Towards Sustainable Satellite Swarms

Report Summary

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Introduction & Context

Satellite swarms are an emerging mission architecture which offer a flexible, robust alternative to traditional space missions. Drawing inspiration from naturally occurring swarms such as honey bees or ant colonies, satellite swarms consist of individual satellite agents working cooperatively towards a common goal. We define satellite swarms as networks of intercommunicating satellites exhibiting complex emergent behaviour, collectively operating as a distributed system. Complex emergent behaviour has been proposed as a means for satellite swarms to perform tasks ranging from collision avoidance to high-resolution multi-point science measurements [1].

The topic of space sustainability has become increasingly common in discussions of space policy as the dangers of space debris have become more evident [2] [3]. Accidental collisions, satelltie fragmentations, routine operations and even the intentional destruction of satellites have already added huge amounts of space debris to Low Earth Orbit.

Mitigating the build-up of space debris is necessary to preserve our access to space and space-enabled services and is the goal of the Space Debris Mitigation Guidelines of the UN Committee on the Peaceful Uses of Outer Space as well as various pieces of national legislation. Technical efforts to work towards space sustainability include the development of a satellite sustainability rating as well as servicing and deorbiting hardware. [3].

The potential of satellite swarms to add to the debris population has been noted [4] but swarm-specific space sustainability measures have not yet been developed. As well as contributing many individual swarm agents to the growing population of space debris in orbit, mega-constellations or swarms comprising numerous small satellites are difficult to track with current Earth-based sensor networks. Satellite swarms also increase the risk of collisions, particularly during end-of-life when small swarm agents cannot be manoeuvred to avoid collisions with functional satellite systems.

The potential applications of satellite swarms and the responsibility to assume a sustainable approach to space exploration raise an interesting question. How can we deploy satellite swarms sustainably? In this thesis we explored two routes to make satellite swarms more sustainable. The first project was to explore the possibility of autonomous health monitoring within a satellite swarm to help to predict and pre-empt satellite failures. The second, larger project was to determine if inter-satellite links in a satellite swarm could be used to improve space situational awareness using Phase 1 of the mega-constellation Starlink as a case study.

This report focuses mainly on determining the potential of cooperative localisation in satellite swarm, though preliminary investigations and ongoing research in the autonomous health monitoring project are also presented.

Project 1: Autonomous Health Monitoring

Methodology

We developed a satellite health indicator to represent the health of swarm satellites as a single number. The value of the satellite health indicator is denoted by θ, and is expressed as a product of critical factors $P_i \ldots P_n$ with normalised weightings α_i. The sum includes non-critical factors $P_j \ldots P_m$ with normalised weights α_j. Each factor is scaled to the range $0 \le P_{i,j} \le 1$, using 1 to denote perfect functionality and 0 to denote a complete failure of the relevant subsystem. As such, the satellite health indicator maps the aggregate health of a satellite's subsystems onto a single real number in the range $0 \le \theta \le 1$.

$$\theta = \prod_{i=1}^{n} \alpha_i^c P_i^c \cdot \sum_{j=1}^{m} \alpha_j P_j$$

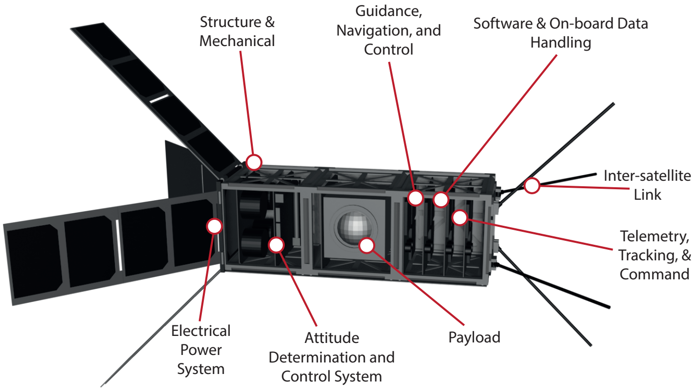

Figure 1: Satellite Health Parameters for a generic CubeSat

Ongoing Research

We chose satellite parameters using CubeSats as model swarm agents and examined a range of proposed satellite swarms in the literature to ensure our parameters are broadly applicable. Figure 1 shows the chosen parameters for a generic CubeSat. Our ongoing research focuses on weighting the satellite health parameters using a Markov Model of a generic swarm satellite and then comparing our results with reported failure rates in CubeSats. The next step in this project will be to map the satellite health indicator onto real telemetry and distribute health monitoring across satellites in a simulated swarm.

Project 2: Improving Space Situational Awareness with Swarms

Methodology

Using the well-studied Starlink satellite internet mega-constellation [6][7] as a case study, we established the potential performance of co-operative localisation between the Starlink satellites by calculating the Cramér-Rao Bound (CRB) for Phase 1 of Starlink. The CRB is a performance bound which can be used to determine the "best case" performance of any estimator given the measurement technique and the information available.

Orbital Mechanics

Calculating the CRB requires the position of the satellites to be known. These were determined using a Python simulation of all 1584 satellites in Starlink Phase 1 with circular Keplerian orbits propagated for one orbital period (5730 seconds) using the Poliastro library. The satellites orbit at 550 km (Low Earth Orbit) in 72 planes at inclinations of 53°. Perturbations such as aerodynamic drag and the J_2 effect were neglected.

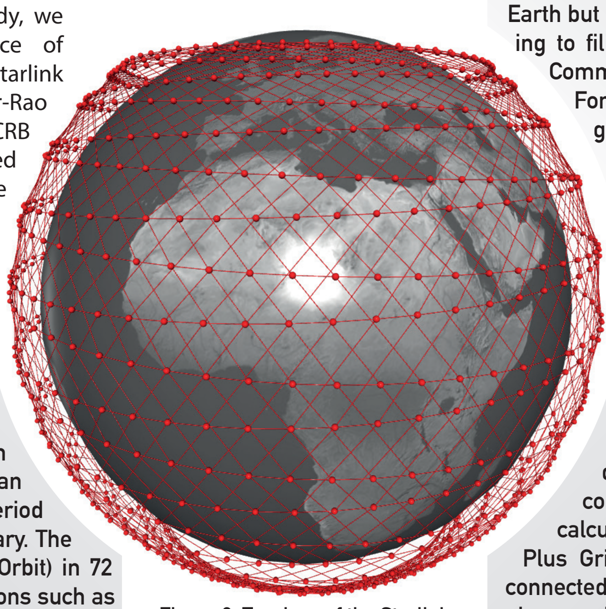

Figure 2: Topology of the Starlink Network

Ground Stations

Starlink's ground stations are spread over the Earth but mainly concentrated in the USA, according to filings with the Federal Communications Commission and other regulatory agencies. For the simulation of Starlink, a total of 87 ground stations were considered with the positions shown as red circles in the upper panel of Figure 3. At each time step, 7.8% to 9.1% of the swarm is connected to a ground station — an average of 126 satellites.

Network Topology

The network topology of Starlink is determined by which satellites are connected, which is constrained by the physical constraints of visibility and distance and the technological constraints of the satellites themselves. To calculate the CRB for Starlink, we assume a Plus Grid topology [8], in which satellites are connected to two satellites in the same orbital plane and two in neighbouring planes. Figure 2 shows this network for the full Phase 1 of Starlink.

Results

Calculating the CRB for Starlink over one orbital period gives the results shown in Figure 3. The average Root Mean Square Error has a constant value of approximately 10.15 m. The value of the CRB is the maximim accuracy possible with any location estimation technique. This is comparable to GNSS hardware currently on satellites and is consistent with previous research [9]. Figure 3 shows the varaition in the CRB over the course of a single satellite's orbit. The CRB has prominent peaks at high and low latitudes. There is also a noticeable dip in the value as the satellite passes over a ground station in Tierra del Fuego. The larger CRB at high and low latitudes is caused by the geometry of the Starlink network, a similar effect to dilution of precision in GPS navigation. The results in Figure 3 can be improved in future research by incorporating a model of the system dynamics in the CRB calculations. However, the results already indicate that cooperative localisation offers a viable, redundant method of localising swarm satellites.

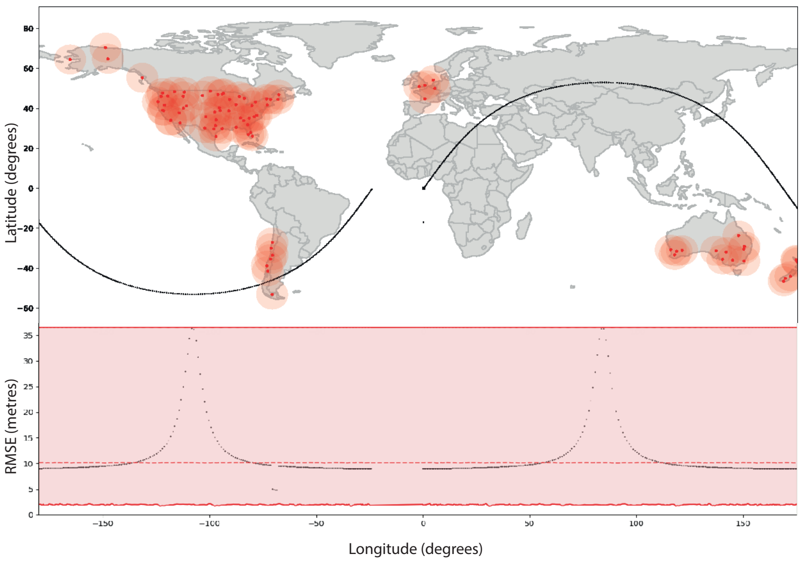

Figure 3: CRB over the orbit of a single Starlink satellite

The red circles on the map show the location of ground stations and the black line shows the gorund track.

Conclusions

Ensuring that satellite swarms are deployed sustainably is an important field of research, and both the projects presented here represent steps towards more sustainable swarms. The results of Project 2 indicate that the locations of a large swarm such as Starlink can be determined from inter-satellite measurements to an average RMSE of approximately 10.15 metres during most of their orbit. This could improve space situational awareness by providing a redundant way to localise swarm satellites. The results also show that cooperative localisation is dependent on geometry and topology of the swarm network as well as the characteristics of inter-satellite links, which could inform the design of future satellite swarms. The ongoing work on Project 1 could eventually help predict and pre-empt satellite failures via a composite health indicator which enables autonomous health monitoring within a swarm.

References

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