UNIVERSITI PUTRA MALAYSIA

A COMBINED ATTITUDE AND SUN TRACKING SYSTEM FOR SPACECRAFT USING FUZZY LOGIC CONTROL

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Faculty : Engineering

Many spacecraft attitude control systems today use reaction wheels to deliver precise torques to achieve a three-axis attitude stabilization. Despite the extensive studies in attitude controllers, failures still can occur in a spacecraft system. For example, if a spacecraft suffers multiple reaction wheel failure, external disturbances will cause the spacecraft to tumble and lose its ability to correct the attitude error. If the failure is irrecoverable, it may cause the spacecraft to spin uncontrollably and jeopardize the space mission. The most common way to recover a tumbling spacecraft is by firing chemical thrusters sequentially to generate a torque, which can control the total momentum of the spacecraft. Since the thrusters expel reaction mass to produce a torque, this leads to increased fuel consumption and eventually shortened operational life.

Most spacecraft have their solar arrays mounted on the y-axis and oriented perpendicular to the sun to receive the maximum amount of solar energy. The solar arrays are rotated using Solar Array Drive Assemblies to track the sun. As a result of the rotations of the solar arrays, internal torques are generated. The main objective in this research is to design a combined attitude and sun tracking system (CASTS) that can utilize the internal torques produced by the solar arrays for attitude control while tracking the sun simultaneously. Two mechanisms are proposed for the CASTS to generate the internal control torque by rotating the solar arrays at different angular speeds. In order to counteract the external disturbance torque, several non-fuzzy logic and fuzzy logic controllers are designed for CASTS. The performance of the proposed CASTS control strategy is tested through numerical simulations. The findings show that all fuzzy logic-based control schemes are able to achieve smaller pitch angle errors compared to the non-fuzzy logic controllers. Overall, the research results show that the proposed CASTS control strategy is effective for controlling the spacecraft attitude and tracking the sun simultaneously.

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

SISTEM GABUNGAN PENJEJAKAN ATTITUD DAN MATAHARI BAGI KAPAL ANGKASA LEPAS MENGGUNAKAN KAWALAN LOGIK SAMAR

Oleh

CHAK YEW CHUNG

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Kebanyakan sistem kawalan attitud kapal angkasa hari ini menggunakan roda reaksi untuk memberikan tork tepat untuk mencapai kestabilan attitud tiga paksi. Walaupun kajian yang luas dalam pengawal attitud, kegagalan masih boleh berlaku dalam sistem kapal angkasa. Sebagai contoh, jika kapal angkasa mengalami kegagalan roda reaksi yang banyak, gangguan luaran akan menyebabkan kapal angkasa jatuh berguling dan kehilangan keupayaannya untuk membetulkan kesilapan attitud. Jika kegagalan itu tidak dapat dipulihkan, ia boleh menyebabkan kapal angkasa berputar tanpa kawalan dan ini menjejaskan misi angkasa. Cara yang paling biasa untuk memulihkan kapal angkasa yang bergolek adalah menggunakan tujahan kimia secara serentak untuk menghasilkan tork yang berupaya mengawal jumlah momentum kapal angkasa. Oleh kerana penujah menghembuskan jisim tindak balas untuk menghasilkan tork, ini menyebabkan peningkatan penggunaan bahan api dan akhirnya memendekkan tempoh hayat operasi.

Kebanyakan kapal angkasa mempunyai panel suria yang dipasang pada paksi-y dan ditujukan serenjang menghala ke matahari untuk menerima jumlah maksimum tenaga suria. Panel suria diputar menggunakan Pemasangan Pemandu Panel Suria untuk menjejaki matahari. Hasilan daripada putaran panel suria, tork dalaman dijanakan. Objektif utama dalam penyelidikan ini adalah untuk mereka bentuk sistem gabungan penjejakan attitud dan matahari (CASTS) yang boleh menggunakan tork dalaman yang dihasilkan oleh panel suria untuk mengawal attitud dan menjejaki matahari dengan serentak. Dua mekanisme dicadangkan bagi CASTS untuk menghasilkan tork kawalan dalaman dengan memutar panel suria pada halaju sudut yang berbeza. Untuk mengatasi tork gangguan luaran, beberapa pengawal bukan logik samar dan pengawal logik samar direka untuk CASTS. Prestasi strategi kawalan CASTS yang dicadangkan diuji melalui simulasi berangka. Penemuan menunjukkan bahawa semua skema kawalan berasaskan logik samar dapat mencapai ralat sudut kecondongan dari paksi-y yang lebih kecil berbanding dengan pengawal bukan logik samar. Secara keseluruhannya, keputusan kajian menunjukkan bahawa strategi kawalan CASTS yang dicadangkan adalah

berkesan untuk mengawal attitud kapal angkasa dan menjejaki matahari pada masa yang sama.

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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:

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LIST OF ABBREVIATIONS

ADC	Attitude Determination and Control
AFC	Active Force Control
ANFIS	Adaptive Neuro-Fuzzy Inference System
AUC	Area Under Curve
CASTS	Combined Attitude and Sun Tracking System
CATCS	Combined Attitude and Thermal Control System
CEACS	Combined Energy and Attitude Control System
CLF	Control Lyapunov Function
CSMC	Conventional Sliding Mode Control
DOBC	Disturbance Observer-Based Control
DOF	Degree of Freedom
EPS	Electrical power system
ESA	European Space Agency
FLC	Fuzzy Logic Control
FPI	Fuzzy Proportional-Integral
FPID	Fuzzy Proportional-Integral-Derivative
FPD	Fuzzy Proportional-Derivative
FSMC	Fuzzy Sliding Mode Control
GN&C	Guidance, Navigation, and Control
HI	High
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory (US agency)
LMI	Linear Matrix Inequality
LO	Low
LQG	Linear Quadratic Gaussian
LQI	Linear Quadratic Integral
LQR	Linear Quadratic Regulator
LTI	Linear Time-Invariant
LTR	Loop Transfer Recovery
MF	Membership Function
MIMO	Multi-Input, Multi-Output
MPC	Model Predictive Control
MRAC	Model Reference Adaptive Control
NASA	National Aeronautics and Space Administration (US agency)
NEG	Negative
NTSM	Nonsingular Terminal Sliding Mode

PD	Proportional-Derivative
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
POS	Positive
QFT	Quantitative Feedback Theory
SADA	Solar Array Drive Assembly
SMC	Sliding Mode Control
SRP	Solar Radiation Pressure
TSM	Terminal Sliding Mode
T–S	Takagi–Sugeno

LIST OF SYMBOLS

Latin Symbols:

$\mathcal{F}_b$	Spacecraft's body-fixed frame
$\mathcal{F}_I$	Inertial reference frame
$\mathcal{F}_o$	Orbiting reference frame
$\mathbf{C}_{bI}$	Rotation matrix for the Euler angles from $\mathcal{F}_b$ to $\mathcal{F}_I$
$\mathbf{C}_{bo}$	Rotation matrix for the Euler angles from $\mathcal{F}_b$ to $\mathcal{F}_o$
$\tilde{\boldsymbol{q}}$	The vector part of the quaternion, $[\tilde{q}_1 \quad \tilde{q}_2 \quad \tilde{q}_3]^T$
$\tilde{q}_4$	The scalar part of the quaternion
$\mathbf{I}$	Spacecraft's inertia matrix
$\mathbf{I}_p$	Spacecraft's principal inertia matrix
I_X	Spacecraft's principal moment of inertia about the x_b-axis
I_Y	Spacecraft's principal moment of inertia about the y_b-axis
I_Z	Spacecraft's principal moment of inertia about the z_b-axis
I_x	Rigid hub's principal moment of inertia about the x_b-axis
I_y	Rigid hub's principal moment of inertia about the y_b-axis
I_z	Rigid hub's principal moment of inertia about the z_b-axis
I_a	Solar array's principal moment of inertia about the y_b-axis
$\hat{I}_y$	Estimated rigid hub's moment of inertia about the y_b-axis
$\boldsymbol{T}$	Torque vector that acts about the center of mass of the spacecraft
T_x	Torque that acts about the spacecraft x_b-axis
T_y	Torque that acts about the spacecraft y_b-axis
T_z	Torque that acts about the spacecraft z_b-axis
$\boldsymbol{T}_c$	Control torque vector
T_{cx}	Control torque that acts about the spacecraft x_b-axis
T_{cy}	Control torque that acts about the spacecraft y_b-axis
T_{cz}	Control torque that acts about the spacecraft z_b-axis
$\boldsymbol{T}_d$	External disturbance torque vector
T_{dx}	External disturbance torque that acts about the spacecraft x_b-axis
T_{dy}	External disturbance torque that acts about the spacecraft y_b-axis
T_{dz}	External disturbance torque that acts about the spacecraft z_b-axis
$\boldsymbol{T}_g$	Gravity-gradient torque vector
T_{gx}	Gravity-gradient torque that acts about the spacecraft x_b-axis
T_{gy}	Gravity-gradient torque that acts about the spacecraft y_b-axis
T_{gz}	Gravity-gradient torque that acts about the spacecraft z_b-axis
$\boldsymbol{T}_a$	Aerodynamic torque vector
$\boldsymbol{T}_s$	Solar radiation pressure torque vector
$\boldsymbol{T}_B$	Magnetic torque vector
$\boldsymbol{T}_{\boldsymbol{\eta}}$	Bending torque vector by the rotation of the solar arrays
$T_{\boldsymbol{\eta}_x}$	In-plane bending torque by the rotation of the solar arrays
$T_{\boldsymbol{\eta}_y}$	Torsional bending torque by the rotation of the solar arrays
$T_{\boldsymbol{\eta}_z}$	Out-of-plane bending torque by the rotation of the solar arrays
T_{Ly}	Lumped disturbance torques that acts about the spacecraft y_b-axis
$\hat{T}_{Ly}$	Estimated lumped disturbance torques

T_{net}	Differential net torque resulted by the rotations of both solar arrays
T_n	Torque generated by the rotation of the North array
T_s	Torque generated by the rotation of the South array
T_m	Torque produced by the motor actuator
$\breve{T}_{dc}$	Direct component of the disturbance torque
$\breve{T}_{ac}$	Alternating component of the disturbance torque
T_Σ	Total torque acting on the spacecraft
$\hat{T}_\Sigma$	Estimated total torque acting on the spacecraft
$\hat{T}_{dy}$	Estimated disturbance torque acting on the spacecraft
$\hat{T}_{dy}^+$	Non-negative part of the estimated disturbance torque
$\boldsymbol{r}_b$	Orbital position vector of the spacecraft in body coordinates
$\boldsymbol{\mathcal{J}}_\omega(\boldsymbol{\Theta})$	Spacecraft's Jacobian matrix for rotational transformation
$\widehat{\mathbf{B}}$	Rigid-flexible coupling matrix denoted by $[\overline{\boldsymbol{b}}\hat{\mathbf{C}}_p]^T$
$\overline{\boldsymbol{b}}$	Rigid-flexible coupling vector denoted by $\sqrt{2}\boldsymbol{\varsigma}$
$\hat{\mathbf{C}}_p$	Rotation matrix due to the solar array's rotation about the y_b-axis
$\mathcal{S}$	A symbol for the mathematical expression of $\operatorname{sgn}(\sin\omega_\odot t)$
B_p	Band-pass filter of $\cos^2(\omega_\odot t)$ in the frequency domain
L_p	Low-pass filter of $\sin^2(\omega_\odot t)$ in the frequency domain
R^k	k-fuzzy rule
N_E	"Negative" fuzzy set for Error
N_{CE}	"Negative" fuzzy set for Change in Error
P_E	"Positive" fuzzy set for Error
P_{CE}	"Positive" fuzzy set for Change in Error
S_N	"Negative" singleton for fuzzy Output
S_Z	"Zero" singleton for fuzzy Output
S_P	"Positive" singleton for fuzzy Output
S_k	Singleton value under Rule k
w_k	Rule k's firing strength
E	Error (input signal to fuzzy system)
CE	Change in Error (input signal to fuzzy system)
$\mathcal{F}(E, CE)$	Fuzzy output as a function of Error and Change in Error
$\mathcal{F}(\alpha_{dy})$	Fuzzy output as a function of Disturbance angular acceleration
$e(t)$	Error signal in the time domain
$\dot{e}(t)$	Change in Error signal in the time domain
K_E	Fuzzy gain to the input signal of Error
K_{CE}	Fuzzy gain to the input signal of Change in Error
K_U	Fuzzy gain to the output signal of Output
K_{CU}	Fuzzy gain to the output signal of Change in Output
K_p	Proportional gain of a typical PID controller
K_i	Integral gain of a typical PID controller
K_d	Derivative gain of a typical PID controller
K_a	Adaptive gain of a typical MRAC controller
K_c	Control gain of a typical MRAC controller
K_I	Integral gain of a typical LQI controller
u_{PD}	Output of a PD controller
u_{FPD}	Output of a Fuzzy PD controller
u_{PI}	Output of a PI controller
u_{FPI}	Output of a Fuzzy PI controller

u_{PID}	Output of a PID controller
u_{FPID}	Output of a Fuzzy PID controller
$G_a(s)$	Transfer function of the actuator model
$G_m(s)$	Transfer function of the reference model
$G_p(s)$	Transfer function of the plant model
$\mathbf{A}$	State matrix in the LQI state-space model
$\mathbf{B}$	Control input matrix in the LQI state-space model
$\mathbf{C}$	Output matrix in the LQI state-space model
$\mathbf{E}$	Disturbance input matrix in the LQI state-space model
$\boldsymbol{x}$	State vector in the LQI state-space model
x_I	Auxiliary state variable in the LQI state-space model
$\mathbf{A}_{ry}$	State matrix in the DOBC's rigid state-space model
$\mathbf{B}_{cy}$	Control input matrix in the DOBC's rigid state-space model
$\mathbf{B}_{Ly}$	Lumped disturbance matrix in the DOBC's rigid state-space model
$\boldsymbol{x}_{ry}$	State vector in the DOBC's rigid state-space model
$\mathbf{A}_{fy}$	State matrix in the DOBC's flexible state-space model
$\mathbf{B}_{fy}$	Input matrix in the DOBC's flexible state-space model
$\mathbf{C}_{fy}$	Output matrix in the DOBC's flexible state-space model
$\boldsymbol{x}_{fy}$	State vector in the DOBC's flexible state-space model
z_y	Internal state variable of the disturbance observer
$\boldsymbol{L}_y$	Disturbance observer gain in the DOBC scheme
$\boldsymbol{K}_y$	Feedback controller gain in the DOBC scheme
ξ	Parameter 1 used in the LMI computation
β_1	Parameter 2 used in the LMI computation
β_2	Parameter 3 used in the LMI computation
P_2	Parameter 4 used in the LMI computation
$\mathbf{Q}_1$	Parameter 5 used in the LMI computation
$\mathbf{Q}_2$	Parameter 6 used in the LMI computation
$\mathbf{R}_1$	Parameter 7 used in the LMI computation
s	Sliding surface
V	Lyapunov function
K_x	Exponential gain of the SMC controller
K_w	Switch gain of the SMC controller
ε	Small positive constant as part of the SMC switch gain
$\mathcal{D}_{\text{CSMC}}$	A static gain as the major part of the SMC switch gain
$\mathcal{D}_{\text{FSMC}}$	A dynamic gain as the major part of the Fuzzy SMC switch gain
A^{LO}	Input fuzzy set of "Low" in the fuzzy-based estimator
A^{HI}	Input fuzzy set of "High" in the fuzzy-based estimator
B^{LO}	Output fuzzy singleton of "Low" in the fuzzy-based estimator
B^{HI}	Output fuzzy singleton of "High" in the fuzzy-based estimator

Greek Symbols:

$\boldsymbol{\Theta}$	Euler angle vector denoted by $\{\phi, \theta, \psi\}$
ϕ	An angular rotation about the x_b-axis, known as the "roll angle"
θ	An angular rotation about the y_b-axis, known as the "pitch angle"
ψ	An angular rotation about the z_b-axis, known as the "yaw angle"

θ_{ref}	Pitch attitude reference trajectory
$\omega_{y\text{ref}}$	Angular velocity reference trajectory about the y_b-axis
$\boldsymbol{\omega}_{bI}$	Spacecraft's angular velocity vector from $\mathcal{F}_b$ to $\mathcal{F}_I$
ω_x	Spacecraft's angular velocity about the x_b-axis
ω_y	Spacecraft's angular velocity about the y_b-axis
ω_z	Spacecraft's angular velocity about the z_b-axis
$\boldsymbol{\omega}_{bo}$	Spacecraft's angular velocity vector from $\mathcal{F}_b$ to $\mathcal{F}_o$
$\dot{\phi}$	Roll rate
$\dot{\theta}$	Pitch rate
$\dot{\psi}$	Yaw rate
$\boldsymbol{\omega}_{oI}$	Spacecraft's angular velocity vector from $\mathcal{F}_o$ to $\mathcal{F}_I$
α_y	Spacecraft's angular acceleration about the y_b-axis
α_{cy}	Control angular acceleration about the y_b-axis
α_{dy}	Disturbance angular acceleration about the y_b-axis
$\alpha_{\eta y}$	Vibration angular acceleration (flexible arrays) about the y_b-axis
μ	Gravitational constant of the Earth
$\omega_{\odot}$	Orbital velocity of the spacecraft
$\boldsymbol{\eta}$	Flexible modal coordinates
$\boldsymbol{\varsigma}$	Vector of the solar array's scalars
ϑ	Angular rotation of the solar array about the spacecraft's y_b-axis
$\mathbf{Z}$	Elastic damping matrix
$\boldsymbol{\Lambda}$	Stiffness matrix
ζ_i	Damping ratio of i-bending mode
Ω_i	Modal frequency of i-bending mode
Ω_m	Motor shaft's angular velocity in the frequency domain
Ω_m^n	North array motor shaft's angular velocity in the frequency domain
Ω_m^s	South array motor shaft's angular velocity in the frequency domain
Ω_a	Angular velocity of the solar array in the time domain
Ω_c	Command input of the angular velocity in the frequency domain
τ_m	Motor's electrical time constant
κ_m	Motor's output gain
$\mu_A(x)$	Membership function of a fuzzy set A for an element x of X
κ	Scaling factor for the fuzzy system
λ	Sliding surface parameter

Other symbols:

$\angle_i$	Angle of incidence of the solar array
$\angle_d$	Average deviation angle of the solar arrays

CHAPTER 1

INTRODUCTION

1.1 Background of Spacecraft Attitude Control

Without a reliable spacecraft attitude control system, any space mission that requires pointing requirements, such as safe modes, acquisition modes, science modes, and orbital maneuver would be very difficult, if not impossible. On 4 October 1957, the Soviet Union launched Sputnik 1 into low Earth orbit and this marks the dawn of the space age. In the early days, the spacecraft are spun around the axis of maximum moment of inertia so that it can be fixed stably at one axis. This method, known as spin stabilization, was most employed due to lack of technological advancements in computer hardware to perform complicated control algorithms. Because of the balancing requirement, all components and devices have to be carefully designed, albeit the spin-stabilized spacecraft is as stable as a spinning top. However, this is difficult to achieve as the trade-off between the desired accuracy and payload design has to be made. Moreover, design contingencies must also be included for the unknown risks associated with everything onboard that can move during launch and flight, such as motors, pumps, and fluid sloshing in propellant tanks.

Generally, humans launch spacecraft into space for the reason of pointing an equipment or an instrument at something of interest due to the desire to explore. Man-made spacecraft that orbit celestial objects are known as artificial satellites. For example, in astronomy and astrophysics missions, the purpose is to point a telescope at planets in our solar system, distant stars, or other interstellar objects beyond the Milky Way galaxy. In Earth observation missions, the objective is to point high resolution optical cameras, radars or imaging spectrometers toward a desired location on the Earth surface to collect spatial data. For communications between satellites and ground stations, the transmitting and receiving antennas are oriented to point towards each other to achieve the optimum directive gain. These examples imply that the orientation of the spacecraft (also known as attitude) needs to be regulated so that it holds stably at some desired pointing direction. To accomplish this task, some forms of attitude control, whether active or passive, is required. The choice of active or passive control entirely depends on the type of mission, which is directly related to the required attitude accuracy, and the mission budget. If the accuracy requirements are low, then passive attitude control exploits the spacecraft's surrounding natural energy sources such as gravity gradients, Earth's magnetic field, or aerodynamic drag of the atmosphere at low Earth orbits to stabilize in the neighborhood of a stable equilibrium at the desired attitude. Otherwise, actuators capable of affecting the attitude, such as thrusters, reaction wheels, control moment gyroscopes, and magnetic torquers must be installed on the spacecraft for active attitude control.

1.1.1 Problem Statements

In the last five decades, semiconductor technology had evolved from the first transistor made in the Bell Laboratory to solid-state electronics, exponentially accelerating technological change in microprocessor, microcontrollers, actuators, and sensors. Not only more and more three-axis stabilized spacecraft are launched, but attitude control schemes also have been extensively studied and improved, ensuring the stability of attitude control systems. However, the control of spacecraft attitude becomes a challenging problem when large angle maneuvers are required. The governing equations of attitude dynamics are inherently nonlinear, and thus the linearized dynamical model is no longer valid for large angle maneuvers. Another issue deals with saturation nonlinearities, where all physical actuators and sensors are subject to the maximum limits of angular velocities, torques, and measuring ranges. If large Euler angle (approaching 90°) is commanded, the spacecraft attitude stability could be ruined by kinematic singularity, where some elements of the attitude matrix become infinitely large and problematic for control computation. Fortunately, the kinematic singularity issue can be avoided by using other computationally-efficient kinematic expressions such as quaternions and modified Rodrigues parameters.

Despite the extensive studies in attitude control laws, failures still can occur in a spacecraft system, either in actuators, control hardware, or sensors. For example, if a three-axis stabilized spacecraft suffers multiple reaction wheel failure, external disturbances will cause the spacecraft to lose its ability to correct the attitude error. If the failure is irrecoverable, a tumbling spacecraft may jeopardize the missions, or even a total loss, as experienced by EchoStar 5, FUSE, and Navstar 2-08 [1]. One of the headline-grabbing incidents was the NASA's exoplanet-hunting space telescope, Kepler, where the original mission had to be modified to search for exoplanets at different constellation fields [2].

In 2005, Hayabusa, the asteroid sample-return spacecraft, lost two reaction wheels on the roll and pitch axes, forcing it to stabilize its attitude using only the Xenon cold gas jets [3]. Having depleted its chemical fuel, the spacecraft switched to ion engine thrust. To save the remaining fuel (xenon gas), the solar radiation pressure approach was used on the Hayabusa spacecraft for attitude control in a recovery mode. However, this approach becomes ineffective during the orbital eclipse phase. Adding to the list, the JAXA's X-Ray Astronomy Satellite, Hitomi, broke up into five pieces due to an uncontrolled tumbling, leading to a total loss. After ceasing efforts to recover the satellite one month later, the final investigation showed that the mishap was caused by the malfunctioning sensor and flawed attitude controller [4].

A common practice to recover a tumbling spacecraft is by firing multiple ion thrusters or cold gas jets sequentially to generate a desired torque, which can control the total momentum of the spacecraft. Since the thrusters expel propellant to produce a control torque, this leads to increased fuel consumption and eventually shortened operational life, if the faulty reaction wheel is irrecoverable.

All these unforeseen events show that it is important to have redundancy for the attitude control system. But having redundant actuators means adding extra payload weight to the spacecraft as well as increasing the system complexity. Therefore, the most cost-effective way is to use the existing subsystems as the potential alternative attitude actuators in a synergistic way, without losing their original functions [5]. For the sake of maintaining operations, the principal preference for a fuel-saving approach is to exploit the existing subsystem, Solar Array Drive Assembly (SADA).

1.1.2 Space Modeling and Simulation

In the field of space modeling and simulation, models and simulators are used to produce results that resemble a spacecraft system's motion in a virtual simulation environment. Simulations are performed not only to investigate a spacecraft system's performance, but also to identify the cost parameters in the design and to eliminate flawed control algorithms, which can help to reduce the budget strategically without compromising the space mission.

In fact, the models designed by the engineers can be used in various ways. They can be used to predict the spacecraft system's behavior, which has enabled rapid technological advancement in spacecraft system engineering over the last few decades. This is especially true when the experimental methods are very difficult, if not impossible. For example, it is very difficult to create a sufficiently large weightlessness and frictionless environment on Earth to test the costly prototypes and bulky satellites. Thus, engineers are able to make good use of the simulation studies to make strategic decisions without having to construct an expensive prototype of a real spacecraft.

The models can also be used for data collection, especially in dealing with structural vibration and thermal management of the spacecraft, because once the engineers know which data are most critical to the spacecraft architecture and design process, they can design the subsystems more reliably and perform system integration more effectively.

More importantly, the models should be used to build potential solutions to the control problems by applying physical constraints in design to potential solutions and then conduct feasibility assessment on the potential solutions. Furthermore, having multiple solutions enables the engineers to compare real-world observations with the observation of model behaviors, which then provide sufficient knowledge to the engineers to make decisions whether to discard or to improve the original solutions.

1.1.3 Motivations

Knowing that the actuators are part of the active attitude control system, the research task is to determine the appropriate amount of attitude control torque the actuator should produce and deliver to the spacecraft. This becomes the fundamental problem of the control system design. In control system design, engineers have to deal with three major subsystems, namely Guidance, Navigation, and Control (commonly abbreviated GN&C). In the Guidance subsystem, the task is to determine the desired attitude trajectory from the spacecraft's current attitude, including the required changes in angular velocity, and angular acceleration necessary for tracking that trajectory. The task of the Navigation subsystem refers to the determination of the spacecraft's current attitude and angular velocity vector from the attitude sensor measurements. Technically, this task is known as attitude determination, and the techniques involved can be largely divided into methods that perform statistical analysis on a series of measurements taken over time and methods that do not. The control subsystem determines the amount of torque to be delivered to the spacecraft to execute the guidance command by correcting the attitude error and at the same time maintaining the attitude stability.

Considering that most spacecraft that provide real-time communication services do not tolerate service disruptions or degradation due to attitude control system failure, instead of relying the thrusters expel propellant to produce a control torque (that eventually leads to shortened operational life), it is important to look for new ideas to create a fuel-free option for generating a control torque from the existing subsystems. The synergisms for spacecraft attitude control system are crucial for the sustainable development of future spacecraft that demand optimum collaborative payload design approach, and thus, reducing the number of subsystems for spacecraft.

With the aim to determine the stabilizing torque, it is essential to acquire the knowledge of how the spacecraft attitude will respond to the control torque. Since this response is dictated by the attitude dynamics, the spacecraft attitude dynamics and control are studied in this research work via modeling and simulation. This work will be the basis to ensure a successful in-orbit operation in terms of the spacecraft attitude control task.

1.2 Research Aims

In general, spacecraft attitude control poses a number of challenges, with the nonlinear dynamics and in particular stabilizing the attitude in three axes using two reaction wheels, as the most challenging one, involving both hardware and software issues. Because the SADA is used to rotate and point a solar array toward the Sun, it can be treated as an unconventional momentum exchange device for the purpose of attitude control. For this reason, the idea of Combined Attitude and Sun Tracking System (CASTS) is conceived so that the actuation of attitude control stays active during both sunrise and eclipse phases. Therefore, the research aim is to investigate the CASTS capabilities of the spacecraft using the fuzzy logic-based control schemes.

For this work, the research objectives to be achieved are stated as follows:

i. To develop a combined attitude and Sun tracking control architecture for a flexible spacecraft with a nadir pointing capability.
ii. To design various fuzzy logic-based attitude control laws to ensure the attitude stabilization in the presence of external disturbance while the solar arrays track the Sun closely.

iii. To test and validate of the proposed CASTS architectures together with all the governing equations through numerical treatments with the in-orbit conditions.

1.3 Scope of the Study

This study focuses on the control system simulation for rigid and flexible spacecrafts with the CASTS architecture from the domain of spacecraft development. For the flexible case, the spacecraft is a bi-wing Earth-orbiting satellite with two solar arrays typically mounted on the pitch-axis. Since the CASTS is about the in-orbit attitude stabilization using the solar arrays, naturally, the research considers only the pitch-axis rotational maneuver of the spacecraft. Therefore, the roll and yaw-axes are assumed to be controlled separately by the well-functioning reaction wheels.

Likewise, since most large Earth-orbiting satellites have two solar arrays mounted on the pitch-axis, therefore, it is natural that the CASTS modeling procedure is limited to large satellites. The models are neither for small satellites nor microsatellites.

The simulation of the spacecraft system requires the modeling of a rigid spacecraft hub and the flexible solar arrays. The elastic deformations of the spacecraft hub are extremely small, and thus are negligible. The models of spacecraft and CASTS only reflect the real motion functionally and does not reflect the internal design of the solar array and SADA component such as the electric motor control circuits. The model is also assumed to consist of one rigid hub and two flexible appendages.

For a nadir-pointing satellite, where the spacecraft points directly towards the center of Earth, it is reasonable to consider small deviations in the Euler angles (which are used to represent the attitude) and the angular velocities, so that the proper linearization procedure can be applied to the spacecraft kinematics and dynamics.

In the CASTS architecture, the solar arrays are driven by the SADA, which has one degree of rotational freedom with respect to the pitch-axis of rotation. The SADA typically consists of a bipolar stepper motor, however, in the CASTS, the SADA must be driven by a brushless DC motor in order to achieve high attitude accuracy.

All solar cells on the solar array are assumed to align perfectly on the absolutely flat surface of the solar array. Because the power loss of the solar array is dependent on the angle of incidence, this assumption allows the power loss of the entire solar array to be computed from the angle of incidence of the solar array, instead of the effective angle of incidence of each solar cell.

The scope of the fuzzy control design procedure is restricted by the scope of linear controllers, and thus, the design procedure is relevant whenever the linear control methods such as PID control, state feedback, pole placement, and Linear-Quadratic Regulator are feasible, or already implemented previously.

In the simulation work of spacecraft systems, it is relevant to precisely define terms “to test” and “to validate”:

i. “To test” is to analyze the designed spacecraft control system for gaining an insight to its dynamical motion through simulations that implies conducting numerical experiments on the mathematical model of the spacecraft system using the MATLAB® computational software.
ii. “To validate” is to check that the spacecraft control system performs as required by the specifications in terms of the attitude accuracy and the desired Sun tracking capability.

1.4 Outline of Thesis

The thesis consists of seven chapters and focuses on the control design problems on spacecraft attitude dynamics. Chapter 1 serves as the introductory chapter on some fundamental information on the attitude control and simulation. Chapter 2 presents the discussions of scholarly papers on three topics, namely the conventional control methods, the computational intelligence methods, and the synergisms for spacecraft attitude control system. Chapter 3 covers spacecraft kinematics and dynamics, modeling of flexible spacecraft using Euler–Lagrangian method, and the analysis required to understand the deformation of multiple-degree-of-freedom solar arrays. Typical external disturbance torques that act on a spacecraft are also introduced in this chapter. Chapter 4 focuses on the architecture of combined attitude and Sun tracking system (CASTS) development, where the attitude control system and solar tracking system are discussed profoundly. The design of attitude control laws is treated in Chapter 5, and the fundamentals of fuzzy control are introduced in the chapter as well. Chapter 5 also discusses the versatility of fuzzy controller for CASTS, the disturbance observer-based fuzzy control, and the fuzzy switch-gain sliding mode control. Chapter 6 deals with the simulations of multiple scenarios based on the proposed attitude control laws designed in Chapter 5. The final chapter concludes the thesis work and recommends the future direction of research towards spacecraft synergisms.

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LIST OF PUBLICATIONS

[1] Y.-C. Chak and R. Varatharajoo, “A novel design of spacecraft combined attitude & sun tracking system using a versatile fuzzy controller,” *Aircraft Engineering and Aerospace Technology*, vol. 87, no. 6, pp. 530–539, Oct. 2015.

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