Chapter 9

Conclusion

This dissertation discusses the design, inputs, and validation of a Passive Magnetic Attitude Control system for small satellites. Passive Magnetic Attitude Control (PMAC) is useful for a variety of satellite missions as it is simple to install, low-cost, and does not require on-orbit computation. Additionally, some science missions may be aided by alignment with the local magnetic field.

However, the drawbacks of this attitude control method are twofold. First, a lack of understanding of the basic concepts behind PMAC has sometimes led to poor control system design which negatively affects the attitude performance. Second, a lack of accurate simulation has artificially limited the satellite missions which may use PMAC. The ability to accurately predict settling times is key for a satellite mission which relies upon a stable attitude, especially for small satellites which typically have a short mission duration. This dissertation aims to counter the drawbacks listed above.

9.1 Summary

Chapter 2 outlined the basic theory of PMAC, which is a marriage of rigid body dynamics and ferromagnetism; an overview of both of these components is described. Chapter 3 outlined the development history of PMAC. The mission history covers PMAC satellites from 1960 to 2012. Previous attempts at analytical and numeric attitude models are reviewed.

Chapter 4 introduced the Colorado Student Space Weather Experiment (CSSWE), a 3U

CubeSat for space weather investigation which is an example of good PMAC design complementing a science mission. We have access to the on-orbit data; this is useful because CSSWE used a PMAC system. Chapter 5 discussed best practices for designing a small satellite PMAC system; the CSSWE design is used as an example when applicable. Chapter 6 developed a Multiplicative Extended Kalman Filter specially suited for attitude determination of PMAC systems. Simulation- and empirical-based filter tuning is performed before the filter is applied to the CSSWE attitude measurements. After on-orbit calibration and on-orbit magnetic moment fitting, the MEKF output regularly achieved a 3σ uncertainty of 4° or less using magnetometer and partial sun vector measurements at a six second period without a rate gyro. The filtered data validated the CSSWE PMAC design, showing attitude settling within 15° of the local magnetic field after 7 days.

Chapter 7 outlined magnetic measurements which are key inputs to an accurate dynamics simulation. A Helmholtz cage was designed and built for magnetic testing. The cage was used in parallel with other hardware and control software to characterize the CSSWE bar magnet and hysteresis rods. Testing showed that for the CSSWE magnetic material distribution, the system-level hysteresis rod positioning effects are negligible compared to the variation in individual rod dampening ability. Simulated hysteresis loop parameters were derived using a least-squares fit to the experimentally-measured hysteresis loop data collected at magnetizing field cycle amplitudes of ±10 and ±20 A/m. The best-fit hysteresis parameters defined a loop with a ±20 A/m energy dissipation ability of $0.0448\ \text{J}\cdot\text{m}^{-3}$ per cycle, which is approximately 100 times less than the area based upon the material datasheet closed magnetic circuit parameters.

Chapter 8 described a simulation capable of accurately modeling PMAC dynamics. Simulation comparisons over a variety of time steps showed that a fourth-order fixed Runge-Kutta integrator at 0.1s time step has adequate energy conservation performance. Further analysis showed that for certain initial conditions, the absolute attitude cannot be modeled accurately at the considered time steps due to chaotic motion encountered during the settling period. However, the settling time was found to converge as simulation accuracy improved, though small variations in the initial conditions caused the true settling time to be decrease substantially for approximately 20% of the considered sample size. However, the simulations with abnormally decreased settling times could be identified by their dynamic settling response. In this way, the true worst-case settling time may be predicted accurately by dynamic simulation. The full simulation was run given initial inputs from the CSSWE satellite properties and the early-mission filtered attitude; the predicted settling time was within 20% error of both the higher-order integrator simulation output and the filtered on-orbit attitude data.

9.2 Recommendations

The most obvious recommendation is to improve the hysteresis model. An ideal hysteresis model would be able to model low and high cycle amplitudes equally well for the same loop parameters. It may be that more hysteresis parameters are needed to characterize the empirical data at various magnetization cycle amplitudes. If the mission cannot afford to overestimate the predicted settling time by 20-30% to account for the simulation error, the hysteresis model is the simulation component which should be improved first. Any discontinuties which occur during the settling (such as mechanical deployment) should be investigated as another possiblility to improve the simulation.

The satellite magnetic moment should be measured in the fully deployed configuration. This is especially important if the satellite does not have a rate gyro and a dynamic model will be used in the attitude determination. Measuring the hard magnet alone is not sufficient as there can be significant sources of magnetic offset within the satellite. In some cases, as with the CSSWE antenna, the magnetic moment of the spacecraft can change between the stowed and deployed configurations.

The uncertainty of the hysteresis measurement could be decreased by building a sense coil with more turns. We do not recommend using a wire gauge higher than 36 AWG; instead the wire turns should be layered two or more times. This decreased uncertainty will allow the testing to be performed at lower cycle amplitudes. Because of the limitations of the Flatley model, these low cycle amplitudes are key to accurate simulation.

If more computer processing power is available, further simulations are possible. A deeper understanding of the underlying dynamics could be discovered by using the described simulation to calculate the attitude performance when given initial conditions over the entire attitude sphere. Also, the full simulation could undergo the same perturbation analysis that was performed on the simplified simulation. Such studies would likely take computational years to run (the analysis of Section 8.3.4 alone took 68 computational days to run), but given enough processors (or more time for Moore's law to take effect), further analysis is possible.