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ATTITUDE CONTROL SIMULATION OF SMALL SATELLITES WITH REACTION WHEELS

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By

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Nowadays, most of the designed satellites are dedicated for high performance missions, which require high attitude pointing accuracies. The reaction wheel is the most suitable satellite actuator that can provide high attitude pointing accuracies (0.1°-0.001°). Commonly, three or four reaction wheel configurations are used for a 3-axis satellite attitude control. In fact, higher power is consumed when multiple reaction wheels are employed. Thus, it is rather challenging to adopt multiple reaction wheels for the small satellite missions because of the power constraint. On the other hand, reaction wheels lack of the ability to remove the excess angular momentum and that the wheels have a limited capacity to store momentum. Without a momentum management control, the satellite may be uncontrollable. Therefore, to make the implementation of multiple reaction wheels reliable for a small satellite, it is necessary to find a way to minimize the wheel's power consumption. Also, it is compulsory for a satellite to be equipped with a momentum management scheme in order to maintain the angular momentum within their allowable limits. Momentum management control using magnetic torquers are chosen in this work.

Indeed, the wheel's power consumption can be lowered by particularly arranging the reaction wheels' orientation onboard the satellite. In this research, several configurations, based on three or four reaction wheels, are investigated in order to identify the most suitable orientation with the total minimum power. All the related mathematical models are implemented in Matlab®-Simulink™ software. Numerical simulations are performed for all the possible reaction wheel configurations with respect to an identical reference mission. Two simulation analyses are presented for their performance evaluations. First simulation focuses on the satellite attitude control only and the second simulation focuses on the satellite attitude control with momentum management control. Based on the simulations, the reaction wheel configuration that produces a minimum total control torque is identified, which also corresponds to the configuration with a minimum power intake. The wheel angular momentums and satellite attitude accuracies are also well maintained during the control task.

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

SIMULASI KAWALAN ATTITUD UNTUK SATELIT KECIL DENGAN RODA TINDAK BALAS

Oleh

ZULIANA BINTI ISMAIL

Disember 2009

Pengerusi: Profesor Madya Dr.-Ing. Ir. Renuganth Varatharajoo

Fakulti : Kejuruteraan

Pada masa kini, kebanyakan satelit yang direka bentuk adalah bertujuan untuk misi berprestasi tinggi, di mana keperluan kejituan attitud adalah tinggi (0.1°-0.001°). Roda tindak balas adalah penggerak yang paling sesuai untuk satelit kecil di mana ia dapat memberikan kejituan attitud yang tinggi. Kebiasaannya, tiga atau empat konfigurasi roda tindak balas digunakan untuk kawalan 3 paksi satelit. Menurut fakta, kuasa yang tinggi diperlukan apabila beberapa bilangan roda tindak balas digunakan. Jadi, penggunaan beberapa bilangan roda tindak balas untuk satelit kecil adalah tidak bersesuaian disebabkan oleh had kuasa. Selain dari itu, roda tindak balas juga tidak berkebolehan untuk menyingkir momentum yang terkumpul dan roda ini juga mempunyai kapasiti terhad untuk menyimpan momentum. Satelit mungkin akan hilang kawalan tanpa pengurusan kawalan momentum. Oleh itu, adalah perlu untuk meminimumkan penggunaan kuasa oleh roda tindak balas agar penggunaannya di dalam satelit kecil dapat direalisasikan. Juga, adalah perlu untuk melengkapkan satelit dengan skim pengurusan momentum untuk memastikan momentum roda tindak balas sentiasa berada di dalam had yang optimum. Penggerak kedua (rod magnetik dan penujah) boleh digunakan untuk tujuan pengurusan kawalan

momentum. Di dalam kajian ini, pengurusan kawalan momentum adalah menggunakan rod magnetik.

Sebenarnya, penggunaan kuasa oleh roda tindak balas boleh diminimakan melalui penyusunan roda tindak balas yang sesuai di dalam satelit. Di dalam kajian ini, beberapa konfigurasi yang terdiri dari tiga atau empat roda tindak balas diselidik untuk mengenalpasti susunan roda tindak balas yang paling sesuai dengan jumlah kuasa paling minimum. Semua model matematik yang berkenaan dilaksanakan di dalam perisian Matlab®-Simulink™. Simulasi dijalankan untuk kesemua susunan roda tindak balas yang dicadangkan berdasarkan rujukan misi yang tertentu. Dua simulasi dilakukan untuk penilaian prestasi. Simulasi pertama tertumpu kepada kawalan attitud satelit sahaja dan simulasi kedua tertumpu kepada kawalan attitud satelit beserta pengurusan kawalan momentum. Berdasarkan simulasi, konfigurasi roda tindak balas yang memberikan jumlah kilasan kawalan yang paling minimum dapat dikenalpasti. Konfigurasi ini juga menunjukkan penggunaan kuasa paling minimum. Simulasi juga menunjukkan kadar momentum dan attitud yang memuaskan sewaktu proses kawalan.

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I certify that an Examination has met on **date** to conduct the final examination of **Zuliana Binti Ismail** on her **degree** thesis entitled **"Attitude Control Simulation of Small Satellites with Reaction Wheels"** in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The committee recommends that the student be awarded the Masters of Science.

Members of the Examination Committee are as follows:

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Date: 8 April 2010

DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other Institution

ZULIANA BINTI ISMAIL

Date: 20 March 2009

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a	:	Semi-major axis
ζ	:	Damping Ratio for the attitude control loop
$\mu_{\oplus}$	:	Earth gravitational constant, $\mu_{\oplus} = 3.986 \times 10^{14}\,\mathrm{m^3/s^2}$
μ_{f}	:	Magnetic field's dipole strength. $\mu_{\mathrm{f}} = 7.9 \times 10^{15}\,\mathrm{Tesla\ m^3}$
ω_{o}	:	Orbital frequency [rad/s]
$\omega_{\oplus}$	:	Earth's rotation frequency, $\omega_{\oplus} = 7.29211515 \times 10^{-5}\,\mathrm{rad/s}$
ω_{n}	:	Natural Frequency for the attitude control loop [rad/s]
$\dot{\omega}_{\mathrm{x}}, \dot{\omega}_{\mathrm{y}}, \dot{\omega}_{\mathrm{z}}$	:	Satellite's body angular acceleration [$\mathrm{rad^2/s^2}$]
$\omega_{\mathrm{x}}, \omega_{\mathrm{y}}, \omega_{\mathrm{z}}$	:	Satellite's body angular rate [rad/s]
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
$\mathrm{A_w}$	:	Reaction wheel configuration matrix
B^2	:	Magnitude of the Earth's magnetic field vector [Tesla]
$\mathbf{B}_{\mathrm{B}}$	:	Earth's magnetic field vector in the Body coordinate system [Tesla]
$\mathbf{B}_{\mathrm{LVLH}}$	:	Earth's magnetic field vector in the LVLH coordinate system [Tesla]
$\mathrm{B_o}$	:	Average magnetic field intensity in low earth orbit, $\mathrm{B_o} = 2.5 \times 10^{-5}$ Tesla

Cs	:	Solar radiation constant, Cs =1358 W/m^2
c	:	Speed of light, c = 3 ×10^8 m/s
$\mathbf{e}$	:	Euler axis of rotation
h	:	Satellite's Altitude
$\mathbf{h}_{wo}$	:	Initial Reaction Angular Momentum [kgm^2s^{-1}]
$\mathbf{h}_w$	:	Angular momentum vector of a reaction wheel [kgm^2s^{-1}]
$\mathbf{h}_s$	:	Angular momentum vector of a satellite [kgm^2s^{-1}]
i	:	satellite orbit inclination with respect to the equatorial plane
i_m	:	satellite orbit inclination with respect to the magnetic equator
$\mathbf{I}$	:	Satellite moments of inertia [kgm^2]
Kd	:	Derivative attitude control gain
Ki	:	Integral attitude control gain
Kp	:	Proportional attitude control gain
LEO	:	Low Earth Orbit
$\mathbf{m}$	:	Magnetic dipole moments of the magnetic torquers [Am^2]
q	:	Quaternion
$\mathbf{q}_e$	:	Error of quaternion
q_r	:	Solar reflectance factor
R_e	:	Radius of the Earth, $R_e = 6378$ km
T	:	Simulation time
T_o	:	Period of orbit
$\mathbf{T}_w$	:	Applied torque vector by reaction wheels [Nm]
$\mathbf{T}_m$	:	Magnetic torque vector induced by magnetic torquers [Nm]
$\mathbf{T}_d$	:	External disturbance torque vector [Nm]

$\mathbf{T}_a$	:	Commanded control torque vector [Nm]
X_{IE}, Y_{IE}, Z_{IE}	:	Inertial Earth (IE) coordinate system
X_B, Y_B, Z_B	:	Satellite's Body (B) coordinate system
$X_{LVLH}, Y_{LVLH}, Z_{LVLH}$	:	Local Vertical Local Horizontal coordinate system (LVLH)
$(\cdot)\times(\cdot)$	:	The cross product of two vectors
$(\cdot)\bullet(\cdot)$	:	The dot product of two vectors

CHAPTER 1

1 INTRODUCTION

1.1 General Overview

Low cost, shorter time development, simplicity and the ability to provide valuable scientific returns are the main reasons of the increasing development in small satellites. Serious attention in their development is not only considered by the countries with emerging space programs but also by the developing countries. For developing countries, small satellites are considered as the best solution for enabling them to be involved in space activities (Paul and Rhoda, 2005). Thus, such research on small satellites has become most significant nowadays. A lot of effort has been put in designing small satellite; such as, miniaturization and optimization of all components onboard. The purpose is to reduce costs and development time of the satellite while retaining their high performances (Alale et al., 2008)

Either larger satellites or smaller one, the same subsystems are being equipped as depicted in Figure 1.1. The reason is that the satellites deal with the same fundamental features (e.g., space dynamics, kinematics law, environmental disturbances, etc.) in the space environments. However, the methods and components integrated inside the subsystems might differ based on the satellite missions. There are various methods in designing the satellites, and they are upgraded simultaneously with the advancement of the technology. Thus, by having the smart design solution, any satellite can perform its mission successfully and consequently provide benefits for any country that have high enthusiasm in the space exploration.

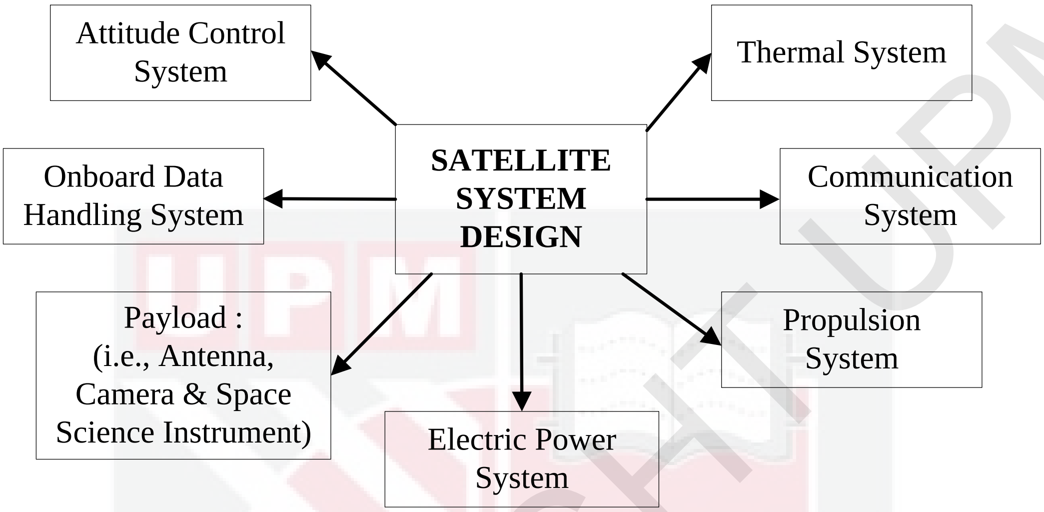


Figure 1.1: Satellite Components

In order to realize the satellites mission objectives with the best return in scientific results and the control performances, the satellites especially their payloads have to be strongly controllable. For instance the satellite's antenna is pointed directly towards the ground station's antenna and the camera, at a single point of trajectory, is targeted constantly to the desired object.

Being stable will help the satellites to hold their target pointing steadily in the space environment that is susceptible to many external disturbances torques, i.e., Earth's magnetic field, gravity gradient effect, solar radiation pressure and aerodynamic drag (Larson and Wertz, 1999). The Attitude Control System (ACS) therefore can be said as the one of the important subsystems that guarantees the stability of a satellite and its payloads.

1.2 Satellite Attitude Control System

Generally, the means of accurately controlling a satellite is referred to the term of 'attitude' which can be defined as an angular orientation of the satellite body axes with respect to a defined orbit coordinate system (Sidi, 1997). Satellite's attitude must be continuously controlled for all the duration of the mission. It can be controlled in many ways, and the attitude control method is usually relied on what types of hardware (e.g., actuators and sensors) and software (e.g., controllers) is being equipped. The standard closed-loop satellite attitude control system is shown in Figure 1.2 .

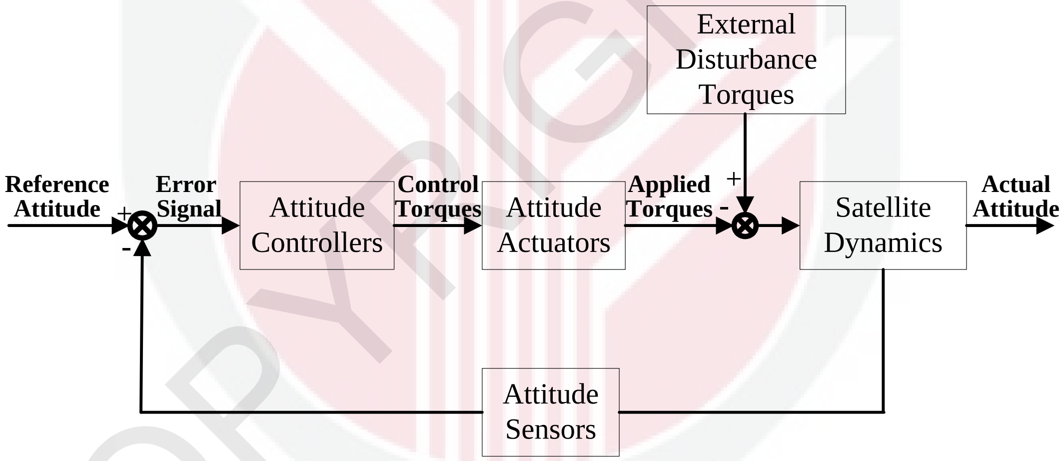


Figure 1.2: Block Diagram of a Closed-Loop Satellite Attitude Control System

The objective of the control loop is to ensure the current attitude of the satellite approximately equal to the satellite's reference attitude. The sensors measure the orientation of the satellite. The controller calculates the command torque to be applied by the actuators based on the attitude error in order to counteract the external disturbance torques and then correcting the satellite's attitude. Generally, the control method and the types of actuator or sensor to be utilized by a satellite are chosen based on the satellite's mission requirements (e.g., cost, lifetime, pointing accuracy and maneuverability) and satellite's applications (e.g., remote sensing, communications, space explorations, technology demonstrations, etc).

1.3 Satellite Attitude Control Methods

In the earliest day of small satellite developments, the passive control methods were usually adopted for attitude stabilization due to their attractive low cost and hardware simplicity. However, only poor attitude accuracy and limited control torques can be offered from these low cost methods (Chen et al., 2000; Silani and Lovera, 2005). The achievement of typical attitude accuracy with comparison between passive and active control techniques are simplified in Figure 1.3.

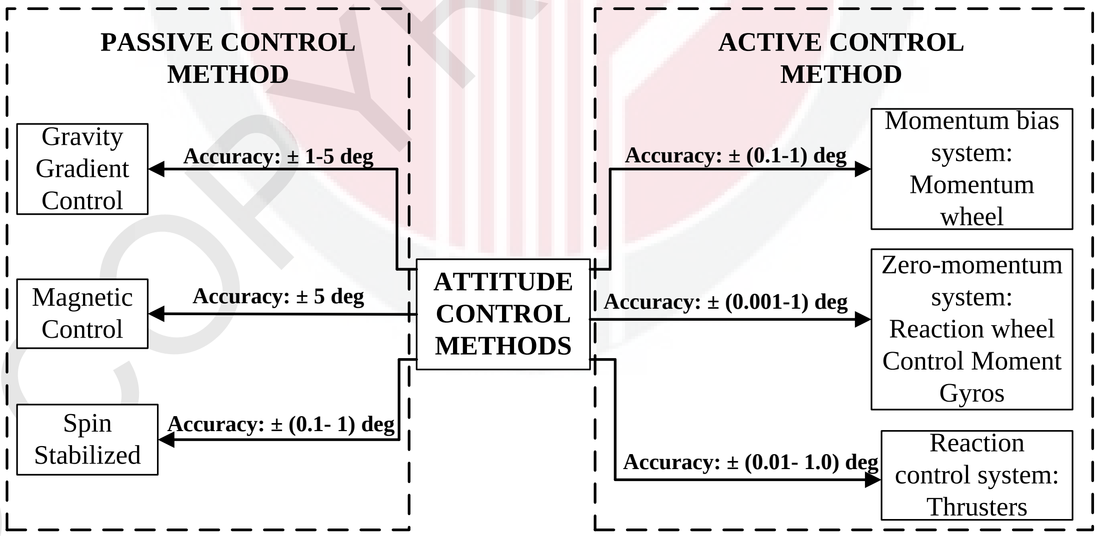
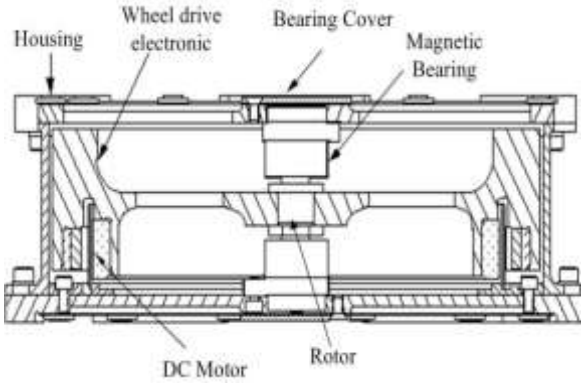


Figure 1.3: Satellite Attitude Control Methods

Basically, high attitude accuracy and 3-axis attitude control can be achieved by the active control methods. For small satellites mission however, the use of control moment gyros and thrusters are considered as unreasonable options due to their high mass budget and high fuel consumption, respectively (Sidi, 1997). The reaction wheel and momentum wheel are more appropriate for small satellites. Reaction wheel and momentum wheel are distinguished by the nominal spin rate of the wheels. Reaction wheels have zero nominal angular velocity (zero momentum), while momentum wheels have a nominal spin rate above zero to provide a nearly constant angular momentum (bias momentum). The combination of a single momentum wheel along pitch axis and 2-axis magnetic torquers along the roll and yaw axes have been popular in many low cost small satellite missions. However, their achieved attitude pointing accuracies were still inadequate for high performance missions.

Alternatively, either two or three reaction wheels configuration are employed for a full 3-axis attitude control and high attitude pointing accuracies. A set of four reaction wheels is a common option for a satellite, in which the last wheel can be a back-up in case of any other operated wheel fails. Reaction wheels act as a source of action-reaction energy to generate the control torques. The reaction wheel concept relies on the principle angular momentum conservation. When a satellite rotates one way due to the disturbance torque, the reaction wheel will be counter rotated to produce a same magnitude reaction torque in order to correct the attitude (Sidi 1997). Typically, reaction wheel consists of a motor that provides torque to drive the wheel, high-inertia rotor, wheel drive electronic and housing to place all components, see Figure 1.4.



(a) (b)

Figure 1.4: (a) Reaction Wheel Cross-Sectional View by Ithaco
(b) Reaction Wheel by Sunspace (Walchko, 2003)

1.4 Motivation

Actually, 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. The pointing control system for both the spacecraft consists of four reaction wheel assemblies for higher attitude pointing accuracies, i.e., ±0.00002º and ±0.0014º, respectively (Beals et al., 1988 and Radford et al., 1996). However, it is important to point out that the reaction wheel has been also used in many small satellites such as BIRD, ODIN and MOST microsatellites (Berge et al., 1997; Jacobsson et al., 2002; Zee et al., 2002 and Brieβ et al., 2005).

It is evident that the ACS determines the success of the satellite missions. The reaction wheel is the most suitable small satellite actuator that can provide high attitude pointing accuracies. Having precision pointing, high performance missions can be accomplished. Therefore, small satellite attitude control using the reaction wheels is indeed an important subject of research.

1.5 Problem statements

The ACS is one of the highest power consumers of all of the satellite subsystems, see Table 1.1.

Table 1.1: Power Consumption of Satellite Subsystems (Larson and Wertz, 1999)

Satellite Subsystems	% of operating power (~200W)
Payload	40
Propulsion	0
Attitude Control	**15**
Communications	5
Data Handling	5
Thermal	5
Power	30
Structure	0

In fact, higher power is consumed when multiple reaction wheels are employed. The power represents the cost. Thus, it is rather challenging to adopt multiple reaction wheels for the small satellite missions because of the power constraint.

Table 1.2: Power consumption of ACS (Larson and Wertz, 1999)

Attitude Control Hardware	Typical Power (Watt)
Earth Sensor	2 to 10
Sun Sensor	0 to 0.2
Star Sensor	2 to 20
Magnetometer	0.2 to 1
Gyroscope	5 to 20
Processors	2 to 25
Reaction Wheels	**10 to 110**
Magnetic torquers	0.6 to 16

Table 1.2 gives an overview of the required power by typical attitude control hardwares. Note that, the reaction wheel's power consumption varies with respect to the wheel speed and the control torques. Thus, under high control torque demands, the amount of power can increase up to 110 W in order to drive the motor to spin the reaction wheel (Larson and Wertz, 1999). Therefore, to make the implementation of multiple reaction wheels reliable for a small satellite, it is necessary to find a way to minimize the wheel's power consumption. Particularly arranging the reaction wheels' orientation onboard satellites actually can minimize the consumed power in the attitude control thus reduces the mission cost as well.

Moreover, reaction wheel lacks capability to remove the excess angular momentum that accumulates over time. Therefore, the reaction wheels' angular momentum unloading scheme is needed so that the wheel speed is always within the acceptable limit. Magnetic torquers have been used for angular momentum unloading scheme in this work. In this regards, suitable attitude control strategies are required for a small satellite equipped with the combination of reaction wheels and magnetic torquers as the control actuators.

1.6 Research Objectives

Suitable attitude and wheel angular momentum control strategies for small satellites using multiple reaction wheels and magnetic torquers are proposed in this thesis. The aims of this research are:

- To implement the attitude control and momentum control laws of a satellite attitude control system using reaction wheels and magnetic torquers.
- To seek and investigate the best orientation of reaction wheels onboard a satellite corresponding to a minimum power consumption.
- To implement the wheel angular momentum unloading techniques magnetic torquers without compromising satellite attitude controls.

1.7 Scope of Study

This research performs a study of reaction wheels's configurations for a 3-axis small satellite attitude control, which includes the reaction wheel angular momentum management controls using magnetic torquers. The study is performed through the mathematical modeling and simulation analysis using Matlab®-Simulink™. Two simulation analyses are performed i.e., first for only the satellite attitude control and second is for the satellite attitude control with wheel angular momentum unloading controls. Conventional PD (proportional-derivative) and PI (proportional-integral) type controllers are employed to effectively control the satellite system with respect to its attitudes (roll, pitch and yaw) considering three and four reaction wheel systems in the presence of disturbance torques in two different inclinations.

1.8 Thesis Outline

In this first chapter, a brief description about small satellites and attitude control methods are introduced, which is focused on reaction wheels. Apart from that, motivation, problem statement and objective of the research are also presented.

Chapter 2 presents literature review which includes the previous and current researches on the 3-axis satellite attitude control using reaction wheels. It covers the implementation of different control laws, issues on the reaction wheel's angular momentum unloading and the reaction wheel power requirement.

Chapter 3 details all the satellite fundamental theories, which are used in this study. The standard satellite attitude dynamics and kinematics equation are formulated. The reaction wheel's control strategies and the angular momentum unloading scheme are also presented in the chapter.

The numerical simulations based on the proposed control strategy are presented in Chapter 4. The satellite attitude control and wheel angular momentum unloading performances for all the test cases are presented and discussed as well.

The conclusion is drawn in Chapter 5 and some suggestions are given for future research works.

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