CUBESAT PROPULSION-EXPANDING THE POSSIBILITIES OF THE AFFORDABLE SPACE PLATFORM

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CUBESAT PROPULSION – EXPANDING THE POSSIBILITIES OF THE AFFORDABLE SPACE PLATFORM

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ABSTRACT

Since the CubeSat platform was proposed in 1999–with the first launches in 2003–they have provided affordable access to space for new players. Until 2013, the majority of CubeSats served educational purposes and research projects for universities, but since then, private actors have made the number of CubeSat launches per year rapidly increase. Still, with more than 750 CubeSat missions to date, less than ten have used thrusters.

This paper examines emerging and existing thruster technologies for CubeSats. It explores how these technologies can provide CubeSats with new capabilities such as stationkeeping, orbital adjustments and phasing, and how these capabilities can be relevant in certain mission types. Both single CubeSats and swarms/constellations are looked at, mostly with 3U CubeSats. To show examples of use for CubeSat thrusters, several scenarios was examined and simulated using the software Systems Tool Kit by AGI. The main results from the paper is how CubeSat propulsion can be used to rapidly deploy and lock a constellation. One scenario looked at how three CubeSats can be deployed simultaneously from the ISS, be given different delta-v to drift into an optimal, evenly spread constellation, before firing the thrusters again to lock the constellation. Such a procedure could enable an optimal constellation a week after deployment, with a delta-v cost per CubeSat feasible with current CubeSat propulsion modules. Another scenario examined how a two-CubeSat setup where only one of the CubeSats had a propulsion module could work as a relatively cheap setup while still providing a locked constellation. For this setup, an optimal constellation could also be achieved within days, but at a higher delta-v cost for the propulsion-CubeSat, however still within limits of current technology. Several of the CubeSat propulsion modules studied also provide attitude control. Thus, available CubeSat propulsion technology can be used to deploy constellations fast, perform orbital maneuvers and make CubeSats viable options for missions requiring more orbital accuracy than traditional CubeSat missions.

1 Background and Motivation

At least 798 CubeSats have been launched to date (08.04.18), and 287 of these were launched in 2017 [1]. There is a clear tendency towards increased CubeSat activity, especially among private players, such as Spire and Planet, which together has launched more than 300 CubeSats [1]. However, by May 2017, less than ten CubeSats had featured propulsion systems [2].

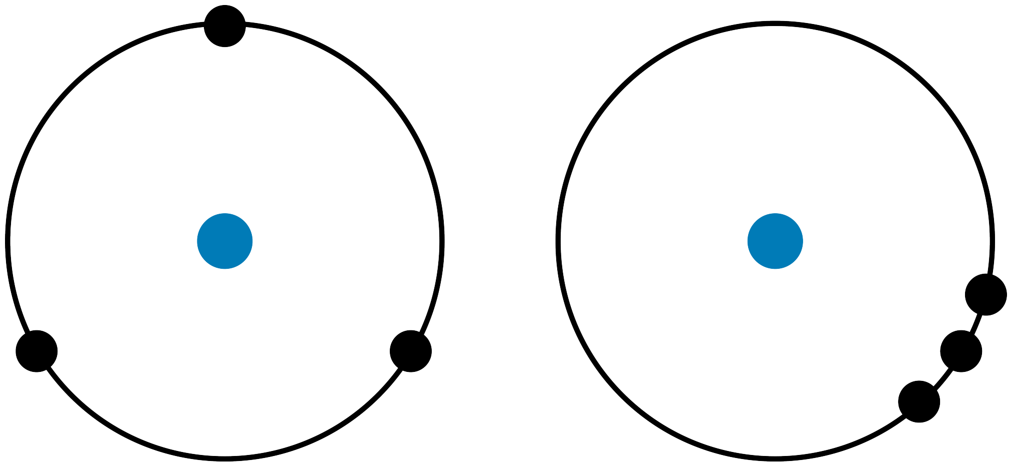

Figure 1: Two of the possible permutations a satellite swarm will cycle through. On the left is an optimal configuration with good coverage, while the right shows a poor configuration with longer periods without coverage.

Commercial CubeSat constellations are becoming more widespread, mainly through actors as Planet and Spire. Un-controlled swarms have also been discussed as possible uses for communication systems based on CubeSats [3]. In this paper, a constellation is defined as a group of satellites with propulsion units working together in synchronised orbits optimised for coverage (such as the GPS). A swarm is defined as a group of free-flying satellites without propulsion, which are working together in the same orbital plane. A study performed in 2010 claimed that conventional satellites will outperform nanosatellite swarms for most missions right now, but that there is a niche for nanosatellite swarms when it comes to maintaining a constant flow of low quality data, such as monitoring ships. There has also been a proposal to build a swarm-based radio telescope around the Moon, known as the OLFAR project [4].

If a swarm of CubeSats is deployed from deployment pods from the same launch, they will generally get slightly different delta-vs. The NanoRacks CubeSat deployer on ISS gives a delta-v in the range of $0.5\,\mathrm{m/s}$ to $1.5\,\mathrm{m/s}$ [5]. Such differences in delta-v will over time make the CubeSats drift away from each other, as they are in slightly different orbits with slightly different orbital periods, which makes their relative distances increase for every revolution around the Earth. Due to this drift, the members of the a swarm will sometimes be gathered in a cluster, and sometimes perfectly spread out, as shown in Figure 1.

2 Propulsion Technologies

The main advantage of CubeSats is their affordability and simplicity, and adding thrusters will make a CubeSat system more complex and expensive. However, companies as Busek Co. Inc. [6] and VACCO Industries [7] have already developed propulsion modules specifically for CubeSats. In 2018, two CubeSats will be sent to Mars, and will use thrusters for course corrections along the trajectory from Earth [8].

By adding thrusters to CubeSats, one can improve maneuvering capabilities. Today, CubeSats are able to perform attitude control by using actuators as reaction wheels and magnetic torquers, but orbit maneuvering and station keeping have been out of reach (with a few exceptions [2]).

CubeSats are following several regulations, including limits for the amount of pressurized gas and the total amount of chemical energy stored in the CubeSat [2]. However, these regulations are based on the assumption that CubeSats will continue to be secondary payloads, and that they should not pose risks to the primary payloads. There are currently several smaller launchers in development built specifically for launching nanosatellites, including the North Star Launch Vehicle [9]. Virgin Orbit's LauncherOne is another launcher in development with a relatively small payload capacity of 500 kg to LEO [10]. Dedicated CubeSat launchers give more freedom to CubeSat developers in the future, and thus the limitations and regulations mentioned above will not limit the scope of this paper. Various propulsion technologies are presented below.

2.1 Cold Gas

Cold gas is a simple, mature, and cheap form of propulsion. The technology is based on a tank with pressurised gas. Instead of combustion, cold gas uses the stored entalpy of the gas. A nozzle releases gas from the tank, thus creating thrust. Power consumption is low, as the only power required is to regulate valves and provide low levels of heat to maintain the minimum propellant temperature. Cold gas systems has flight heritage on CubeSats. Because they do not utilize the chemical energy of the gas, they give a lower specific impulse, thrust and delta-v [2].

2.2 Green Monopropellant

Chemical propulsion systems use the energy from chemical bonds through combustion. The traditional monopropellant fuel has been hydrazine. Hydrazine has extensive flight heritage through traditional space missions, but is also highly toxic and requires careful handling. This increases the mission cost, and makes it less suited for university missions due to the dangers involved. An alternative is green monopropellant systems. Two of the most relevant green monopropellants are hydroxylammonium nitrate (HAN)-based, and ammonium dinitramide (AND)-based [2]. These have higher thrust, density and performance, and burn at higher temperatures than other propellants, which gives a higher specific impulse. The drawbacks with a higher burn-temperature are developing a catalyst than can withstand these temperatures, as well as the necessity of pre-heating the propellant before ignition, which costs power.

2.3 Thermoelectric Resistojets

Thermoelectric reistojet propulsion systems have currently no flight heritage on CubeSats. They have, however, flown on conventional satellites, and even microsatellites (10 kg to 100 kg) [2]. In a resistojet, electric power is used to heat a gas, and it otherwise works similarly to cold gas propulsion. This gives higher I_{sp} than cold gas, but it's typically lower than chemical propulsion. The lack of combustion makes electrothermal propulsion less affected by launch regulations.

2.4 Electrodynamic Vacuum Arc Thrusters

Another type of electric propulsion is the electrodynamic Vacuum Arc Thruster (VAT). Instead of heating a propellant with electric power, a VAT uses an electric field to start the emission of electrons from a metal electrode in vacuum. The propellant comes from sputtering from a cathode material, so no extra propellant or other systems are needed [2]. VATs have flight heritage on CubeSats. One VAT design is the Micro Cathode Arc Thruster (μCAT) desgined at the George Washington University [2]. The United States Naval Academy's 1.5U CubeSat BRICSat-P, featured four μCATs. The thrust levels for this module were too low to perform orbit maneuvers, but could be used to de-tumble a spinning spacecraft.

2.5 Comparison

Available key parameters for specific modules from the different propulsion technologies presented are listed in table 1.

Table 1: Operational parameters of VACCO's NASA C-POD Micro Propulsion System (Cold Gas) [11], Busek's BGT-X5 thruster (Green Monopropellant) [12], Busek Micro Resistojet [13] and the μCAT VAT (Vacuum Arc) [2]. Delta-v is here the total delta-v each thruster is able to give a 4 kg spacecraft, such as a 3U CubeSat.

System	F_{thrust}	I_{sp}	delta-v	Mass	Volume
Cold Gas	25 mN	40 s	46.5 m/s	1244 g	1U
Green Monopropellant	0.5 N	225.5 s	146 m/s	1500 g	1U
Resistojet	10 mN	150 s	60 m/s	1250 g	1U
Vacuum Arc	20 µN	3000 s	N/A	N/A	N/A

2.6 Other Technologies

Other technologies includes solar sails, traditional monopropellant systems (of which the Hydrazine-fueled variant is the most common), bi-propellant, solid propellant, pulsed plasma thrusters, magnetic nozzle systems, electrospray thrusters, miniature ion engines and electrodynamic tethers. The selection made in this paper was made based on recommendations from other papers about promising CubeSat propulsion technologies [2].

3 Method

Several simulations were run, and phasing maneuvers were chosen as the main focus for the simulations. In addition, there were several aspects and areas of use for CubeSat propulsion that were briefly analysed, and can hopefully function as springboards for future projects. In order to simulate practical uses for CubeSat propulsion, a software called Systems Tool Kit (STK) by Analytical Graphics, Inc. (AGI) was used. Relevant orbit and spacecraft parameters for CubeSats were specified in the program, and propulsion maneuvers were tested.

4 Analysis, Results and Discussion

4.1 Simulations

In STK, one specifies what propagator to use for simulating satellites in orbit. These vary in terms of physical assumptions, the effects they take into their calculations, and the time and computer power needed for the simulations. For scenarios 1 and 2, the J4Perturbations propagator was chosen, as this is recommended for long-duration simulations (spanning months or years). This takes gravitational asymmetries and the next most important oblateness effects into account, but not effects as atmospheric drag and solar radiation pressure [14]. Thus the propagator can be used for simulating ideal orbits, but for lifetime analysis, another tool had to be used. For simulations including thrusts, the Astrogator propagator had to be used, as this allows making the mission control sequences needed for such simulations. However, the propagator elements within this sequence was set to use the Earth HPOP Default v10 propagator, which takes atmospheric drag and radiation pressure into account [15].

4.1.1 Scenario 1

A swarm of three freely drifting satellites in a polar orbit at 98° inclination were initialized. In order to simulate a small drift due to different delta-v from deployment, the satellites were put into circular orbits with altitudes 598, 600 and 602 km. The inclination and altitude were chosen to resemble the AISSat parameters [16], thus a resemblance to an real (and Norwegian) satellite was ensured. While the AISSat orbits are slightly elliptical, these orbits were chosen to be circular for simplicity. In STK, a ground station was set up in Longyearbyen, and the coverage for this ground station was simulated. All satellites started at the same location, and the simulation was run over one year.

4.1.2 Scenario 2

Scenario 2 studies a phased constellation, in order to compare it with the swarm from Scenario 1. Two CubeSats were put in a circular orbit with 600 km altitude and 98° inclination. The phase difference between the satellites was 180°. The same ground station at Longyearbyen was used, and the average and maximum revisit time was analysed.

4.1.3 Comparing Scenarios 1 and 2

For the swarm of three freely drifting CubeSats, several different configurations was observed over the course of the one-year simulation. After about two months, the satellites were in the evenly spread out configuration, then went through different configurations, including a cluster of two at 180° separation from the third, before they were all gathered in one cluster more than five months after start. A comparison of the average and maximum revisit time of the swarm and constellation is presented in table 2. To sum up, a mission using a two-CubeSat phased constellation instead of a three-CubeSat swarm, will see an average revisit time of 34% more, while the maximum revisit time will be reduced by 54%, with a much higher consistency than the freely drifting swarm. The maximum revisit time will occur rarely, and for daily operations it will be a less relevant measure than the average revisit time.

Table 2: Maximum and average revisit time of the three-CubeSat swarm and two-CubeSat constellation, at around 600 km altitude and 98 ° inclination.

	Three-CubeSat swarm	Two-CubeSat Constellation
Average revisit time	1660 s	2220 s
Maximum revisit time	5410 s	2470 s

4.1.4 Scenario 3

Scenario 3 and 4 looks at deploying CubeSats from the ISS and then phasing them by using thrusters. This first one deploys three CubeSats from ISS, then gives them three different delta-vs: 1 m/s, 10.5 m/s and 20 m/s. After around 6 days, they are evenly spread out in orbit. By then giving CubeSat 1 an 19 m/s boost and CubeSat 2 a 9.5 m/s boost, the constellation will lock. It was found that the thrust will have to be given at the right time. Since an engine burn will bring a spacecraft with a circular orbit to an elliptical orbit with the apogee 180° away from the thrust point, it is important that all engine burns happen in the same point, so the CubeSats get into the exact same orbits with the same apogee and perigee. If not paying attention to this, the orbits will drift with some degrees per week, while a near-perfect lock can be achieved by using thruster burns at the right time. A total of 20 m/s delta-v per CubeSat is achievable with all propulsion modules discussed. A discussion about finite and impulsive thrust is found on the next page.

4.1.5 Scenario 4

A two-CubeSat phased setup was also studied, where only one of the CubeSats was outfitted with propulsion, in order to reduce cost. CubeSat 1 was given a delta-v of 1 m/s, and CubeSat 2 20 m/s. When the phase difference was 180°, CubeSat 2 was given a reverse thrust of 19 m/s to bring it into the same orbit as CubeSat 1 and keep the phase difference stable. Worth noting is that this procedure will require attitude control, as the CubeSat needs to point its main engine in two different directions. It was found that it will take 4 days and 7 hours for them to be at 180° angle.

4.1.6 Thrust Considerations in the Simulations

The maneuvers in Scenario 3 and 4 assumed infinite thrust in order to give the satellites instantaneous delta-v boosts. For a green monopropellant thruster with a thrust of 0.5 N, it will take 160 s to give a 4 kg CubeSat a delta-v of 20 m/s. This is about 3% of the orbital period when deployed from the ISS. It is certainly not instantaneous, and the full thrust will not be applied at the correct point. One possible way around this is to apply the thrust over several orbits. By giving 16 boosts with durations of 10, the thrust is quite instantaneous and can be applied quite accurately at the correct point, but the maneuver will take 24 hours to perform (the total deployment time for both constellations will still be less than a week).

Using the cold gas thruster with an F_{thrust} of 25 mN increases the thrust time with a factor of 20 compared to the green monopropellant thruster, meaning that the total burn time would be more than half an orbital period. Finite thrust simulations in STK showed that using cold gas for maneuvers like this will increase the deployment time for the constellation and/or make the constellation unstable, so small corrections will be needed to keep the desired phase difference.

These results points to green monopropellant as a good candidate for orbit maneuvers. The high total delta-v provided by the BGT-X5 thruster can also give the freedom to manipulate a constellation over the course of its lifetime.

4.2 Analysis

4.2.1 Extended Lifetime

In LEO, where most CubeSats are positioned today, atmospheric drag is present, and will de-orbit any spacecraft given enough time. Lifetimes can be extended by using thrusters, but one will also need to consider for how long it is worth keeping a CubeSat alive. The design lifetime of small satellites might be so short that a rapid natural de-orbit actually is favourable in some cases. Planet operates with a design lifetime of three years [17], and AISSat-1, Norway's first national satellite, and similar in size and weight to an 8U CubeSat, also had a mission design lifetime of three years [18].

Already at the altitude of the ISS at 400 km, the natural minimum lifespan of a 3U CubeSat will approach three years. This was found by using STK's Lifetime tool, using the NRLMSISE 2000 Atmospheric Density model, and setting the satellite's weight to 4 kg. The lifetime was found to be between 2.2 and 5.6 years, depending on the area of drag and area exposed to the Sun (a value between 0.01 m^2 and 0.03 m^2 is possible for such a CubeSat, and unless ACS is used, the actual area will vary during each orbit. In other words, the simulation results indicate that at ISS' altitude and above, using thrusters to extend the lifetime of a CubeSat will in many cases be unnecessary, given a design lifetime of three years.

It is worth noting that estimates of CubeSat lifetimes vary. Already in the authors simulations, rather large intervals can be found, due to variations in drag area. Orbital lifetimes are estimated by [19] as less than a day at 200 km, a month at 300 km, a year at 400 km and ten years at 500 km, for a 4 kg CubeSat.

By combining an equation from [20] with data from [21], an upper limit for annual delta-v loss due to atmospheric drag on a 3U CubeSat (under mean solar activity) was found to be 12 m/s for a 500 km circular orbit. Similar values for 400 km and 300 km are 60 m/s and 400 m/s, respectively. All thrusters discussed are able to extend lifetime with several years at 500 km (although unnessecary in the light of the previous paragraph), while at 400 km, only the green monopropellant module is able to extend lifetime with more than a year. At 300 km, resistance is futile.

4.2.2 Deorbiting

A 4 kg CubeSat will have a lifetime of around 25 years at an altitude in the 500 km to 550 km range [19]. STK gives 24.2 years as an upper lifetime for a 4 kg CubeSat at 550 km, so by lowering the altitude of a high-altitude CubeSat to 550 km, it should be possible to meet the 25 year limit. The majority of CubeSats are well below this limit already [1], so deorbiting measures will not be necessary in most missions. However, there are still roughly a hundred CubeSats above 550 km, and for these, the altitude needs to be lowered. The majority of these are around 600 km, with some at 800 km. Examining the delta-v needed to go from these orbits to a 550 km orbit: By using Hohmann transfers, it was found that a delta-v of 27 m/s was needed to go from a 600 km orbit to a 550 km orbit, while 134 m/s is needed to go from a 800 km orbit to a 550 km orbit.

As can be seen from the numbers, 600 km to 550 km is feasible with the relevant propulsion modules, while for 800 km satellites, other technologies might be better suited.

A drag sail is a passive deorbit technology that deploys a large sail at the end of the mission, in order to increase drag and making the satellite deorbit. The technology has been tested on a 3U CubeSat called FASTSAT. The dragsail Nanosail-D2 was deployed from the CubeSat in late January 2011 in a 650 km orbit and caused it to reenter Earth's atmosphere in September 2011 [22].

Another drag sail demonstration mission was the 3U DeorbitSail CubeSat, which featured a 25 m^2 drag sail packed into a 1U volume. It launched in July 2015 and was planned to deorbit after 180 days [22]. However, the drag sail failed to deploy [23].

4.2.3 Cost

The cost of a CubeSat has been difficult to find. One estimate is less than 50,000$ for a 1U CubeSat [24]. This cost will necessarily vary based on whether the CubeSat is built by university students for free or by a company. The same source gives an estimate of over 100,000$ for a launch, and Spaceflight gives an exact price of 295,000$ for a 3U CubeSat to LEO [25], in other words 100,000$ per U. The cheapest CubeSat propulsion system on CubeSatShop.com is available for 30,000$. This is an electric propulsion system, and given the simpler nature of cold gas systems, it can be expected that cold gas systems may be cheaper. If so, a propulsion module will make up less than 10% of the total price of a 3U CubeSat. CubeSatShop also has two other propulsion systems, both electric, and costing 50,000-210,000$ and 81,000-129,000$. These will make up a bigger part of the total cost of a CubeSat, but will still be cheaper than the launch.

5 Conclusion

It was found that the propulsion technology for CubeSats is mature enough to make CubeSats more powerful and versatile tools for the space industry. This paper focused on how to deploy and phase CubeSats within a constellation, and found that an orbital plane can be evenly populated by three CubeSats deployed from the ISS at the cost of $20\,\mathrm{m/s}$ delta-v pr. satellite, or by two CubeSats at the cost of $40\,\mathrm{m/s}$ for one of them, and both constellations can be deployed in less than a week. The total time depends on how much thrust the propulsion system is able to give, and for bigger maneuvers, high-thrust systems such as green monopropellant are recommended. Thrusters can also be used for deorbiting CubeSats from orbits up to around 600 km, while for CubeSats in 800 km orbits, other means should be considered. Extending lifetimes is also possible, but will only make sense for altitudes around 400 km. Exact prices have been difficult to find, but some thruster modules can be found for less than 10% of the cost of a 3U CubeSat.

5.1 Future Work

This project became a broad and initial study of the possibilities given by CubeSat propulsion. Many areas discussed deserves more attention, and can be worth looking into for future projects. Suggestions for further areas of study includes using trusters to phase CubeSats accurately enough for virtual-aperture mission, comparing the performance of thruster-based ACS with reaction wheels and magnetorquers, as well as creating thrust procedures for doing orbital maneuvers with low-thrust propulsion modules. Another major element not discussed in this paper, is how the power requirements of the thrusters will affect cost and other aspects of the CubeSats.

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