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CUBESAT CONSTELLATION DEPLOYMENT STRATEGIES

Christophe Vakaet* and Alessandra Menicucci†

CubeSat based constellations are limited by launch opportunities, manoeuvring, and reliability. In this paper, an approach is proposed to determine the performance of a constellation, using different deployment strategies. Due to low maneuverability and limited launch options, CubeSats require deployment strategies that determine the optimal launch method and maneuvers to ensure rapid deployment, and replacement in case of failure. To do so, a model is developed that applies a Monte Carlo method through repeated sampling of the satellite lifetimes. By simulating discrete realizations of the constellation, over the mission lifetime, the probability distribution of the strategies performance is derived. By comparing deployment strategies, the model can be used to design for the optimal deployment strategy.

INTRODUCTION

Throughout the history of spaceflight, most spacecraft have been designed with reliability as one of the top priorities. More recently a new design philosophy has emerged focusing instead on price, state of the art technology, and quantity of spacecraft to ensure success. Examples of this philosophy are the CubeSats: small, cheap and light spacecraft consisting of $10 \times 10 \times 10 \text{ cm}$ units. However, compared to other satellites, CubeSats are generally less reliable, maneuverable, and can not be individually inserted into orbit due to costs. Following the rise in popularity of CubeSats, a demand for distributed systems or constellations has developed. Due to the limitations of CubeSats it necessary to apply new methods to operate such a constellation, to maximize the operating performance.

This paper proposes a method to determine the expected operational performance of a deployment strategy. The model can be used to analyze both launch and maneuvering strategies. By applying the model one can design the optimal strategy for a given mission, through comparison of different strategies. To determine the operational performance the model uses a Monte Carlo approach. In this approach a finite number of constellation realizations are generated by assigning unique lifetimes to the satellites, based on the expected reliability of the satellites. Even though each realization performs differently, through the law of large numbers, a probability distribution of the performance can be found. The model is currently limited to constellations consisting of circular orbits with the same height and inclination. Furthermore the model does not consider maintenance launches or partial failure. In the future these limitations could be overcome by increasing the complexity of the model, making it more efficient, and having more data from flight proven constellation. The model has not been validated since no flight proven constellation has used the model yet.

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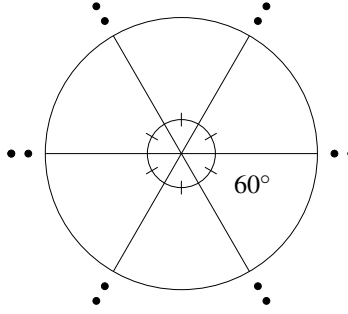


Figure 1. Distribution of the CubeSats in RAAN after launch, top view on Earth

The model described in this paper is developed for a design exercise of a Small Satellites Constellation for Earthquake Precursors. The mission requires a constellation consisting of six groups of satellites with 60° right ascension of the ascending node (RAAN) between each group, as seen in Figure 1. Each group of satellites consists of two 6U CubeSats. The mission is assumed to have two dedicated launches with twelve satellites each, providing the mission twelve replacement satellites. Because successful deployment of 12 satellites with a single 12 satellites launch is unlikely (in 81% of the cases at least one satellite will be dead on arrival), it was decided to launch twice, nearly simultaneously, at opposite RAAN to initially deploy the satellites. Once in orbit, the satellites use their 2U propulsion system to induce a relative RAAN drift of $0.33^\circ/day$.

This paper is divided into three sections. The first section describes the methodology used to determine the operational performance. The second section discusses the applications, limitations, and potential future expansion of the model. The final section concludes the content of this paper.

METHODOLOGY

To determine the operational performance of the constellation, over its intended lifetime ($t_{mission}$), a Monte Carlo approach is used. In most reliability problems an analytical approach is preferred due to its efficiency. However due to the complexity of this problem such an approach cannot be applied. In comparison, a Monte Carlo approach divides the system into simpler elements with predictable behaviour. In this model the elements considered are the satellite reliability and positioning. By combining these elements as indicated in Figure 2, the system performance of a single realization can be calculated. From statistical analysis of a discrete set of realizations, the probability distribution of the operational performance can be derived.¹ In this section the reliability, positioning, and analysis of the results is discussed.

Reliability

To determine the reliability of CubeSats either a component failure rate database or in-orbit failure data can be used.² However, no component failure rate database is available that can be used accurately for CubeSat operating conditions, environment and stress levels. Hence analysis of in-orbit failure data performed by Langer has been used.³ More specifically the double Weibull distribution, as seen in Equation 1, has been used with: $\alpha = 0.2115$, $\theta_1 = 57.9715$, $\beta_1 = 0.9017$, $PNZ = 0.8146$, $\theta_2 = 4837.3947$, $\beta_2 = 1.0710$.

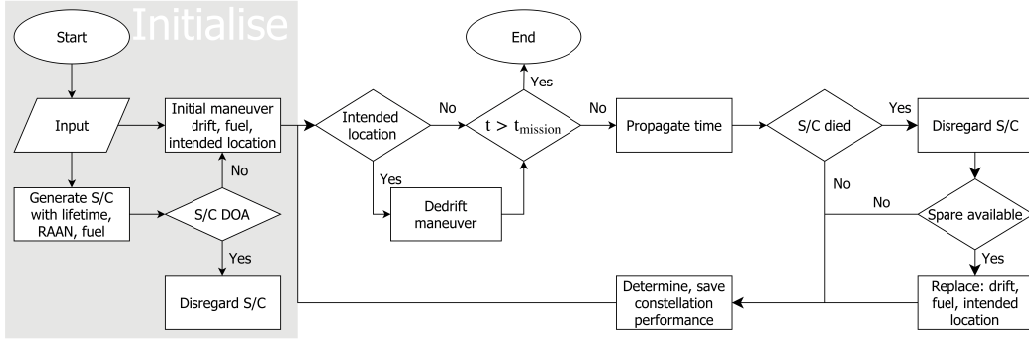


Figure 2. Logical flow of the simulation of a single realization

$$R(t) = \alpha \cdot \exp \left[- \left(\frac{t}{\theta_1} \right)^{\beta_1} \right] + PNZ \cdot (1 - \alpha) \cdot \exp \left[- \left(\frac{t}{\theta_2} \right)^{\beta_2} \right] \quad (1)$$

When using in-orbit failure data to determine the reliability of a CubeSat, one has to be aware of the inaccuracies of such a model. Firstly, the model by Langer is derived from a CubeSat failure database consisting of 178 CubeSats over a 12 year period (2003-2014). Because in this period significant technological advancement has been made, this data may not be entirely accurate for the current technology. Secondly each CubeSat in the database has a different design, manufacturing, assembly, and verification approach. To improve accuracy one should only consider CubeSats using similar technology, and a similar approach to design, manufacturing assembly, and verification. However due to the current low number of flown CubeSats this is currently unfeasible. Lastly this model does not consider partial failures. By considering partial failures one may again use different strategies to optimize the use of the satellites.

Positioning

The position of a satellite is determined by the deployment from the launcher, and its subsequent maneuvers. The model in this paper assumes that the CubeSats are deployed by the launcher in circular orbits at the altitude and inclination of the intended operating constellation. These assumptions can be used for most constellations due to two reasons. Firstly the most common types of constellations, such as the Walker constellation, uses circular orbits at the same altitude and inclination. Secondly, due to the required ΔV to change the inclination and altitude of a spacecraft, it is often more beneficial to either use an optimal launch method, or deploy in a less optimal constellation, rather than using a propulsion system.

These assumptions mean that a change in altitude or inclination is not considered to improve the operating performance, once the satellites are initially deployed. Hence, the only two orbital parameters that can be changed by operation of the satellites are true anomaly and RAAN. Because a change in RAAN uses significantly more ΔV and time, and because RAAN has a larger effect on operating performance, the effect of the true anomaly on performance is not considered. In the following paragraphs potential launch and maneuvering strategies are discussed.

Launch methods Because dedicated launchers have not been cost effective, CubeSats have been launched using piggyback launches up until now.⁴ By using a piggyback launch, the release point

of the CubeSat is determined by the primary payload. Hence, due to the assumptions made in the previous paragraph, it follows that the intended constellation is in turn determined by the primary payload. Luckily, due to the development of small satellite launchers, dedicated launchers are becoming viable options.* Dedicated launchers can furthermore be used to select a specific RAAN to deploy the satellites. This allows the mission designer to select the best RAAN to launch at using the model.

Maneuvering To change the relative RAAN of CubeSats, launched by a single vehicle, multiple approaches have been proposed such as using the Earth-Moon Lagrange point or nodal precession by natural orbital perturbations.⁵ Nodal precession requires significantly less ΔV but a lot more time for given RAAN shift. Because nodal precession is slow, it is more important to have an optimal deployment strategy, such that the replacement time of a satellite is minimal. Hence the model described in this paper will have the largest impact on the performance of constellations where satellites are RAAN separated through nodal precession.

The precession rate, using nodal precession, is determined by Equation 2 with: Earth's radius (R_e), semi-major axis (a), eccentricity (e), orbital period (P), geopotential coefficient (J_2), and inclination (i). Hence a , e , and i of two satellites can be changed through a propulsive maneuver such that both satellites drift apart. Once at a desired relative RAAN another propulsive maneuver can reduce the relative drift back to zero. The optimal combination of changes to a , e and i for a certain time or ΔV required can be calculated using an optimization strategy.

$$\dot{\Omega}_p = -\frac{3}{2} \left[\frac{R_e}{a(1-e^2)} \right]^2 \frac{2\pi}{P} J_2 \cos(i) \quad (2)$$

The performance of the propulsion system determines to which extent a maneuver, providing a certain relative drift, can be undertaken. With the current technological limitations of CubeSats it is expected that each CubeSat is only able to perform two maneuvers. One to induce a drift and one to reduce the drift back to its initial value. Due to the limitations in number and rate of RAAN changes it is essential to have the best strategy to determine the time and direction of each maneuver, such that optimal use is made of the available fuel.

To apply the model one has to determine a RAAN separation strategy to analyze. In this section three example strategies for the mission, described in the introduction, are discussed in the list below:

1. Once deployed the satellites not dead on arrival (DOA) are distributed over the three closest intended satellite RAAN locations (0° and $\pm 60^\circ$ from launch RAAN).
2. Once deployed, 6 not DOA satellites are assigned to the three closest intended RAAN locations. The other not DOA satellites are kept in their initial orbit. Once an assigned satellites fails, an satellite unassigned satellite takes its place.
3. Once deployed, 6 not DOA satellites are assigned to the three closest intended RAAN locations. The other not DOA satellites are given one by one a nodal drift such that the relative RAAN between each spare is equally distributed.

*<https://spaceflightnow.com/2017/11/16/second-electron-rocket-shipped-to-new-zealand-launch-site/>

The third strategy has not yet been simulated for the mission, but provides an insight in the more creative design options that could be considered. Because the spares are continuously rotating around the constellation one will always be close to a failed satellite, reducing the time to replace the satellite compared to the second strategy.

Results

Using the reliability, launch method, and maneuvering strategy, realizations of the constellation can be simulated over the mission lifetime with the logical flow visualized in Figure 2. This flow diagram is slightly simplified as the replacement of satellites is also dependant on the maneuvering strategy, and hence the input of the model. From each realization the location and health of every satellite throughout the mission lifetime can be retrieved. This data can be summarized into performance parameters, relevant for a mission, such as whether the constellation ever attained its intended form (success), and the time it took to do so (time to success). By simulating a finite number of realizations, the probability of a successful constellation (success rate), and the distribution of the time to success can be derived through the law of large numbers.

In Table 1 the success rate, the mean time to success, and the 90th percentile of time to success of the first two maneuvering strategies for the example mission is given. From the Table it can be found that the first strategy has a lower rate of success but, when successful, the time to success is constant at 183 days. In contrast, the second strategy has a higher rate of success with a varying, and significantly longer time to success. From the results the designer may still choose any of the two strategies depending on the mission requirements between success rate and time to success.

Table 1. Success rate and time to operations calculated from 1000 cycle of a Monte Carlo simulation for separation strategy 1 and 2

Case	Success rate (%)	Time to success	
		mean (days)	90th percentile (days)
1	48	183	183
2	83	251	362

Verification & Validation

From the output of the model, discussed in the previous section, all sections of the code can be verified. Firstly to check the implementation of the reliability, one can recreate the graphs by Langer to verify correspondence to the reliability model. Next using the location and status data of each satellite over the mission lifetime, the constellation can be animated. With this animation one can verify whether the initial deployment and maneuvering is correctly implemented and correspond to the calculated performance parameters of the realization.

The model has not been validated with historical flight data, because this data is currently unavailable. To validate the model, the model should be applied to multiple constellations which have are subsequently operated using the deployment strategy used in the model. The results from the model should than be compared to actual data from the constellations. Because no constellation has applied this method yet, it is currently impossible to validate the model.

DISCUSSION

In this section limitations of the model, accompanied with potential solutions, are discussed. These limitations are related to the following five problems:

1. Complex constellations, and deployment strategies
2. Computational power
3. Maintenance launches
4. Partial failures
5. Validation

The model described in this paper is currently limited to determine the operating performance for limited types of constellations and deployment strategies. The model could be expanded to include constellations consisting of orbits with different heights, and inclinations. But to determine the performance of such a constellation, one has to be able to model the exact deployment strategy that would be applied to every possible realization. This becomes very complex due to the large number of possibilities.

Next to the complexity of modelling certain constellations and deployment strategies, also the computational power to simulate hundreds of realizations of a strategy should be considered. Research in the theory of simulations can provide more efficient methods to construct realization, and reduce the number of realizations needed, compared to what is done in the current model. For example, in the current model a fixed time interval method is applied where the time is propagated by a constant interval. Subsequently at each interval the program checks if an event occurs, and applies the corresponding actions. Instead, it is possible to determine the time to the next event and propagate directly to that time, skipping the analysis of unnecessary time intervals. This method would reduce the required computational power but increases implementation complexity.

In the future it is expected that the model will be expanded to include maintenance launches. The current problem is to find a model to determine when and where to launch potential maintenance launches. An easy way would be to do a maintenance launch at a fixed time. However in reality, when the constellation would underperform, the maintenance launch would happen earlier. Hence the model would not accurately represent reality, and therefore present incorrect results. A more accurate model would be to assume a launch at a fixed time (for launch preparations) after the constellation reaches a certain state. The best launch model is expected to estimate the probability that a maintenance launch would be needed in a certain time frame, needed to prepare the launch. However to estimate this probability a Monte Carlo simulation would have to be performed, creating a simulation in a simulation, and therefore exploding the required computer power.

The current model does not consider partial failure due to a lack of reliability data. As more CubeSats constellations have been launched it is expected that a reliability model including partial failure could be used. By taking into account partial failures the model would more closely represent the actual constellation, and therefore predict the performance of a deployment strategy better. More reliability data would also improve the current reliability model, again improving the performance of the model.

CONCLUSION

To conclude, the model provides a method to determine and compare the performance of different deployment strategies. The tool is limited to constellations with circular orbits of constant height and inclination. But, it is expected that in the future the model can be expanded to include more complex cases, thanks to the flexibility of the Monte Carlo approach.

The accuracy of the model is limited by the uncertainty in the reliability estimate used, which is based on the scarce information provided by launched CubeSats. As more CubeSats are flown, more reliability data will become available which will increase the accuracy of the model. Moreover, in-flight data from CubeSats constellations will allow in the future the full validation of the described model.

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