Pointing Control for Low Altitude Triple Cubesat Space Darts

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Code 8231-Attitude Control System

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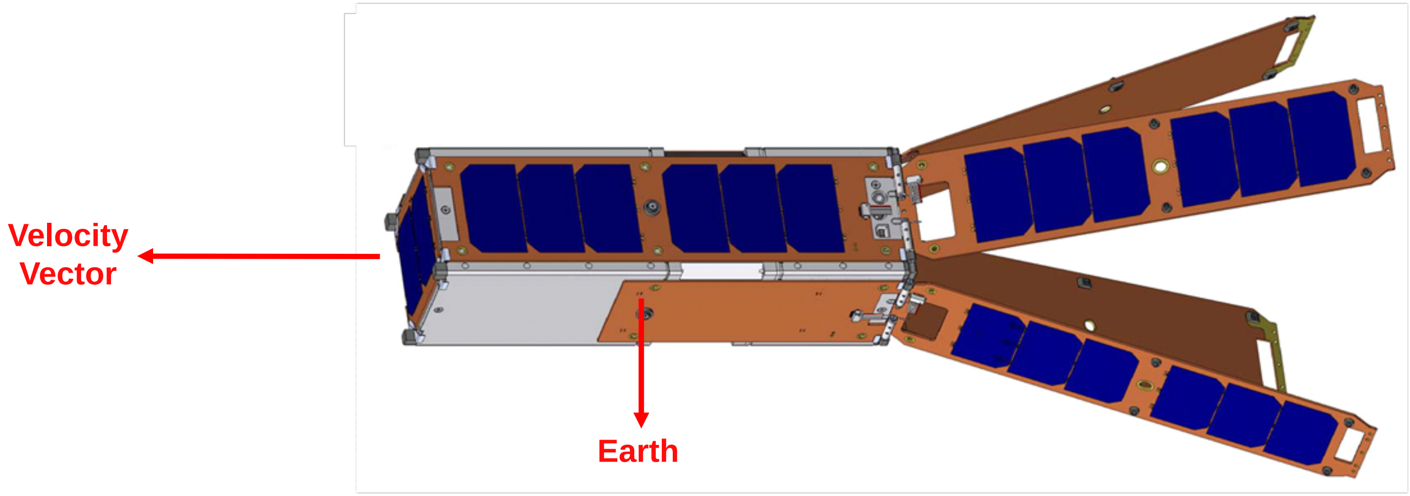
Introduction

Cubesat Overview

- 24 Cubesats launched since 2003
- Most have been of the 1U class, with relatively few in the 3U sized class (Pharmasat-1, QuakeSat, CanX-2, Delfi-C3, GeneSat-1)
- Pointing control is very challenging due to volume and mass constraints
- Most have to rely on tumbling, or magnetic rate control with large attitude errors
- New payload demands and mission opportunities will require more accurate and precise attitude control systems
- Our simple control system offers experiment pointing capability to less than 5 degrees of nadir without the need for attitude knowledge

Spacecraft Configuration



Space Dart configuration

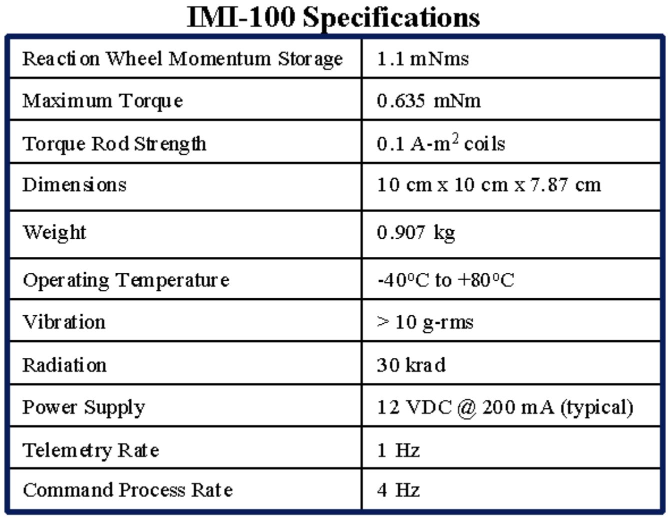
- Pumpkin Inc. bus design (3U “Triple” Cubesat)
- Fits into a standard Poly Picosat Orbital Deployer (P-POD) dispenser with solar panels folded
- 4 Deployable solar panels
- Solar panels deployed at 160º
- Approximately 10 cm x 10 cm x 35 cm
- Mass: 4.5 kg

Attitude Control System Hardware

Attitude Control System

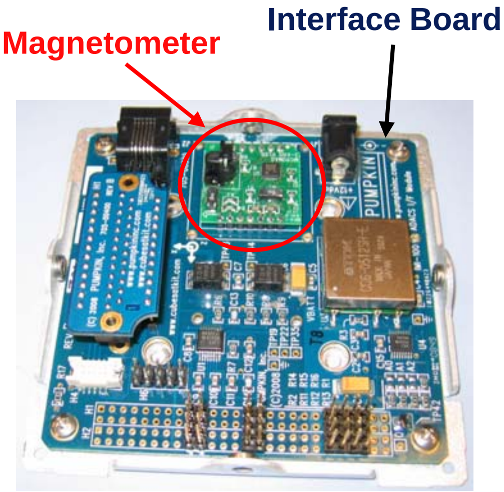
- IntelliTech Microsystems Inc., IMI-100
- 3 miniature reaction wheels
- 3 torque coils
- Processor board to calculate attitude and orbit state vectors, and International Geomagnetic Reference Field (IGRF) model vectors
- 3 axis magnetometer (PNI Corp. MicroMag 3) integrated onto circuit board that interfaces to the IMI unit
- Only one wheel is required for pointing with no attitude knowledge necessary

Intellitech Microsystems Inc., IMI-100

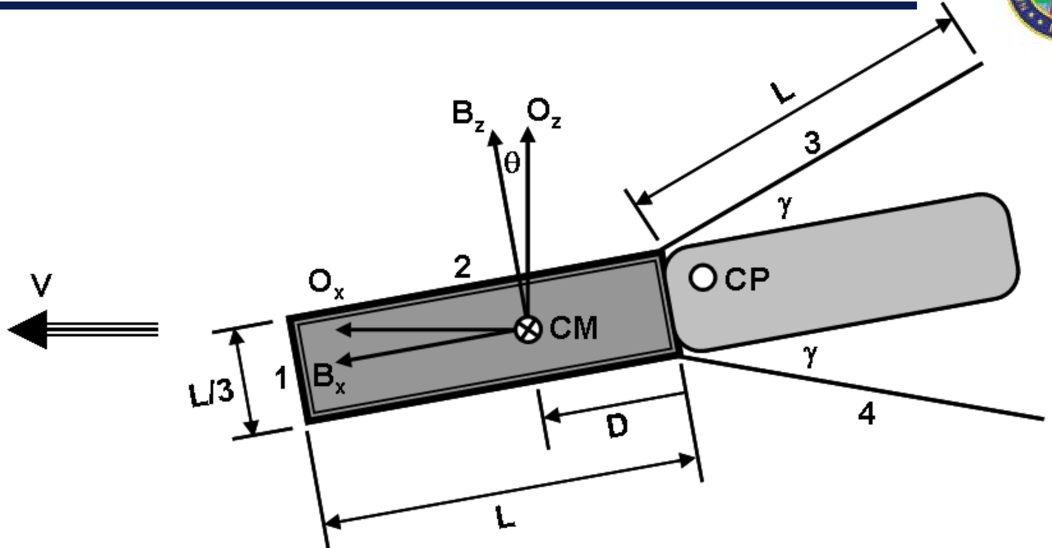


IMI-100 Specifications

Reaction Wheel Momentum Storage	1.1 mNms
Maximum Torque	0.635 mNm
Torque Rod Strength	0.1 A-m^2 coils
Dimensions	10 cm x 10 cm x 7.87 cm
Weight	0.907 kg
Operating Temperature	-40°C to +80°C
Vibration	> 10 g-rms
Radiation	30 krad
Power Supply	12 VDC @ 200 mA (typical)
Telemetry Rate	1 Hz
Command Process Rate	4 Hz



Space Dart Pointing Control Logic



Passive Attitude Stabilization

- B = Body frame
- O = Local orbit frame
- D is positive which results in a negative valued (restoring) torque for small attitude errors
- Axis symmetry of the space dart creates the same stable, restoring torque under small yaw motion
- Equilibrium point (pitch error = 0º) is aerodynamically stable as long as the panel angle (γ) satisfies the relation (for small errors):

$$\gamma > \frac{L-D}{6(L+2D)}$$

- Under the above relation, the center of pressure (CP) is located behind the center of mass (CM) relative to the airflow
- Pitch reaction wheel provides additional passive dynamic stabilization for both yaw and roll motion

Space Dart Pointing Control Logic (cont.)

Active Magnetic Rate Damping

- **Modified B-dot control law using known spacecraft position provided by the IMI-100 orbit propagator and the IGRF model**
- **Following assumptions are made:**
    - **If the initial tip-off rates are large, the derivative of the field vector with respect to the inertial frame is considered negligible (the classical B-dot law)**
    - **After brief period of time, passive aerodynamic and dynamic stability coupled with the active B-dot law will remove the majority of rates and errors**
- **Augmented B-dot law implemented becomes:**

$$\{M\} = k\left(\frac{d([C_{o/I}]\{B\}^{I} - \{B\}^{B})}{dt}\right)$$

- **B = Magnetic field vector**
- **$C_{o/I}$ = Direction cosine matrix relating inertial frame to the orbit frame**
- **M = control dipole vector**
- **k = scalar gain**
- **This modified control law coupled with the inherent passive control removes body rates and aligns the body frame with the orbit frame without the need for attitude determination**

Space Dart Pointing Control Logic (cont.)

Local Pointing Stability Control

- Linearized equations of motion can be approximated as:

$$I_t\ddot{\theta}+k_m\dot{\theta}+k_a\theta=0$$

$$\begin{bmatrix} I_l & 0 \\ 0 & I_t \end{bmatrix}\begin{Bmatrix} \ddot{\phi} \\ \ddot{\psi} \end{Bmatrix}+\begin{bmatrix} k_m & -h_w \\ h_w & k_m \end{bmatrix}\begin{Bmatrix} \dot{\phi} \\ \dot{\psi} \end{Bmatrix}+\begin{bmatrix} h_w\omega_o & k_m\omega_o \\ -k_m\omega_o & I_t\,\omega_o^2+h_w\omega_o+k_a \end{bmatrix}\begin{Bmatrix} \phi \\ \psi \end{Bmatrix}=\begin{Bmatrix} 0 \\ 0 \end{Bmatrix}$$

k_a = Effective aerodynamic stiffness coefficient

k_m = Effective magnetic damping coefficient

I_t = Transverse inertia

I_l = Longitudinal inertia

ψ = Yaw

θ = Pitch

ϕ = Roll

ω_o = Circular orbit rate

- Uncoupled pitch motion is asymptotically stable to the origin
- Routh-Hurwitz stability analysis shows that the coupled roll/yaw motion is asymptotically stable to the origin as long as the wheel momentum is in the same direction as the orbit momentum
- Inverted roll orientation (ϕ=180°) is an unstable equilibrium point
- Satellite will automatically align its body frame with the orbit frame from any arbitrary initial dynamic state once wheel momentum bias is achieved

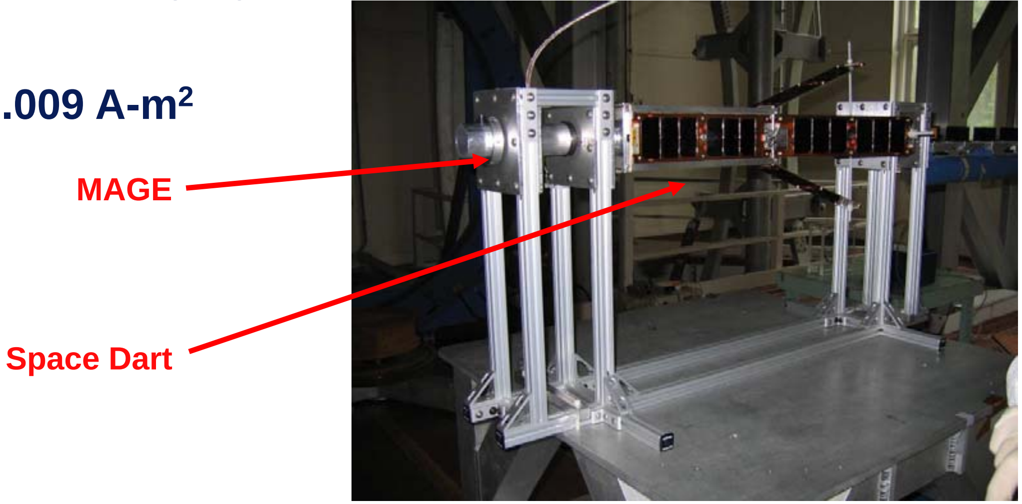
Space Dart Magnetic Testing

Hardware

- Magnetic balancing performed at NASA Goddard’s Spacecraft Magnetic Test Facility
- Helmholtz coil used to eliminate the effect of Earth’s field on the measurements
- The spacecraft Mechanical Aerospace Ground Equipment (MAGE) magnetic effect is also nulled

Capability and Results

- IMI-100 torque coils have a maximum capability of 0.1 A-m^2
- Pulse width modulation reduces the effective dipole capability to 0.0374 A-m^2
- To ensure sufficient control margin, a design goal of less than 0.01 A-m^2 for the residual dipole was imposed
- Spacecraft dipole measured was 0.009 A-m^2

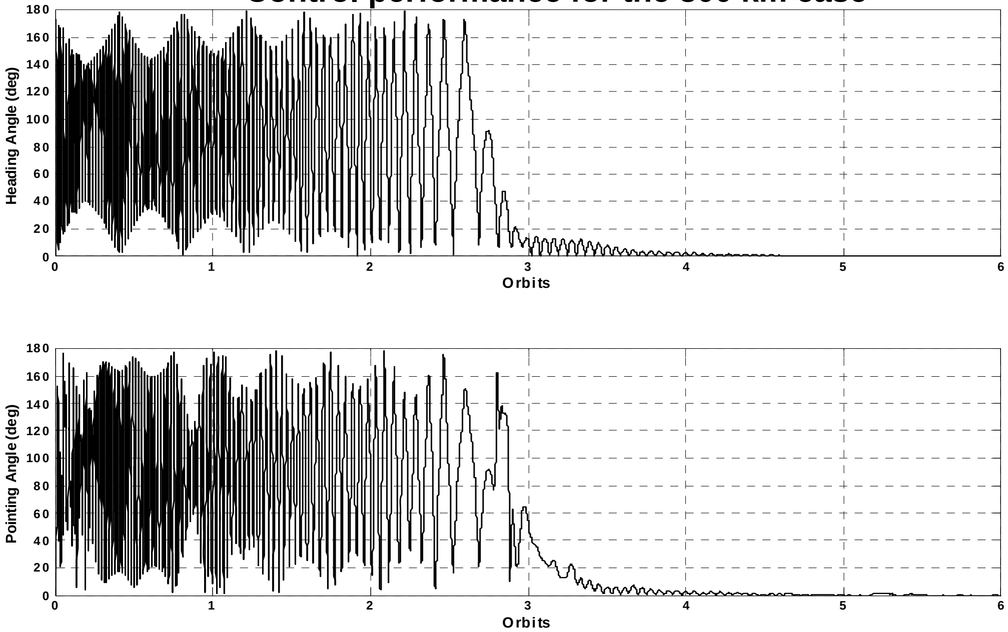


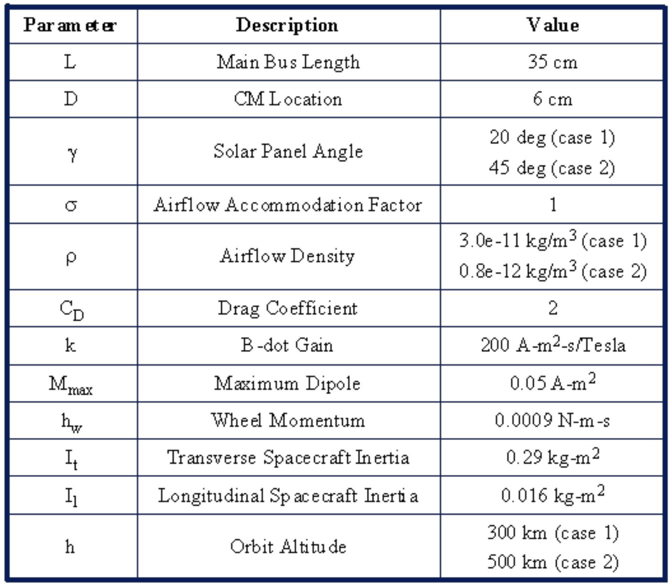
Control Performance

Simulations

- 2 cases run, one at 300 km, the other at 500 km
- 3 deg/sec tipoff rates
- Pointing performance < 5^{o} is achieved within about 4 orbits for case 1 (results shown below), and 5 orbits for case 2
- At 300 km, the aerodynamic torque greatly exceeds the gravity gradient torque
- At 500 km, the aerodynamic torque is only slightly larger than the gravity gradient torques

Control performance for the 300 km case





Parameter	Description	Value
L	Main Bus Length	35 cm
D	CM Location	6 cm
γ	Solar Panel Angle	20 deg (case 1) 45 deg (case 2)
σ	Airflow Accommodation Factor	1
ρ	Airflow Density	3.0e-11 kg/m^3 (case 1) 0.8e-12 kg/m^3 (case 2)
C_D	Drag Coefficient	2
k	B-dot Gain	200 A-m^2-s/Tesla
M_{max}	Maximum Dipole	0.05 A-m^2
h_w	Wheel Momentum	0.0009 N-m-s
I_t	Transverse Spacecraft Inertia	0.29 kg-m^2
I_l	Longitudinal Spacecraft Inertia	0.016 kg-m^2
h	Orbit Altitude	300 km (case 1) 500 km (case 2)

Conclusions

Space Dart Advantages

- Triple cubesat bus allows for payload real estate to be tripled
- Space dart solar array configuration allows sixfold power increase over single cubesats and twofold power increase over simple triple stacks
- Exploitation of aerodynamic characteristics to eliminate any need for attitude determination
- Payload pointing capability of <5º can be accomplished using one magnetometer, one pitch momentum wheel, and a simple B-dot control law
- Space Dart configuration will not work well above 500 km since the de-stabilizing gravity gradient torque exceeds the stabilizing aerodynamic torque, with both becoming almost negligible

Questions?