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Assessing Reaction Wheel Sizing for CubeSat Attitude Control

Tiffany A. Joseph, Guy Benari, Hugh Podmore, and Regina S. K. Lee
York University
North York, Ontario, Canada

Abstract

CubeSats are a class of modular satellites with mass between 0.5 and 36 kg that have emerged in recent years as a popular satellite platform for Earth observation missions. CubeSat-class satellites typically use magnetorquers and/or reaction wheels as their primary attitude control system actuators to achieve mission objectives. In this study, the relationship between CubeSat size and available reaction wheel size is examined, based on simulations of 15 satellites in CubeSat configurations performing slew maneuvers using 17 commercially available reaction wheels as ACS (attitude control system) actuators. In each simulation using MATLAB, the CubeSat was initially at a 90-degree rotation offset from its desired attitude. Each CubeSat configuration was then detumbled using three reaction wheels and the power consumption for each system was examined. The results of the simulations suggest that more than 15% of the power generated on a spacecraft is required for the attitude control system below a 2U-size spacecraft. For example, approximately 40% of total power generated in a 1U CubeSat is required to operate reaction wheels for a simple slew maneuver, making reaction wheels unfeasible for missions that require complex slews.

1. Introduction

CubeSats are a class of modular nanosatellites with mass between 0.5 and 36 kg. As their name suggests, they consist of cube-shaped units (“U”), with 1U measuring 10x10x10 cm. Typically, a 1U CubeSat is used for technology demonstration, whereas a team will send up an instrument or payload in a small satellite for cost efficiency and use CubeSats 3U or larger for full missions.

CubeSats have only become popular for such use over the past decade, but as the scientific community reaches further into space for longer, more extensive, and more complex missions, reliance on them is increasing. This is mainly due to their modular design, relatively low cost, and the ease with which they can be configured as multiples of a single base unit. Their modularity, in particular, improved the satellite design process and simplified the construction of small satellite systems, lending to their popularity.

A 2017 survey of CubeSat missions by Michael Swartwout at Saint Louis University catalogued a total of 870 missions that have been launched (or scheduled for launch) as of July 2018 (Swartwout, 2017); these include a greater proportion of Earth Observation (EO) and science missions over the last few years, compared to traditional missions focused on training. Additionally, according to Swartwout’s survey, the number of CubeSat launches has steadily grown from fewer than ten per year in the early 2000s to a peak of 288 launches in 2017. Launch projections made for 2018 by SpaceWorks Enterprises Inc. foresee a continuing increase in launches of nanosatellites such

Corresponding Author: Regina S. K. Lee – reginal@yorku.ca
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as CubeSats and microsatellites over the next few years, with commercial operators accounting for over 70% of these launches (SpaceWorks Enterprises, Inc., 2018). A breakdown of the mission types for these projected launches shows that EO and remote sensing missions are expected to make up 50% of upcoming missions, with communication missions rising to 20% of upcoming missions. Scientific and technology demonstration missions are expected to make up only 26% of projected nanosatellite and microsatellite missions. CubeSats are expected to make up over 70% of future nanosatellite and microsatellite missions, with the 30x10x10 cm 3U CubeSat as the most common form factor used.

Attitude control system (ACS) design is an integral and important part of developing advanced CubeSat-class satellites to meet the growing demand in pointing accuracy for science and commercial CubeSat missions. ACS design consists of several areas of specialized study to achieve the level of accuracy required for satellite mission objectives. ACSs, in broad terms, consist of attitude sensors, actuators, attitude determination, and control algorithm.

Typical attitude sensors for a small spacecraft include rate sensors (also known as gyroscopes), star trackers, magnetometers, sun sensors, and horizon sensors. There are numerous commercial attitude sensors with well-documented specifications and characterizations. In comparison, there are fewer attitude actuators commercially available for CubeSat-class missions. Numerous technology demonstration small satellites rely on magnetorquers only, and use simple magnetic control where agility is not a requirement, uncertainty in actuator model could be ignored, and degree-level accuracy is deemed sufficient.

Alternatively, in missions where satellite agility is an essential element of the mission success, reaction wheels are a key factor in achieving arc-minute level accuracy. In such missions, the wheel dynamical model should be available with negligible uncertainty. In this paper, we examine the reaction wheel sizing required for typical CubeSat satellites in order to understand the limitations of reaction wheels as a means of attitude control for CubeSat missions, and to demonstrate the optimal range of CubeSat size for which reaction wheels are the most efficient means of attitude control.

2. Reaction Wheels for CubeSat-Class Satellites

Previous surveys of small satellite actuators have shown that reaction wheels are well suited for small spacecrafts that perform large angle slews (Maryland Aerospace, Inc., 2015). In particular, satellites with moment of inertia less than 1 kgm^2 and mass less than 30 kg were found in these surveys to be suitable for the use of reaction wheels. Since most CubeSats meet these specifications, further analysis of their power consumption when performing slew maneuvers using commercially available reaction wheels was undertaken to further determine any constraints on the use of reaction wheels for attitude control. In addition to the slew maneuvers performed, the effect of external disturbance torques on the spacecraft was considered.

As described previously, there are limited number of commercial reaction wheels applicable for CubeSat missions. Seventeen commercially available reaction wheels for nanosatellites and microsatellites were evaluated for their use in CubeSat missions, as shown in Table 1.

Table 1 demonstrates a considerable range in size, torque capability, and power consumption of the CubeSat-compatible, commercially available reaction wheels. Reaction wheel size is of particular importance, as fewer possible wheels are available to use for smaller CubeSats due to the lack of available size. In practice, the lack of available reaction wheel options could further constrain the ability of CubeSats to use reaction wheels for attitude control.

3. Simulation Model Specification

In developing a simulation model to study reaction wheel sizes for CubeSat missions, we defined several conditions based on the typical low-earth orbit (LEO) CubeSat missions. We assumed that all CubeSats in this study are operated in LOE in the altitude range of 100 km to 650 km. Forces from the space environment act on the satellite, disturbing its motion and changing its attitude or orientation. These disturbances consist of aerodynamic drag torque, gravity gradient torque, magnetic disturbance torque, and, to a lesser extent, solar radiation pressure.

Table 1. Summary of CubeSat-Compatible Reaction Wheel Characteristics

Manufacturer	*Wheel Model*	*Diameter, [m]*	*Torque, [Nm]*	*Power, [W]*
Blue Canyon Tech	RWP015 (Blue Canyon Technologies)	0.042	0.0040	0.60
	RWP050 (Blue Canyon Technologies)	0.058	0.0070	0.50
	RWP100 (Blue Canyon Technologies)	0.070	0.0070	0.50
	RWP500 (Blue Canyon Technologies)	0.011	0.0250	3.00
	RW1 (Blue Canyon Technologies)	0.150	0.1000	3.00
	RW4 (Blue Canyon Technologies)	0.170	0.3000	4.00
	RW8 (Blue Canyon Technologies)	0.190	0.3000	5.00
CubeSat Shop	MAI-400 (Maryland Aerospace, Inc., 2015)	0.033	0.000635	0.45
Surrey Satellite Technology US	200SP-M (Surrey Satellite Technology US)	0.240	0.2400	3.30
Honeywell	HR04 (Honeywell Aerospace, 2018)	0.160	0.0300	2.00
MicroSat Systems Canada Inc (MSCI)	MicroWheel 200 (Microsat Systems Canada Inc.)	0.090	0.0300	2.00
	MicroWheel 1000 (Microsat Systems Canada Inc.)	0.130	0.0300	2.00
	MicroWheel 4000 (Microsat Systems Canada Inc.)	0.218	0.1500	2.50
Sinclair Interplanetary	RW-0.01 (Picosatellite Reaction Wheels (RW-0.01))	0.050	0.0010	0.75
	RW-0.03 (Sinclair Interplanetary)	0.050	0.0020	1.50
	RW3-0.060 (Sinclair Interplanetary)	0.077	0.0200	14.00
	RW3-1.0 (Sinclair Interplanetary)	0.150	0.0500	21.00

The satellite attitude control system must compensate for the effects of all the disturbance torques acting on the satellite, in addition to orienting the satellite to its desired attitude. In this study, the ability of various reaction wheels to counteract these effects was studied by determining the power, attitude adjustments, and time required for a given set of reaction wheels to return the satellite to a desired attitude from an initial attitude that is misaligned from the desired state. In this study, this initial misalignment is referred to "tumbling with an initial rotation."

When reaction wheels are used as control actuators, this means that some momentum storage capability is required to handle the effects of disturbance torques, even when attitude maneuvers are not taking place. This causes a reduction of the total momentum available for performing attitude maneuvers, unless momentum dumping is performed using magnetorquers or thrusters.

3.1. Theoretical Model

Two quantities were considered for this paper: inertia, which is related to the function of the reaction wheels in performing maneuvers and correcting attitude orientation; and power, which is related to the energy drawn by the wheels to perform these maneuvers.

A spacecraft's attitude control system must reorient the satellite in two significant instances: when performing slews or other attitude maneuvers; and compensating for the effects of external disturbance torques. These disturbance torques, T_{dist}, cause undesired angular accelerations, $\dot{\omega}$, on the spacecraft, proportional to the satellite moment of inertia, I_{sat}.

$$T_{dist} = I_{sat}\dot{\omega} \leftrightarrow \dot{\omega} = \frac{T_{dist}}{I_{sat}} \ . \quad (1)$$

For a cube-shaped satellite, both T_{dist} and I_{sat} may be expressed as a function of the side-length of the satellite, L. Since all dimensions are the same, the moment of inertia of the CubeSat in any plane can be determined using the inertia formula of a parallelepiped to get:

$$I_{sat} = \frac{1}{12}m(L^2 + L^2) = \frac{1}{6}mL^2 \quad (2)$$

and

$$T_{dist} = I_{sat}\dot{\omega} = \frac{1}{6}(mL^2).\dot{\omega} \ . \quad (3)$$

Atmospheric drag torques, residual magnetic dipole and, to a lesser extent, gravity gradient torques and solar radiation pressure, scale with the area of the CubeSat faces so that I_{sat} is proportional to L^2. When rewriting for $\dot{\omega}$, we get:

$$\dot{\omega} = T_{dist} \cdot \frac{6}{mL^2} \quad . \tag{4}$$

When we assume that the mass of the satellite, m, is given by a density function with a power-law dependence on L (eg. $m = \rho L^3$ for constant density, ρ), we can express the density of the CubeSat with the expression:

$$\rho = \frac{mass}{volume} = \frac{m}{L^3} \tag{5}$$

to get:

$$m = \rho L^3 \quad . \tag{6}$$

Substituting (6) in (4), we get:

$$\dot{\omega} = T_{dist} \cdot \frac{6}{(\rho L^3)L^2} \tag{7}$$

Here, we can see that angular acceleration, $\dot{\omega}$, due to external disturbances should increase exponentially for smaller satellites, i.e., satellites with smaller L.

We can further manipulate (5) to get:

$$m = (\rho L^2)L \tag{8}$$

$$\rho L^2 = \frac{m}{L} \quad . \tag{9}$$

Since we have assumed a constant linear density, (7) becomes:

$$\dot{\omega} = \left(T_{dist} \cdot \frac{6}{\frac{m}{L}}\right) \cdot \frac{1}{L^3} = \left(T_{dist} \cdot \frac{6}{m}\right) \cdot \frac{1}{L^2} \, , \tag{10}$$

and we can see the relationship emerge where the moment of inertia, $\dot{\omega}$, of a CubeSat is given by:

$$\dot{\omega} \; \alpha \; \frac{1}{L^2} \, . \tag{11}$$

Since satellites do not strictly rotate about one axis, it is possible that the mass of the satellite is not described by a constant density function. This would result in a centre of mass of the satellite that is offset from the geometric centre of mass. With this consideration in mind, the simulation used for the experiment incorporates this offset to yield more realistic results.

Meanwhile, CubeSat power generation is performed using solar panels. Assuming no deployable solar panels are used, panels can only be mounted along the surface of the satellite. From an International Journal of Photoenergy article (Vertat and Vobornik, 2014), we know that the power generated, $Power_{gen,}$, by the CubeSat can be modelled by

$$Power_{gen} = \eta_n \cdot S \cdot A \cdot sin\varphi \;\; , \tag{12}$$

where η_n is the % nominal efficiency of the solar cells used, S [Wm^{-2}] is the solar power density incident on the solar panels, A is the area of the solar panels used, and φ is the angle of sunlight irradiance, relative to the panel base plane. This, of course, implies, that the larger the surface area of the panel, the larger the area of the CubeSat faces, and the more power is generated by the satellite.

However, we are more interested in the portion of the power generated by the CubeSat, P_{gen}, that is then consumed by the reaction wheels to perform the attitude control maneuvers described above is proportional to the surface area available for mounting panels, such that the power consumed by the wheels can be modelled by the equation:

$$Power_{rxnwheel} = torque \text{ x } angular\ velocity = \tau \ x \ \dot{\omega} \, . \tag{13}$$

From (11), we know that $\dot{\omega}$ is inversely proportional to the volume, L^3, of the satellite, so we can see that the power consumption of the reaction wheels is also proportional to L^3:

$$Power_{rxnwheel} \; \alpha \, \frac{1}{L^3} \;\; . \tag{14}$$

There is an inverse relationship between the power consumed by the wheels and the volume of the satellites. To determine the power budget for the Attitude Control System, we consider the power of the wheels as a percentage of the power generated:

$$\frac{Power_{rxnwheel}}{P_{gen}} \; \alpha \; \frac{\frac{1}{L^3}}{L^2}$$

$$ACS\ Power\ Budget\ \alpha\ \frac{1}{L^5}. \qquad (15)$$

The power consumed by the reaction wheels, however, does not scale in the same manner as the generated power, resulting in a much greater proportion of generated power being used by the attitude control system for smaller CubeSats than for larger ones. This, in turn, would restrict the possible attitude maneuvers available to smaller CubeSats, even with the presence of reaction wheels.

3.2. Evaluation Matrix

A simulation of multiple CubeSats with three reaction wheels as attitude actuators was performed using a CubeSat Toolbox for MATLAB, created by Princeton Satellite Systems (Mueller et al., 2013). This toolbox performs simulations of the orbit of a satellite using any system of attitude control. Fifteen CubeSats ranging in size from 1U to 27U were simulated, with each simulation changing the reaction wheel size in the satellite as follows.

The wheels were constrained by size and torque requirements so that the satellites were constrained to use reaction wheels that could be physically accommodated by the dimension of the satellite, and the wheels could provide the minimum torque required by the satellite. Additionally, the centre of mass of each CubeSat was offset by 10% of its side length from the geometric centre of mass to provide a more realistic approximation of the non-uniform mass distribution of a typical CubeSat. Each simulation was performed for an 18-minute portion of a 350 km polar orbit, in which the satellite was required to execute an inertial pointing maneuver. The satellite was required to complete a 90˚ rotation to align its z-axis with the J2000 vernal equinox.

As discussed previously, in addition to the attitude maneuver, disturbance torques were simulated for each satellite, specifically aerodynamic drag, solar radiation pressure, and gravity gradient. Magnetic disturbance torques were neglected, as these depend on the size of any residual magnetic dipole moments in the satellite.

The power generated for each satellite was calculated by modelling the presence of solar panels covering four sides of each CubeSat, each with an efficiency of 29.5%. The power generated over a full orbit was then computed and compared to the power consumption of the reaction wheels when performing the inertial pointing maneuver. The reaction wheel power consumption was determined from the data sheets of the 17 modelled reaction wheels. A linear relationship between wheel speed and power consumption was assumed, with the effects of zero speed crossings and back EMF neglected. These assumptions are valid for reaction wheels initially spinning at non-zero nominal speeds that are not commanded at maximum torque for long periods of time.

4. Simulation Results

The simulation was run for nanosatellites ranging in size and configuration from 1U to 27U; the result was a rapidly decreasing relationship between the fraction of the power budget used by the wheels for performing the attitude maneuver and the satellite size, as shown in Figure 1.

Figure 1 shows that as the satellite size decreases towards the left of the graph, the fraction of the power budget used increases; in some cases, it even results in a majority of the generated power being consumed by the reaction wheels. This large variation in power consumption for smaller nanosatellites is partially the result of sample size, i.e., there are fewer available reaction wheels that fit the volume constraints of the satellite. Additionally, many of the reaction wheels consume less than 10% of the generated power, especially for larger CubeSats, making these reaction wheels particularly attractive for attitude control systems.

For each CubeSat type, the average power consumption of all available reaction wheels was determined and used to establish a relationship between the power consumption and the satellite size, as shown in Figure 2.

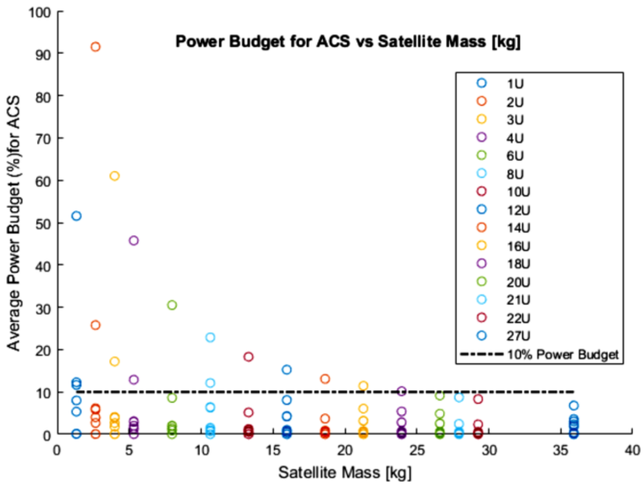

Figure 1. Power consumption versus satellite mass, showing that for smaller satellites, a larger fraction of the available power budget is used to support the ACS—leaving a reduced fraction of the power budget for payload operations.

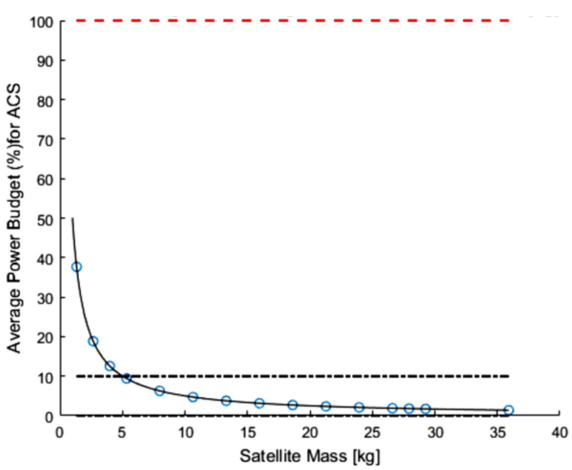

Figure 2. Average power consumption versus satellite mass following an inverse relationship indicating that as CubeSats get larger a larger fraction of generated power is available for non-ACS operations.

An inverse power relationship was found to fit the data, which agrees with the theoretical model described in section 3.1. Spacecraft smaller than 3U in size appear, in this simulation, to consume significant fractions of their generated power performing simple attitude maneuvres. These results imply that the use of reaction wheels in very small CubeSats (e. g. <2U) may hinder the ability of very small CubeSats to perform scientific operations requiring large amounts of power, particularly if good attitude control is a simultaneous requirement. It should be noted that the results of this study are most applicable to the instances in which CubeSats experience significant atmospheric drag, and that the same conclusion may not be true for CubeSats operating in higher LEO orbits (e.g., 650 km and above). Nonetheless, the results of this study imply that the designers of low-altitude CubeSat missions featuring very low mass and volume, would do well to consider the potential outsize impact of ACS systems on their overall mission budget.

While it is clear that there are limitations on the use of reaction wheels for small satellite attitude control, further analysis could be done to investigate additional arrangements of reaction wheels, such as pyramid arrangements discussed in *Sun-Tracking Commands and Reaction Wheel Sizing with Configuration Optimization* (Hablani, 1994). An additional consideration for minimizing the mass of the reaction wheels is explored in *Small Satellite Reaction Wheel Optimization* (Michaelis, 1990), and could be used to further the selection of wheels to make them more suitable for the desired satellite. Furthermore, further investigation on alternate actuators such as control moment gyroscope, as in Viswanathan, Sanyal, Leve et al. (2015), is also required to examine efficient ACS design of small spacecraft.

5. Conclusion

We examined the average power consumption for a simple slew maneuver, and the result is consistent with previously published results on reaction wheel power consumption. The same analysis also suggests that below a 2U size spacecraft, a significant portion (greater than 15%) of the power generated on a spacecraft is required for the attitude control system. Nominally, no more than 15% of the total power is allocated for ACS for small satellites (Wertz, 2010). For example, approximately 40% of total power generated in a 1U CubeSat is required to operate reaction wheels for a simple slew maneuver, making reaction wheels unfeasible for missions that require complex slews.

Therefore, an alternative solution needs to be sought for a small CubeSat-class spacecraft for missions that have stringent ACS requirements, such as the use of deployable solar panels to increase power production.

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