

Neural Network based Three Axis Satellite Attitude Control using only Magnetic Torquers

N.Sivaprakash\*, J.Shanmugam\*\*, and P.Natarajan\*\*\*

\* Student, Division of Avionics (N.Sivaprakash@gmail.com)

\*\* Prof & Head, Department of Electronics Engineering, MIT - Anna University, Chennai, India

\*\*\* Head, Control Dynamics & Analysis Division, ISRO Satellite Centre, Bangalore, India

**Abstract:** Magnetic actuation utilizes the mechanic torque that is the result of interaction of the current in a coil with an external magnetic field. A main obstacle is, however, that torques can only be produced perpendicular to the magnetic field. In addition, there is uncertainty in the Earth magnetic field models due to the complicated dynamic nature of the field. Also, the magnetic hardware and the spacecraft can interact, causing both to behave in undesirable ways. This actuation principle has been a topic of research since earliest satellites were launched. Earlier magnetic control has been applied for nutation damping for gravity gradient stabilized satellites, and for velocity decrease for satellites without appendages. The three axes of a micro-satellite can be stabilized by using an electromagnetic actuator which is rigidly mounted on the structure of the satellite. The actuator consists of three mutually-orthogonal air-cored coils on the skin of the satellite. The coils are excited so that the orbital frame magnetic field and body frame magnetic field coincides i.e. to make the Euler angles to zero. This can be done using a Neural Network controller trained by PD controller data and driven by the difference between the orbital and body frame magnetic fields.

**Keywords:** Neural control, Three axis attitude control, magnetic control, PD controller, attitude stabilization, attitude control, micro-satellites.

1. INTRODUCTION

The main sub-system in Satellite development is Attitude control system. The attitude control system requirements are decided by the payload of the satellite as given in [7] - [9]. Also there exists so many disturbance torques in space which may deviate the satellite from the desired attitude. To overcome the effects of the disturbance torques some stabilization has to be provided to the satellite. Satellite stabilization takes three possible forms: (1) spin stabilization, whereby the satellite is spun at 10-30 rpm; (2) gravity gradient stabilization using a large weight attached to the satellite by a length of line; (3) inertial stabilization using heavy wheels rotating at high speed - typically three wheels, one for each axis, providing three-axis stabilization.

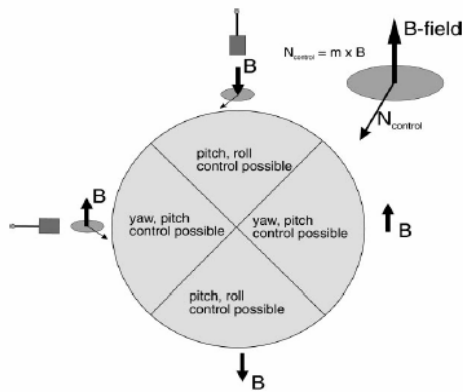


Fig.1: Three axis Magnetic control problem

Three-axis stabilization and control: A type of stabilization in which a spacecraft maintains a fixed attitude relative to its orbital track. This is achieved by nudging the spacecraft back and forth within a dead-band of allowed attitude error, using small thrusters or reaction wheels. In this paper this is achieved using Magnetic-torquers by Neural Network based controller. [3] - [6] describes the same three

axis control using different methods. With a three-axis stabilized spacecraft, solar panels can be kept facing the Sun and a directional antenna can be kept pointed at Earth without having to be de-spun. On the other hand, rotation maneuvers may be needed to best utilize fields and particle instruments. The problem in three axes magnetic control is shown in Fig. 1.

2. DISTURBANCE TORQUES

A spacecraft is subject to small but persistent disturbance torques and forces. The main disturbance torques for a satellite orbiting Earth is briefly discussed in this section. For low orbit satellites the air density is high enough to influence the satellite's attitude dynamics. The drag force also decreases the satellite's velocity, resulting in a lower altitude. Unless the orbit is maintained using thrusters, a satellite will ultimately reenter the atmosphere. Solar radiation and particles is also a source of disturbances. Radiation can damage the on board electronics and temperature changes distort the structure of the satellite. Several internal effects can generate disturbance torques. The electronics in the satellite may create an unwanted residual magnetic dipole. This field will interact with the Earth's geomagnetic field and generate a disturbance torque. When thrusters are used, fuel sloshing is a challenging problem. Another problem is flexible structures like antennas and solar panels.

2.1 Gravity gradient torque

The gravity gradient torque will affect a non symmetric body in the Earth's gravity field. This effect can be exploited with a gravity boom for passive stabilization. Assuming a homogeneous mass distribution of the Earth, the gravity gradient can be written as given in [1] and [2]

$$\tau_g = 3 \mu u_e \times (M u_e) / R_o^3 \tag{1}$$

Where

- $\mu$  - Earth's Gravitational constant ( $3.986 \times 10^{14} m^3/s^2$ )
- $R_o$  - Distance from Earth's center (m)

M - Spacecraft Inertia matrix

$\mathbf{u}_e$  - Unit vector towards Earth's center

writing in the body frame yields

$$\tau_g^b = \frac{3\mu}{R_0^3} \mathbf{c}_3^b \times (\mathbf{M} \mathbf{c}_3^b), \tag{2}$$

where  $\mathbf{C}_3^b = [C_{13} \ C_{23} \ C_{33}]^T$  is the third column in the rotation matrix describing the orientation between a local reference frame and the body frame.

Assuming a diagonal inertia matrix  $\mathbf{M} = \text{Diag} (M_{11}, M_{22}, M_{33})$ , the gravitational torque simplifies to

$$\tau_g^b = 3\omega_o^2 \begin{bmatrix} (m_{33} - m_{22})c_{23}c_{33} \\ (m_{11} - m_{33})c_{33}c_{13} \\ (m_{22} - m_{11})c_{13}c_{23} \end{bmatrix}, \tag{3}$$

where  $\omega_o^2 = \frac{\mu}{R_0^3}$ . (4)

### 2.2 Aerodynamic Drag

The interaction of the upper atmosphere molecules with satellite's surface introduces an aerodynamic torque. Assuming that the energy of the molecules is totally absorbed on impact with the spacecraft, the force  $d\mathbf{f}_{aero}$  on a surface element  $dA$  is described by

$$d\mathbf{f}_{aero} = -\frac{1}{2} C_D \rho v^2 (\hat{\mathbf{n}} \cdot \hat{\mathbf{v}}) \hat{\mathbf{v}} dA, \tag{5}$$

where  $\hat{\mathbf{n}}$  is an outward normal to the surface,  $\hat{\mathbf{v}}$  is the unit vector in the direction of the translational velocity of the surface element relative to the incident stream of the molecules. The atmospheric density is denoted by  $\rho$ , and the drag coefficient by  $C_D$ . The total aerodynamic torque is determined by integration over the total spacecraft surface.

### 3. ORBITAL MODEL

The orbit model shown in Fig.2 is used to give the orbital locations of the satellite at a particular time after launch. The input to the model is the clock signal.

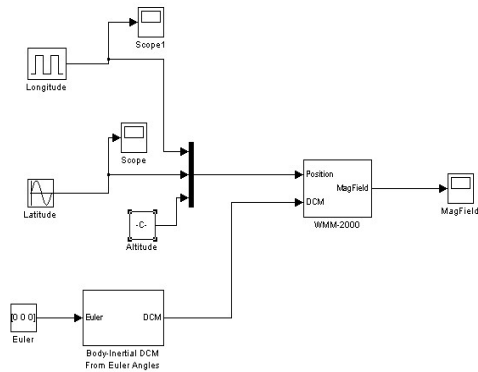


Fig.2: Orbit model in Simulink

### 4. SPACECRAFT MODEL

The model of a rigid spacecraft with magnetic actuation can be described in various reference frames [9]. For the purpose of the present analysis, the following reference systems are adopted.

**Orbital Frame** - This frame is a right orthogonal co-ordinate system fixed at the centre of mass of the satellite. The z axis points at zenith (is aligned with the Earth's centre and points away from Earth), the x axis points in the orbit plane normal direction and its sense coincides with the sense of the orbital angular velocity vector. The Orbit frame is the reference for the attitude control system.

**Satellite Body Frame** - The origin of these axes is in the satellite centre of mass; the axes are assumed to coincide with the body's principal inertia axes. The attitude dynamics can be expressed by the well known Euler's equations [9].

The spacecraft dynamics can be modelled using the following equations (linearized for small angles, for a circular orbit, and including the effect of gravity gradient stabilization):

$$\begin{aligned} \frac{d^2\phi}{dt^2} &= \frac{T_x - 4\omega_o^2(I_y - I_z)\phi + \omega_o(I_x - I_y + I_z)d\psi/dt}{I_x} \\ \frac{d^2\theta}{dt^2} &= \frac{T_y - 3\omega_o^2(I_x - I_z)\theta}{I_y} \\ \frac{d^2\psi}{dt^2} &= \frac{T_z - \omega_o^2(I_y - I_x)\psi - \omega_o(I_x - I_y + I_z)d\theta/dt}{I_z} \end{aligned} \tag{6}$$

Where  $T_x, T_y, T_z$  represent the sum of disturbances and control torque components applied to the subsystem in X,Y and Z axes respectively and  $\omega_o$  represents the orbital rate. I terms are the inertial terms for the satellite, with subscripts x, y, and z denoting inertia of the satellite about the roll, yaw, and pitch axes, respectively. Roll, pitch, and yaw angles are represented by  $\phi, \theta,$  and  $\Psi$ , respectively called Euler angles as shown in Fig.3. Euler angles describe a sequence of three rotations about different axes in order to align one coordinate system with a second coordinate system.

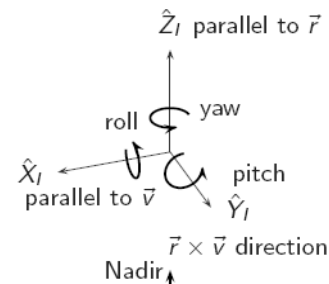


Fig.3: Euler angle definition

### 5. EARTH'S MAGNETIC FIELD MODEL

The magnetic field model used in this simulation is International Geomagnetic Reference Field (IGRF) model. The International Geomagnetic Reference Field is a mathematical description of the Earth's main magnetic field used widely in studies of the Earth's deep interior, the crust and the ionosphere and magnetosphere. Production of the IGRF is an international collaborative effort relying on co-operation between magnetic field modelers and institutes and agencies responsible for collecting and publishing geomagnetic field data. The IGRF incorporates data from permanent observatories and from land, airborne, marine and satellite surveys. The latest version of the model - the 9th Generation IGRF - was finalized by IAGA's Division V Working Group MOD (formerly WG V-8) in July 2003 at the IUGG XXIII General Assembly in Sapporo, Japan. It includes models of the main field at five-year intervals from 1900 to 2000, and a secular variation model for 2000-2005. The model here takes input as latitude, longitude and altitude. The outputs corresponds to geomagnetic field along the three axes X, Y and Z in gamma i.e. nano-tesla.

### 6. CONTROLLER DESIGN

The controller here selected for collecting training data for Neural controller is a simple PD controller as shown in Fig.4

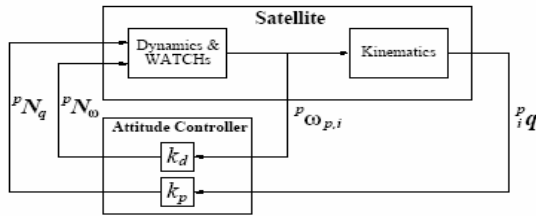


Fig.4: General PD attitude controller

#### 6.1 Magnetic Control

Coils in the X, Y and Z-axes will produce a dipole moment vector **M**. This vector then reacts with the local geomagnetic field **B** to produce a torque vector,

$$\mathbf{T} = \mathbf{M} \times \mathbf{B} \tag{7}$$

From the above equation it is clear that the torque is limited by the direction of the **B** vector. For a polar orbit, the pitch and yaw attitude angles can be controlled over the equatorial region and pitch and roll attitude angles over the polar region.

$$\mathbf{M} = -K_p (\mathbf{B}_{exp} - \mathbf{B}_{mes}) - K_d (d\mathbf{B}_{exp}/dt - d\mathbf{B}_{mes}/dt) \tag{8}$$

Where  $B_{exp}$  is Expected Magnetic field,  $B_{mes}$  is Measured Magnetic field,  $K_p$  is Proportional gain,  $K_d$  is Derivative gain.

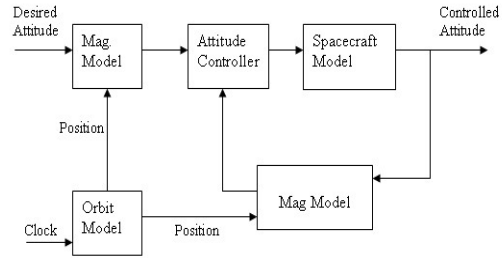


Fig.5: Simple PD Magnetic attitude controller

#### 6.2 Magnetic-torquer

Torque can be produced to change the attitude of a satellite by generating a magnetic moment  $M$ . This moment can be produced by a current flowing in a coil. The generated torque is largest when the magnetic-torquer and the earth magnetic field are parallel, and they have no effect when they are perpendicular. The coil can either have an air core or a ferrite core made from a special type of magnetic alloy with low remanence and good flux linearity. The magnetic moment is calculated from the current  $I$ , the number of turns  $n$  and the area enclosed  $A$ :

$$M = k n I A \tag{9}$$

For an air core magnetic-torquer the gain factor  $k = 1$  and for a ferrite core torque rod  $k = 100$  to  $300$ . The latter value depends on the length over diameter shape factor of the rod and the permeability of the core material.

### 7. NEURAL NETWORK CONTROLLER

There are many unknowns that are not accounted for when designing conventional control algorithms such as non-rigidity, accurate atmospheric effects, and changes in the system like a malfunctioning torque coil. The controller employs a neural network (NN) to determine the appropriate controls as given in [10]. The network shown in Fig.6 contains synaptic weights, like gains, that can be updated to obtain a better solution. For the attitude controller, the set of inputs is defined as the state vector  $x$ . For each layer, there is a vector of weights,  $w_i$ , and a bias vector,  $b_i$ , where  $i$  is the corresponding layer. The basic neural network equation then looks like:

$$\mathbf{g} = \mathbf{w}_2 [\tanh(\mathbf{w}_1 \mathbf{x} + \mathbf{b}_1)] + \mathbf{b}_2 \tag{10}$$

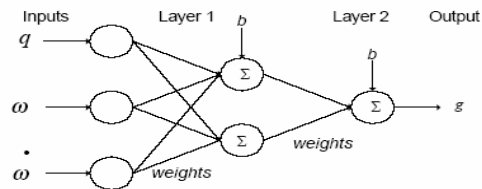


Fig.6: Network Structure

where  $g$  is the desired control moment required to stabilize the attitude to the desire value, and the output of the neural network that uses tanh as the squashing function to limit saturation. The network control structure is as shown below.

The Neural network controller shown in Fig.7 is trained by the method of back propagation from the data obtained from various constant gain PD controller simulated with different

initial conditions and different spacecraft inertia tensor. The neural controller outputs the value of current necessary to be given to the torquers to produce the required torque.

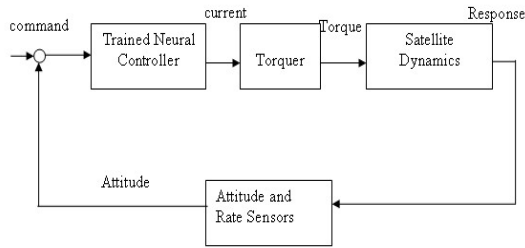


Fig.7: Neural Controller

8. SIMULATION RESULTS

The Neural Network controller is tested using the model developed with the test data as follows.

Satellite Configuration  
 $I = \text{Diag} [1.4 \ 1.3 \ 1.1] \text{ Am}^2$

Initial Euler angles  
 Phi - 90 deg  
 Theta - 90 deg  
 Psi - 180 deg

The plots in Figs.8 ~ 10 clearly show how the attitude stabilizes after two to three orbits.

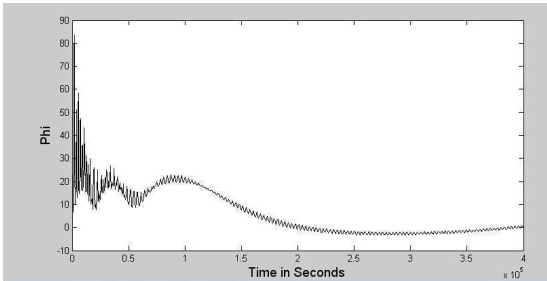


Fig.8: Phi versus Time plot

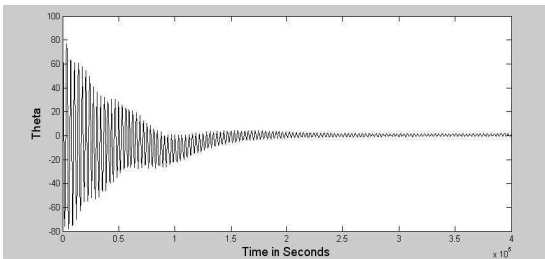


Fig.9: Theta versus Time plot

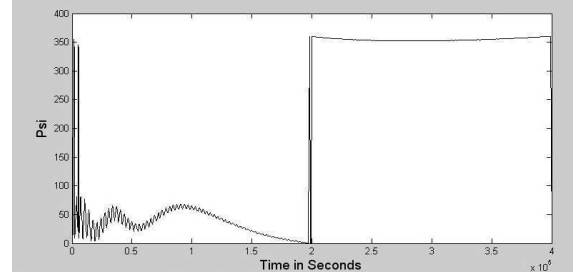


Fig.10: Psi versus Time plot

9. CONCLUSION

From the above proposed Neural Network controller it is possible to stabilize the satellite's attitude in three axes using only electro-magnetic torquers. The network is trained using constant gain PD controllers whose gains are selected depending on the satellite's configuration and its inertia tensor. This can be extended by to Adaptive Neural Network controller to handle the uncertainties in space.

REFERENCES

- [1] F. Martel, P. K. Pal, and M. L. Psiaki, "Active magnetic control system for gravity gradient stabilized spacecraft," In Proc. 2nd Annual AIAA/USU Conference on Small Satellites, Utah State University, USA, 1988.
- [2] C. Arduini and P. Baiocco, "Active magnetic damping attitude control for gravity gradient stabilized spacecraft," Journal of Guidance, Control, and Dynamics, vol. 20, pp. 117-122, Jan. 1997.
- [3] R. Wisniewski and M. Blanke, "Fully magnetic attitude control for spacecraft subject to gravity gradient," Automatica, vol. 35, no. 7, pp. 1201-1214, 1999.
- [4] M. L. Psiaki, "Magnetic torquer attitude control via asymptotic periodic linear quadratic regulation," Journal of Guidance, Control, and Dynamics, vol. 24, pp. 386-393, Mar. 2001.
- [5] Makovec, K. L., A Nonlinear Magnetic Controller for Three-Axis Stability of Nanosatellites, Master's thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, July 2001.
- [6] M.Guelman, R.Waller, A.Shiryayev, "Design and Testing of Magnetic Controllers for Satellite Stabilization,"
- [7] James R. Wertz and Wiley J. Larson: "Space Mission Analysis and Design", Second Edition, Space Technology Series, Space Technology Library, Microcosm Inc, Kluwer Academic Publishers.
- [8] Marcel J.Sidi, "Spacecraft Dynamics and Control; A Practical Engineering Approach,"
- [9] J. R. Wertz, Ed., "Spacecraft Attitude Determination and Control," Holland: Kluwer Academic Publishers, 1978.
- [10] Nasser Sadati, Ali Meghdaru, "Optimal Tracking Neuro-Controller in Satellite Attitude Control", IEEE - ICIT'02, Bangkok, Thailand, pp. 54-59, 2002.