satellite's angular rate is reduced to a lower speed through the attitude acquisition process. Then, the satellite will be put into the safe mode (sun pointing) where the satellite slews such that its solar panels face the sun to allow the battery to be charged and this mode is also used in backup emergency in case normal operation mode fails. Next, in the idle mode, the satellite's batteries will be charged efficiently and is standby for inertial pointing mode, nadir pointing mode and target pointing mode (Pong et al., 2010).

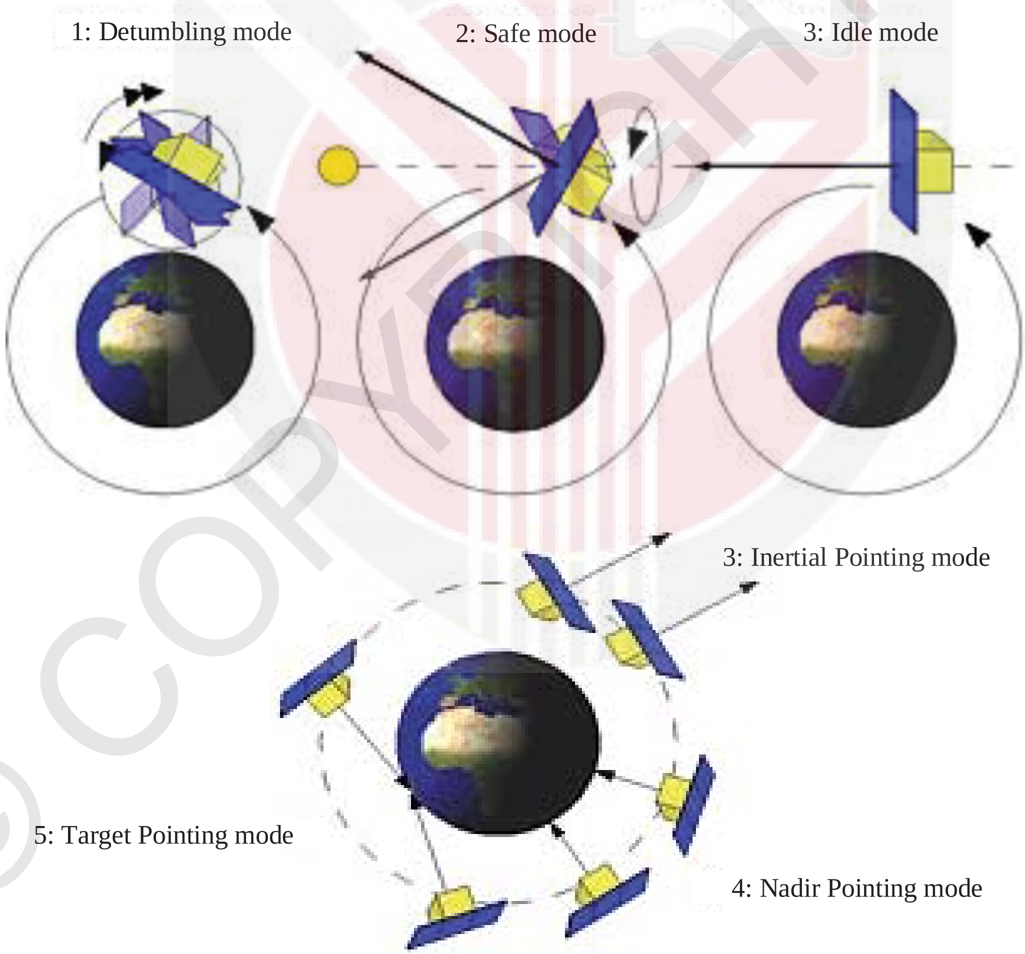

Figure 1.1: Satellite's phase (Klinkner, 2012)

In the inertial pointing mode, the cameras can be pointed to a celestial object like stars, the sun, or the moon. In the nadir pointing mode, the payload cameras are pointed "directly down" towards the Earth and while in target pointing mode, the satellites are pointed towards a specific target. Besides the attitude pointing, the attitude tracking is also required to be performed for specific missions especially for the satellite with a limited supply of electrical power where it has to track a Sun-optimal trajectory. Other than that, the communication satellites have to track other satellites passing by either for transmitting or receiving data. Furthermore, some satellites need the attitude tracking if the satellites have the mission to collect measurement and to take pictures of objects from far away (Mohammad & Ehsan, 2008). Thus, to enable the attitude control for the entire duration of the mission with agile manoeuvring capabilities and high pointing accuracies, the robust attitude control system is highly desired.

Besides, the satellite's lifespan is in the range of 1 to 10 years, and throughout the mission, the satellite design, development, and operation can be affected by the natural space environment. In addition, the satellites in their orbits are also influenced by unwanted motions such as the libration, nutation, and precession if no countermeasures are performed by the satellite. The attitude stabilisation methods can be categorised into two main methods, which are the active control method and the passive control method. The brief description of both methods is summarised as illustrated in Figure 1.2.

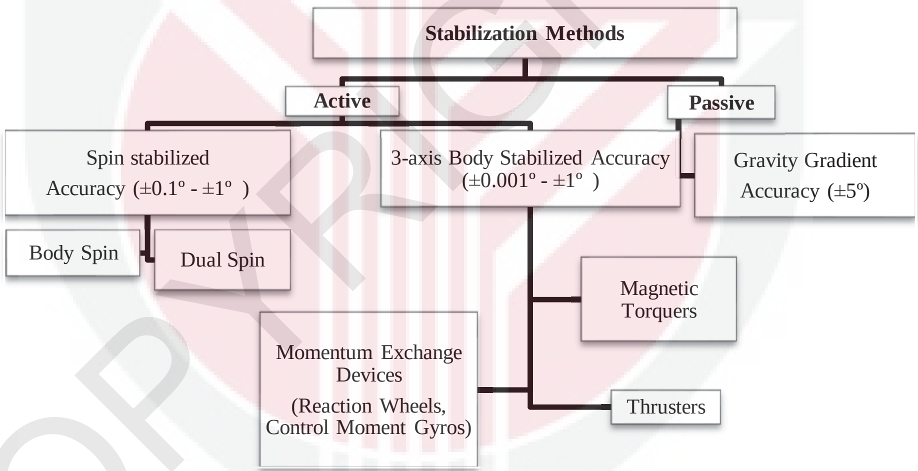

Figure 1.2: Satellite attitude stabilization methods (Larson & Wertz, 2005)

In the early days of the space era, passive controls were the favoured option for a space mission. A passive technique using gravity gradient stabilisation is sufficient enough for early satellite missions such as Explorer 1 and Intelsat 1. Less hardware used, fuel-free, simple, and low cost are the factors contributing to the adoption of passive techniques (Sidi, 1997). In the middle of the space era, passive techniques were no longer relevant due to the transition from a small space mission to the more massive satellite with the sizes ranging in hundreds of kilograms.

Meanwhile, three-axis stabilisation technique is preferable compared to spin stabilisation because the three-axis stabilisation could provide greater pointing accuracy in the order of very accurate milli-radians and could allow solar arrays to be continuously oriented towards the sun (Ram S & Joseph N, 2014). Nevertheless, in an effective three-axis stabilisation technique, the satellite must have the actuators to produce angular torque. The selection of actuator is based on the mission of the satellite. For a short mission duration, a thruster is a good option for spacecraft like Shuttle and Soyuz which does not require high fuel consumption for attitude control. Furthermore, these spacecraft are not built for high pointing accuracy requirements. Besides the thrusters, the momentum exchange devices like reaction wheels (RWs) and control moment gyroscopes (CMGs) are also the common actuators adopted. Both RWs and CMGs are capable of spinning freely and are functioning based on the conservation of angular momentum (zero-momentum biased). When their angular momentum is changed, the angular momentum of the satellite must also change to conserve its net angular momentum.

Either RWs or CMGs are the ultimate options that can provide higher attitude accuracy for satellite attitude control (Larson & Wertz, 2005). RWs spin along a fixed axis at a variable speed and the angular momentum is varied by increasing or lowering the speed. Meanwhile, CMGs spin along a rotating axis at a constant speed and the angular momentum is varied by rotating their spin axis. The reaction torque of RWs acts on the satellite as the wheel speed varied, while the wheel speed is fixed for CMGs resulting in the change of spin axis's direction relative to the satellite. CMGs are suitable for the three-axis control but are often not considered to be used on small satellites due to the complexity of the mechanical and control system needed to implement an effective CMG, see Figure 1.3.

Figure 1.3: Diagram of a) RW torque and b) CMG torque (Votel & Sinclair, 2012)

The magnetic control via the use of magnetic torquers (MTQs) is another favoured option for small satellites either for attitude control or momentum unloading tasks. MTQ are advantageous regarding their low cost and lightweight as they contain no moving parts, making them less vulnerable to failure. The major obstacle in the magnetic actuation is that a magnetic torque will only produce a maximum torque when aligned with the local magnetic field vector. The available torque, therefore, depends on the current local magnetic field vector, and independent torques on all three axis of a control system using three orthogonal magnetic torques are hard to achieve. Accordingly, the yaw axis of the satellite is not controllable over the magnetic poles of the Earth, and the roll axis will lose its torque over the equator. Since the magnetic field is continuously changing, magnetic control has become nonlinear and time-varying. In this study, the RWs are used to control the satellite's attitude while the MTQs are used to unload the wheel momentum.

1.2 Problem statements

Technically, the satellite systems are complicated due to several issues such as time variant, delays, and nonlinearities. Moreover, other factors that contribute to the complexity of the dynamic satellite systems are the presence of uncertainty, actuator saturation, and the actuator faults itself. In general, the significant uncertainties are due to the changes of satellite's inertia matrix as well as the external environmental disturbances. Frequently, the satellite's inertia uncertainties are due to the measurement errors during the pre-launch testing, changes in the overall satellite system configuration, and fuel consumption during the mission (Tiwari et al., 2016). In most cases, the uncertainties and disturbances degrade the satellite attitude control performance and could cause mission failure. Besides, the attitude control system (ACS) needs to provide a high accuracy pointing and manoeuvring capabilities by the selected earth observation instruments and the space missions. Therefore, the attitude controller must be robust enough to cope either the uncertainties or external disturbances and the satellite's attitude is supposed to be in controlled and have good attitude ponting performances for the entire mission.

The RW is chosen as an actuator in this study since it can provide high precision torque and high accuracy. The effectiveness of reaction wheels as satellite actuators is already well known. The famous Hubble Space Telescope (HST) and Midcourse Space Experiment (MSX) spacecraft have proven the capability of reaction wheels in controlling the spacecraft attitude. Despite their known advantages, these momentum exchange may suffers from the drawback of wheel momentum saturation (Yang, 2017). Thus, attitude control system is impractical without the momentum unloading control. Commonly, the MTQs are chosen as the secondary actuators to unload the momentum, and the challenge is to ensure continuous controllability for all three axis. Therefore, the optimum momentum unloading control technique is significant and needs to be designed according to the mission requirements.

Another issue deals with underactuated satellite attitude control which refers to satellite with less than three attitude control actuators. A set of four RWs in a pyramid configuration have been used in this study due to its controllability and redundancy reasons. If one of the RWs fails, the attitude control system can still generate any direction of torque by the remaining wheels. However, if two out of four RWs fail, external disturbances will cause the satellite to lose its ability to correct the attitude error. If the failure is irrecoverable, the satellite's mission could be loss, as experienced by Hayabusa (Choi, 2005) and NASA Kepler spacecraft (Cowen, 2013). However, the three-axis attitude stabilisation is still can be achieved by using the two RWs left and with the assistance of specialised technique by which only a few have been investigated. Hence, this study proposed a control allocation technique to ensure controllability of the underactuated satellite specifically for the satellite with four RWs in a pyramid configuration.

1.3 Research Objectives

The objectives of this research are:

a. To develop robust satellite attitude controllers, namely the active force control (AFC) and the fractional order sliding mode control (FOSMC); and to design a Fuzzy-proportional integral (Fuzzy-PI) controller for the momentum unloading control of satellite reaction wheels.

b. To design a novel attitude control scheme for an underactuated satellite with two reaction wheels through the control allocation technique.

c. To validate the numerical testings and attitude control performances of all the developed satellite attitude architectures together with their governing equations both for nominal and underactuated satellite attitude controls.

1.4 Scope and Limitation of Studies

Several assumptions are set for this research. The satellite is assumed to be a rigid body actuated by four RWs in a pyramid configuration and employs three MTQs for wheel momentum unloading. The satellite is a small satellite that the mass is less than 100kg (microsatellite). The principal axes are aligned with the body axes. The satellite is built for Low Earth Orbit (LEO) and also for the attitude pointing mission. The controllers provided for the typical space missions during the Euler angles are relatively small. The attitude parameterisation via quaternion is employed in this work. The satellite's moment of inertia matrix is known, and its value is constant for the entire duration of the mission. However, the inertia matrix and the external disturbance torques are considered to be uncertain, for instance, 10% of variation is set for the satellite's inertia matrix (Tiwari et al., 2016). The satellite is assumed to be positioned at high inclination orbit because the Earth's magnetic field strength at low inclinations is relatively weak. Thus, the use of MTQs in low orbit inclination is ineffective as only small magnetic control torques can be produced for wheel momentum unloading tasks. Since this study is considered for small satellites, it is essential to define the reasonable magnetic dipole moment saturation limits, especially in the simulation model. For small satellites, the range of the dipole saturation is from 1 Am^2 to 35 Am^2 (J. Lee et al., 2002).

1.5 Thesis Outline

In the first chapter, a brief description regarding small satellites and attitude control methods are introduced. Apart from that, the problem statement and the objectives of the research are also presented. Chapter 2 presents a summary of the literature that has been reviewed which includes the previous and current researches on the satellite attitude control, in both the actuator and controller studies. It covers the implementation of different attitude control laws, the issues on the RW's momentum unloading, the RWs configuration, and an underactuated satellite.

Chapter 3 details all the fundamental satellite theories used in this study such as coordinate systems, attitude representations, and angular velocity. The satellite attitude dynamics and kinematics equation are formulated. The RW's control strategies and the wheel momentum unloading scheme are also presented in this chapter. Chapter 4 describes in details the enhanced control structure for the satellite attitude control with RWs.

The numerical simulations based on the proposed control strategy are presented in Chapter 5. The satellite attitude control and wheel momentum unloading performances for all the cases tested are presented and discussed as well. The conclusion is drawn in Chapter 6, and some suggestions are given for future researches.

REFERENCES

Abdelhamid, D., Bouden, T., & Boulkroune, A. (2014). Design of Fractional-order Sliding Mode Controller (FSMC) for a class of fractional-order non-linear commensurate systems using a particle swarm optimization (PSO) algorithm. *Control Engineering and Applied Informatics*, *16*(3), 46–55.

Acar, Y., & Horri, N. M. (2013). Optimal momentum unloading of reaction wheels in the presence of attitude control errors. In *AIAA Guidance, Navigation, and Control (GNC) Conference*.

Ajorkar, A., Fazlyab, A., Saberi, F. F., & Kabganian, M. (2015). Design of an adaptive-neural network attitude controller of a satellite using reaction wheels. *Journal of Applied and Computational Mechanics*, *1*(2), 67–73.

Al-Khalidy, M. M. M., & Al-Attar, F. A. (2011). Step by step modeling and tuning for fuzzy logic controller. In *Lecture Notes in Electrical Engineering* (Vol. 132 LNEE, pp. 81–92).

Asaee, A. L. I., Balochian, S., & Heshmati, S. (2013). Attitude determination and control of microsatellite using type-1 and type-2 fuzzy logic. *Bulletin of the Polytechnic Institute of Iasi*, *59*(Lxiii), 51–70.

Bandyopadhyay, B., & Kamal, S. (2015). *Stabilization and Control of Fractional Order Systems: A Sliding Mode Approach* (Vol. 317). Springer International Publishing Switzerland.

Benzeniar, H., & Fellah, M. K. (2009). A microsatellite reaction wheel based on a fuzzy logic controller for the attitude control system. *International Review of Automatic Control*, *2*(1), 102–107.

Bonyan, H. (2010). *Looking into Future - Systems Engineering of Microsatellites*. *INTECH Open Access Publisher*.

Bouarroudj, N., Boukhetala, D., & Boudjema, F. (2016). Sliding-mode controller based on fractional order calculus for a class of nonlinear systems. *International Journal of Electrical and Computer Engineering*, *6*(5), 2239–2250.

Burdess, J., & Hewit, J. (1986). An active method for the control of mechanical systems in the presence of unmeasurable forcing. *Mechanism and Machine Theory*, *21*(5), 393–400.

Burns, T. F., & Flashner, H. (1992). Adaptive control applied to momentum unloading using the low Earth orbital environment. *Journal of Guidance, Control , and Dynamics*, *15*(2).

Cao, L., Chen, X., & Sheng, T. (2013). Fault tolerant small satellite attitude control using adaptive non-singular terminal sliding mode. *Advances in Space Research*, *51*(12), 2374–2393.

Chak, Y. C., & Varatharajoo, R. (2015). A novel design of spacecraft combined attitude & sun tracking system using a versatile fuzzy controller. *Aircraft Engineering and Aerospace Technology*, *87*(6), 530–539.

Chen, G., & Pham, T. T. (2001). *Introduction to Fuzzy Sets, Fuzzy Logic and Fuzzy Control Systems*. CRC Press.

Chen, X., Steyn, W. H., Hodgart, S., & Hashida, Y. (1999). Optimal combined reaction-wheel momentum management for Earth-pointing satellites. *Journal of Guidance, Control, and Dynamics*, *22*(4), 543–550.

Chen, Y. Q., Petráš, I., & Xue, D. (2009). Fractional order control - A tutorial. *Proceedings of the American Control Conference*, 1397–1411.

Cheng, C.-H., Shu, S.-L., & Cheng, P.-J. (2009). Attitude control of a satellite using fuzzy controllers. *Expert Systems with Applications*, *36*(3), 6613–6620.

Choi, B. C. Q. (2005). Japan's Asteroid Sample-Return Mission Has Problems. *Space.Com*. Retrieved from http://www.space.com/1642-japan- asteroid-sample-return-mission-problems.html

Chou, J. C. K. (1992). Quaternion kinematics and dynamic differential equations. *IEEE Transactions on Robotics and Automation*, *8*(1), 53–64.

Chulliat, A., Macmillan, S., Alken, P., Beggan, C., Nair, M., Hamilton, B., … Thomson, A. (2015). *The US / UK World Magnetic Model for 2015-2020*. *NOAA Technical Report NESDIS/NGDC.*

Cowen, R. (2013). The wheels come off Kepler. *Nature*, *497*(7450), 417–418.

Efe, M. Ö. (2011). Fractional order systems in industrial automation — A survey. *IEEE Transactions on Industrial Informatics*, *7*(4), 582–591.

El-Khazali, R. (2013). Fractional-order PID controller design. *Computers and Mathematics with Applications*, *66*(5), 639–646.

El-Raffie, A., & Farrag, A. (2006). A hybrid attitude control of a microsatellite via under-actuated reaction wheels and magnetorquers ; last saving action redundancy. *Conference: ICNPAA-2006: Mathematical Problems in Engineering and Aerospace Sciences*, (July).

Eshghi, S., & Varatharajoo, R. (2017). Singularity-free integral-augmented sliding mode control for combined energy and attitude control system. *Advances in Space Research*, *59*(2), 631–644.

Fortescue, P., & Stark, J. (1996). *Spacecraft System Engineering*. John Wiley & Sons.

Fukaishi, T., Sekiguchi, K., & Nonaka, K. (2017). Attitude control of two-wheel spacecraft based on dynamics model via hierarchical linearization. *Sice Journal of Control Measurement & System Integration*, *10*(4), 310–316.

Ge, S. (2006). A comparative design of satellite attitude control system with reaction wheel. *First NASA/ESA Conference on Adaptive Hardware and Systems (AHS'06)*, 359–364.

Ghadiri, H., & Sadeghi, M. (2016). Optimized Fuzzy-Quaternion attitude control of satellite in large maneuver. In *SpaceOps Conferences,16-20 May 2016, Daejeon, Korea* (pp. 1–8).

Giulietti, F., Quarta, A. A., & Tortora, P. (2006). Optimal control laws for momentum-wheel desaturation using magnetorquers. *Journal of Guidance, Control, and Dynamics*, *29*(6), 1464–1468.

Godard, G., & Kumar, K. D. (2011). Robust attitude stabilization of spacecraft subject to actuator failures. *Acta Astronautica*, *68*(7–8), 1242–1259.

Guan, P., Zhang, W., Liu, X., & Li, M. (2011). The direct adaptive fuzzy control for satellite attitude control. *2011 Chinese Control and Decision Conference (CCDC)*, (3), 2185–2190.

Gui, H., Jin, L., & Xu, S. (2013). Attitude maneuver control of a two-wheeled spacecraft with bounded wheel speeds. *Acta Astronautica*, *88*, 98–107.

Hablani, H. B. (1994). Sun-tracking commands and reaction wheel sizing with configuration optimization. *Journal of Guidance, Control, and Dynamics*, *17*(4), 805–814.

Hashemi-Dehkordi, S. M., Abu-Bakar, A. R., & Mailah, M. (2012). Reducing friction-induced vibration using intelligent active force control (AFC) with piezoelectric actuators. *Sadhana - Academy Proceedings in Engineering Sciences*, *37*(6), 637–655.

Hewit, J., & Burdess, J. (1981). Fast dynamic decoupled control for robotics, using active force control. *Mechanism and Machine Theory*, *16*(5), 535–542.

Hogan, E., & Schaub, H. (2013). Three-axis attitude control using redundant reaction

wheels with continuous momentum dumping. *AAS/AIAA Spaceflight Mechanics Meeting*.
Horri, N., & Hodgart, S. (2003). Large angle manoeuvre of an underactuated small satellite using two wheels. *4th IAA Symposium on Small Satellites for Earth …*, (July), 2–5.
Horri, N., & Palmer, P. (2012). Practical implementation of attitude-control algorithms for an underactuated satellite. *Journal of Guidance, Control, and Dynamics*, *35*(1), 40–45.
Hu, Q. (2010). Sliding mode attitude control with L2-gain performance and vibration reduction of flexible spacecraft with actuator dynamics. *Acta Astronautica*, *67*(5–6), 572–583.
Hua, C., Li, Y., Liu, D., & Guan, X. (2016). Stability analysis for fractional-order PD controlled delayed systems. *Journal of the Franklin Institute*, *353*(13), 3118–3132.
Huang, J., Li, H., Chen, Y., & Xu, Q. (2012). Robust position control of PMSM using fractional-order sliding Mode controller. *Abstract and Applied Analysis*, *2012*.
Huo, M., Huo, X., Karimi, H. R., & Ni, J. (2014). Finite-time control for attitude tracking maneuver of rigid satellite. *Abstract and Applied Analysis*, *2014*.
Hur-Diaz, S., Wirzburger, J., & Smith, D. (2008). Three axis control of the Hubble Space Telescope using two reaction wheels and magnetic torquer bars for science observations. In *Advances in the Astronautical Sciences* (Vol. 132, pp. 335–350).
Hurtado, R., & Villota, Y. (2014). Power consumption based on four reaction wheels in a pyramidal configuration. *Advances in Astronautical Sciences Second IAA DyCoss*, *153*, 1–9.
Ibrahim, A. E., Tobal, A. M., & Sultan, M. . (2012). Satellite attitude maneuver using sliding mode control under body angular velocity constraints. *International Journal of Computer Applications*, *50*(13), 41–46.
Inamori, T. (2012). Attitude control system for arc-second stabilization of 30-kg Micro Astronomy Satellite. *1st Interplanetary CubeSat Workshop Massachusetts, USA, 29-30 May 2012*, (May), 29–30.
Ismail, Z., & Varatharajoo, R. (2010). A study of reaction wheel configurations for a 3-axis satellite attitude control. *Advances in Space Research*, *45*(6), 750–759.
J. Liu, X. W. (2011). *Advanced Sliding Mode Control for Mechanical Systems: Design, Analysis and MATLAB Simulation*. Springer.
Jantzen, J. (2013). *Foundations of Fuzzy Control: A Practical Approach*. Wiley.
Kailil, A., Mrani, N., Touati, M. M., Choukri, S., & Elalami, N. (2004). Low Earth-orbit satellite attitude stabilization with fractional regulators. *International Journal of Systems Science*, *35*(10), 559–568.
Kalender, S., & Flashner, H. (2011). Design of spacecraft momentum unloading using discrete-time formulation. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, *225*(3), 312–324.
Kang, J., Zhu, Z. H., Wang, W., Li, A., & Wang, C. (2017). Fractional order sliding mode control for tethered satellite deployment with disturbances. *Advances in Space Research*, *59*(1), 263–273.
Kaplan, M. (1976). *Modern spacecraft dynamics and control*. *New York, John Wiley and Sons, Inc., 1976. 427 p.*
Karami, M. a., & Sassani, F. (2007). Spacecraft momentum dumping using less than three external control torques. *2007 IEEE International Conference on Systems, Man and Cybernetics*, 4031–4039.
Khalil, H. K. (2015). *Nonlinear Control*. *Pearson*.

Kim, B., Lee, H., & Choi, S. (1996). Three-axis reaction wheel attitude controlsystem for Kitsat-3 microsatellite. *Space Technology Research Center*, *16*(5–6), 291–296.

Klinkner, S. (2012). Flying Laptop.

Kosari, A., Peyrovani, M., Fakoor, M., & Pishkenari, H. N. (2013). Design of LQG/LTR controller for attitude control of Geostationary satellite using reaction wheels. *Vehicle Power and Propulsion Conference, IEEE*, 411–415.

Kovacic, Z., & Bogdan, S. (2006). *Fuzzy controller design: theory and applications*. *CRC Press, Florida*.

Krishnan, H., McClamroch, N. H., & Reyhanoglu, M. (1995). Attitude stabilization of a rigid spacecraft using two momentum wheel actuators. *Journal of Guidance, Control, and Dynamics*, *18*(2), 256–263.

Kristiansen, R., Egeland, O., & Nicklasson, P. J. (2005). A comparative study of actuator configurations for satellite attitude control. *Modeling, Identification and Control*, *26*(4), 201–219.

Kruk, J. W. (2003). FUSE In-Orbit Attitude Control with Two Reaction Wheels and No Gyroscopes. *Astronomical Telescopes and Instrumentation. International Society for Optics and Photonics.*, 274–285.

Lai, L.-C., Yang, C.-C., & Wu, C.-J. (2007). Time-optimal maneuvering control of a rigid spacecraft. *Acta Astronautica*, *60*(10–11), 791–800.

Larson, W. J., & Wertz, J. R. (2005). *Space Mission Analysis and Design* (Vol. 7th printi). Microcosm, Inc., Torrance, CA (US).

Lebedev, D. V. (2008). Momentum unloading excessive reaction-wheel system of a spacecraft. *Journal of Computer and Systems Sciences International*, *47*(4), 613–620.

Lee, H., & Utkin, V. I. (2007). Chattering suppression in sliding mode control system. *Annual Reviews in Control*, *31*(2), 179–188.

Lee, J., Ng, A., & R.Jobanputra. (2002). On determining dipole moments of a magnetic torquer rod - experiments and discussions. *Canadian Aeronautics and Space Journal*, *48*(1), 61–67.

Leve, F. A., Dueri, D. A., & Acikmese, B. A. (2014). Reaction wheel dissipative power reduction control allocation via lexicographic optimization. *AIAA/AAS Astrodynamics Specialist Conference*, (August).

Li, S., Yang, J., Chen, W. H., & Chen, X. (2014). *Disturbance Observer-Based Control Methods and Applications*. CRC Press Taylor & Francis.

Liang, Y., & Jianying, Y. (2008). Nonsingular fast terminal sliding-mode control for nonlinear dynamical systems. *International Journal of Robust and Nonlinear Control*, *18*(October 2014), 557–569.

Loo, C. K., Mandava, R., & Rao, M. V. C. (2004). A hybrid intelligent active force controller for articulated robot arms using dynamic structure neural network. *Journal of Intelligent and Robotic Systems*, *40*(2), 113–145.

Lovera, M. (2000). Optimal magnetic momentum control for inertially pointing spacecraft. *European Journal of Control*, *0*(March), 1–10.

Mailah, M., Hewit, J. R., & Meeran, S. (1996). Active force control applied to a rigid robot arm. *Jurnal Mekanikal*, *2*(3), 52–68.

Mailah, M., & Priyandoko, G. (2007). Simulation of a suspension system with adaptive fuzzy active force control. *International Journal of Simulation Modelling*, *6*(1), 25–36.

Makovec, K. L. (2001). *A nonlinear magnetic montroller for three-axis stability of nanosatellites*. Virginia Polytechnic Institute and State University.

Manabe, S. (2002). A suggestion of fractional-order controller for flexible spacecraft attitude control. *Nonlinear Dynamics*, *29*(1–4), 251–268.

Mazzini, L. (2016). *Flexible Spacecraft Dynamics, Control and Guidance*. Italy: Springer International Publishing Switzerland 2016.

Merrikh-Bayat, F. (2012). Rules for selecting the parameters of Oustaloup recursive approximation for the simulation of linear feedback systems containing PIλDμcontroller. *Communications in Nonlinear Science and Numerical Simulation*, *17*(4), 1852–1861.

Mohammad, A., & Ehsan, S. S. (2008). Fuzzy sliding mode controller design for spacecraft attitude tracking in terms of quaternion. *2008 27th Chinese Control Conference*, 753–757.

Moradi, M. (2012). Satellite neuro-PD three-axis stabilization based on three reaction wheels. *Journal of Aerospace Engineering*, (February), 177–184.

Mudi, R. K., & Dey, C. (2011). Performance improvement of PI controllers through dynamic set-point weighting. *ISA Transactions*, *50*(2), 220–230.

Mujumdar, A., Kurode, S., & Tamhane, B. (2013). Fractional order sliding mode control for single link flexible manipulator. *2013 IEEE International Conference on Control Applications (CCA)*, 288–293.

Nasri, M. T., & Kinsner, W. (2014). A comparison between fuzzy, fractional-, and integer-order controllers for small satellites attitude control. *Canadian Conference on Electrical and Computer Engineering*, 1–5.

Nicolai, A., Raschke, C., & Stoltz, S. (2014). Smart attitude control components for small satellites. *IEEE Aerospace Conference Proceedings*.

Noshadi, A., Mailah, M., & Zolfagharian, A. (2012). Intelligent active force control of a 3-RRR parallel manipulator incorporating fuzzy resolved acceleration control. *Applied Mathematical Modelling*, *36*(6), 2370–2383.

Oustaloup, A., Levron, F., Mathieu, B., & Nanot, F. M. (2000). Frequency-band complex noninteger differentiator: Characterization and synthesis. *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, *47*(1), 25–39.

Passino, K. (2010). *Fuzzy Control* (Vol. 20103237). Addison Wesley Longman, Inc.

Pedrycz, W., Peters, J. F., & Ramanna, S. (1997). Hierarchical fuzzy neural attitude control for satellites. *In Aerospace Conference Proceedings., IEEE, 3*, 385–400.

Petersen, C. D., Leve, F., & Kolmanovsky, I. (2016). Underactuated spacecraft switching law for two reaction wheels and constant angular momentum. *Journal of Guidance, Control, and Dynamics*, *39*(9), 2086–2099.

Phillips, A. E. (2014). *A Study of Advanced Modern Control Techniques Applied to a Twin Rotor MIMO System*. Rochester Institute of Technology.

Pittet, C., Despre, N., Tarbouriech, S., & Prieur, C. (2008). Nonlinear controller design for satellite reaction wheels unloading using anti-windup techniques. In *AIAA Guidance, Navigation and Control Conference and Exhibitit*.

Pong, C. M., Lim, S., Smith, M. W., Miller, D. W., Villaseñor, J. S., & Seager, S. (2010). Achieving high-precision pointing on ExoplanetSat: initial feasibility analysis. In *Proc. of SPIE* (Vol. 7731, p. 77311V).

Pukdeboon, C. (2011). Optimal sliding mode controllers for attitude stabilization of flexible spacecraft. *Mathematical Problems in Engineering*, *2011*, 1–20.

Pukdeboon, C., Zinober, A. S. I., & Thein, M. L. (2010). Quasi-continuous higher order sliding-mode controllers for spacecraft-attitude tracking maneuvers. *IEEE Transactions on Industrial Electronics*, *57*(4), 1436–1444.

Ram S, J., & Joseph N, P. (2014). *Small Satellites and their Regulation*. *Springer* (Vol.

30).
Ranjan, V. (2016). *Nonlinear Control of Robots and Unmanned Aerial Vehicles An Integrated Approach*. CRC Press Taylor & Francis.
Sabzehmeidani, Y., Mailah, M., & Hussein, M. (2010). Modelling and control of a worm-like micro robot with active force control capability. *Proceedings of the World Congress on Engineering*, *2*, 1624–1629.
Salim, M. A. (2010). A Robust of fuzzy logic and proportional derivative control system for monitoring underwater vehicles. In *Second International Conference on Computer Research and Development* (pp. 849–853).
Sharma, R., Gaur, P., & Mittal, A. P. (2016). Design of two-layered fractional order fuzzy logic controllers applied to robotic manipulator with variable payload. *Applied Soft Computing*, *47*, 565–576.
Shengyong, T., Xibin, C. A. O., & Yulin, Z. (2012). Configuration optimization of four dissimilar redundant flywheels with application to IPACS. In *Proceedings of 31st Chinese Control Conference* (pp. 4664–4669).
Shirazi, A., & Mirshams, M. (2014). Pyramidal reaction wheel arrangement optimization of satellite attitude control subsystem for minimizing power consumption. *International Journal of Aeronautical and Space Sciences*, *15*(2), 190–198.
Shtessel, Y., Edwards, C., Fridman, L., & Levant, A. (2014). *Sliding Mode Control and Observation*. *Springer*.
Sidi, M. J. (1997). *Spacecraft dynamics and control: a practical engineering approach. Vol. 7. New York, John Wiley and Sons, Inc., 1976. 427 p.* Cambridge university press.
Silva, C. W. De. (2009). *Modeling and control of engineering systems*. CRC Press Taylor & Francis.
Slotine, J.-J., & Li, W. (1991). *Applied Nonlinear Control*. Englewood Cliffs, NJ: Prentice hall.
Tanaka, K., & Sugeno, M. (1992). Stability analysis and design of fuzzy control systems. *Fuzzy Sets and Systems*, *45*(2), 135–156.
Tang, Y., Zhang, X., Zhang, D., Zhao, G., & Guan, X. (2013). Fractional order sliding mode controller design for antilock braking systems. *Neurocomputing*, *111*, 122–130.
Tewari, A. (2006). *Atmospheric and Space Flight Mechanics: Modeling and Simulation with MATLAB and Simulink*. Boston: Birkhauser.
Tissera, M. S. C., Low, K.-S., Xing, Y., & Goh, S. T. (2015). An efficient momentum dumping method through an alternative sun pointing strategy for small near equatorial orbit satellites. *International Astronautical Congress*, *IAC-15*-(October).
Tiwari, P. M., Janardhanan, S., & Nabi, M. U. (2013). Spacecraft attitude control using non-singular finite time convergence fast terminal sliding mode. *International Journal of Instrumentation Technology*, *1*(2), 124.
Tiwari, P. M., Janardhanan, S., & Un Nabi, M. (2016). Attitude control using higher order sliding mode. *Aerospace Science and Technology*, *54*, 108–113.
Tsiotras, P. (1996). Stabilization and optimality results for the attitude control problem. *Journal of Guidance, Control, and Dynamics*, *19*(4), 772–779.
Tsiotras, P., & Doumtchenko, V. (2000). Control of spacecraft subject to actuator failures- State-of-the-art and open problems. *Journal of the Astronautical Sciences*, *48*(2), 337–358.
Uhlig, T., Sellmaier, F., & Schmidhuber, M. (2015). *Spacecraft operations*. *Spacecraft*

Operations. London: Springer.
Urakubo, T., Tsuchiya, K., & Tsujita, K. (2004). Attitude control of a spacecraft with two reaction wheels. *Journal of Vibration and Control*, *10*(9), 1291–1311.
Utkin, V. (1977). Variable structure systems with sliding modes. *IEEE Transactions on Automatic Control*, *22*(2), 212–222.
Utkin, V. I. (1993). Sliding mode control design principles and applications to electric drives. *IEEE Transactions on Industrial Electronics*, *40*(1), 23–36.
Varatharajoo, R. (2006). Operation for the combined energy and attitude control system. *Aircraft Engineering and Aerospace Technology*, *78*(6), 495–501.
Varatharajoo, R., Tech Wooi, C., & Mailah, M. (2011a). Attitude pointing enhancement for combined energy and attitude control system. *Acta Astronautica*, *68*(11–12), 2025–2028.
Varatharajoo, R., Tech Wooi, C., & Mailah, M. (2011b). Attitude pointing enhancement for combined energy and attitude control system. *Acta Astronautica*, *68*(11–12), 2025–2028.
Votel, R., & Sinclair, D. (2012). Comparison of control moment gyros and reaction wheels for small Earth-orbiting satellites. In *Proceedings of the 26th Annual AIAA/USU Conference on Small Satellites* (pp. 1–7).
Wang, Y., Zhu, M., Wei, Y., Peng, C., & Zhang, Y. (2013). Attitude control of solar sail spacecraft using fractional-order PID controller. In *Proceedings of 2013 Chinese Intelligent Automation Conference, Lecture Notes in Electrical Engineering* (Vol. 255, pp. 779–787).
Wie, B. (2008). *Space Vehicle Dynamics and Control*. Iowa: AIAA Education Series.
Wie, B., & Lu, J. (1995). Feedback control logic for spacecraft eigenaxis rotations under slew rate and control constraints. *Journal of Guidance, Control, and Dynamics*, *18*(6), 1372–1379.
Wisniewski, R., & Kulczycki, P. (2002). Slew maneuver control for spacecraft equipped with star camera and reaction wheels. *IFAC Proceedings Volumes (IFAC-PapersOnline)*, *15*(1), 193–198.
Wood, M., & Chen, W. H. (2008). Model predictive control of low Earth-orbiting satellites using magnetic actuation. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, *222*(6), 619–631.
Wu, B., Cao, X., & Li, Z. (2009). Multi-objective output-feedback control for microsatellite attitude control: An LMI approach. *Acta Astronautica*, *64*(11–12), 1021–1031.
Wu, S., Sun, Z., & Li, H. (2009). Sliding mode controller design for rigid satellite attitude tracking. *2009 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 2238–2243.
Xue, D., Chen, Y., & Atherton, D. P. (2007). *Linear Feedback Control Analysis and Design with MATLAB*.
Xue, D., Zhao, C., & Chen, Y. (2006). A modified approximation method of fractional order system. *2006 IEEE International Conference on Mechatronics and Automation, ICMA 2006*, *2006*(November 2016), 1043–1048.
Yang, Y. (2017). Spacecraft attitude and reaction wheel desaturation combined control method. *IEEE Transactions on Aerospace and Electronic Systems*, *53*(1), 286–295.
Yoon, H., Seo, H. H., & Choi, H. T. (2014). Optimal uses of reaction wheels in the pyramid configuration using a new minimum infinity-norm solution. *Aerospace Science and Technology*, *39*, 109–119.
Young, K. D., Utkin, V. I., & Ozguner, U. (1996). A control engineer's guide to sliding

mode control. *Proceedings. 1996 IEEE International Workshop on Variable Structure Systems. - VSS'96* -, 1–14.
Zadeh, L. a. (1965). Fuzzy sets. *Information and Control*, *8*(3), 338–353.

BIODATA OF STUDENT

Zuliana Binti Ismail was born on 20 Oct. 1983 in Kuantan, Pahang, Malaysia. She received her Bachelor in Aerospace Engineering from Universiti Sains Malaysia, Penang in August 2006. Since then she worked as a research assistant at the Satellite Laboratory, Department of Aerospace Engineering Universiti Putra Malaysia, Selangor.

In January 2007, she registered as a M.Sc candidate in Faculty Engineering, Universiti Putra Malaysia to conduct research in the field of space system engineering under the supervision of Prof. Dato' Dr.-Ing. Ir. Renuganth Varatharajoo at the Aerospace Engineering Department and she completed her M.Sc in 2010. In 2013, she started her PhD programme in the field of Aerospace Engineering at the Faculty of Engineering, Universiti Putra Malaysia, Malaysia.

LIST OF PUBLICATIONS

Ismail, Z., Varatharajoo, R., Ajir, R., & Mohd Rafie, A. S. (2015). Enhanced attitude control structure for small satellites with reaction wheels. *Aircraft Engineering and Aerospace Technology: An International Journal*, *87*(6), 546-550.

Ismail, Z., & Varatharajoo, R. (2015). Reaction Wheel Configurations for High and Middle Inclination Orbits. *ARPN Journal of Engineering and Applied Sciences, 21(10)*, 10034-10042.

Ismail, Z., & Varatharajoo, R. (2016). Satellite cascade attitude control via fuzzy PD controller with active force control under momentum dumping. *IOP Conference Series: Materials Science and Engineering, Vol (152), No.1*.

Ismail, Z., Varatharajoo, R., & Chak, Y. C. (2020). A fractional-order sliding mode control for nominal and underactuated satellite attitude controls. *Advances in Space Research, , Vol (66), No.2.*

UNIVERSITI PUTRA MALAYSIA

STATUS CONFIRMATION FOR THESIS / PROJECT REPORT AND COPYRIGHT

ACADEMIC SESSION : First Semester 2019/2020

TITLE OF THESIS / PROJECT REPORT :

ENHANCED ATTITUDE CONTROL STRUCTURE FOR SMALL SATELLITES WITH REACTION WHEELS

NAME OF STUDENT: ZULIANA BINTI ISMAIL

I acknowledge that the copyright and other intellectual property in the thesis/project report belonged to Universiti Putra Malaysia and I agree to allow this thesis/project report to be placed at the library under the following terms:

1. This thesis/project report is the property of Universiti Putra Malaysia.
2. The library of Universiti Putra Malaysia has the right to make copies for educational purposes only.
3. The library of Universiti Putra Malaysia is allowed to make copies of this thesis for academic exchange.

I declare that this thesis is classified as :

*Please tick (√)

☐	CONFIDENTIAL	(Contain confidential information under Official Secret Act 1972).
☐	RESTRICTED	(Contains restricted information as specified by the organization/institution where research was done).
☐	OPEN ACCESS	I agree that my thesis/project report to be published as hard copy or online open access.

This thesis is submitted for :

☐	PATENT	Embargo from ____________ until ____________
		(date) (date)

Approved by:

____________________	____________________
(Signature of Student)	(Signature of Chairman of Supervisory Committee)
New IC No/ Passport No.:	Name:
Date :	Date :

[Note : If the thesis is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization/institution with period and reasons for confidentially or restricted.]