On Development of 100-Gram-Class Spacecraft for Swarm Applications

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Abstract—A novel space system architecture is proposed, which would enable 100-g-class spacecraft to be flown as swarms (100 s–1000 s) in low Earth orbit. Swarms of Silicon Wafer Integrated Femtosatellites (SWIFT) present a paradigm-shifting approach to distributed spacecraft development, missions, and applications. Potential applications of SWIFT swarms include sparse aperture arrays and distributed sensor networks. New swarm array configurations are introduced and shown to achieve the effective sparse aperture driven from optical performance metrics. A system cost analysis based on this comparison justifies deploying a large number of femtosatellites for sparse aperture applications. Moreover, this paper discusses promising guidance, control, and navigation methods for swarms of femtosatellites equipped with modest sensing and control capabilities.

Index Terms—Autonomous agents, control systems, distributed control, satellites, space technology.

I. INTRODUCTION

DISTRIBUTED spacecraft systems can deliver a comparable or greater mission capability than monolithic spacecraft, but with significantly enhanced flexibility (adaptability, scalability, evolvability, and maintainability) and robustness (reliability, survivability, and fault tolerance) [1]. In this paper, we introduce a new paradigm-shifting definition of distributed spacecraft technology that could enable flight of swarms of fully capable femtosatellites, as an ultimate form of realizing responsive space that can be made to rapidly react to various forms of uncertainty.

In this paper, “swarm” refers to a collection of hundreds to thousands of spacecraft, whereas “femtosat” implies a 100-g-class spacecraft. There has been significant interest in small spacecraft (e.g., CubeSat [2] and satellites on printed circuit boards or silicon chips [3], [4]). The Silicon Wafer Integrated Femtosatellites (SWIFT) represents a 100-g-class spacecraft capable of six-degree-of-freedom (6-DOF) control, built by novel 3-D silicon wafer fabrication and integration techniques [5]. Each femtosat can be actively controlled in all 6 DOF such that a desirable synergetic behavior emerges from the interactions among spacecraft and between the spacecraft and the environment (see Fig. 1). Potential applications derived from such synergetic behaviors include sparse aperture interferometers, distributed sensors for space weather monitoring, and communication relays.

Femtosat swarms would push the frontier of the existing formation flying spacecraft concepts [6]–[9] by one or two orders of magnitude in two major technological drivers: the enormous number (1000 or more) of spacecraft, compared with the previous two to ten spacecraft formation concepts, and a tiny size and “miniaturized” capability of 100-g-class femtosats. As a result, the feasibility of SWIFT swarms is predicated on two enabling technological developments: 1) fabrication of 100-g-class femtosats and 2) the individual and synergetic guidance, navigation, and control (GN&C) capabilities of femtosats. The synergetic GN&C capabilities of the swarm would permit coordinated maneuvers of femtosats so that the swarm can collectively exhibit or exceed a capability of more complex monolithic space systems. Furthermore, the synergetic GN&C capabilities would drive the practicality of each swarm application and the utility of each swarm configuration. By building on recent technological advances in control, sensing, and wireless networking and breakthroughs in electronic packaging and fabrication, we explore fundamental system-level issues and methodologies that are unique to realizing swarm flight of femtosats. This is the essence of the swarm-centric design process introduced in this paper.

The main contributions of this paper are as follows. First, we present generic, scalable, and adaptable femtosat hardware architectures, based on a 100-g-class wafer-scale spacecraft.
system, including basic spacecraft functionalities and adaptable multifunctionality such as component functional redundancy. Second, we introduce several new synthetic aperture configurations and their cost analysis, which can maximize the benefit of the massively distributed spacecraft architecture. Third, we identify GN&C strategies that are scalable and effective for a large number of spacecraft. In this paper, we challenge conventional thinking that such controlled coordination of thousands of spacecraft is expensive and a massive amount of fuel is needed. Specifically, by studying the high-fidelity physical models of each spacecraft and deriving a collective motion of the swarm, we can indeed design a swarm of 100-g-class femtosats that are capable of forming 3-D shapes in a fuel-efficient manner.

II. OVERVIEW OF THE SWIFT SWARM SYSTEM

A. System Perspectives and Motivation of the Work

The femtosat swarm architecture is motivated by the need for pushing the envelope of flexibility and robustness that can be achieved by distributed spacecraft systems. The status-quo design process always results in increased size and system complexity when faced with technological and programmatic uncertainty. In order to break this trend, we envision a flexible space architecture of a multitude of tiny spacecraft distributed over a certain shape that can be incrementally launched and replaced to cope with uncertainty in demands and technological failures. In other words, each femtosat is becoming an inexpensive “LEGO” block that can comprise a much more complicated space system. In order to articulate cost benefits of the femtosat swarm architecture, we will present a parametric cost analysis on the sparse sensing application in Section IV.

One crucial advantage of SWIFT swarms is a dramatically reduced level of risk associated with technical faults of a single spacecraft or a subset of the swarm. Because of the distributed nature of the swarm architecture, propagation of a single failure to the whole swarm can be prevented by simply retiring the faulty units from the swarm system. The two important aspects of reducing the system cost are breaking the scaling law of manufacturing a complex monolithic system, presented in Section IV, and cost reduction from learning curve effects [10]. The reduced spacecraft cost permits anomalous femtosats to be discarded and replaced gracefully without degrading the overall system performance. If the propellant usage is not uniform across femtosats in some desired swarm configurations, we can easily redistribute the femtosats so that each femtosat maintains the same level of ΔV.1 This way, each spacecraft lifetime can be maximized. Reconfiguration of the swarm formation can also enable upgrading of the functionality of the entire swarm system whenever more advanced femtosats are available (e.g., recall Moore’s law [11], particularly since the SWIFT design relies on semiconductor technology).

B. Baseline Functional Design of Femtosats

Fig. 2 shows two femtosat designs that use two different propulsion systems. The femtosat measures 4 × 4 × 4.25 cm. (a) Digital microthruster system (total power = 1.6 W, and total mass = 95.5 g). (b) Miniaturized warm gas hydrazine system (total power = 1.7 W, and total mass = 104.7 g).

### TABLE I: KEY SUBSYSTEM(599,626),(889,729)(599,626),(889,729)

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Femtosat Configuration</th>
<th>Note</th>
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<tbody>
<tr>
<td>Communication coverage</td>
<td>within swarm (&lt;1 km)</td>
<td>ground link (&lt;1,000 km)</td>
</tr>
<tr>
<td>Attitude sensors</td>
<td>accuracy (0.1 deg)</td>
<td>(&lt;15 deg/hr) for gyro</td>
</tr>
<tr>
<td>Position &amp; ranging</td>
<td>GPS (&lt;10 m [95%]); RFID (&lt;1 m); RF-based (&lt;10 m)</td>
<td></td>
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<tr>
<td>Power generation</td>
<td>power generation (4 W)</td>
<td></td>
</tr>
<tr>
<td>Propulsion</td>
<td>$I_p \geq 100$ s; $\Delta V = 24$ m/s for three months</td>
<td></td>
</tr>
<tr>
<td>Command &amp; data</td>
<td>processor (&gt;8 MIPS) and memory (&gt; 32 kB)</td>
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1 ΔV (in m/s) is a measure of control effort and propellant usage needed to transfer from one orbital trajectory to another.
Chip-level integration along with an adaptation of MCM process offers advantages of increased modularity and low power consumption. In addition, chip-level integration enables efficient thermal management and radiation shielding. We will explore a 3-D integration technique that is attractive from the point of decreasing the overall spacecraft size by increasing the component density. The 3-D integration technique, while can be a highly customized approach, can enable sophisticated spacecraft designs because of 3-D packaging similar to Microscopic Integrated Processing Technology [12]. This can make the packaging multifunctional in that not only does the topology serve as a substrate to run solid state wiring but can also function as a radiation shield and a heat dissipator. Our current effort is focusing on these two techniques to identify technology gaps. The feasibility of new femtosat designs is being explored by using the fabrication and integration techniques outlined above.

Generation of a component trade space is an iterative process. This is undertaken to first establish the baseline of available components for a 100-g-class spacecraft. Furthermore, this matrix of a tradespace will help identify areas of technology development in components and subsystems suitable for a femtosat. The starting criterion is to collect all possible COTS components that have been considered for small spacecraft (1 kg or less). Those components whose masses are greater than 100 g are eliminated from consideration. Components that are not space qualified can be included if their mass, functional capability, and power consumption are highly desirable for a femtosat. Such information immediately shows the technology development areas (e.g., miniature transceivers), as well as future space qualification issues.

Packaging is the glue that brings the subsystems together. Generally, satellites are integrated and interconnected from physically separate subsystems. Through state-of-the-art technologies, electronics can be embedded in a modular fashion to function as a structure, a passive radiator, a radiation shield, an instrument sensor, and/or a mechanical device, eventually resulting in a system on chip containing all subsystem electronics into one module.

Critical packaging factors in consideration include the following: 1) mission life versus disposable spacecraft attributes; 2) test and reworkability (modularity versus integration levels); 3) power and thermal environment (temperature and radiation); 4) instrument electromechanical integration; and 5) emerging technologies (cost) versus mature technologies (mass). The goal is to establish a robust subsystem connectivity for chip integration. We are also considering a foldable/flexible interconnection technology and multifunctional microelectromechanical systems (MEMS)-based structure technologies. The challenges to be overcome include improved reliability based on miniaturization, input/output interfaces (signal and power in–out) capabilities, and semiconductor fabrication techniques that enable such wafer- and chip-level integration.

2) Communication: Within the swarm, a COTS part such as the XBee Pro series 2.4-GHz communication chip with a built-in antenna is suitable. This has a range of 1 km that covers the range required for swarm dimensions under consideration. For ground links, there is no lightweight/low-power COTS communication component with a range of 700–900 km as required for ground link that can be mounted on a femtosat. Hence, this is a technology development area. Swarm configurations that allow a ground link from a mothercraft that can house a heavier high-power communication module can be conceived. This may restrict the communication to serial data transfer and swarm operation.

3) Attitude Sensors/Actuators and Power System: The most suitable attitude sensing option is a Sun sensor. The JPL Sun sensor [13] is conducive to monolithic integration with the femtosat body. It weighs ~1 g with a package and consumes ~25 mW. It can be multifunctional, acting also as a range finder in a swarm through triangulation. Among COTS components, there are three-axis inertial measurement units from Invensense and Analog Devices that can be used as support sensors. Star cameras based on backside-illuminated delta-doped complementary metal–oxide–semiconductor imagers are attractive both for attitude sensing and functioning as imaging payloads. For attitude control options, passive attitude control techniques (magnetic and hysteresis) are lightweight and require no external power source, but they are too slow to respond for some applications. Although MEMS reaction wheels are an attractive option, custom-fabricated monolithic wheels provide too little torque \((10^{-9}–10^{-10} \text{ N·m})\). However, COTS cell phone vibration motors are suitable, providing \(2 \times 10^{-5} \text{ N·m}\).

For position sensing, COTS Global Positioning System (GPS) sensors are the best option. Since space-qualified GPS modules are too heavy (~30% of the femtosat mass), other civilian versions are suitable from the accuracy point of view, but require radiation hardening and space-suitable software upgrade. Hence, a reliable lightweight GPS sensor is a technology development area. For a power system, COTS solar cells are the most suitable, which can generate 135 mW/cm². Typical requirements for femtosats are in the 3- to 4-W range (<30 cm²). Li-ion rechargeable batteries operate in the temperature range identified (−20 °C to +80 °C), and custom fabrication may be required to suit the femtosat form factor.

4) Propulsion: The GN&C requirements on propulsion for a swarm operation result in higher \(I_{sp}\) options, where specific impulse, i.e., \(I_{sp}\), indicates the efficiency of a propulsion system in terms of thrust force with respect to the amount of propellant used per unit time. Passive propulsion options such as Lorentz and solar sail techniques [3] do not offer the response speed and the control resolution required. Suitable candidates for a femtosat are the following: 1) electrospray thrusters using indium or ionic liquid propellants; 2) miniaturized hydrazine warm gas thrusters [14]; and 3) digital microthrusters [15]. Some of these propulsion options were integrated to yield a 100-g-class functional design of a femtosat, as shown in Fig. 2. Except for digital microthrusters, all thruster options require a significant technology development, although they are highly capable options. Digital microthrusters are attractive, but are for one-shot use only with a limited lifetime. Miniature hydrazine thrusters require a cleverly designed microvalve arrangement that can make them power hungry and bulky, resulting in a technology development area. Electrospray thrusters also need a technology development in miniaturized heaters and high-voltage power supplies. In essence, there exists no propulsion system option that meets all of the requirements for a complete thruster system that might consist of up to 16 thrusters. Two thrust levels are desirable with an order of magnitude range. A higher thrust level is required to position the spacecraft, i.e., ~100 \(\mu\text{N}\), whereas a lower thrust level is required for station
keeping, i.e., \( \sim 10 \) \( \mu \)N. The total mass of a propulsion system should be limited to 40 g (see Table I for other requirements).

III. DYNAMICS AND CONTROL OF SWARMS OF FEMTOSATELLITES

The GN&C technologies should simultaneously address the following: 1) such an enormous number of spacecraft in swarms; 2) relatively modest control, sensing, and communication capabilities of femtosats; and 3) the complex 6-DOF motions governed by Earth’s gravity field and various disturbances and their impact on coupled motions or swarm behaviors. In particular, the latter distinguishes the SWIFT swarm from other robotic networks. Here, we present the GN&C strategies that use a wide range of spatial and temporal scales of the spacecraft swarm dynamics by quantifying their dispersion and collision rates.

A. Swarm Orbital Dynamics Under \( J_2 \) and Atmospheric Drag

The stringent limitations of femtosat propulsion systems and sensor/actuators necessitate the use of the accurate set of nonlinear equations of motion for the purpose of high-fidelity modeling, simulation, and development of GN&C algorithms. For example, dominant perturbations in low Earth orbit (LEO) such as \( J_2 \) effects due to Earth’s oblateness [16], [17] and atmospheric drag have to be considered to predict open- and closed-loop swarm spacecraft motions. The Hill–Clohessy–Wiltshire (HCW) equation cannot be used for high-fidelity modeling and simulation due to its assumptions on linearization, circular orbit, and no perturbation. The high-fidelity nonlinear dynamic models for the reference (chief) and relative motions with both the \( J_2 \) perturbation and the atmospheric drag were presented by either hybrid states [16] or the classical orbital parameters [18], based on [19]. We present some key attributes of swarm dynamics based on these new models.

The relative motion of a large number of deputy spacecraft (100 s–1000 s) on concentric passive relative orbits (PROs) can be the most conveniently described in the same local vertical/local horizontal (LVLH) frame (see Fig. 3). In contrast, relative mean orbital elements [20] cannot be used for a large number of spacecraft. The origin of the LVLH frame represents either the location of a real chief spacecraft or a virtual chief orbit defined in the Earth-centered inertial (ECI) frame. The orbital parameters (\( \mathbf{\omega}(t) \)) vary over time due to perturbations, notably \( J_2 \) and atmospheric drag in lower LEO (altitude \( \leq 1000 \) km), unless the motion of the chief spacecraft is perfectly controlled to be a Keplerian orbit, whose first five of the six orbital elements (semimajor axis \( a \), eccentricity \( e \), inclination \( i \), right ascension of the ascending node \( \Omega \), argument of periapsis \( \omega \), and true anomaly \( \nu \)) are constant. Having the fixed orbital parameters of the chief spacecraft might have negative implications for fuel usage, as discussed in Section III-E. The chief orbital motion of the chief spacecraft (or the virtual chief orbit) is derived by Gauss’s variational equations [16], i.e.,

\[
\mathbf{\dot{\omega}} = f(\mathbf{\omega}) + g(\mathbf{\omega})\mathbf{u}_{\text{chief}}(t).
\]

The orbital element vector \( \mathbf{\omega} \) could use a hybrid representation such as \( \mathbf{\omega} = (r, v_r, h, \Omega, i, \theta)^T \), where \( r, v_r, h, \) and \( \theta \) denote the geocentric distance, the radial velocity, the angular momentum magnitude, and the argument of latitude, respectively. Note that \( r = v_r \) and \( \theta = \omega + \nu \). Because of the effects of \( J_2 \) and air drag, the elements of \( f(\mathbf{\omega}) \) determine the rate of change of \( \mathbf{\omega} \), whereas \( g(\mathbf{\omega}) \) maps the three-axis control input \( \mathbf{u}_{\text{chief}} \) into the six-element orbital states \( \mathbf{\omega} \) if the chief spacecraft is controlled. By using (1), we can keep track of the time-varying orbital parameters of the chief orbit. A decision should be made as to which definition of states can reduce the computational burden of the state estimators and the control and guidance algorithms.

The relative motion of the \( j \)th spacecraft with respect to the chief orbital motion given in (1) can be derived as follows [16]:

\[
\dot{x}_j = f_r(x_j, x, \mathbf{\omega}, \dot{\mathbf{\omega}}, \mathbf{u}_j)
\]

where the position \( x_j = (x_j, y_j, z_j)^T \) in the LVLH frame denotes the radial, along-track, and cross-track motions, as shown in Fig. 3, and \( \mathbf{u}_j \) denotes the control input [e.g., see (6)]. Based on (1) and (2) and the attitude dynamics of each spacecraft, we can develop GN&C algorithms that achieve a desired swarm configuration as discussed in Section III-D. In addition, note that \( \mathbf{\omega}(t) \) from (1) enters (2) as time-varying parameters, thereby indicating a hierarchical connection between (1) and (2). For example, the trajectory of the chief orbital motion \( \mathbf{\omega}(t) \) needs to be known to each deputy spacecraft if its control algorithm uses (2). Any controller ignoring time-varying \( \mathbf{\omega}(t) \) is regarded as a controller based on approximate models. This also leads to a state estimation problem of both \( \mathbf{\omega} \) and \( x_j \), as shall be further discussed in Section III-E. We first show results of simulation that quantify the swarm dispersion and collision rate of some useful configuration shapes that can drive the GN&C problems.

B. Swarm Geometric Configurations

Simulation of uncontrolled motions of spacecraft \( \mathbf{u}_{\text{chief}} = 0, \mathbf{u}_j = 0 \) in (1) and (2), initially distributed by a Gaussian distribution, results in fast dispersing unbounded motions primarily along the along-track direction (see Fig. 4). For an initial
Gaussian distribution of spacecraft with $\sigma = 0.5$ km in the 500-km LEO orbit, the average dispersion rate is roughly 8 km per orbit (see Table II). This dispersion is primarily driven by the discrepancy in the energy of each orbit. In other words, each spacecraft is on a different orbit, hence with a different orbital rate, and quickly drifts with respect to one another. In such space, perturbations possess a periodic solution that forms an ellipse in the projected $x$–$y$ plane of LVLH (see Fig. 3). The sufficient and necessary condition for the linear relative equation to have concentric PROs is that the center of the PRO should be at the origin of the LVLH frame, i.e.,

$$\dot{y}_{\text{PRO}} = -2n x_{\text{PRO}}, \quad \dot{x}_{\text{PRO}} = n y_{\text{PRO}} / 2$$

where the first condition results in a bounded elliptical orbit with the orbital rate $n$ in the LVLH frame.

This is a special case of matching the period (orbital rate) of multiple spacecraft in close proximity on a circular orbit. The second condition, which forces the $y$-center of the PRO to zero, is essential in reducing the collision rate of the swarm significantly. By using (3), we can find impulsive $\Delta V$ burns, $\dot{x}_j$ and $\dot{y}_j$ in terms of the current position $x_j$ and $y_j$. Since (3) works only under the assumption of the linear HCW equations, a complete generalization of constructing concentric ellipses by using the exact nonlinear dynamic model in the presence of $J_2$ is presented in [16].

C. $J_2$-Invariant PROs and Bounded Swarm

One important result is the construction of $J_2$-invariant PROs in LEO. In contrast with prior work [17], [20], [21], which uses mean orbital elements for constructing $J_2$-invariant chief orbits, a large number of spacecraft on multiple $J_2$-invariant concentric PROs can be considered only by using the relative dynamics described with respect to the single chief motion of the LVLH frame, given in (1) and (2). We refer the readers to Morgan et al. [16] for details. In essence, we can inflate the orbital rate $n$ of (3), thereby matching the energy of each $j$th orbit with $J_2$ effects as follows:

$$\frac{\| \mathbf{V}_j \|^2}{2} + U_j = \frac{\| \mathbf{V}_{\text{chief}} \|^2}{2} + U_{\text{chief}}$$

where the vector $\mathbf{V}$ with each subscript indicates the velocity vector in the inertial frame, and $U$ indicates the potential energy with $J_2$ effects given in [16].

The $J_2$-invariant periodic relative orbit is determined for any initial position in the LVLH frame, i.e., $x_{\text{PRO}} = (x_{\text{PRO}}, y_{\text{PRO}}, z_{\text{PRO}})^T$, by applying the energy-matching method (4) after correcting for the directional change of the gravity gradient vector caused by the $J_2$ disturbance and $J_2$-perturbed cross-track motions. This results in many deputies that are energy matched as though there were no $J_2$, similar to the PRO solution of the HCW equation (3) as follows:

$$x_{\text{PRO}} = \mathcal{Y}(x_{\text{PRO}}, \mathbf{e})$$

where the exact definition of the function $\mathcal{Y}$ can be found in [16]. We can achieve substantially fewer collisions and less drift by using (5), as shown in Table II, whereas the fuel usage is comparable with the linear period-matched swarm by using (3). Furthermore, a multiple-burn guidance method [16] turns out to be very effective in preventing collisions for hundreds of orbits under both $J_2$ and atmospheric drag perturbations. The proposed $J_2$-invariant PROs constructed by nonlinear energy matching (5) yield a drift rate of 7.6 mm per orbit and no collision for more than 500 orbits if they are reasonably separated at time zero. If the desired trajectory of each controlled femtosat is defined by a concentric PRO, then the controlled configuration is called a bounded swarm. If each concentric PRO has different tip–tilt angles, then, basically, a group of multiple concentric PROs form a 3-D ellipsoid shape. However, if each concentric PRO has the same tip–tilt angle, then the configuration resembling a disk is called a 2-D ellipsoid structure. As shown in Table II, it takes about $\Delta V$ of 0.02 m/s per orbit to maintain a bounded swarm structure defined by multiple concentric PROs. It is found that a higher level of $\Delta V$ is required for tilted PROs than in-plane PROs ($\gamma_{\text{max}} = 0\degree$). However, it takes more propellant to drive the swarm to structured configurations (e.g., 2-D disks) than just to slow dispersion by (5). It is intuitive to think that an elliptical chief orbit requires much larger $\Delta V$ since PROs are derived on the assumption of a circular orbit. In addition, in LEO, the inclination of $i = 45\degree$ of the chief orbit yielded a smaller requirement on $\Delta V$ than a circular orbit with $i = 0\degree$. Optimizing concentric fuel-efficient PROs on highly elliptical chief orbits in the presence of $J_2$ and other disturbances is an important area of research.
D. Guidance and Control Challenges of Swarm Flight

The success of coordination of femtosat swarm flight hinges on the efficient GN&C algorithms that are scalable to a very large number of femtosats. Efficient algorithms here connote both computational efficiency and optimal propellant usage. For a specific swarm application and mission scenario, the guidance and control tasks of swarms of femtosats can be divided into initial swarm deployment and distribution, swarm behavior specification and planning, swarm keeping or containment, swarm reconfiguration or resizing, passive or active collision avoidance, and fault detection isolation and recovery. For each task, the efficient guidance and control algorithms are responsible for control, coordination, and trajectory planning of femtosats by using either centralized or decentralized strategies. Here, we present possible solutions to critical challenges posed by a large number of femtosats (100 s–1000 s) operating in LEO.

1) Fuel-Efficient Algorithms With Highly Nonlinear Dynamics: One challenge unique to the spacecraft swarm is to meet the optimal and robust performance requirement of the desired swarm behaviors governed by both the highly nonlinear orbital dynamics and the attitude dynamics. The relatively modest control, sensing, communication, and computation capabilities of femtosats will further complicate the complexity of the GN&C problems.

When we derive the GN&C algorithms and conduct verification and validation (V&V), we should consider the highly nonlinear coupled time-varying dynamics with various environmental, sensor, actuator, and communication uncertainties.

The attitude control of a rigid body model of the fully 6-DOF capable femtosat is also important, particularly for the synthetic aperture application considered in this paper. A unified synchronization control framework of highly nonlinear attitude dynamic models and relative orbital motions can be employed [24], [25]. A capability of synchronized rotation [26], [25] can integrate attitude control with control of the orbital dynamics on concentric PROs. In addition, due to the modest actuation capability of a femtosat, control of coupled underactuated spacecraft [27]–[29] can be exploited.

2) Decentralized Feedback Control and Synchronization: Fully centralized GN&C algorithms for a large swarm of femtosats result in significant computation and communication requirements. Consequently, decentralized algorithms should be considered, whereas their performance and robustness issues should be verified in comparison with fully decentralized approaches. The decentralized guidance and control approaches provide several advantages that include the following: 1) scalability and algorithmic simplicity; 2) higher accuracy and efficiency with a larger number of femtosats; 3) robustness to individual spacecraft failures; and 4) minimal onboard computational requirements.

One strategy to overcome such complex large-scale networks is to exploit hierarchical synchronization of multiple heterogeneous groups with multiple leaders such that two different types of coupling, such as diffusive coupling with neighbors and leader–follower couplings, are simultaneously employed [24]. This can be a generalization of the leader–follower architecture for a smaller number of spacecraft [26] and typical consensus (diffusive) network couplings [25], [31]. In contrast with other multiagent systems, the femtosat swarm architecture may necessitate different types of leaders. The chief spacecraft defines the origin of the local LVLH frame for a group of femtosats on the same reference (chief) orbit $\omega(t)$, as shown in Fig. 3. On the other hand, the leader spacecraft, which is different from the chief spacecraft, defines the desired trajectory that other femtosats can follow. Concurrent synchronization [24], [32] is defined as a regime where the ensemble of dynamical elements is divided into multiple groups of fully synchronized elements, but elements from different groups are not necessarily synchronized and can exhibit entirely different dynamics. By combining leader–follower connections and local neighbor couplings, the networks are neither strongly connected nor balanced due to the reference input couplings. For example, the concurrent synchronization controller for the $j$th femtosat dynamic model in (2) with respect to the chief motion $\omega(t)$ governed by (1) can be considered for tracking a desired trajectory defined by a physical or a virtual leader spacecraft, $x_{\text{leader}}$ [30] for the details), i.e.,

$$u_j = a_\epsilon(x_j, x_j, \omega, s_j, t) - \sum_{k \in N_j} [c_j(s_j, t) - R(\phi_{jk})c_k(s_k, t)]$$

(6)

where $N_j$ denotes the set of neighboring femtosats, and $s_j = (x_j - R(\phi_{jl})x_{\text{leader}}) + \lambda(x_j - R(\phi_{jl})x_{\text{leader}})$ with a positive gain $\lambda$. This is a generalization of a linear consensus control law of the form $(s_j - s_k)$ by using both the nonlinear feedback function $a_\epsilon(\cdot)$ and the nonlinear coupling function $c_j(\cdot)$ along with a phase rotation $R(\phi_{jk})$ between the $j$th and $k$th femtosats on the periodic relative orbits. A phase-rotating transformation function can be found for $J_2$-invariant elliptical orbits in three dimensions by setting $x_{\text{PHO}} = x_{\text{leader}}$ in (5) [30]. A phase synchronization technique for spacecraft was first introduced in [25] and [30] and more generally for artificial neural oscillators in [33]. In contrast with a completely uncoupled controller for each femtosat (e.g., (6) without the coupling term $R(\phi_{jk})c_k(s_k, t)$), the concurrent synchronization controller in (6) would enhance the reconfigurability of the network, by commanding a selected set of leader spacecraft and having other members of the femtosats follow the leaders. Furthermore, in the presence of external disturbances, the synchronization control is shown to yield smaller synchronization errors than tracking errors [30], i.e.,

$$\lim_{t \to \infty} \|x_j - \mathcal{E}(x_k, \phi_{jk})\| < \lim_{t \to \infty} \|x_j - \mathcal{E}(x_{\text{leader}}, \phi_{jl})\| \leq \Delta$$

(7)

where $\exists \Delta > 0$, and $\mathcal{E}(x_k, \phi_{jk})$ rotates the position of a neighbor $(x_k)$ by the angle $\phi_{jk}$. In other words, maintaining a formation shape takes precedence over following the desired trajectory of a leader motion in the sense of (7). See [30] for rigorous proofs of (7) and establishing connection between nonlinear stability tools for networked systems such as contraction-based incremental stability, passivity, input-to-state stability, and finite-gain $L_p$ stability.

Another strategy to deal with network complexity is to use adaptive graph Laplacians [18], [30] that can be varied by an adaptive control law for the coupling gains in $c_j$ and $c_k$ of (6) based on the relative distances and synchronization errors. A time-varying and switching network topology, constructed by the adaptive graph Laplacian matrix, relaxes the standard...
requirement of consensus stability, even permitting exponential stabilization on an unbalanced digraph or a weakly connected digraph that can sporadically lose connectivity.

3) Decentralized Optimal Guidance and Probabilistic Swarm Guidance: While deploying multiple computation leaders is possible, it is also feasible to put a powerful processor on each femtosat, leveraging the rapid advances in the semiconductor technology (cf., multicore processors used for smartphones). As the number of agents greatly increases, an optimal control and path planning strategy should be decentralized to remain a tractable problem. Popular optimization-based methods for real-time multivehicle guidance [22] include sequential convex programming (SCP) [34], [35], linear programming [23], and mixed-integer linear programming [36], which can be also formulated as model predictive control (MPC). In particular, a decentralized MPC-SCP algorithm [35] has been derived, which provide optimal collision-free motions for thousands of spacecraft transferring between multiple PROs. Decentralization in real-time guidance can be realized by using decentralized onboard computation, intersatellite communication, and relative sensing.

It is clear that (6), which uses (5) as \( x_{\text{leader}} \) of a desired PRO, establishes a robust coupling feedback controller for tracking and stabilizing around the target \( J_2 \)-invariant PROs. If the femtosats have to follow collision-free reconfiguration trajectories connecting between the initial and target PROs, we can exploit the collision-free characteristics of phased-synchronized spacecraft following \( J_2 \)-invariant concentric PROs by using (6), thereby driving each femtosat to a target PRO in a sequential manner by selecting only one departing location in the initial PRO. On the other hand, in order to compute multiple collision-free fuel-optimal trajectories for simultaneous reconfiguration maneuvers between multiple pairs of initial and target PROs, we can first find an optimal mapping function that finds the optimal target location \( \phi \) in the target PRO for each initial location \( \theta \) in the initial PRO. After we find an optimal mapping or assignment function \( \phi = F(\theta) \), we can solve a decentralized optimal guidance problem using those pairs of initial/terminal constraints to compute desired trajectories connecting between the initial and target PROs. The decentralized MPC-SCP algorithm [35] has been successfully applied to the optimal guidance problem of reconfiguring hundreds of spacecraft using the high-fidelity dynamics in (1) and (2).

Another novel idea of handling a large number of femtosats in the swarm is to employ a probabilistic approach of designing a Markov chain that allows each spacecraft to determine its own trajectory in a statistically independent manner. One benefit of probabilistic swarm guidance (PSG) [5], [37] is that the swarm converges to the desired formation with an ability to automatically repair the formation if it is damaged. Recently, an inhomogeneous Markov chain approach to PSG has been proposed in order to minimize the number of transitions required for achieving the desired formation shape and to account for necessary motion constraints [37].

E. Navigation and Estimation for Swarm Flight

The estimation problem for the spacecraft dynamics given in (1) and (2) presents three main challenges: 1) scalability to a large network; 2) integrated intersatellite communication and relative sensing; and 3) nonlinearity of the dynamics and measurement equations. The control methods suggested in Section III-D can be further developed to deal with the issues of scalability and dimensionality of the estimation problem as well. The estimation algorithms for the chief orbit \( \omega(t) \) and relative states \( x_j(t) \) can be formulated for each femtosat by using (1) and (2). Depending on the guidance and control algorithms, each femtosat may need to estimate the states of neighboring femtosats (e.g., the synchronization control law needs estimates of neighbors). How to define coordinate frames for both inertial and relative states will affect computational burden and accuracy of the estimation algorithms given a sensor suite available for each femtosat. The accuracy of state information is critical in computing the desired control inputs [e.g., for impulsive controls in (3) or (5) and closed-loop control in (6)].

For example, notice in (1) that the state information of the chief orbital parameters \( \omega(t) \) is required in order for each spacecraft in the swarm to accurately estimate its own relative states \( x_j(t) \). The easiest method is to assume that \( \omega(t) \) follows a Keplerian orbit, which is inaccurate in the presence of disturbances such as \( J_2 \) and atmospheric drag. Then, relative state estimation with respect to this inaccurately frozen chief orbit would incur more fuel usage for femtosats to fight perturbations. Consequently, each femtosat should propagate the exact chief orbit dynamics (1) by onboard computation, thereby reducing fuel usage since femtosats need not fire thrusters to fight the \( J_2 \) drift of the chief orbit. Such a numerical integration process corresponds to a propagation step for estimation of the chief orbit. A crosslink or relative sensing between the chief spacecraft and the deputy spacecraft can form a measurement model to complete the estimator design for the chief orbit \( \omega(t) \). The mothercraft or the chief spacecraft can house a high-power communication module that can be used to broadcast the chief (reference) orbital parameters to swarm femtosats. Alternatively, as discussed in Section III-D, we can envision having multiple leader spacecraft that are more enhanced in terms of computational power and communication range. The leader or the chief spacecraft communicate either their GPS pseudorange measurements or filtered coordinate states \( \omega(t) \) and may rely on some intermediate communication relays for a large-scale swarm. The challenge is that each spacecraft needs to know the common value of \( \omega(t) \) at each time step despite potential communication errors and delays. A separate consensus-based estimator [38], [39] can simultaneously estimate the common state of the leader spacecraft to reduce the discrepancy among the \( \omega(t) \) estimates. In addition, decentralized observers can estimate their own relative position and that of a neighboring femtosat in the common LVLH frame by using (2). Most distributed estimation algorithms [38], [40] are predicated on the use of communication links, whereas swarm flight of spacecraft may involve relative sensing [41]–[43] such as range and relative bearing measurements in three dimensions.

IV. SPARSE APERTURE APPLICATION AND PERFORMANCE-COST ANALYSIS

A key application of swarms of spacecraft is sparse aperture sensing or stellar interferometry. The swarm dynamics modeling and swarm GN&C technologies described in
Section III would enable swarm keeping and reconfiguration of a large number of apertures in LEO to realize synthetic aperture arrays composed of femtosats. For example, we can find a transformation between the 3-D PRO and a circular projected plane that is normal to the target line-of-sight vector. For observing Earth’s surface, $z_{\text{max}}$ in the LVLH frame can be set equal to the semimajor axis of the PRO projected in the $x-y$ plane so that a circular projected orbit can be obtained in the $y-z$ plane. Enabled by the GN&C strategies described in Section III, we introduce new swarm configuration arrays that can be constructed on projected circular relative orbits. By employing the interferometric imaging metrics, we also present a unique performance and cost analysis that illustrates the cost benefits of the femtosat swarm architecture. A comparative configuration–cost analysis is presented next.

A. Random Sparse Aperture Arrays and Performance Analysis

We can spread out radar or optical telescopes with an aim to achieve a resolution that is comparable with a large monolithic aperture. Because of the stringent requirement on interferometric beam combination [44], that is, the beams should be combined within a fraction of wavelength, telescopes for longer wavelengths, such as radio or submillimeter wavelengths, appear to be a more promising application of sparse aperture sensing for the SWIFT swarm.

Three possible swarm configurations are considered depending on the distribution characteristic of femtosats, as shown in Fig. 5. Previously, random arrays have been studied for communication relay [45], antennas [46], and space-based radars [47]. All the configurations are assumed to be on a projected circular plane. As discussed in Section III, the PROs of femtosats in the relative orbital frame can be of any arbitrary orientation such that the projected plane is always circular and normal to the line of sight [see Fig. 1(b)].

In a Gaussian Random array shown in Fig. 5(a), the locations of femtosats on the projected circular plane follow the Gaussian distribution with a variance of $\sigma^2$. On the other hand, each spacecraft in a Structured Disk array is distributed with a prescribed radial and angular separation, thereby ensuring a certain separation distance between spacecraft. This can be interpreted in the sense of the discrete uniform distribution. This array can be also randomly slightly perturbed due to sensor and control errors of each femtosat, as shown in Fig. 5(c). The third configuration, shown in Fig. 5(e), is called a Uniform Disk array, since femtosats are spread by the continuous uniform distribution. In contrast with the Gaussian Random Array, we can prescribe the maximum radius of the array for both Structured and Uniform Disk arrays.

The angular resolution is determined by the Rayleigh’s criterion $\theta_r = 1.22\lambda/D$. For sparse aperture formations, the diameter $D$ of a monolithic aperture for the wavelength $\lambda$ of interest should be replaced by the effective diameter $D_{\text{eff}}$. Then, the central question is how to determine the effective diameter $D_{\text{eff}}$ for instantaneous $u-v$ filling.

Then, the central question is how to determine the effective diameter $\lambda$ of interest should be replaced by the effective diameter $D_{\text{eff}}$. Then, the central question is how to determine the effective diameter $D_{\text{eff}}$ for instantaneous $u-v$ filling is given in (b), (d), and (f). (a) Gaussian Random, $\sigma = 10$ m (blue), $3\sigma = 30$ m (red). (b) MTF of (a), $D_{\text{eff}} = 28$ m. (c) Structured Disk, $L = 20$ m. (d) MTF of (c), $D_{\text{eff}} = 27$ m. (e) Uniform Disk, $L = 20$ m. (f) MTF of (e), $D_{\text{eff}} = 21$ m.

at half-maximum. However, the angular resolution alone is inadequate for many sparse-aperture or interferometric array applications. As elucidated in [44], a better metric to determine $D_{\text{eff}}$ is the modulation transfer function (MTF), which evaluates the contrast (modulation) transfer characteristic of snapshot imaging of extended objects. A 2-D projection of the MTF plot, which is called $u-v$ points, can be determined by taking the autocorrelation points as follows:

$$u = \pm (x_i - x_j)/\lambda, \quad v = \pm (y_i - y_j)/\lambda$$

where $(x_i, y_i)$ and $(x_j, y_j)$ are any possible pair of points within apertures, and $\lambda$ is the wavelength of interest.

In order to properly compare with monolithic filled apertures, we choose to define the effective diameter as the maximum radius of the MTF plots without singular (zero) $u-v$ points. The $D_{\text{eff}}$ of each configuration is denoted by the red circles

The PSF is the squared modulus of the Fourier transform of the complex pupil function. The optical transform function (OTF) is a Fourier transform of the PSF, and the MTF is an absolute value of the OTF.
in Fig. 5(b), (d), and (f). We assume that each femtosat carries a radar aperture of 10 cm in diameter. By determining the array size that yields an instantaneous filled \( u-v \) coverage in the MTF with 500 apertures, the effective diameters for each configuration are computed as 28, 27, and 21 m, respectively. Hence, the Gaussian Random and Structured Disk arrays can achieve a finer angular resolution for an instantaneous full \( u-v \) coverage.

This result does not imply that a sparse aperture array with 500 femtosats can only achieve the effective diameter of 28 m. If we can integrate images for a longer period of time, similar to synthetic aperture radar and very large baseline interferometry, the finest angular resolution achieved by the array is determined by the largest separation distance between the apertures. In other words, \( D_{\text{eff}} \) becomes the maximum separation distance. For example, a swarm of femtosats can be spread over a distance of 1–5 km, thereby yielding a much finer angular resolution. This is technologically feasible since the apertures distributed on the PROs will be rotating with respect to the center of the relative frame, as discussed in Section III. Such a large separation distance can be beneficial for longer wavelengths, since the angular resolution is inversely proportional to the wavelength. However, such a large baseline length will inevitably lead to much sparser \( u-v \) filling with many singular points (zero contrast), thereby decreasing the sensitivity or signal-to-noise ratio. In addition, a noncompact \( u-v \) coverage cannot be used for snapshot imaging. Hence, the array design of sparse apertures is a tradeoff between the angular resolution of a point target and the sensitivity or contrast characteristics of a filled aperture. In order to properly compare with a fully filled monolithic aperture, particularly for the cost analysis in Section IV-C, we proceed to use an instantaneous \( u-v \) coverage.

### B. Novel Swarm Golay Arrays and Performance Analysis

By examining the \( u-v \) coverage on the MTF plots, we can find that there are many redundant \( u-v \) points that could have been saved to increase the effective diameter. In this paper, we introduce new random sparse arrays that can further optimize the number of spacecraft needed for a target effective diameter, as shown in Fig. 6. Let us recall an optimal imaging configuration designed for a small number of apertures \((N=3-12)\), proposed by Golay [48]. These arrays are all nonredundant and optimized for compactness in the \( u-v \) plot. Since we can construct a filled \( u-v \) coverage by using the proposed random arrays shown in Fig. 5, a nice extension of Golay arrays is to spread multiple femtosats within the fractionated virtual aperture diameters defined by the original Golay configuration. The proposed Swarm Golay-6, Swarm Golay-9, and Swarm Golay-12 are shown in Fig. 6. The MTF characteristic of a Swarm Golay-3 array turns out to be similar to that of a Gaussian Random or a Structured Disk array; hence, Golay-3 is omitted here. By computing the MTF without discontinuous singular \( u-v \) points, the effective diameter \( D_{\text{eff}} \) is determined, as shown in Fig. 6(b), (d), and (f). By using the same number of femtosats \((N=500)\), the Swarm Golay-9 or the Swarm Golay-12 array achieves much larger effective diameters. Hence, we can further reduce the system mass or cost by utilizing Swarm Golay arrays.

The results from Figs. 5 and 6 are summarized in Fig. 7 for various aperture sizes and numbers. In general, the results are in excellent agreement with prior work [46], indicating that a smaller number of apertures are needed in random arrays. What is new here is that we can further reduce the number of apertures required to achieve a comparable aperture performance (e.g., angular resolution) by employing Swarm Golay configurations. As shown in Fig. 7(a), we can more dramatically improve the angular resolution of the swarm aperture arrays by increasing the number of spacecraft. This result can be viewed as a compelling rationale behind the swarm architecture that employs thousands of femtosats.

For the same number of femtosats, the Golay-12 array achieved a larger effective diameter, followed by the Golay-9, Golay-6, and Gaussian Random arrays. Other information we can extract here is the size of the array needed to achieve the desired \( D_{\text{eff}} \) based on the full \( u-v \) coverage requirement. For example, the Gaussian Random array needs the largest array size, hence possibly imposing more demanding communication requirements. As discussed in Section II-B, the long-distance communication subsystem can drive the system mass and cost. However, in the Swarm Golay arrays, a swarm of femtosats can be divided to 6, 9, or 12 subset groups. As a result, such fractionated grouping can be advantageous in swarm controls and communications.
C. System Cost Analysis

We can hypothesize from Fig. 7 that the 400-m effective diameter constructed from 1200 femtosats can be manufactured at a fraction of the manufacturing cost of an immense monolithic spacecraft carrying a 400-m-diameter telescope, which cannot be launched and built with the currently existing technology. Here, we present an important cost analysis corroborating this dramatic cost saving of the spacecraft swarm architecture.

In order to compare the system cost of building and launching a monolithic aperture with that of sparse aperture arrays presented in the previous section, we modify the NASA Advanced Mission Cost Model [49] by multiplying it with \( \frac{1}{\lambda^{0.5}} \), i.e.,

\[
\text{cost} = \$2.25 \text{ billion} \times \left( \frac{\text{mass}}{10000 \text{ kg}} \right)^{0.654} \times (1.555^{\text{difficulty level}}) \times (N^{-0.406}) \times 1/\sqrt{\lambda} \quad (9)
\]

where \( N \) is the number of flight systems, and the difficulty levels are as follows: \(-2 = \text{very low}, -1 = \text{low}, 0 = \text{average}, 1 = \text{high}, \) and \(2 = \text{very high}\).

The cost model given in (9) computes the cost of a 1-kg CubeSat to be $2 million, which is close to the maximum launch cost of a CubeSat. This model also correctly predicts the project cost of infrared (IR) space telescopes such as the Hubble Space Telescope (HST) and the James Webb Space Telescope (JWST) to be about $4 billion by substituting the mass and the difficulty level (2 for JWST and 1 for HST). However, how can we predict a cost for a large monolithic spaceborne radio telescope? Here, we consider the impact of wavelength of diffraction-limited performance by adding a factor of \( \frac{1}{\lambda^{0.5}} \), where \( \lambda \) is in micrometers. The additional factor \( \lambda^{-0.5} \), which was proposed by Stahl et al. [50], matches the existing cost data of ground-based telescopes well. In a nutshell, this additional factor indicates that a radar space telescope with the wavelength 1 m is 1000 times less expensive than a telescope of 1-\( \mu \)m IR wavelength.

The project cost of a large monolithic space radar can be predicted, as shown in Fig. 8, to be a function of the diameter by assuming that the mass of the telescope is proportional to \( D^2 \). Consequently, the cost of a large monolithic space-based radar is proportional to \( D^{1.308} \). The exponent of 1.308 agrees relatively well with the exponent 1.12 of the space telescope parametric cost model by Stahl [49]. Note that this number is smaller by a factor of 2 than the popular Meinel’s cost model \( D^{2.7} \) for ground telescopes, which includes the cost of telescope mount and dome. The key point here is not the exact amount of the predicted cost but the exponent of the diameter that indicates a cost trend as a function of the diameter size. By identifying such a cost estimation relationship, we can determine significant cost drivers in the design process.

Similarly, we can compute the cost of building a 100-g femtosat from (9). The total cost of a swarm array can be computed by multiplying the number of femtosats required in Fig. 7(a) for a given effective diameter. The result is shown in Fig. 8. As summarized in Table III, we can conclude that the cost exponent of the monolithic aperture is much steeper than that of the proposed swarm array configurations. As a result, we can dramatically save the system cost of launching a large radar aperture by deploying swarms of much smaller apertures. If the cost of fabricating a single femtosat is higher than expected, the...
results shown in Fig. 8 still indicate that there exists a break-even point between a monolithic telescope and a swarm array. In other words, in order to take advantage of the cost savings from the swarm, we need to increase the number of apertures or femtosats. This conclusion justifies the rationale behind a large number of femtosats. In addition, it is expected that the benefits from the swarm architecture are more substantial when we factor in the learning cost saving and risk-reduction effects that are not captured in this cost analysis.

V. Conclusion

The proposed SWIFT project aims to develop hundreds or thousands of small femtosatellites and establish effective swarm GN&C strategies for potential synthetic aperture applications. Based on the functional requirements of components, we presented functional baseline femtosat designs. The successful development of a fully capable 100-g-class femtosat hinges on successful miniaturization of the following: 1) propulsion systems; 2) component multifunctionality or MCMs; and 3) low-mass low-power electronics for long-distance communication. We also introduced new random sparse aperture arrays that can further optimize the number of spacecraft needed for a target effective diameter for an instantaneous imaging purpose. By using the same number of femtosats, the proposed Swarm Golay arrays were shown to achieve much larger effective diameters, thereby implying that we could significantly reduce the system mass or cost by utilizing Swarm Golay arrays. The cost analysis presented in this paper provides a compelling rationale behind the swarm architecture employing thousands of femtosats. The number of femtosats (100 s–1000 s) along with their modest sensing, control, and communication capabilities present new GN&C challenges that have not been addressed in previous studies of formation flying. We explored potential solutions to the dynamic modeling and GN&C challenges associated with femtosat swarms. The femtosat swarm architecture builds on a variety of distributed space systems by further maximizing the degree of distribution at a level of what is technologically feasible. Consequently, the enabling GN&C technologies derived from the femtosat swarm would advance the state of the art in distributed sensing and control of multi-agent systems controlled in three dimensions. Furthermore, the successful implementation of the femtosat swarm architecture would result in a transformative innovation in space systems design, which has been dominated by monolithic spacecraft systems.

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References


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