Reaction Wheel for CubeSat Attitude Control

Gabe Maymon – Matt Oslin – Gerardo Cruz-Ortiz (591)

ABSTRACT

Current CubeSat reaction wheels are thick and have a high height to diameter aspect ratio. A 3-axis reaction wheel assembly that allows for larger payload volume within the spacecraft was designed and manufactured. Space and mass efficiency combined with the need to survive launch loads drove the selected wheel design.

The developed procedures for wheel mounting establish a strong connection interface between the reaction wheel and the rotor. Furthermore the implemented balancing features counteract the motor and manufacturing induced imbalances of the wheel. Finally, a PID controller regulates the angular velocity of the reaction wheel.

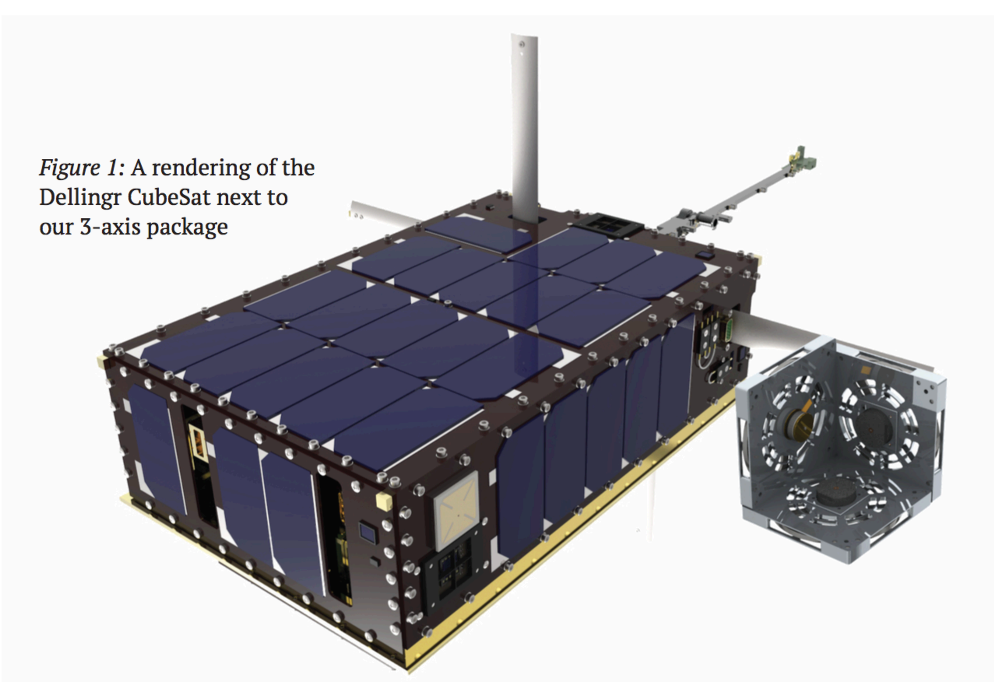


Figure 1: A rendering of the Dellingr CubeSat next to our 3-axis package

INTRODUCTION

Reaction wheels adjust a spacecraft's orientation through momentum transfer. When designing CubeSats like Dellingr (Figure 1), engineers need the ability to easily package their attitude control system with the spacecraft payload. Industry has adapted bulky reaction wheels from larger satellites for CubeSats, but their height makes these wheels take up valuable mass and volume.

We developed two new designs that minimize volume and weight without sacrificing momentum. The first design features a spoked stainless steel wheel pressed onto a cantilevered motor shaft, housed in an aluminum case that can be fastened to the sides of the CubeSat and two other reaction wheel modules. The motors stick into the Cubesat interior, but disrupt much less space than a taller wheel would. The second design includes a brass wheel shrunk fit onto a motor outrunner. This design is nontraditional, but saves space by housing the motor inside the wheel and eliminates the need for a rigid housing as the motor hub can be mounted directly to the CubeSat's walls. We evaluated both designs on their attitude control specs, packaging needs, assembly processes, and imbalances.

	Target Spec	Shaft-Mounted	Bell-Mounted
Max Momentum	> 10 mNm-s	34 mNm-s	24 mNm-s
Available Torque	> 2mNm	2.4 -2.8 mNm	2.4 -2.8 mNm
Power	< 1 W	0.7 W	0.6 W
Package Weight	< 250 g	155 g	119 g
Package Size	90x90x10mm	90x90x10.7mm	75x75x12.5mm
Static Imbalance	< 1.5 g-mm	11 g-mm	0.67 g-mm
Dynamic Imbalance	< 20 g-mm^2	52 g-mm^2	1.8 g-mm^2

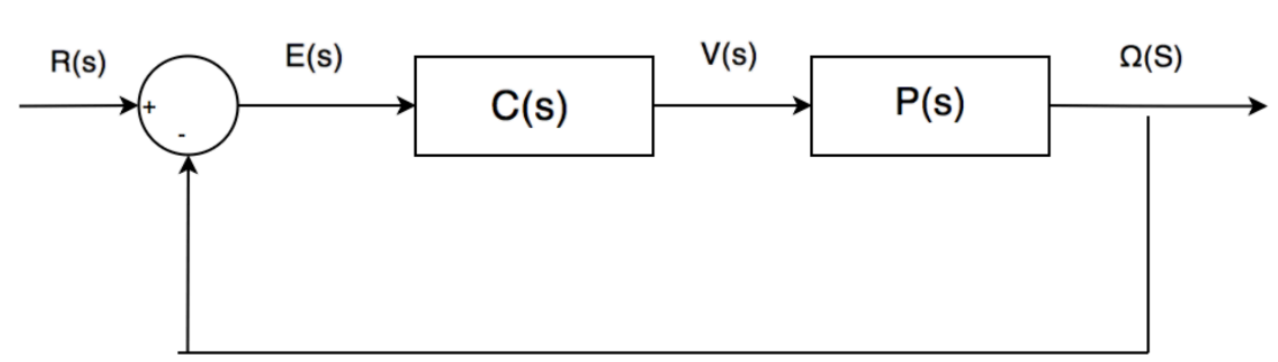
MOTOR TRADE STUDY

We evaluated two motors to drive the reaction wheel. The first is the Faulhaber Flat DC-Micromotor and the second is the Maxon Brushless Flat Motor. The Table below collects the results of our motor trade study compared with our target requirements.

Figure of Merit	Weight	Faulhaber Brushed	Maxon Brushless
Rigidity	0.4	2	4
Mass and Volume	0.2	2	3
Driveability	0.2	5	3
Efficiency	0.2	4	2
Total	1	3.0	3.2

CONTROLLER DESIGN

The wheel's angular velocity profile determines the transfer of angular momentum to the spacecraft. A model of the dynamic system that includes both the mechanical and electrical subsystems can aid in quickly and robustly controlling the velocity of the motor's rotor. Electrical current running through the motor coils creates a mechanical torque. To produce a specified torque, an Arduino microcontroller sends a PWM voltage wave to a motor driver.



To test the robustness of our model, real-world factors such as a time delay and a discrete control cycle were simulated. In our system a discrete controller commands a motor controller with a slight electrical delay. We found that the altered responses only marginally deviated from the ideal system. The control cycle was short enough that continuous time models were considered valid.

WHEEL MOUNTING

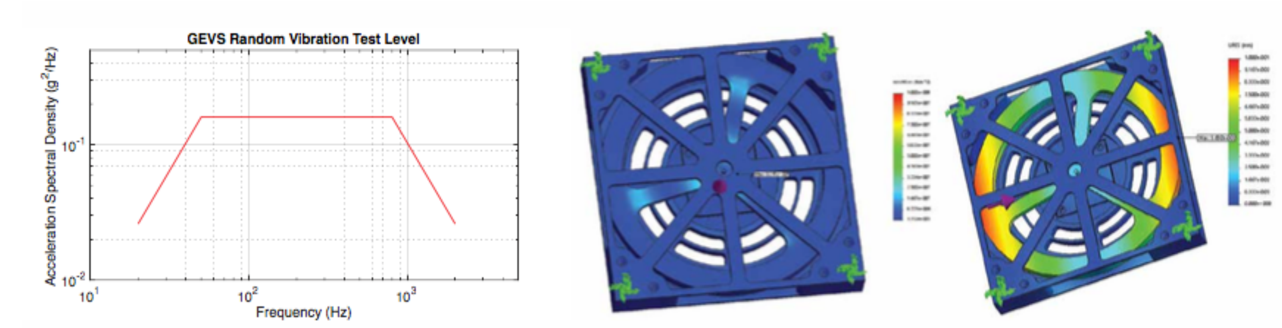
We explored two mounting schemes. First, a traditional mounting to the motor shaft was developed. Guidelines from Machinery's Handbook were followed to design a press fit, and the press loads were verified not to exceed the motor shaft strength. In the second design, a wheel was shrink fitted onto the outrunner bell of the Maxon motor. This saves volume and minimizes cantilevering. The larger diameter of the outrunner meant that the wheel could be expanded at 250°C and shrunk onto the outrunner.

WHEEL BALANCING

Imperfections in the manufacturing and assembly processes result in static and dynamic imbalances. These imbalances produce unwelcome vibrations as the wheel spins. Static imbalance arises when the wheel's center of mass is not located along the axis of rotation, causing a centripetal force that rotates with the wheel at angular velocity ω. To mitigate these imbalances, the outrunner-mounted design features set screws along the wheel's rim that can be used to balance the wheel.

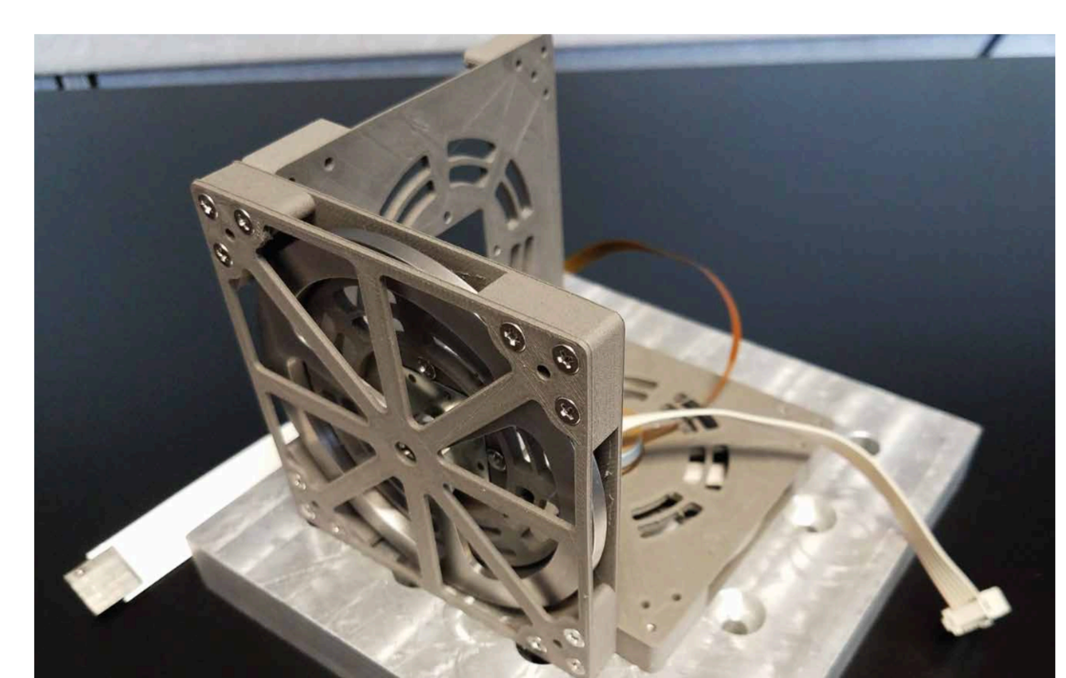
LAUNCH LOADS

The most likely cause of mechanical failure for a satellite component is loading during launch. These loads are a combination of linear acceleration, random vibration, shock, sine vibration, and acoustic disturbance. Sine and acoustic loads do not apply to our structure since it has a low surface area and high natural frequency. The General Environmental Verification Specification (GEVS) was followed in this load analysis.



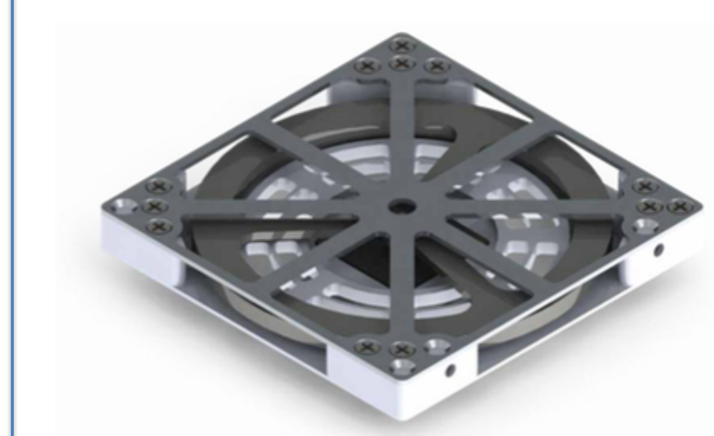
Simulation results for both the single axis and three axis designs, did not show significant differences in the load profiles. This analysis focuses on the shaft-mounted wheel since less is known about the mechanical strength of the outrunner design. The Table below shows the factors of safety derived from this analysis. Further testing under static conditions should be performed to determine the loads the motors can actually withstand.

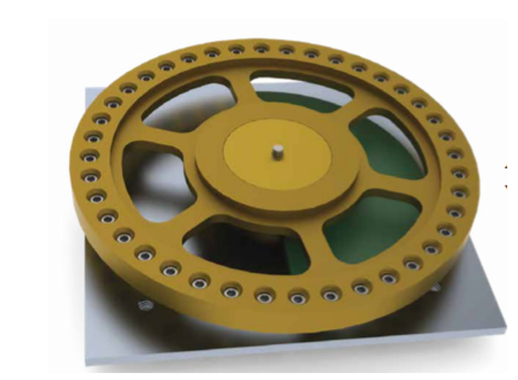
	Faulhaber Bearing	Maxon Bearing	Faulhaber Shaft	Maxon Shaft	Structure	Stainless Wheel
Axial SF	1.32	0.24	200	270	86	28
Radial SF	0.66	0.25	6.5	8.4	400	800



PACKAGING

The goal of this design was to allow the CubeSat designer to add a 3-axis attitude control system to the spacecraft without encroaching on the space being used by the payload and other subsystems. The mechanical packaging allows a 3-wheel unit to be assembled as one component in a corner of the Cubesat, or each reaction wheel can be assembled on its own and added to different points on the spacecraft structure.





What Next?

A lot of work remains before these designs are flight ready. After a full balancing procedure, the wheels will undergo vibration testing to verify that our simulations were accurate and that the wheels survive launch loads. If the wheels survive we can proceed to vacuum and thermal-vacuum functional tests to evaluate the wheel's in-flight characteristics. Electronic components need to be evaluated and repackaged. We look forward to the impact our work will have on future CubeSat systems.