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END-OF-LIFE FOR SATELLITE SWARMS

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Abstract

Satellite swarms offer a high-capability mission architecture with a variety of potential applications in space exploration and discovery. Swarm-based architectures —which comprise multiple agents operating collectively as a distributed system— have been proposed for Earth observation, astronomy, planetary exploration, and heliophysics. Some of the key technology demonstration missions have already successfully flown in the past decades. The increasing interest in satellite swarms suggests that this innovative architecture will be adopted in a variety of future missions in the coming years, raising the question of how to dispose of satellite swarms at the end of their operational lifetimes. Mega-constellations or swarms comprising of numerous small satellites are difficult to track by Earth-based networks. They also increase the risk of collisions, particularly during end-of-life when these small satellites cannot be maneuvered to avoid collisions with functional satellite systems. Previously, distributed small satellite missions such as KickSat-2 and SpaceBEES 1-4 were designed to passively deorbit and burn up during atmospheric re-entry at the end of their lifetimes. However, disposing of satellite swarms outside low LEO (Low-Earth Orbit) has no trivial solution which both meets space situational awareness requirements and aligns with the philosophy of space sustainability. The distributed functionality which makes swarm missions so flexible and adaptable also means that many individual swarm agents have to be disposed of at end-of-life, rendering traditional approaches such as migration to the GEO (Geosynchronous Earth Orbit) graveyard orbit problematic. The challenges of disposing satellite swarms are as varied as the environments they could operate in — swarms used for planetary exploration will have to respect planetary protection policies while swarms engaged in Earth observation missions will have to be safely deorbited amidst an increasingly crowded LEO environment. In this paper we explore how the autonomy and distributed nature of swarms both complicates end-of-life disposal and simultaneously enables novel solutions to post-mission disposal. We then survey existing end-of-life scenarios for satellite swarms and propose a novel research approach to swarm disposal that could comply with both legal requirements and the philosophy of space sustainability.

Keywords: (Satellite Swarms, End-of-Life, Space Sustainability, Space Situational Awareness)

Acronyms/Abbreviations

Low Earth Orbit (LEO)
Space Situational Awareness (SSA)
United Nations (UN)
Committee on the Peaceful Uses of Outer Space (COPUOS)
Active Debris Removal (ADR)
Geosynchronous Earth Orbit (GEO)

1. Introduction

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 honeybees or ant colonies, satellite swarms consist of individual satellite agents working cooperatively towards a common goal.

There is as yet no agreed-upon definition of a satellite swarm, however one working definition is as follows: *a satellite swarm is a network of intercommunicating satellites exhibiting complex emergent behavior, collectively operating as a distributed system* [1]. A noteworthy feature of this definition, and one which distinguishes satellite swarms from satellite constellations, is the exhibition of complex emergent behavior. This can be described as the emergence of structure at a system level arising from interactions between its constituent components [2]. A classic —and beautiful— naturally occurring example of emergent behavior is a *murmuration*, the intricately coordinated mass flight of starlings arising from simple interactions between neighboring birds [3]. In the case of satellite swarms, emergent behavior has been proposed as a means for swarms to perform tasks ranging from collision avoidance [4] to high-resolution multi-point measurements [5], and formal methods to verify and validate the emergent behavior of swarm missions have been proposed [6].

Purpose	Example	Agents	Baseline	Environment
Radio Astronomy	OLFAR	≥10	100 km	Lunar Orbit
Heliophysics	APIS	40	12,000-48,000 km	Eccentric Earth Orbit
Asteroid Exploration	ANTS	≥1000	—	Asteroid Belt
Arctic Satellite Internet	Arctic Internet of Things	3	—	Low Earth Orbit
Planetary Exploration	VaMEx	—	—	Mars Surface

Table 1: A Summary of Planned or Proposed Satellite Swarm Missions. A selection of proposed satellite swarm missions is presented, with their purpose, environment, number of agents and probable baseline — the separation between swarm agents.

Alongside the emerging interest in novel satellite architectures such as satellite swarms, there is also a growing awareness of the need for sustainable space exploration, as evidenced by the UN's COPUOS's adoption of the *Guidelines for the long-term sustainability of outer space activities* in mid-2019 [7]. These guidelines encourage, amongst other recommendations, the investigations of new measures to manage the long-term space debris population as well as the mitigation of risks to the long-term sustainability of space activities.

As well the potential uses of satellite swarms, their potential to increase the debris population in Low Earth Orbit has been noted [8]. The combination of interest in autonomous multi-agent satellite swarms and the clear responsibility to assume a sustainable approach to space exploration raises an interesting question. How should we deal with satellite swarms at the end of their lives?

2. Motivation

The robustness of a satellite swarm lies in the resiliency of the swarm itself, rather than robust individual satellites [9][10]. The difficulty of disposing of a swarm is therefore principally the difficulty of disposing of a large number of individual swarm agents, potentially complicated by unforeseen emergent behavior and the autonomy of the swarm. As discussed later in this paper, a variety of methods to dispose of individual satellites have been proposed, from de-orbiting satellites [11] to passivation and migration to graveyard orbits [12].

We set out to investigate if the key features of satellite swarms—efficiency, adaptability, and scalability [13][14]— can enable novel end-of-life strategies which align with the philosophy of space sustainability.

The remainder of this paper is organized as follows: in section **3**, we present a brief review of proposed satellite swarm missions. In section **4** we present end-of-life strategies for single satellites. In section **5** we state our research questions and how we approached them. Section **6** details our proposed tool to monitor the performance of individual swarm agents, a swarm agent health indicator. Sections **7**, and **8**, present our ongoing investigations and preliminary discussions, respectively. Finally, we outline future work on this subject in section **9**.

3. Satellite Swarm Missions

At present, satellite swarms exist on paper rather than in orbit, with a wide variety of missions having been proposed. The capabilities of satellite swarms have led to a variety of proposed scientific and exploratory applications including asteroid exploration[15], space interferometric arrays in Lunar orbit [16], and planetary exploration [17], and the development of technology demonstration missions is underway [18], and key features of a selection of these proposed missions are presented in Table 1.

Planned satellite swarm technology demonstration missions will take place in Low Earth Orbit (LEO) [18], where the small constituent satellites of a swarm can safely re-enter Earth's atmosphere, burning up in the process. However, LEO is an increasingly crowded environment, already well-served by satellite constellations. Given the competition and growing concerns over space situational awareness, swarms as described by our working definition are unlikely to be adopted in LEO [19].

However, by adopting a more relaxed definition of a satellite swarm as *a network of intercommunicating satellites capable of monitoring one another* we can consider a broader range of example missions in LEO – making our research more widely applicable.

4. Single Satellite End-of-Life

Prior to investigating the end of life of satellite swarms, we briefly summarize the current state of the art for end of life strategies for single satellites, as these are the same mechanisms that will facilitate end of life for individual satellite swarm agents.

The end-of-life mechanism for a single satellite depends on various factors, including its mass, composition, and orbital region. The mass and composition of a satellite are particularly relevant in LEO, as they affect how safely a satellite can be removed from orbit. For example, large Earth observation satellites with optical elements such as heavy lenses have a high probability of producing fragments which survive re-entry into Earth's atmosphere. These fragments pose a danger to people and infrastructure on ground, as such massive LEO satellites should ideally be de-orbited in a controlled manner which results in re-entry over uninhabited regions of the ocean. Specifically, the risk on ground is calculated from factors including the kinetic energy of re-entering fragments and population density — if the probability of a fatal impact is greater than some threshold —10^{-4} in the USA — then a controlled re-entry is required reduce the risk on ground [20]. Smaller satellites such as CubeSats can simply passively re-enter Earth's atmosphere however, safely burning up before reaching the ground.

The Inter-Agency Space Debris Coordination Committee's Space Debris Mitigation Guidelines state that satellites in LEO should be disposed of within 25 years of the end of their mission, and various methods have been suggested to expediate the fiery demise of satellites through atmospheric re-entry. These methods can be active, such as a controlled re-entry through a high-impulse maneuver, or passive, such as devices which increase satellite surface area and consequently atmospheric drag. These passive devices range from sails to inflatable balloons, and have been tested on orbit [21][22]. A further passive deorbit system uses a conductive tether which gathers charge and experiences a electrodynamic force from interactions with Earth's magnetic field [23].

Outside of LEO, satellites can no longer be disposed of in Earth's atmosphere, necessitating a different end-of-life mechanism. In Geosynchronous Earth Orbit (GEO), satellites are migrated to graveyard orbits above the geostationary ring, passivated to remove any stored propellant on-board and to drain all batteries, and finally deactivated so that the satellite cannot charge itself or come online [12]. For satellites and spacecraft which travel further afield, such as planetary science missions, end-of-life scenarios tend to vary. Missions to planetary bodies which must be protected from forward contamination are safely destroyed, such as the Cassini mission [24]. Missions to bodies which are not under the auspices of planetary protection tend to be left *in situ.* Finally, satellites which travel far from the Earth are left adrift, such as the Voyager spacecraft steadily journeying into interstellar space [25].

If the above methods are not successful, or if a satellite fails before it can be disposed of, such as ESA's ENVISAT mission, then the defunct satellite becomes a non-responsive piece of space debris, part of the growing cloud of debris encircling the Earth. Methods to remove defunct satellite and other pieces of debris from orbit — known as Active Debris Removal (ADR)— have been proposed to deal with this problem, but no ADR missions are flying as yet [26]. It is worth nothing that ADR techniques administrated by satellites could potentially be used by a "self-cleaning" swarm to safely dispose of defective swarm agents, but this is an area for further study.

The increasingly crowded debris environment is also relevant for space situational awareness (SSA), which can broadly be defined as the knowledge of our near-space environment [27]. Tracking space debris is one of the key challenges in SSA, and any proposed swarm end of life solutions will have to consider SSA as a fundamental requirement.

5. Research Questions & Approach

With satellite swarms and end-of-life mechanisms now explained in some detail, we are in a position to pose informed questions on deployment agnostic end-of-life strategies for satellite swarms. In this paper, we explore, if not answer, the following questions:

1. **Swarm Degradation**: How can a satellite swarm reliably judge when its performance is too degraded to continue its mission?
2. **Graceful Failure:** How can satellite swarms collectively predict failure of individual swarm agents and pre-empt the resulting disturbance to the mission.
3. **The Endless Swarm:** Can a satellite swarm remain operational by providing it with a steady influx of fresh satellites?

The disposal of individual swarm agents is a promising avenue for future research and, as discussed in the previous section, research into disposing of single satellites is a varied and thriving field. However, our chosen research questions do not depend on the architecture of a swarm — they are equally applicable to a swarm of rovers on a planetary body and to communications satellites in Low Earth Orbit. In this work we therefore pursue *deployment agnostic* solutions

— solutions which are applicable to satellite swarms in general, rather than specific solutions for individual missions. To that end, we focused on strategies relying on prediction and processing instead of actuation.

Such strategies rely on a detailed understanding of the performance and degradation of swarm satellites, which currently requires a long list of satellite parameters to be investigated. The first step towards swarm end of life solutions is to develop a single figure of merit reflecting the performance of a swarm agent — a quantity we refer to as a satellite health indicator. This figure, which is detailed below, combines various factors to provide a convenient metric to state and predict the 'health' of a swarm agent.

6. Satellite Health Indicator

We propose a satellite health failure indicator which allows us to differentiate between factors which are absolutely critical for continued mission operations, and those which simply degrade the performance of a satellite. For example, a heliophysics satellite could have a payload consisting of a suite of instruments, with the failure of any one instrument representing a degradation in performance. However, if the power supply system of the satellite failed then the satellite essentially becomes defunct. The status of any one instrument is a non-critical factor, but a functional power supply is a fundamental, critical factor. These failures are interconnected and can be modelled using approaches such as Markov chains [9]. At this early stage however, we will consider component failures to be unrelated and unconnected.

$$\theta = \prod_{i=1}^{n} w_i^{crit}\ x_i \sum_{j=1}^{m} w_j^{noncrit}\ y_j \qquad \textbf{Equation 1}$$

The equation for the satellite health indicator is denoted by θ, and is expressed as a product n critical factors $\mathrm{x_1 \ldots x_n}$ each with a normalized weighting w_i^{crit}. The sum covers m non-critical factors $\mathrm{y_1 \ldots y_m}$ with respective normalized weights $w_j^{noncrit}$. Each factor is scaled to the range $0 \leq x_i, y_j \leq 1$, with 1 denoting perfect functionality and 0 denoting a hard —or major— failure of the relevant subsystem [28].

In our proposed satellite health indicator, critical factors included as product and non—critical factors as a sum. Any failure in a critical factor is reflected in a total satellite health indicator of 0, whereas failure of a non-critical system simply degrades the health of the satellite.

With the form of the satellite health indicator defined, we now have to define the factors and weightings. We consider a promising first step to be to consider past satellite failures and investigate historically failure-prone subsystems.

In a failure analysis of 156 satellite failures between 1980 and 2005, M. Tafazoli established the most failure-prone subsystems from a sample of 129 satellite [29]. The four most failure-prone subsystems, from most to least failure prone were the Attitude and Orbital Control System (AOCS), Power, Command and Data Handling (CDH), and Telemetry, Tracking, and Command (TTC). We chose to focus on these subsystems as a starting point for the satellite health indicator —a more refined, and possible broader, set of factors remains to be defined.

However, we cannot simply take these four subsystems as factors — each subsystem consists of a variety of components with different criticalities. To take the example of the power subsystem, the loss of a single solar

Table 2: Selected factors for the Satellite Health Indicator. These factors are extrapolated from A Study of on-orbit Satellite Failures [25]. The weighing for each component is proportional to the occurrence of failure in both the component and its parent subsystem.

Subsystem	Subsystem Weighting	Component	Failure Rate	Normalized Weighting	Critical?
AOCS	0.37	Momentum Wheel	0.1	0.07	Yes
		Gyroscope	0.17	0.12	No
		Thrusters	0.24	0.18	Yes
Power	0.31	Solar Arrays	0.49	0.22	No
		Batteries	0.22	0.10	No
CDH & TTC	0.31	Processor	0.26	0.11	Yes
		Antenna	0.17	0.07	Yes
		Transponder	0.14	0.06	No
		Electric circuitry	0.17	0.07	Yes

panel or battery may not catastrophic, but the failure of the satellite harness would result in loss of mission.

To obtain a more usable set of factors, we selected the most failure-prone components of each subsystem and assigned weightings based on the proportion of failures due to that component. The total weighting for each subsystem was proportional to the number of failures caused by that subsystem in the sample of 156 failures. The criticality of each factor was judged on whether a complete failure of the subsystem would necessarily result in mission failure.

These factors are presented in Table 2. This set of factors provides a good starting point for investigation of the satellite health indicator concept and was the starting point for our ongoing investigations. However, the factors considered here are derived from single satellite failures — swarm satellites may well require further factors such as the performance of inter-satellite links.

To take an example of calculating the satellite health indicator, a solar array functioning at 50% capacity would have the following contribution to total θ:

$$\theta_{solarpanel} = w^{noncrit} * y = 0.22 * 0.5 = 0.11$$

Equation 2

With our satellite health indicator defined, our current focus is to refine the satellite health indicator and to use real satellite telemetry to calculate the satellite health indicator. No sensor will provide, for example, the precise percentage health of an Attitude and Orbital Control System Momentum Wheel— such a quantity is not defined, let alone measurable. We therefore need to define a relationship between real telemetry data and the abstract quantities we wish to determine when we calculate the health indicator for an operational satellite.

An appropriate dataset for would be telemetry data from a CubeSat, which would provide a good model for the systems on a simple swarm satellite and will allow us to test the applicability of the satellite health indicator.

Once this has been achieved, we aim to simulate prediction and autonomous optimization based on the satellite health indicator in a toy satellite swarm — leaving us in a position to delve into the research questions we have outlined in this paper.

7. Discussion & Conclusions

In this paper we have detailed the conflict between satellite swarms and the philosophy of space sustainability and outlined a new research direction aiming to resolve this conflict. The satellite health indicator concept provides a single figure-of-merit that could allow satellite swarms to engage in self-aware autonomous end-of-life independent of the configuration of the swarm. Our future work will delve deeper into this topic, test the satellite health indicator on real telemetry data, and apply this concept to our overarching research questions.

8. Future Work

The swarm agent health indicator introduced here is only a first step towards accurate swarm-wide prognostics. Future work will further refine this health indicator. In addition, two research questions we initially considered fell outside the scope of this work as they are not deployment agnostic — they both rely on ADR, an inherently mechanistic research area. These questions are:

- **The Self-cleaning Swarm**: Can ADR methods be coupled with satellite swarms to enable self-cleaning swarms which leave no residue?
- **The Orbit-Cleaning Swarm**: as a logical extension of the previous question, can satellite swarms feasibly be used for active debris removal?

As mentioned in section 6, our immediate goal is to apply the satellite health indicator to real telemetry data from operational missions to test its applicability and fine-tune our choice of factors.

Once we are confident that our formulation is robust and applicable to a real-world setting, we aim to simulate a dataset for a toy swarm and calculate the satellite health indictor for each satellite — we want to ascertain if the satellite health indicator can be used for distributed optimization of the swarm. This will inform our approach to the overriding research questions we have outlined in this paper.

A further avenue for investigation is to incorporate prognostics into the satellite health indicator concept. As is stands, it can be used to observe and monitor a satellite's health — but we are interested in discovering if it can also be used to predict a satellite's future health.

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