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Small Satellite Modelling and Attitude Control Using Fuzzy Logic

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***Abstract*—**Small satellites have become increasingly popular recently as a means of providing educational institutes with the chance to design, construct, and test their spacecraft from beginning to the possible launch due to the low launching cost. This approach is remarkably cost saving because of the weight and size reduction of such satellites. Weight reduction could be realised by utilising electromagnetic coils solely, instead of different types of actuators. This paper describes the restrictions of using only "Electromagnetic" actuation for 3D stabilisation and how to make the magnetorquer based attitude control feasible using Fuzzy Logic Control (FLC). The design is developed to stabilize the spacecraft against gravity gradient disturbances with a three-axis stabilizing capability.

***Keywords*—**Fuzzy, Attitude Control, Small Satellite, Fuzzy Logic Control, Electromagnetic, Magnetic Control.

I. Introduction

MANY common control methods have been researched during more than four decades for attitude control system of satellites based on electromagnetic actuation [1, 2, 3, 4, 5]. However, the area of electromagnetic attitude control using intelligent and adaptive methods is not yet fully explored. The Fuzzy Logic Control (FLC) has been successfully used in several complex systems. This paper suggests using fuzzy control as it is a robust control method against parameter variations and system disturbances [6]. To develop a FLC it is required to define input-output variables and the rule table, based on decision making procedure.

The first section addresses the notations that are used in the paper, followed by the electromagnetic theory which quantifies the torque generated through the Earth's magnetic field interaction with the satellite magnetic coils and a brief description of FLC followed by the description of the control laws. The control system is supposed to calculate the magnetic moment to be created in the magnetic coils which results in the desired mechanical torque to stabilise the satellite.

II. Magnetic Torquers

Magnetic torquers or in short "Magnetorquers" are essentially coils, mounted close to the panels of the satellite. A control system which merely relies on electromagnetic actuation has the advantages of being light, low cost and low power consuming [3]. Interaction of the magnetic field generated by the constant current driven in coils with the local geomagnetic field produces a control torque capable of the satellite stabilisation.

Using geomagnetic field as a form of control drive alone is a strategy that has been used where low precision control was required. The fact that force cannot be generated alongside the earth's magnetic field vector adversely affects the accuracy and efficiency of the satellite attitude determination and control system (ADCS) unit. In the other words, the magnetic moment has to be always perpendicular to the geomagnetic field to generate a control torque (Fig. 3) [7].

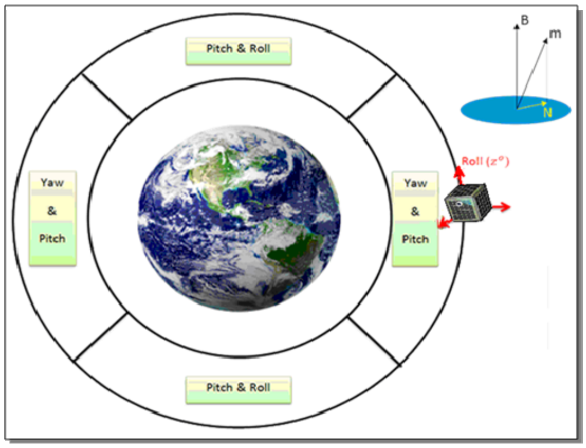

Fig. 1 Yaw is not controllable over poles and Roll is not controllable over the equator

Nevertheless, the theory presented in 1996 [7] described the possibility of the previous hypothesis. For each of illustrated cases, one of the actuators corresponding to roll and yaw angle control is active for a determined duration and then switched to another one. The controller have to evaluate the time and sign of the switch of each actuator. It is assumed that the measurements of each attitude angle and each angular rate are available.

III. Notation

Described below, is the notation used throughout this paper: [7]

Control CS: control right orthogonal coordinate system on principal axes of the satellite, the x-axis along the axis of maximal moment of inertia and the z-axis along the axis of the minimal

Zenith: a unit vector in the Control CS along the line

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connecting the satellite centre of gravity and the Earth centre pointing away from the Earth

Orbit CS: orbit right orthogonal coordinate system fixed in orbit with the x-axis in the orbital plane normal direction and the z-axis along zenith away from the earth World CS: inertial right orthogonal coordinate system Pitch, Roll, Yaw: the angles referred to the rotation about the x-axis, y-axis and axis of the Orbit CS respectively.

N_{ctrl}	Control Torque
N_{gg}	Gravity Gradient Torque
N_{dist}	Disturbance Torques
c_v, o_v, m_v	General notation for vector v resolved in Control CS, Orbit CS and World CS respectively
I	Inertia tensor of the satellite
Ω_{cw}	Angular velocity of Control CS w.r.t World CS
Ω_{co}	Angular velocity of Control CS w.r.t Orbit CS
Ω_{cw}	Angular velocity of Orbit CS w.r.t World CS
m	Coil dipole moment
ω_o	Orbital rate
$\mathbf{B}$	Geomagnetic field vector
i_o, j_o, k_o	unit vectors along x, y and z axis of Orbit CS

IV. Modelling

Here are the equations, dominating magnetorquers dynamic behaviour:

$$m(t) = n_{coil} \times i_{coil} \times A_{coil} \quad (1)$$

Magnetic control torque is generated by three mutually orthogonal coils whose dipoles are along pitch roll and yaw axes

$$N_{ctrl} = m(t) \times B(t) \quad (2)$$

The above equation reinforces the stated fact that the only control torques perpendiculars to B are possible.

Following equations form the entire mathematical model of the satellite motion [7]:

$$I \dot{\Omega}_{cw}(t) = -\Omega_{cw}(t) \times I\Omega_{cw} + N_{ctrl} + N_{gg} + N_{dist} \quad (3)$$

Equation (3) relates the satellite's angular velocity to the applied mechanical torque.

It should be noted that the disturbance torques rather than the gravity gradient are negligible. Gravity gradient torque is quantified as follows:

$$N_{gg} = 3\Omega_0^2 (k_0 \times Ik_0) \quad (4)$$

Illustrated below is the simulation result for gravity gradient observed from orbit CS.

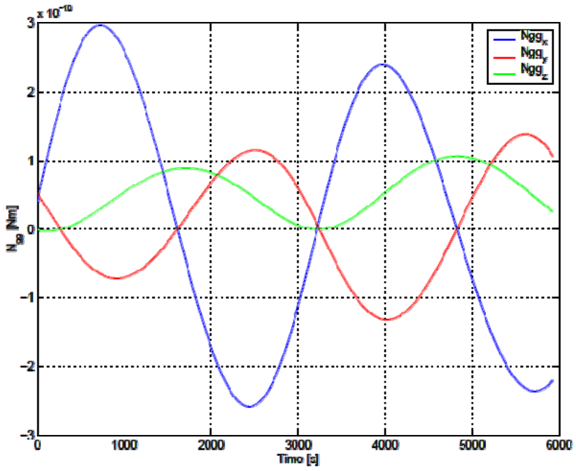

Fig. 2 Gravity Gradient Torque observed from OrbitCS

The attitude of the satellite can be defined as orientation of the Control CS relative to the Orbit CS. Additionally, the Euler Theorem that claims the rotation of coordinate systems can be uniquely modelled by a unit vector, giving an axis of rotation as well as its sense and an angle of rotation. As a result, the satellite attitude can be described as a unit quaternion:

$$^c_o q = [q_1 \quad q_2 \quad q_3 \quad q_4] \quad (5)$$

The vector part of the above quaternion consists of the first three components which is parameterised as $\mathbf{q}$ and q_4 is the scalar part. Therefore the satellite kinematics can be modelled as:

$$\dot{q} = \frac{1}{2}\Omega_{co} q_4 + \frac{1}{2}\Omega_{co} q \quad (6)$$

$$\dot{q}_4 = \frac{1}{2}\Omega_{co} q \quad (7)$$

$$\Omega_{co} = \Omega_{co} - \omega_o i_o \quad (8)$$

The above kinematics equations relate the instantaneous satellite's attitude to its angular velocity.

V. Fuzzy Logic Controller (FLC)

The objective of ADCS unit is to generate a control torque using magnetorquers as such the Control CS coincides with the Orbit CS [7]. The input linguistic variables are chosen to be the Euler angle error and the error rate. As the fuzzy controller has the same structure for each rotation, the following analysis holds for any of the three errors in the attitude angles.

Having the quaternion components and angular velocities measured in the Control CS, it is possible to have a set of multi-input single-output (MISO) fuzzy controllers generating the control torque (Fig. 3).

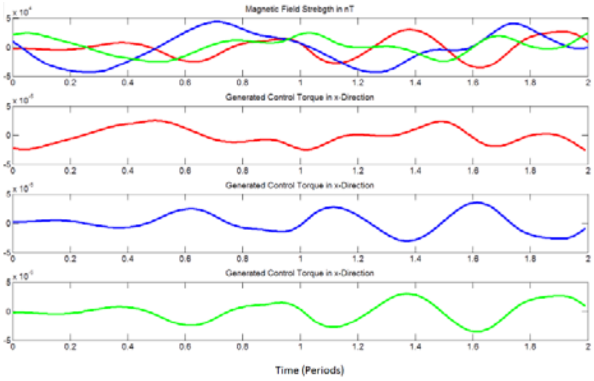

Fig. 3 Control Torque Generated by Fuzzy Controller

A Mamdani type FLC is used in this study with triangular type fuzzy sets. This method is known to be faster than other fuzzy set types. The FLC system has two inputs, error and its first differential. The designed controller de-vectorize the satellite dynamics using a set of linear equations:

$$x[k+1] = f(x[k], u[k], u[k], k, h) \tag{9}$$

$$x[0] = x_0 \tag{10}$$

where

$$f = h\begin{pmatrix} (-\omega_x q_1 - \omega_y q_2 - \omega_z q_3)/2 \\ (\omega_x q_0 + \omega_z q_2 - \omega_y q_3)/2 \\ (\omega_y q_0 - \omega_z q_1 + \omega_x q_3)/2 \\ (\omega_z q_0 - \omega_y q_1 + \omega_x q_2)/2 \\ (\omega_y \omega_z (I_{yy} - I_{zz}) + m_y B_z - m_z B_y + N_{dist_x})/I_{xx} \\ (\omega_x \omega_z (I_{zz} - I_{xx}) + m_z B_x - m_x B_z + N_{dist_y})/I_{yy} \\ (\omega_x \omega_y (I_{xx} - I_{yy}) + m_x B_y - m_y B_x + N_{dist_z})/I_{zz} \end{pmatrix} + \begin{pmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \\ \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} \tag{11}$$

Next step is to predict the desired torque for set-point following. Having calculated the ideal control torque for the next step, the FLC rules generate the nearest possible magnetic moment to achieve the desired attitude using the shown Fuzzy Associative Memory (FAM).

TABLE I
RULES OF THE SECOND STAGE FUZZY CONTROLLER

		Desired Mechanical Torque				
		-2	-1	0	1	2
Magnetic Field	-2	1	1	0	-1	-1
	-1	2	1	0	-1	-2
	1	-2	-1	0	1	2
	2	-1	-1	0	1	1

Following fuzzy membership functions describe the input and output linguistic variables:

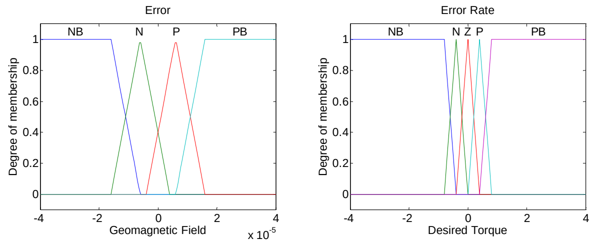

Fig. 4 Control Torque Generated by Fuzzy Controller

VI. SIMULATION

The above FAM table is the result of trial an error experiments but the idea was to not to produce any magnetic moment when a control torque is not required or there is no significant magnetic field available to interact with. That is the reason why there is no rule defined for the geomagnetic field of zero. Not quite clearly, it can also be verified from the fuzzy surface:

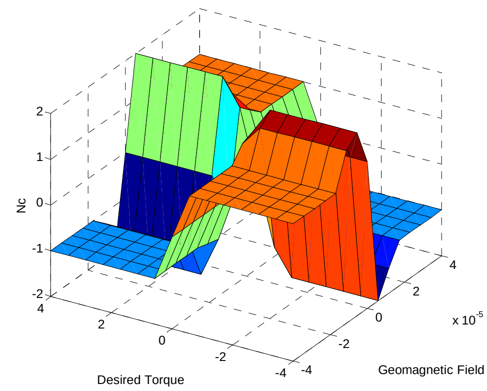

Fig. 5 FLC2 Generated Surface

Therefore, while the satellite is orbiting around the earth, the controller switches between different set of coils based on the availability of the geomagnetic field surrounding the satellite at each specific time which is clearly energy saving.

VII. SIMULATION & DISCUSSION

Characteristics of the orbit and the satellite for the simulation are listed as follows:

$$Initial \quad Euler \quad angles = [-80, 50, 80]^{\circ}$$

$$Initial \quad angular \quad velocity = [1, 0, 5, -1] \times 10^{-3} \frac{rad}{s}$$

As mentioned before, the satellite could maintain the communication link with up to 20 degrees of deviation from set-point which shows that the above conditions can test the stability and capabilities of the controller.

As can be seen from the simulation results the controller is able to detumble the satellite in less than three orbits. Although it would not be counted as a quite responsive control method, but it should be noted that once the satellite is detumbled from the initial phase after separation from P-POD, the disturbance torques are insignificant and not capable of destabilising the controller.

VIII. Conclusion

The electromagnetic interaction governing the dynamics of the satellite is explained clearly through the mentioned equations. The kinematic relations must also be used to determine the physical attitude variables such as Euler angles. Utilizing FLC approach, it is feasible to achieve three-axis attitude control having the desired magnetic torque and the method for calculating the required magnetic torque has been reviewed. Interestingly, the controller performance is comparable to the conventional controllers while the simplicity and flexibility of the controllers due to the fuzzy based approach is another considerable benefit.

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