A Comparison of Two Magnetic Coil Control Systems for a Small Satellite

Dan Stormont
Utah State University
stormont@cc.usu.edu

Overview

• Paper 1 — Analog Neural Network Control Method for Backup Satellite Control
• Paper 2 — Time Optimal Magnetic Control for Small Spacecraft
• Method of Comparison
• Simulations
• Results
• Conclusions
• Future Work

Paper 1

• This paper proposes the use of a neural network composed entirely of analog components to control magnetic torque coils based on coarse sun sensing using the current from the satellite’s solar cells
• The objective is to keep the satellite’s solar cells aligned with the Sun in case of primary control system failure
• This system is intended for use with microsatellites, such as the SatBot illustrated in the photograph

Paper 1

• As can be seen from the circuit for a neuron in the neural network, the approach the authors take to the nonlinear magnetic torque control is to use nonlinear analog circuits as the closed-loop controllers
• These neural circuits tend to a stable bias point as a result of the RLC time constants in the neural circuitry
• If the neurons are properly connected, they will provide bang-bang control of the magnetic torque coils to bring the currents from the spacecraft solar cells into balance

Paper 1

• The authors provided the simulation results shown
• Notice that while the system does achieve a stable state in a fairly short period of time, the results are only provided for one axis of the spacecraft with a very small perturbation of the attitude (1°) – the real question is how the system will perform with a large perturbation in multiple axes

Paper 2

• This paper presents the design of a primary magnetic torque control system for a small satellite using time optimal control and a bang bang controller to rapidly realign the spacecraft when it is misaligned in the x, y, and z axes
Paper 2

• The authors of this paper, based on research done here at USU, started with the classic Euler equations and the quaternion representation for the spacecraft

\[\begin{align*}
I_1\dot{\omega}_1 + \omega_2\omega_3 (I_2 - I_3) &= T_z, \\
I_2\dot{\omega}_2 + \omega_3\omega_1 (I_3 - I_1) &= -T_y, \\
I_3\dot{\omega}_3 + \omega_1\omega_2 (I_1 - I_2) &= T_x, \\
\dot{q} &= \frac{1}{2}(\Theta q).
\end{align*}\]

• By including equations for the torque induced by the magnetic coils, \(M\), and the effects of the Earth’s magnetic field on the body of the spacecraft, \(B\), in the Euler equations, the following state-space equation is developed

\[\begin{pmatrix}
\dot{q}_1 \\
\dot{q}_2 \\
\dot{q}_3 \\
\dot{q}_4
\end{pmatrix} =
\begin{pmatrix}
\frac{(-\omega_2 q_3 + \omega_3 q_2)}{2} \\
\frac{(-\omega_3 q_1 + \omega_1 q_3)}{2} \\
\frac{(-\omega_1 q_2 + \omega_2 q_1)}{2} \\
\frac{-\omega_2^2 (I_1 - I_3) + \omega_3^2 B_y (t, q) - M_y B_y (t, q)}{2} \\
\frac{-\omega_3^2 (I_2 - I_1) + \omega_1^2 B_x (t, q) - M_x B_x (t, q)}{2} \\
\frac{-\omega_1^2 (I_3 - I_2) + \omega_2^2 B_z (t, q) - M_z B_z (t, q)}{2}
\end{pmatrix}.
\]

• The key to this algorithm is the selection of the following minimum time objective function and its endpoint penalties, \(c\)

\[J = \int \left( \sum a_1 |v_1| + \sum a_2 |v_2| \right) dt + c_1 f(v_1, x, \Theta (q), t \in [0, T_f])
\]

• Because the time, \(T\), in the above equation is not fixed, a fixed time, \(T_f\) needs to be selected, resulting in the following equation

\[J = g(v_1(x, T_f)) + \int_0^{T_f} l(v_1, x, \Theta (q), t \in [0, T_f])
\]

• Finally, the following state space control equation can be derived

\[\begin{pmatrix}
\dot{q}_1 \\
\dot{q}_2 \\
\dot{q}_3 \\
\dot{q}_4
\end{pmatrix} =
\begin{pmatrix}
\frac{x_1 - \omega_2 q_3 + \omega_3 q_2}{2} \\
\frac{-\omega_3 q_1 + \omega_1 q_3}{2} \\
\frac{-\omega_1 q_2 + \omega_2 q_1}{2} \\
\frac{-\omega_2^2 (I_1 - I_3) + M_y B_y (t, q) - M_y B_y}{2} \\
\frac{-\omega_3^2 (I_2 - I_1) + M_x B_x (t, q) - M_x B_x}{2} \\
\frac{-\omega_1^2 (I_3 - I_2) + M_z B_z (t, q) - M_z B_z}{2}
\end{pmatrix}.
\]

• For a maneuver from \([30°, 35°, 40°]\) to \([0°, 0°, 0°]\) the magnetic moments shown to the right are generated, which illustrates the bang-bang nature of the controller.

• The effects of these control torques are illustrated in the Euler angle plot.

• It can be seen that this large angle movement is completed much faster than many traditional magnetic torque controllers, which can take a factor of 10 longer to achieve the same results.

Method of Comparison

• Paper 1 provides Simulink diagrams for the controller and limited results for a very small angle error (1°) in the x-axis, but few details about the parameters of the spacecraft.

• Paper 2 provides a thorough mathematical analysis of the control approach, extensive results for large angle errors (35° - 45°), and details the parameters of the spacecraft, but only gives a general overview of the modeling approach and the tools used.

• For ease of comparison, the control model from paper 1 was run in Simulink using the spacecraft parameters and angular errors from paper 2.
Simulations

• System diagram in Simulink

Simulations

• Neuron model in Simulink

Simulations

• Controller model in Simulink

Simulations

• Actuator model in Simulink

Simulations

• Plant dynamics in Simulink

Results

• Once I started working on the model for the neural net controller, I discovered (as is typical for Mark Tilden) that a couple of key elements of the model were missing – these are some placeholders I put in just to complete the model.
Results

- With the missing models for the Sun sensor and lead filter, along with some other parameters left out of the paper (like the values of R and C for the time constant in the neurons), it shouldn’t be surprising that the system doesn’t respond
- Fixing the model is going to require extensive “reverse engineering” to find the right values

Conclusions

- I wasn’t able to perform the comparison I had planned
- Besides being frustrated by Mark Tilden’s “secrets” in the papers he writes about his NvNet architecture, I suspect that the controller wouldn’t be capable of the large angle movements described in the USU paper
- The USU paper on the time-optimal controller was very interesting and very impressive – I look forward to studying it further

Future Work

- I would like to continue the comparison of different methods for magnetic torque control of small satellites
- I hope to write a student paper for this year’s SmallSat conference on this topic

Questions?