Modeling and Control of A Pico-satellite Attitude Using Fuzzy Logic Controller

By

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ABBREVIATIONS

InnoSAT	Innovation Satellite
UniMAP	Universiti Malaysia Perlis
ADCS	Attitude Determination and Control System
OBC	On-Board Computer
ACS	Attitude Control System
ANGKASA	Malaysia National Space Agency
FLC	Fuzzy Logic Controller
PFLC	Predictive FLC
APFLC	Adaptive Predictive Fuzzy Logic Controller
PID	Proportional Integral Derivative
GA	Genetic algorithm
ADS	Attitude Determination System
AI	Artificial Intelligent
ZOH	Zero Order Hold
SISO	Single Input Single Output
MIMO	Multi Input Multi Output
MISO	Multi Input Single Output
NE	Negative
ZE	Zero
PO	Positive
LO	Low
NO	Normal
HI	High

U	Universe of Discourse
FIS	Fuzzy Inference System
FAM	Fuzzy associate memory
MF	Membership Function
RMSE	Root Mean Square Error
EA	Evolutionary Algorithms
L	Lower point
H	Upper point

NOMENCLATURES

F	Force
a	Acceleration
m_s	Mass
To	Time per orbit
g	Gravitational attraction at Earth's surface
R	Radius of Earth
r	Radius of the orbit
v	Velocity
T	Torque
I	Moment of inertia
$\dot{\omega}$	Angular acceleration
ω	Angular velocity
T_c	Control moments
T_d	Disturbance moments
T_{gg}	Gravity gradient torque
h	Angular momentum
h_b	Momentum of the rigid body
h_w	Momentum of exchange devices
ω_{bi}	Velocity vector of the body frame relative to the inertial frame
ω_{br}	Angular velocity vector of the body frame relative to the reference frame
ω_{rib}	Angular velocity vector of the reference frame relative to the

	inertial frame
p, q & r	Body angular rates
ϕ	Roll Angle
θ	Pitch Angle
ψ	Yaw Angle
$m(s)$	Controller Input in S-Domain
$\theta(s)$	Attitude angle in S-Domain
$m(k)$	Controller Output
$\theta(k)$	Satellite Output
Ts	Sampling time
$e(k)$	Error Input
$\Delta e(k)$	Change of error Input
$r(k)$	Reference Input
e_p	Predictor error
Δe_p	Predictor change of error
θ_m	Output of Reference Model
a_1, a_0, b_1 & b_0	Model Reference parameters
Q	Adaptation gain
$\mu(k)$	Convergence factor
α , δ	Positive constant
k_p	Proportional gain
k_i	Integral gain
k_d	Derivative gain
K	Coupling Factor
T_p	Peak time

T_s	Settling time
T_r	Rise Time
%OS	Percent overshoot
θ_{ref}	Measured Attitude
h	Momentum of the satellite in the body frame
ω_0	Orbital rate

ABSTRACT

Modeling and Control of A Pico-satellite Attitude Using Fuzzy Logic Controller

Fuzzy logic concept was first conceived by Lotfi Zadeh in 1965 by incorporating rule based approach to solve control problems. The advantage of Fuzzy Logic Controller (FLC) is that the control process can be controlled without knowing much knowledge of their dynamics. FLC is applied as the controller to most of commercial mercantile products in past 25 years. Since that, many applications of the FLC in controlling the Pico-satellite's attitude have been proposed successfully. In this regards, a new method of Pico-satellite attitude control using Mamdani Fuzzy Logic Principles is introduced. The design of the APFLC is initially started with the designation of Basic FLC with two input and single output system. Then, a Predictive FLC is designed to compensate the effects of delay time which occurs in the Pico-satellite control system. The predictor is a one step-ahead predictor which estimates the required control at the next sampling time and applies to the system at current sampling time. Finally the adaptive portion of FLC is applied in order to compensate the effect of unknown parameter variations in the Pico-satellite system by using an adaptable gain which is connected in the forward path of the FLC. The response of the Pico-satellite is compared with a model reference adaptive system, derived on the basis of deviation in the responses and updates the adaptive gain. The adaptation continues until the Pico-satellite attitude reaches the set-reference attitude. The design schemes of modeling adaptive and predictive FLC (APFLC) is described as follow: Basic FLC, Predictive FLC (PFLC) and APFLC. The APFLC is compared with a conventional Proportional Integral Derivative (PID) controller. The simulation results are presented and the output responses indicate that this approach of FLC is acceptable even in the case of a Pico-satellite subjected to input noise, measurement noises, intermittent disturbances and also with sensor nonlinearity. It is observed that the APFLC showed convincing performance over the entire simulation of the Pico-satellite. Genetic Algorithm (GA) is a computational model inspired by evaluation. This algorithm encode a potential solution to a specific problem on a simple chromosome like data structure and apply recombination operators to this structure to preserve critical information. The contribution of this work is to optimize the base of Fuzzy membership function of the APFLC by using GA technique. The optimization technique involved from two points to four points and end with six points. The performances obtained show that the optimized APFLC is better than the non-optimize APFLC in terms of RMSE and the settling time.

ABSTRAK

Pembangunan dan Kawalan Sikap Sebuah Piko Satelit Menggunakan Pengawal Logik Kabur

Konsep logik kabur adalah pertama yang difikirkan oleh Lotfi Zadeh pada 1965 dengan menggabungkan undang-undang berpangkalan pendekatan untuk menyelesaikan masalah kawalan. Kelebihan bagi Pengawal Logik Kabur adalah proses kawalan itu boleh dikawal tanpa mengetahui banyak pengetahuan tentang dinamik mereka. FLC Pengawal Logik Kabur diaplikasikan sebagai pengawal kepada kebanyakan produk dagangan di dalam lebih 25 tahun. Sejak itu, banyak permohonan Pengawal Logik Kabur di dalam kawalan sikap sebuah Piko Satelit telah dicadangkan dengan jayanya. Di dalam anggapan ini, satu kaedah baru bagi kawalan sikap sebuah Piko Satelit dengan menggunakan Pengawal Logik Kabur Mamdani diperkenalkan. Reka bentuk Pengawal Ramalan Logik Kabur Mudah Suai adalah dimulakan daripada Asas Pengawal Logik Kabur dengan dua masukan dan satu keluaran. Kemudian, satu Ramalan Pengawal Logik Kabur adalah direkabentuk untuk memampas kesan masa mati yang berlaku di dalam sistem kawalan Piko Satelit tersebut. Peramal adalah satu langkah meramal masa hadapan yang menganggarkan keperluan kawalan pada masa pensampelan yang akan datang dan digunakan ke atas sistem pada masa pensampelan semasa. Akhirnya bahagian Pengawal Logik Kabur Mudahsuai diaplikasikan dengan tujuan memampas kesan variasi parameter yang tidak diketahui di dalam sistem Piko Satelit tersebut dengan menggunakan satu keuntungan yang boleh disesuaikan dan dikaitkan di dalam laluan yang di hadapan Pengawal Logik Kabur. Sambutan Piko Satelit tersebut dibandingkan dengan satu sistem mudah suai rujukan yang contohnya perolehan tentang asas sisihan di dalam jawapan-jawapan dan kemaskini keuntungan ubah suai. Penyesuaian diteruskan sehingga sikap Piko Satelit tersebut sampai ke set rujukan sikap. Skim-skim reka bentuk peragaan Ramalan Pengawal Logik Kabur Mudahsuai disifatkan seperti berikut: Asas Pengawal Logik Kabur, Ramalan Pengawal Logik Kabur dan Ramalan Pengawal Logik Kabur Mudahsuai. Ramalan Pengawal Logik Kabur Mudah Suai dibandingkan dengan satu konvensional pengawal Terbitan Kamiran Berkadar. Hasil simulasi dibentangkan dan hasil keluaran menunjukkan pendekatan bagi pengawal logic kabur adalah diterima juga di dalam kes seperti sebuah Piko Satelit dengan menakluki hingar masukan, bising ukuran, gangguan-gangguan terputus-putus dan juga dengan penderia ketaklelurusan. Ianya diperhatikan bahawa Ramalan Pengawal Logik Kabur Mudahsuai menunjukkan prestasi yang meyakinkan kepada hasil simulasi seluruh Piko satellite. Algoritma Genetik adalah satu model pengiraan cemerlang oleh penilaian. Algoritma ini membina kod penyelesaian yang berpotensi untuk satu masalah yang khusus sedang satu selapis kromosom seperti struktur data dan memohon gabungan semula pengendali-pengendali untuk struktur ini untuk mengekalkan maklumat kritikal. Sumbangan kerja ini adalah bagi mengoptimumkan asas bagi keanggotaan logic kabur fungsi Ramalan Pengawal Logik Kabur Mudahsuai dengan menggunakan teknik Algoritma Genetik. Teknik pengoptimuman terlibat daripada dua mata ke empat mata dan diakhiri dengan enam mata. Persembahan keputusan menunjukkan yang Ramalam Pengawal Logik Kabur Mudahsuai adalah lebih baik daripada Ramalan Pengawal Logik Kabur Mudah Suai yang tidak dioptimumkan di dalam soal ralat min punca kuasa dua dan masa penyelesaian.

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Aerospace is a branch of engineering that includes design and construction of a spacecraft or aircraft. Aerospace refers to a flight within the atmosphere and applying the principles of science and technology to highly sophisticated products such as space satellites (Wallace, 2002). Space satellite is defined as an object orbiting another object. Satellites can be celestial such as the moon orbiting a planet in the solar system or a man-made satellite which is typically launched into outer space from the Earth to collect data or images. A man-made satellite is an extremely complicated piece of equipment that includes propulsion system, power system, telemetry and command system, thermal control, superstructure, attitude control system and communication subsystem (Kim, 2007).

In view of a limited research attention in the area of satellite system in Malaysia, Malaysia National Space Agency (ANGKASA) and Astronautic Technology (M) Sdn. Bhd. organized a research collaboration with Universiti Malaysia Perlis (UniMAP) concerned with the development of a Pico-satellite called the InnoSAT Project. The purpose of this program is to provide an opportunity for UniMAP to design a control algorithm for the Attitude Controller System (ACS) of the InnoSAT payload. The controller is designed by the School of Mechatronic Engineering, Universiti Malaysia Perlis (UniMAP) known as UniMAP ACS. UniMAP ACS is basically an embedded control algorithm firmware that produces necessary control parameters to the three magnetorquers based on the measured signals of three axis magnetometer to maintain the satellite in a fixed orientation with respect to the Earth. The firmware of UniMAP ACS is simulated using MATLAB program and embedded to RCM3400 Rabbit-Core Microcontroller Board using C language. The effectiveness of the control methodology is thoroughly and exhaustively tested by simulation studies with a satellite model before being implemented to the InnoSAT system.

1.2 Problem Statements

Immediately after launched and placed in its Low Earth Orbit (LEO), the Pico-satellite can be tumbling at an undefined angular rate. At this time the satellite needs to reduce the roll and yaw angular rates and align to the normal orbit. The proposed controller need to maintain a certain attitude while orbiting to allow accurate orientation towards the Earth. In addition, the proposed controller is necessary to maintain the satellite's stability even if the satellite is affected with interferences such as magnetic fields, solar wind, disturbance torque reduce the tumbling rate. These phenomena tends to disturb the satellite's attitude, so it is necessary to control the attitude and keep the satellite stable even in addition of noise and disturbances. Although several control laws have been used to design the attitude control of a Pico-satellite (Tisa & Vergez, 2006), a new approach is expected to be more robust and can be efficiently used in real-time control. To handle these difficulties, a study of designing an Adaptive Predictive Fuzzy Logic Controller (APFLC) for the application of attitude control for a Pico-satellite is carried out. Fuzzy logic is selected as the controller suited for situations where the plant is too complex to model. A Predictive controller is introduced to compensate the effects of time delay and the adaptive portion is applied in order to compensate the effect of unknown parameter variations in the satellite system.

1.3 Research Methodology

In this study, three schemes of Fuzzy Logic Controller (FLC) are design to complete the APFLC in a package. The design of the APFLC is initially started with the designation of Basic FLC with two inputs and single output system. After that, a Predictive FLC is designed to compensate the effects of time delay which occurs in the satellite system. The predictor is a one step-ahead predictor which estimates the required control at the next sampling time and applies to the system at current sampling time. Later, the adaptive portion of FLC is applied in order to compensate the effect of unknown parameter variations in the Pico-satellite system by using an adaptable gain which is connected in the forward path of the FLC. The measured attitude is compared with a reference model derived on the basis of deviation in the responses and the adaptive algorithm updated the adaptable gain to correct the orientation. By referring to the complex Euler's equation, a simplified but effective model to represent a Pico-satellite system is introduced. This model is considered to represent the tumbling behavior of a Pico-satellite in space after deployment and used to study the performances of Pico-satellite behavior under various conditions throughout this thesis. The simulations carried out for several reference input such as step input, square wave input reference and Y-Thompson spin. As it is necessary to control the attitude and keep the satellite stable even in addition of noise and disturbances, the simulations are carried out with presence of Pseudorandom noise and short pulse disturbances. Finally, the APFLC is compared with a conventional Proportional-Integral-Derivative (PID)

Controller and Genetic algorithm (GA) is presented to optimize the performances of the triangle base of Fuzzy membership function of the APFLC.

1.4 Research Objectives

This research attempts to examine the application of fuzzy logic principle in the development of attitude control of a Pico-satellite. More specifically the objectives of this study are given as follows:

- To design APFLC which consists of a controller using Fuzzy Logic principle named FLC, a Predictive controller to compensate the effects of delay time which occurs in the Pico-satellite system and apply Adaptive algorithm to reduce the effect of variations in unknown parameters due to various environmental phenomena in a single package.
- To develop a satellite model incorporating the APFLC and simulate the Pico-satellite system against disturbances, noises, nonlinearity and cross-coupling effect.
- To compare the APFLC with other conventional controller.
- To optimize the base membership points of APFLC using GA.

1.5 Thesis Outline

The research works carried out are presented in seven chapters in this thesis. In this First Chapter, a brief introduction is given for the proposed controller.

The Second Chapter briefly reports the review of the literature that necessitate the scope of the present work.

The Third Chapter presents the dynamics modeling of a Pico-satellite using Euler’s method. The dynamics model has been simplified and discretized to form a discrete transfer function model and used throughout all simulation studies.

The Fourth Chapter describes the theoretical background for designing the FLC. The three different variants of FLC namely Basic FLC, Predictive FLC (PFLC) the APFLC are discussed. All the three methods are simulated with one, two and three axis satellite system. The APFLC being compared with a conventional controller, PID.

The Fifth Chapter presents the simulation results of basic FLC, PFLC, APFLC and conventional PID controller. The advantages of applying APFLC for the attitude control are also discussed in this chapter. The performances of the designed controllers with off diagonal cross-coupling effect are also simulated with noise and disturbances.

The Sixth Chapter proposes an optimization technique of Fuzzy membership function of APFLC using GA. Several potential solutions are obtained and simulations have been carried out for analyzing the performance of APFLC. hence

The Seventh Chapter provides the conclusion of the study and offers some suggestion for further research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Satellite Attitude Control

A satellite's life commences with a specific booster transferring it to an initial orbit called a transfer orbit. The satellite begins to circle the earth in its orbit and it has to be maneuvered to reach the precise final orbit in which the satellite is designed to fulfill its mission. This is achieved by the hardware and software embedded in the satellite system which continuously calibrate its instrumentation and optimizing its control performance in space (Sidi, 2000). The standard size (Cal poly standard) of a Pico-satellite (CubeSAT) is a single CubeSAT should be a 10-cm cube and have a total mass of not more than 1 kg (Nugent, et al., 2008). Though the Pico-satellite is very small, it exhibits virtually all the complex characteristics of a conventional larger one but in a microcosm which requires more manageable infrastructure (Said, et al., 2004) .

The orientation of a Pico-satellite body coordinate with respect to a defined frame is called attitude. This attitude is represent by the relationship between axis (ϕ, θ and ψ) and reference frame. Reference system is the attitude coordinate system and has its origin at the center of the Earth. There are two defined frame in the reference system namely inertia frame and orbit frame. The inertial frame is shown in Figure 2.1.