CHAPTER 4

CONVENTIONAL CONTROL FOR
SATELLITE ATTITUDE

4.1 INTRODUCTION

Attitude control is the process of achieving and maintaining an orientation in space. The orientation control of a rigid body has important applications from pointing and slewing of aircraft, helicopter, spacecraft and satellites to the orientation control of a rigid object held by a single or multiple robot arms (Wen and Delgado 1991). There is a number of attitude control strategies discussed in the literatures. The ACS for ANUSAT is based on magnetic ACS. The concept of magnetic attitude control is the interaction of magnetic dipole of the torquer with the earth’s magnetic field. Magnetic control techniques have been subject of a number of prior investigations (Stickler 1976, Hodgart and Ong 1994 Steyn 1994 and Lovera et al 2002).

A magnetically actuated satellite has a limitation in control, as it is possible to control the satellite in only two axes at a time. This is due to the torque produced by the interaction of the magnetic field produced by the magneto-torquers and the geomagnetic field. The generated torque is always perpendicular to the geomagnetic field, this implies that yaw is not controllable over poles, and roll is not controllable over equator. The geomagnetic field changes its orientation when the satellite changes its position in orbit. Simplicity of construction, absence of moving parts, less
volume, low weight and less power consumption are the features of magnetic attitude control systems.

The functional requirements of the attitude control system of the spin stabilized satellite are:

1. To detumble the angular velocity along the entire 3 axis
2. To make the satellite spin about the spin axis at the rate of 8rpm
3. To orient the spin axis.

Implementation of control law in ANUSAT, a class of micro satellite being developed by Anna University is described here. Its specifications are given in Appendix 1.

Two magnetic torquers, one along the spin axis and the other along the transverse axis of the spacecraft give control signals to the satellite. During detumbling mode, the spin axis torquer is used to damp out the transverse rates. In the normal phase, the spin axis torquer is used for spin axis orientation control and the transverse plane torquer is used for spin rate control.

The magnetic control logic is based on the simple cross product law given by equation (4.1).

\[ T = m \times B \]  

(4.1)

- \( m \) - Dipole moment of the torquer
- \( B \) - Flux density of the earth’s magnetic field
- \( T \) - Torque produced in the spacecraft
The magnetic torque tends to rotate the loop towards an equilibrium position with $m$ in the same direction as $B$. Few conventional ACS methods used for the above satellite are described in the following sections along with the simulation and results.

4.2 ATTITUDE CONTROL SYSTEM

A controller that makes the satellite expel excess kinetic energy is required in order to detumble the satellite and keep it aligned with the geomagnetic field without librations around the field lines is designed. There are a number conventional control schemes (Tabuada et al. 1998, 1999 and Tavares et al. 1998). One such basic control technique is the b-dot controller. The objective of this controller is to generate a magnetic moment, such that the kinetic energy of the satellite is dissipated and it is turned in the direction of the local geomagnetic field vector. This type of control can be implemented using the “B-dot” control law, which has flight heritage from e.g. the Ørsted3 and PROBA4 satellites, where it in both cases was used successfully for detumbling and contingency mode control. The control law formulated in the body-frame is given by (Alminde 2005):

$$m = -kB^*$$

(4.2)

It generates a magnetic moment using the on-board electromagnetic coils that is negatively proportional to the derivative of the magnetic field as measured in the body-frame. This derivative will be sensitive to two things; the body rates of the satellite and the curvature of the geomagnetic field as the satellite traverse its orbit. The simulation of the satellite attitude control system for the above control law is given in Figure 4.1.
Figure 4.1 Detumbling with initial spin-up (B-dot control)

To analyze stability then not only equation (4.1) should be considered, but also the contribution from the permanent magnet, which also provides control torques. Including this, the control law becomes (Alminde 2005 and Bogh 1996a):

\[ m = -kB^* - m_{\text{perm}} \]  

(4.3)

\( m_{\text{perm}} \) is the constant magnetic field provided by permanent magnet.

The algorithm for the rate detumbling controller has been verified by simulation. Figure 4.2 shows simulation results for the worst-case initial value of the satellite angular velocity.
Figure 4.2 Detumbling with initial spin-up (Modified B-dot control)

4.3 ENERGY BASED CONTROL

A magnetic generated mechanical torque is always perpendicular to the geo-magnetic field vector. The geomagnetic field is varying along the orbit. Since the control torque is always perpendicular to the geomagnetic field vector, it is desirable that the magnetic moment is also perpendicular to the geomagnetic field vector, as only this component produces a non-zero control torque.

It is concluded that magnetic control moment must include information about angular velocity of the satellite, and also about time propagation of the geomagnetic field. The generation of the magnetic moment is an angular velocity feedback. The energy controller contains a number of parameters that
can be adjusted to change their performance. To improve the overall controller performance, the controller parameters can be tuned in closed loop (Clements et al 1995). This method contributes to the dissipation of kinetic energy of the satellite (Wisniewski 1996). The control law is given below in equation (4.4) (Overby 2004).

\[ m(t) = h \omega(t) \times B(t) \]  

(4.4)

where \( h \) is a positive constant.

The result of the simulation is given in Figure 4.3. Gain value \( h \) is \( 7 \times 10^7 \).

Figure 4.3 Detumbling with initial spin-up (Energy based control)
To improve the overall controller performance, the controller parameters have to be tuned in closed loop. Only limited exploration of this sort of tuning has been possible during this work as it is only for comparison with the intelligent control techniques. Usually, the energy controllers are said to produce bad results with restricted actuators.

### 4.4 PROPORTIONAL DERIVATIVE CONTROL

A very robust and fully autonomous design for attitude control can be fulfilled by the use of a proportional-plus-derivative controller (Jan and Tsai 2005, Mohammed et al 2003, 2007). The magnetic dipole moment for control is given in equation (4.5) (Makovec 2001).

\[
m = k_p (B_o - B_r) + k_d (B_o^* - B_r^*)
\]  

(4.5)

Bo is measured magnetic field
Br is reference magnetic field

\(k_p\) and \(k_d\) are control position and rate gains. Control laws were numerically tested to show that the magnetic control system works within resolution limits. The response of a PD controller for attitude control is that of a second order system; thus \(K_p\) and \(K_d\) are to be chosen appropriately to get the desired response (Nagarajan et al 2001). The challenge of a P-D controller is determining gain matrices that damp the system. After the two gain elements are chosen, the resulting system is examined the checked for damping. The elements are altered to obtain desired results. It is inferred that as the proportional value \(k_p\) is decreased the frequency of oscillation decreases and as the derivative gain value \(k_d\) is increased the system damps faster. The result of the simulation for detumbling with initial spin-up is given in Figure 4.4.
4.5 SPIN AXIS ORIENTATION CONTROL

After detumbling and initial spin-up the orientation of the spin axis comes into picture. There are number of conventional control laws available for spin axis orientation of satellite. The well known and widely is B-Dot control law. This proposed work is done with B-Dot control.

Mathematical Model of SAOC

The forward transformation (inertial frame to nodal frame) and the backward transformation (nodal frame to inertial frame) are given below:
Forward transformation

\[
X_n = \begin{bmatrix}
\cos i & \sin i \sin \Omega & -\sin i \cos \Omega \\
0 & \cos \Omega & \sin \Omega \\
\sin i & -\cos i \sin \Omega & \cos i \cos \Omega
\end{bmatrix} X_i
\]

\[
Y_n = \begin{bmatrix}
0 & \cos \Omega & \sin \Omega \\
\sin i \sin \Omega & \cos \Omega & -\cos i \sin \Omega \\
\sin i \cos i & \sin \Omega & \cos i \cos \Omega
\end{bmatrix} Y_i
\]

\[
Z_n = \begin{bmatrix}
\sin i & -\cos i \sin \Omega & \cos i \cos \Omega
\end{bmatrix} Z_i
\]

(4.6)

Backward transformation

\[
X_i = \begin{bmatrix}
\cos i & 0 & \sin i \\
\sin i \sin \Omega & \cos \Omega & -\cos i \sin \Omega \\
\sin i \cos i & \sin \Omega & \cos i \cos \Omega
\end{bmatrix} X_n
\]

\[
Y_i = \begin{bmatrix}
0 & \cos \Omega & \sin \Omega \\
\sin i \sin \Omega & \cos \Omega & -\cos i \sin \Omega \\
\sin i \cos i & \sin \Omega & \cos i \cos \Omega
\end{bmatrix} Y_n
\]

\[
Z_i = \begin{bmatrix}
\sin i & -\cos i \sin \Omega & \cos i \cos \Omega
\end{bmatrix} Z_n
\]

(4.7)

These transformations are mainly used for input/output purposes in the associated simulation software. Henceforth, throughout this section, the problem of the spin axis orientation control is dealt in the nodal frame only.

The values of various parameters used in simulation are given below:

\[
J_2 = 1.8263 \times 10^{-3}
\]

\[
R = 6378100 \text{ m}
\]

\[
a = 7195.102 \text{ Km}
\]

\[
i = 98.3
\]

\[
e = 0.001
\]

The following expression is useful in computing value of \( \omega \) at any time instant.

\[
d\omega/dt = \frac{(3J_2 R^2 (2-5\sin i / 2))}{2 a^2 (1-e^2)^2}
\]

(4.8)
Energizing the magnetic torquer with a positive current produces the torque.

Hence the torquer in the component form is given by,

\[
\begin{align*}
T_{xn} &= m_o \left( \sin \alpha_c \cos \gamma_c B_{zn} - \sin \gamma_c B_{yn} \right) \\
T_{yn} &= m_o \left( \sin \alpha_c \sin \gamma_c B_{xn} - \cos \alpha_c B_{zn} \right) \\
T_{zn} &= m_o \left( \cos \alpha_c B_{yn} - \sin \alpha_c \cos \gamma_c B_{yn} \right)
\end{align*}
\] (4.9)

The drawback of this method is that it is possible only to orient spin axis of the satellite normal to the orbit, since the produced torque is in the transverse plane, to reduce the deviation of the spin axis from the negative orbit normal becomes a constraint. The response of spin axis orientation control for orbit normal is given in Figure 4.8. Two sample equals 1 second.

![Figure 4.5 Spin axis orientation control (orbit normal)](image-url)
4.6 CONCLUSION

A few of the conventional control methods adopted for the micro-satellite for spin stabilization have been explained and the simulation and results have been explained in this chapter. The settling time taken for detumbling with initial spin up for b-dot control is around 25,000 s. For modified b-dot it is around 26,000 s and that of energy based and PD control comes to around 23,229 s and 26,200 s respectively. The modified b-dot control law gives almost the same performance as that of b-dot control law. This proves the stability of b-dot control law for the constant magnetic field provided by permanent magnet. The PD control law makes it clear that there is an improvement in the transient response of the satellite attitude. There is almost no change in the time taken for detumbling but an improvement in time is found for initial spin-up. The energy-based control has oscillations in its response when compared to b-dot, modified b-dot and the PD controller. In conclusion the simulation results show that the time taken for detumbling and initial spin-up is less for PD control than other control methodologies. A robust PD control has been designed for the satellite attitude control and can be concluded that when the initial deviation is not large, the attitude convergence can be achieved quickly by Proportional-derivative control. SAOC takes around 29,690 s.