Small Satellite Passive Magnetic Attitude Control

by

David T. Gerhardt

B.S., Virginia Polytechnic Institute and State University, 2008

M.S., University of Colorado, 2011

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

Department of Aerospace Engineering Sciences

2014

This thesis entitled:
Small Satellite Passive Magnetic Attitude Control
written by David T. Gerhardt
has been approved for the Department of Aerospace Engineering Sciences

---

Professor Scott Palo

Professor Hanspeter Schaub

Date ____________________

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Gerhardt, David T. (Ph.D., Aerospace Engineering Sciences)

Small Satellite Passive Magnetic Attitude Control

Thesis directed by Professor Scott Palo

Passive Magnetic Attitude Control (PMAC) is capable of aligning a satellite within 5 degrees of the local magnetic field at low resource cost, making it ideal for a small satellite. However, simulation attempts to date have not been able to predict the attitude dynamics at a level sufficient for mission design. Also, some satellites have suffered from degraded performance due to an incomplete understanding of PMAC system design. This dissertation alleviates these issues by discussing the design, inputs, and validation of PMAC systems for small satellites.

Design rules for a PMAC system are defined using the Colorado Student Space Weather Experiment (CSSWE) CubeSat as an example. A Multiplicative Extended Kalman Filter (MEKF) is defined for the attitude determination of a PMAC satellite without a rate gyro. After on-orbit calibration of the off-the-shelf magnetometer and photodiodes and an on-orbit fit to the satellite magnetic moment, the MEKF regularly achieves a three sigma attitude uncertainty of 4 degrees or less. CSSWE is found to settle to the magnetic field in seven days, verifying its attitude design requirement.

A Helmholtz cage is constructed and used to characterize the CSSWE bar magnet and hysteresis rods both individually and in the flight configuration. Fitted parameters which govern the magnetic material behavior are used as input to a PMAC dynamics simulation. All components of this simulation are described and defined. Simulation-based dynamics analysis shows that certain initial conditions result in abnormally decreased settling times; these cases may be identified by their dynamic response. The simulation output is compared to the MEKF output; the true dynamics are well modeled and the predicted settling time is found to possess a 20 percent error, a significant improvement over prior simulation.

Dedicated to Alana, my shelter in the storm.

Acknowledgements

Thank you to my advisor, Scott Palo. You have been a continual source of encouragement and guidance when it was sorely needed (which was always). Thank you Xinlin Li for always believing in my abilities (even when I didn't have them yet). Thank you Hanspeter Schaub for continuing to teach me attitude dynamics from Blacksburg to Boulder. Thanks as well to Albin Gasiewski, Paul Graf, and Delores Knipp for your guidance.

Thank you CSSWE team. I will never forget the time we spent working together to produce an operational(!) satellite. I enjoyed every minute of serving as your system engineer. I know our friendship will continue long after the beacons cease. Thank you Therese Jorgensen and the National Science Foundation for funding the little box that could.

Thank you to my parents, who set the bar high with their own example. You instilled the curiosity that prompts me to open the black box, as messy as the process may be.

Finally, the greatest thanks goes to my wife Alana. We did it. How it happened I'll never know, but we did it together. I can't wait to see where we end up next.

Contents

Chapter

1 Introduction 1

2 Basic Theory 5

2.1 Euler's Rotational Equation of Motion 5

2.2 Magnetic Theory 6

2.2.1 Magnetizing Field H vs. Magnetic Flux Density B 6

2.2.2 Hysteresis Loops 8

2.2.3 Magnetic Property Dependencies 10

2.2.4 Demagnetizing Fields 11

2.2.5 Magnetic Torques 16

2.2.6 Hysteresis Rods 17

3 Background 19

3.1 Mission History 19

3.1.1 Early History of Passive Magnetic Attitude Control 20

3.1.2 Modern Use of Passive Magnetic Attitude Control 22

3.1.3 CubeSats using Passive Magnetic Attitude Control 26

3.2 Analytical Models 29

3.2.1 Fischell Analytical Model (1961) 29

3.2.2 Mesch et al. Analytical Model (1966) 32

3.2.3 Kammüller Analytical Model (1971) . . . 32
3.3 Numerical Simulations . . . 33
3.3.1 Chen (1965) . . . 34
3.3.2 Ovchinnikov & Penkov (2002) - Munin . . . 34
3.3.3 CUBESIM (2004) and SNAP (2009) . . . 35
3.3.4 Park et al. (2010) & Lee et al. (2011) - RAX . . . 36
3.4 Hysteresis Measurement to Date . . . 36

4 The Colorado Student Space Weather Experiment 38
4.1 Science Mission Success . . . 38
4.2 Coordinate System . . . 40
4.3 Sensors and Telemetry . . . 43
4.3.1 Housekeeping . . . 43
4.3.2 Attitude . . . 43
4.4 Latch-up Anomaly . . . 52

5 Control System Design 55
5.1 Maximum Expected Environmental Torques . . . 55
5.2 Bar Magnet Design . . . 56
5.3 Hysteresis Rod Design . . . 57

6 Attitude Determination 61
6.1 Filter Design . . . 61
6.2 Filter Tuning . . . 67
6.2.1 Simulation-based Filter Tuning . . . 67
6.2.2 Empirical Filter Tuning . . . 70
6.3 CSSWE Attitude Determination . . . 75
6.3.1 Filter Output . . . 75

6.3.2 Attitude Determination Validation 89

7 Magnetic Measurement 98

7.1 Helmholtz Cage 98

7.1.1 Theory 99

7.1.2 Design 101

7.1.3 Assembly 104

7.1.4 Characterization 108

7.2 Bar Magnet Measurement 110

7.3 Hysteresis Measurement 112

7.3.1 Theory 112

7.3.2 Setup 115

7.3.3 Method 119

7.3.4 Results 121

8 Simulation 134

8.1 Components 135

8.1.1 Frames 135

8.1.2 Attitude Parameters 136

8.1.3 Equations of Motion 138

8.1.4 Orbit Propagation 138

8.1.5 Inertial Vector Models 139

8.1.6 External Torque Estimation 143

8.1.7 Numeric Integrators 151

8.2 Considerations 155

8.2.1 Torque-Free Rigid Body Motion 155

8.2.2 3D Pendulum Comparison 156

8.3 Simplified Simulation Analysis 159

8.3.1 Description 159

8.3.2 Energy Conservation Analysis 160

8.3.3 Angular Error Analysis 161

8.3.4 Settling Time Analysis 163

8.3.5 Summary 171

8.4 Results 174

8.4.1 Nominal Input 174

8.4.2 Nominal Output 176

8.4.3 High-Order Integrator Comparison 183

8.4.4 On-Orbit Data Comparison 183

9 Conclusion 192

9.1 Summary 192

9.2 Recommendations 194

Bibliography 196

Appendix

A Notation 202

B Explicit Runge-Kutta Integrator Definitions 203

Tables

Table

4.1 CSSWE Housekeeping Sensors . . . 44

5.1 Expected 3U CubeSat Environmental Torques . . . 56

7.1 Helmholtz Cage Hardware . . . 104

7.2 HyMu-80 Hysteresis Parameters . . . 133

8.1 Simplified Simulation Input Sets . . . 160

8.2 PMAC Simulation Inputs . . . 175

B.1 General Butcher Tableau . . . 204

B.2 RK2: Midpoint Method . . . 204

B.3 RK3: Kutta Method . . . 204

B.4 RK4: Runge-Kutta Method . . . 204

B.5 RK5: Dormand-Prince Method . . . 204

B.6 RK6: Hammund Scheme . . . 205

B.7 RK7: Fehlburg Method . . . 205

Figures

Figure

2.1 Magnetic Domains 7
2.2 Example B vs. H Hysteresis Loop 9
2.3 Effect of Magnetization Cycle Magnitude 12
2.4 Effect of Magnetization Cycle Magnitude 13
2.5 Hysteresis Loop Frequency Variation 14
2.6 Bar magnet **H** and **B** with no applied field 15

3.1 Transit 1B Satellite 21
3.2 Injun 3 Satellite 22
3.3 Azur Satellite 23
3.4 Munin Satellite 25
3.5 UNISAT-4 Satellite 25
3.6 QuakeSat CubeSat 27
3.7 RAX-1 CubeSat 28

4.1 CSSWE CubeSat & P-POD 39
4.2 REPTile Instrument 41
4.3 CSSWE Coordinate System 42
4.4 Magnetometer Position 46
4.5 Magnetometer Error 48

4.6 Photodiode Illumination 49

4.7 Photodiode Degradation and Scale Factor Correction 51

4.8 Investigation of TLE Position Error 53

4.9 ADC1 Latch-up Bit Damage 54

5.1 B-Field Error Angle 59

5.2 CSSWE PMAC Design 60

6.1 MEKF Simulation EA123 Error 68

6.2 MEKF Simulation Angular Velocity Error 69

6.3 MEKF Simulation Magnetometer Residuals 71

6.4 MEKF Simulation Photodiode Residuals 72

6.5 MEKF Simulation Error Angles 73

6.6 Magnetometer Position and Orientation 76

6.7 MEKF Empirical Magnetometer Residuals 77

6.8 MEKF Empirical Photodiode Residuals 78

6.9 MEKF Empirical Error Angles 79

6.10 First Month: Angular Velocity 81

6.11 First Month: Beta Angle 82

6.12 First Month: Energy 83

6.13 First Month: Histogram 84

6.14 First Month: Error Angle Magnitude 87

6.15 First Month: C&DH Temperature 88

6.16 Pre-settling Orbit: Beta 90

6.17 Pre-settling Orbit: Angular Velocity 91

6.18 Post-settling Orbit: Beta 92

6.19 Post-settling Orbit: Angular Velocity 93

6.20 Post-settling Orbit: Sun and Error Angles 94

6.21 Antenna Deployment Event . . . 96

6.22 Solar Panel Temperature Distribution . . . 97

7.1 Helmholtz Geometry . . . 100

7.2 Helmholtz Coil Spacing Analysis . . . 103

7.3 As-Built Theoretical Helmholtz Performance . . . 105

7.4 Finished Helmholtz Cage . . . 106

7.5 Helmholtz Support Hardware Chain . . . 109

7.6 XY Plane Test . . . 111

7.7 Bar Magnet Measurement Fit . . . 113

7.8 Integrator Circuit for Magnetic Measurement . . . 115

7.9 Hysteresis Measurement Setup Block Diagram . . . 116

7.10 Hysteresis Measurement Sense Coil . . . 118

7.11 Hysteresis Measurement Analysis Block Diagram . . . 122

7.12 Fitted ±100A/m Hysteresis Loop . . . 123

7.13 Isolated Rod Performance . . . 125

7.14 On-Orbit Hysteresis Rod Magnetizing Field Component . . . 127

7.15 Simulated Loops from ±100 A/m Measure . . . 128

7.16 Simulated Loops from ±10A/m Measure . . . 129

7.17 System Hysteresis Rod Measurement . . . 130

7.18 System Rod Performance . . . 131

7.19 Bar Magnet Offset at Each Hysteresis Rod . . . 132

8.1 ECI & ECEF Coordinate Frames . . . 137

8.2 Global IGRF Magnitude . . . 141

8.3 Hysteresis Model Output at ±8 and ±3 A/m . . . 147

8.4 Energy Ellipse and Momentum Sphere . . . 157

8.5 Integrator Energy Conservation . . . 162

8.6 Integrator Beta Angle Error 164

8.7 Integrator Euler Angle Error Breach Time 165

8.8 Settling Time Convergence 167

8.9 "Truth" Settling Time for Bar-Magnet-and-Hysteresis Case 169

8.10 "Truth" Settling Time for All-Torques Case 170

8.11 "Truth" Angular Velocity Response for Bar-Magnet-and-Hysteresis Case 172

8.12 "Truth" Angular Velocity Response for All-Torques Case 173

8.13 Nominal Output: Angular Velocity 177

8.14 Nominal Output: Energy 178

8.15 Nominal Output: Beta Angle 179

8.16 Nominal Output: External Torques 181

8.17 Nominal Output: Hysteresis Loops 182

8.18 RK4/7 Comparison: Angular Velocity 184

8.19 RK4/7 Comparison: Energy 185

8.20 RK4/7 Comparison: Beta 186

8.21 Orbital Data Comparison: Angular Velocity 188

8.22 Orbital Data Comparison: Energy 189

8.23 Orbital Data Comparison: Beta 191