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Emulating SmallSat Missions with UAVs: Remote Sensing and Formation Flying Testbeds

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With the increasing deployment of small satellite formations for Earth observation and scientific missions, there is a growing need for flexible and low-risk testing platforms to validate remote sensing applications and autonomous formation flying. This research explores the use of Unmanned Aerial Vehicles (UAVs) as terrestrial surrogates for small satellite formations, allowing the development and testing of algorithms, sensing payloads, and coordination strategies in a representative and controlled environment. We discuss recent efforts that use UAVs, such as Crazyflie, to emulate spacecraft dynamics. We highlight the effectiveness of this approach towards the development of advanced formation flying, planning, and control techniques. This research will also introduce the project GLITTER (Gnss-r sateLlITe earTh obsERvation), which investigates the use of GNSS Reflectometry (GNSS-R), an approach that relies on reflected signals from Global Navigation Satellite Systems for Earth observation. GLITTER aims to improve GNSS-R technology by building a synchronized constellation of CubeSats. The project relies on UAV-based testbeds as critical components for validating formation control strategies and antenna beamforming techniques. This research will briefly outline these benefits and key simulation insights, emphasizing how UAVs can accelerate innovation in small satellite mission design. This work demonstrates that the same guidance, autonomy, and sensing algorithms developed for satellites can be evaluated safely, repeatedly, and cost-effectively on Earth by transferring scaled formation geometries generated in Simulink to a UAV testing simulation and validating them through simulation UAV flight tests.

I. Introduction

The use of small satellite formations is growing rapidly, from space exploration and global internet coverage to environmental monitoring, wildfire prediction, and Earth observation [1]. At the European Space Agency (ESA), spacecraft in the 350–700 kg range are referred to as "small satellites," whereas those between 80–350 kg and 50–80 kg are classified as mini- and micro-satellites, respectively [2]. Small satellite missions can be constructed and deployed in very short periods of time and at a much lower cost, significantly enhancing access to space. In the context of small satellite Earth observation missions, these advantages include improved launch vehicle availability and performance, distributed ground station networks for cost-effective data dissemination, and efficient mission management and quality assurance procedures [3]. Formation flying missions involve a group of spatially distributed small satellites capable of autonomous interaction and cooperation to maintain a prescribed configuration [4]. For satellite formations, terrestrial testbeds are used to verify mission requirements that do not depend on actual orbital dynamics. Requirements depending on the latter are difficult to verify on Earth. Recently, terrestrial testbeds have emerged that utilize drones to validate flight and autonomy of spacecraft formations [5] [6] [7]. UAVs are considered lightweight and low-cost platforms. There are a few commonly available UAV platforms that are open-source, allowing for extensive modification of both hardware and software. They can be equipped with various sensors and positioning systems, allowing for versatile experimentation. They are capable of indoor flight, which provides a controlled and disturbance-free environment that enables safe and repeatable emulation of complex small satellite formations, making them an effective and economical tool for testing formation and control algorithms on Earth [8]. UAV testbeds also enable the validation of collision avoidance systems, wildfire monitoring, and precision agriculture applications before space deployment. The testbeds

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employing UAV platforms provide a practical means to perform a range of assessments, including formation geometry, formation tracking performance, satellite error characterization, and remote sensing experiments. Recent efforts, such as those using the Crazyflie platform, demonstrate the advantages of UAVs in the prototyping of satellite missions. Their modular expansion decks allow integration of positioning systems, motion sensors, wireless charging, and AI-driven capabilities [8] [9].

In this paper, we explore the use of UAVs as terrestrial surrogates for small satellite formations, providing a realistic, yet controlled environment to develop and test algorithms, sensing payloads, and mission-critical operations. The main focus lies on showcasing how UAV platforms provide a practical means to perform a range of assessments, including formation geometry and formation tracking performance. As an example of how drones can be used for small satellite formation testing, the study introduces the GLITTER project. GLITTER advances Global Navigation Satellite System Reflectometry (GNSS-R), a remote sensing technique that uses reflected navigation satellite signals from the Earth's surface for environmental monitoring [10]. The project seeks to address the inherently limited spatial resolution of traditional GNSS-R by deploying a synchronized constellation of low-cost small satellites through the use of beamforming and interferometric processing. UAV-based testbeds have been proposed as a means of supporting the development of GLITTER by enabling ground validation of formation control strategies, antenna beamforming, and RF synchronization. The scope of this study is limited to assessing methods for validating formation geometry and tracking. UAVs serve as useful surrogates because they can replicate the relative motion, coordination techniques, and sensing performance that characterize formation-flying Small Satellite missions.

II. Background

A. The GLITTER Project

GLITTER [11] seeks to develop a CubeSat constellation capable of delivering high-resolution GNSS-R measurements, thus advancing a passive remote sensing technique that leverages GNSS signals reflected from the Earth's surface. GNSS-R offers wide spatial and temporal coverage and is inherently low-power and cost-efficient, as it is based on existing GPS and Galileo transmissions rather than active radar systems [12]. Reflected signals encode surface properties such as soil moisture [13], ocean roughness [14], ice thickness [15], and vegetation conditions [16], making GNSS-R an increasingly valuable tool for large-scale environmental monitoring. A central motivation behind GLITTER is the use of coordinated small satellites (see Fig. 1) to overcome the spatial-resolution limitations of traditional GNSS-R systems through interferometric and beamforming techniques applied in multiple CubeSats flying in formation [17]. The adoption of CubeSats, which are cost effective and deployable in clusters [18], makes such constellation based sensing technically feasible and economically attractive.

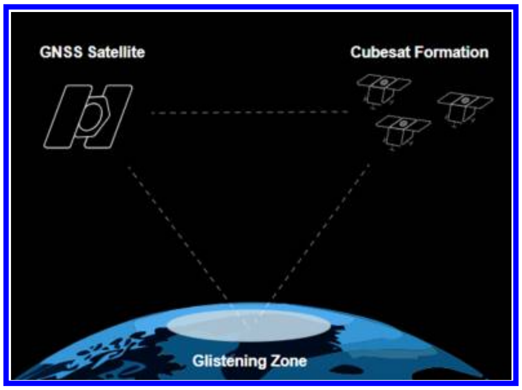


Fig. 1 Schematic of the GNSS-based positioning and navigation architecture for the GLITTER Project [19]

Although the full GNSS-R instrumentation is beyond the scope of this paper, GLITTER provides a relevant contextual example because it relies on precise multi-satellite coordination, synchronization, and formation-flying strategies that can be emulated and validated through UAV-based testbeds. UAV platforms offer a controlled and repeatable environment to assess fundamental formation-flying behaviors, bridging the gap between simulation and eventual space deployment. In this work, we focus specifically on how UAVs can be used to validate formation-state geometry and monitoring performance, demonstrating the broader potential of UAV testbeds to support missions such as GLITTER that depend on accurate relative navigation within distributed satellite systems.

B. Existing Large-Scale Formation Flying Testbeds

NASA's Jet Propulsion Laboratory (JPL) developed a Formation Control Testbed (FCT) consisting of ground-based robots designed to test and validate precise formation flying techniques [20]. In addition to the FCT, JPL also designed a Formation Algorithm Simulation Testbed (FAST) and a Formation Sensor Testbed. The primary goal of the FCT was to evaluate the accuracy of the FAST simulations by comparing the simulated results with the physical motion of the robots. The system was designed for three robots to move in a precise triangular formation, maintaining accurate positions and orientations. To emulate motions under low-gravity conditions to a certain extent, the platform floats on compressed air regulated by tanks, with safety valves that prevent overpressure [20].

Another such testbed is the SPHERES (Synchronized Position Hold, Engage, Reorient, Experimental Satellites), which was developed by the MIT Space Systems Laboratory to support research on spacecraft dynamics and control using the unique microgravity environment of the Space Shuttle and the International Space Station (ISS). The testbed consists of several autonomous free-flying satellites which are located inside the ISS, a laptop that functions as a ground station, and ultrasonic beacons that form the position and attitude determination system [21]. Each satellite is self-contained, capable of six-degree-of-freedom motion, and uses carbon dioxide cold gas thrusters, arranged in 12 directions, to provide both translational and rotational control. The positioning system works through ultrasonic beacons that emit sound signals detected by the microphones on the satellites; the time delay between emission and reception allows the satellites to determine their distance from each beacon [22].

Although these testbeds provide sophisticated environments for evaluating control algorithms for satellite formation flying, they remain insufficient and are often inaccessible due to their very specialized experimental setups, high costs and operational complexity.

C. UAV-based Formation Flying Testbeds

UAV testbeds provide an effective platform for evaluating remote sensing and formation flying control methods. However, replicating the space environment and its dynamics on Earth remains highly challenging, hence there are multiple researches that have been conducting tests on how to make such testbeds more realistic with respect to the test purposes.

The study by de la Barcena et al. [8] demonstrated the use of Crazyflie drones as satellite surrogates for spacecraft formation flying experiments. They presented research on how the Bitcraze Crazyflie 2.1 quadcopters [9] can be used as substitutes for satellites. The study used the Clohessy–Wiltshire (CW) equations to simulate the movements of satellites and to maintain them in specific formations. CW equations are a set of linearized differential equations that describe the relative motion of a chaser spacecraft around a target in a circular reference orbit [23]. Since satellites move over kilometer-scale distances while drones operate over meters, the researchers calculated real satellite motion, scaled it down to fit a small lab environment, simulated it using Crazyflie drones inside a physics simulator called gym-pybullet-drones (a Python-based environment), and then flew real drones in a lab using the same motion paths [8]. Another recent advancement in the field is the Reconfigurable and Empirical Spacecraft Emulation Testbed (RESET) [5], which employs a custom drone to embed a small CubeSat, using its propellers to counteract Earth's gravity and emulate space-like dynamics, including variable mass, inertia, and environmental effects. This setup allowed the CubeSat to execute control algorithms and navigation tasks as if in orbit, providing a cost-effective, reconfigurable, and high-fidelity platform for validating novel satellite control strategies [24].

Although UAV testbeds provide significant advantages, the physical disparity between the space environment and the terrestrial setting introduces fundamental constraints that must be actively managed to achieve high fidelity (see Table 1). The primary challenge is to address the effects of Earth's gravity and atmosphere. An intelligent scaling method is required to map large orbital distances and velocities in a confined laboratory environment, with quadrotor UAVs typically tracking only the translational components of a spacecraft trajectory [25]. Various compensation techniques can be used to address gravity and friction, ranging from planar air-bearing testbeds for high-fidelity 2D motion simulation [26] to more sophisticated methods such as cable-suspension systems that passively counterbalance the vertical gravitational force on the robot [27]. The fidelity of the emulation is directly constrained by the performance of these active disturbance rejection and compensation mechanisms. Moreover, an additional challenge is terrestial testing, especially in dense or urban environments, is due to the impact of RF interference on navigation sensors. In these cases, positioning often leads to significant errors due to signal reflections (multipath) and obstructions (Non-Line-of-Sight). To overcome this, UAV testbeds are evolving into navigation resilience testbeds, which are designed to rigorously evaluate guidance, navigation, and control (GNC) systems under conditions that mimic complexity and signal disruptions [28].

In conclusion, the use of small UAVs, particularly platforms such as the Bitcraze Crazyflie and the RESET system, demonstrate a practical and efficient approach to emulating spacecraft formation flying in controlled environments. These systems enable the replication of orbital behaviors and the testing of control strategies at a significantly reduced cost and scale. These studies highlight the effectiveness of UAV-based testbeds in bridging the gap between simulation and real-world experimentation, offering valuable tools for advancing research in small satellite formation flying and control.

Table 1 Comparison of UAV testbeds and their strategies for addressing key limitations

Aspect	**Limitation**	**RESET [5]**	**Crazyflie [8]**	**Air-Bearing [26]**
Microgravity / Gravity Compensation	UAVs must constantly counteract gravity; cannot naturally drift like spacecraft	Active gravity counteraction using fully-actuated platform: emulates full 6-DOF	No microgravity emulation; only scaled orbital paths	Air-bearing provides near-frictionless 2D “microgravity”
Orbital Relative Motion	Orbital scales too large; km-scale trajectories must be compressed	Focus on ADCS, not orbital motion	CW-based scaling; accurate relative motion	Simplified 2D CW equations
Attitude Dynamics (ADCS)	Rotor disturbances + different inertia than satellites	Capability to decouple the position and attitude dynamics	Attitude follows drone controller, not spacecraft rotational dynamics	1D rotation with reaction wheel
Propulsion Emulation	True space propulsion difficult to replicate; UAVs rely on rotors	Internal thrusters for CubeSat + drone forces	UAV rotors used only for motion	Ventilator thrusters emulate cold-gas propulsion
Disturbance-Free Environment	Air drag, turbulence, RF noise	High-fidelity disturbance compensation	Indoor flight reduces but does not eliminate disturbances	Air table minimizes friction; ventilators add noise

III. Research Significance

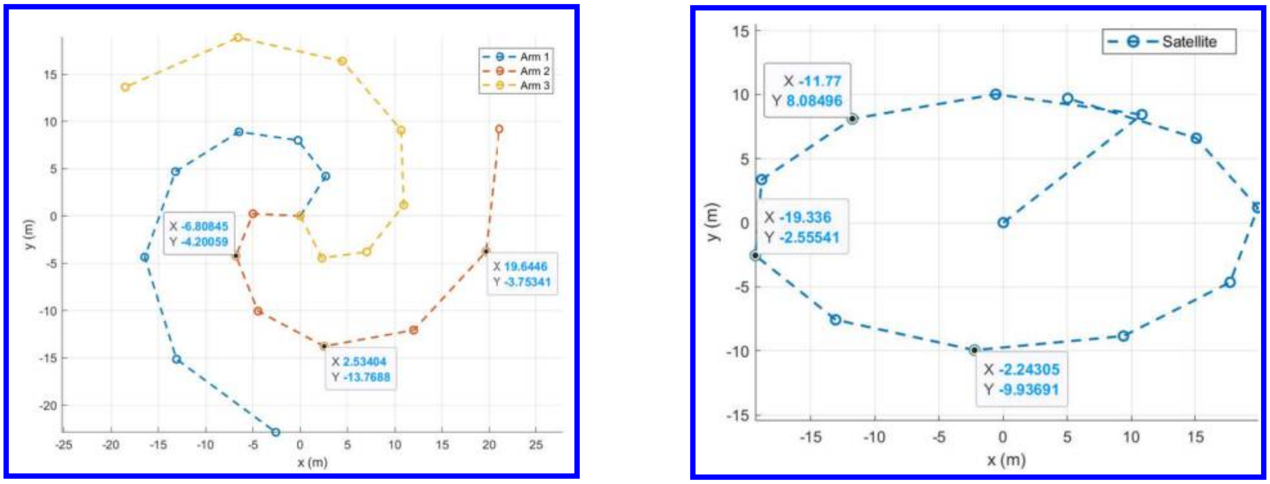
While prior research has demonstrated the feasibility of recreating satellite-like behavior using UAV platforms, existing testbeds have predominantly focused on replicating orbital dynamics through scaled propagation models, evaluating control algorithms under microgravity-analog conditions, or employing high-fidelity custom hardware to emulate space-like dynamics. In contrast, the contributions of this work extend beyond these efforts by introducing a more generalizable and accessible framework for formation-flying emulation, bridging orbital-level formation design with practical UAV-based implementation. The important points to note are:

1) Unlike previous UAV-based emulation studies that rely on simplified relative-motion models, our approach starts with generating formation geometries directly in the Locally Vertical, Locally Horizontal (LVLH) frame, then converting them to the inertial International Celestial Reference Frame (ICRF) frame, propagating them under full orbital dynamics, and finally scaling and mapping these trajectories into UAV-feasible motion plans. This offers a precise end-to-end pipeline that preserves the true geometric development of multi-satellite formations while making them executable in a terrestrial UAV environment.
2) We show that non-standard, mission-driven geometric formations, such as spiral-shaped structures, can be reproduced, irrespective of their complexity. This establishes a general structure for assessing formation geometries relevant to advanced sensing missions like GNSS-R interferometry.
3) Instead of utilizing bespoke hardware (RESET) or proprietary swarms (Crazyflie-based configurations), this effort uses the open and platform-independent Aerostack2 environment for formation-flying research. This delivers a testbed that is reproducible, easily extensible, and hardware-agnostic, allowing heterogeneous UAV operations and future multi-sensor experiments to be conducted without the need for specific equipment.
4) The primary novelty is the illustration, using actual UAV tracking findings, of how small satellite formations degrade in the absence of formation-keeping control. This yields two insights that were not previously highlighted:

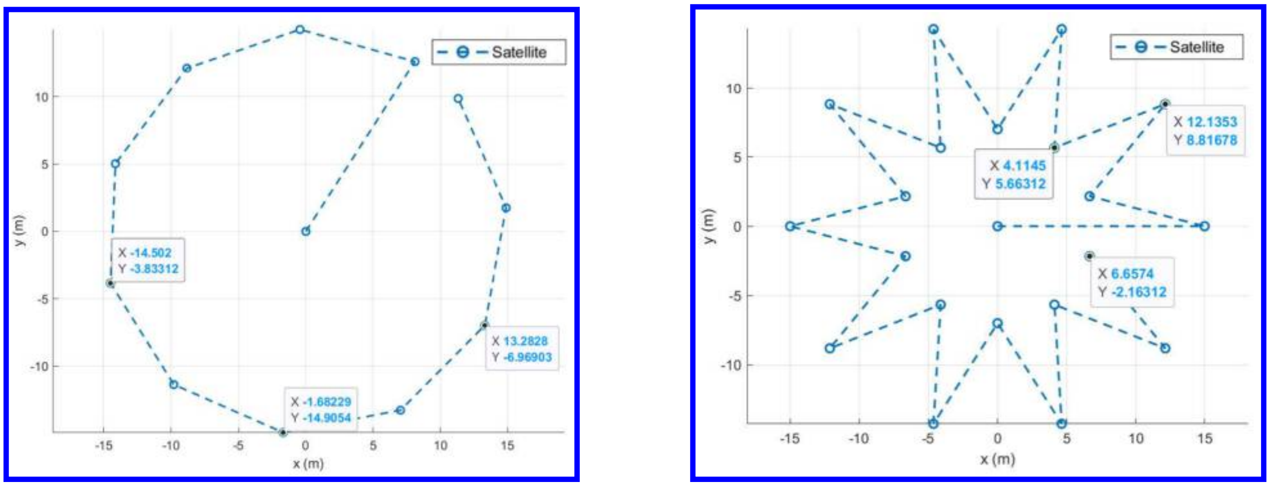
UAVs visibly emulate relative drift, phase mismatch, and approach risks similar to those encountered in orbit. Even when the initial geometry is perfectly scaled and mapped, open-loop motion rapidly loses coherence, which highlights the need of relative navigation and closed-loop control in satellite formations. This is a new empirical verification of formation sensitivity on a generic UAV testbed.

IV. Experimental Design and Methodology

This study aims to replicate the geometric formation patterns of multiple small satellites. The formations were initially designed and analyzed in MATLAB Simulink, then scaled for implementation in a UAV-based simulation intended to demonstrate whether the UAVs can reproduce analogous path-following behaviors. The primary focus is on the time-varying relative positions among the satellites within each formation. Four trajectory configurations were examined: spiral, elliptical, circular, and star-shaped formation (as shown in Fig. 2). The MATLAB Simulink models incorporated around ten to twenty satellites, although the scaled simulation employed only three representative agents just for the initial testing phase and can be increased for future work. The simulation evaluates whether the UAVs can maintain the prescribed trajectories individually. Successful replication of these trajectories indicates that UAVs can effectively emulate the control challenges associated with maintaining the formation.



(a) Spiral Formation **(b) Ellipse Formation**



(c) Circle Formation **(d) Star Formation**

Fig. 2 Representative geometric formations used for relative-positioning experiments

A. Geometric Formation Generation in MATLAB

Designing precise formations requires a careful approach that integrates two primary reference frames. The foundational orbital mechanics for all satellites is computed and propagated in the ICRF. This global, inertial frame provides a stable, non-rotating reference essential for numerical integrators that account for various orbital perturbations. In contrast, the specific geometries and relative dynamics of the formations are defined using the LVLH frame, which is a local rotating coordinate system centered on the chief spacecraft. The initial relative positions and velocities determined in the LVLH frame must be accurately transformed into the ICRF frame using direction cosine matrices and angular velocity transformations. These absolute ICRF coordinates are the inputs for an orbital propagator simulation in Simulink, allowing for the propagation and visualization of the multi-satellite system. Figs. 2a–2d illustrate the formations resulting in the LVLH frame.

In order to generate the formations used in this study, a set of MATLAB routines were developed to algorithmically translate the analytical expressions into discrete cartesian coordinates. Each script implements the governing geometric model in a parameterized form. For the spiral configuration, the Archimedean law ([29])

$$r = a + b\theta \tag{1}$$

is evaluated over a sequence of uniformly spaced angular increments, with arm-to-arm phase shifts applied to realize the multi-arm structure. The ellipse and circle formations are constructed using their respective parametric representations

$$(x, y) = (a\cos\phi,\ b\sin\phi) \tag{2}$$

and,

$$(R\cos\phi,\ R\sin\phi) \tag{3}$$

ensuring a uniform distribution of points along the curves. The star geometry is synthesized by alternating between inner and outer radii while assigning angular positions offset by half-step increments, thereby producing the characteristic radially oscillating pattern. In all cases, the scripts convert the resulting polar or parametric quantities into cartesian coordinates, assemble the corresponding point sets, and render the configurations in a consistent plotting framework.

B. Orbit Propagation for Multiple Formation Geometries

This section describes the methodology used to propagate and analyze the relative motion of three satellites initially configured according to the formation geometry generated in MATLAB. Each plot in Fig. 2 illustrates the selected points corresponding to each formation. These points are then propagated using MATLAB Simulink. Although Fig. 2 incorporates approximately ten to twenty satellites, only three points were utilized for orbit propagation to examine the temporal evolution of their relative positions. To model the motion of the satellites, a custom Simulink framework was developed to propagate the orbits from the three initial positions. The simulation was conducted over a duration of 2.2 hours, with the resulting state vectors exported to the MATLAB workspace for post-processing. The subsequent analysis focused on visualizing the evolution of the satellite' positions relative to each other during this period. For comparison, one of the satellites was treated as a fixed reference by translating its initial position into the origin $(0, 0)$. The positions of the remaining satellites were then expressed with respect to this reference point, allowing a clear examination of their relative motion and mutual drift during the simulation period.

C. Normalization and Resizing of the Formations

The initial step involved exporting the Cartesian coordinates (x, y, z) of one of the satellites to a CSV file. A MATLAB script was then developed to perform a series of transformations to standardize and scale the formation, ensuring that it is feasible for safe operation within a designated UAV flight arena. First, the geometric center (centroid) of all points in the formation was computed. The formation was then translated such that this centroid coincided with the origin of the coordinate system, using,

$$\mathbf{c} = \frac{1}{N}\sum_{i=1}^{N}\mathbf{p}_i \tag{4}$$

where:

$\mathbf{c}$ is the centroid of the formation.

N is the total number of small satellites in the formation.

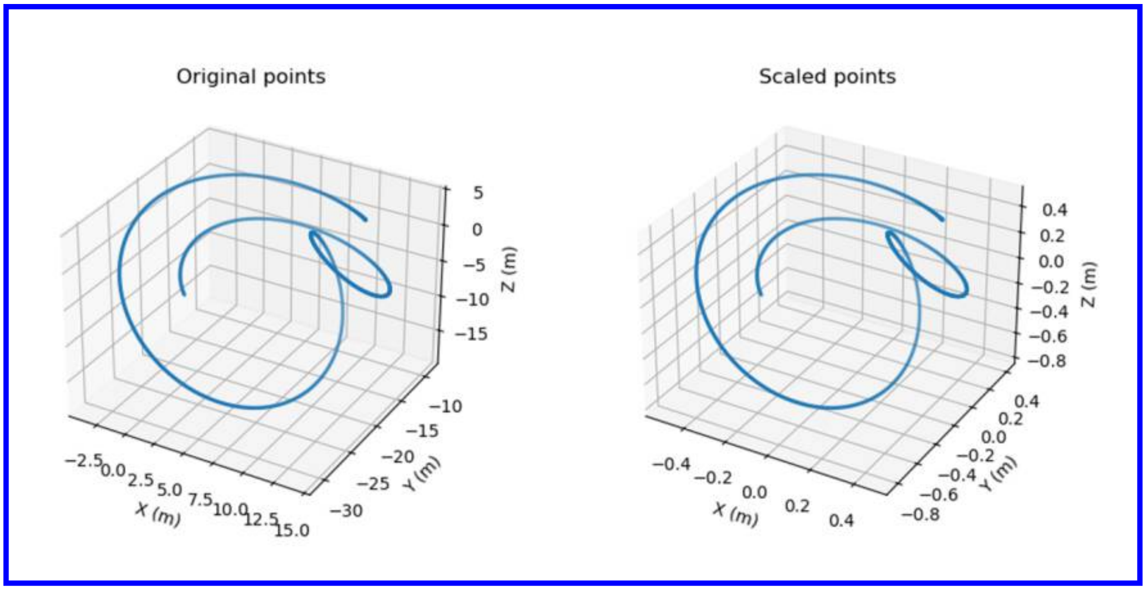


Fig. 3 Scaled coordinates illustrating the spiral formation executed by one satellite

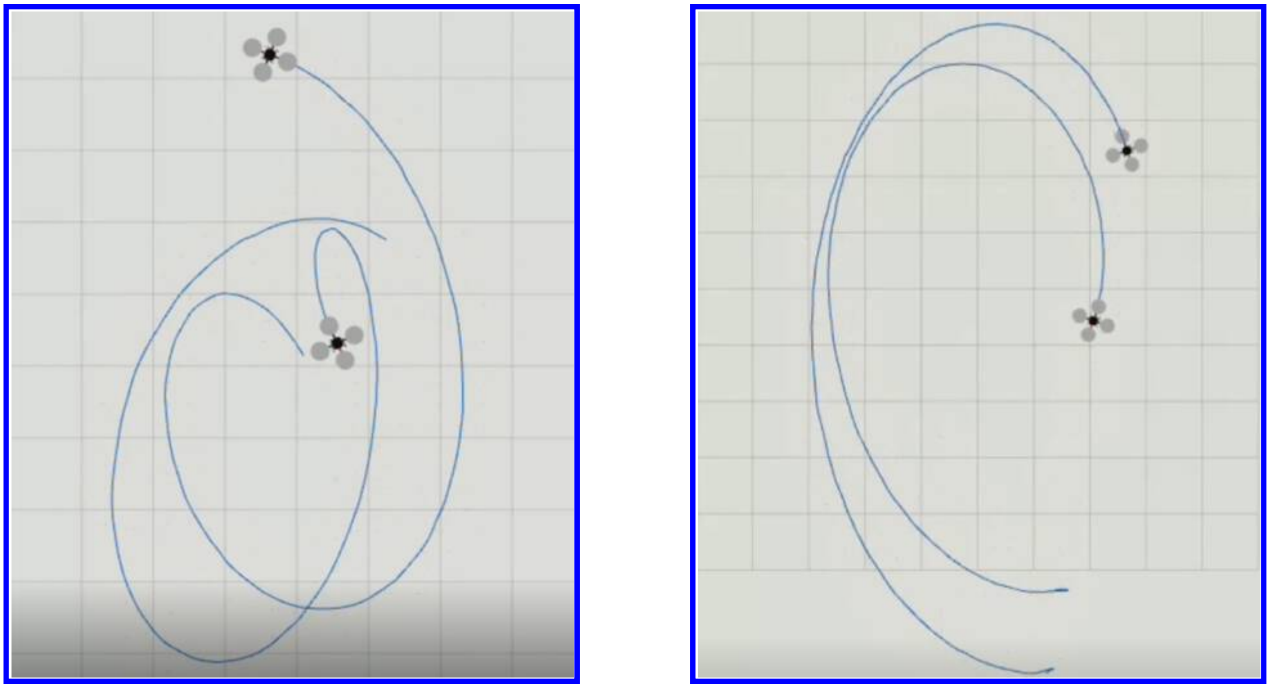
$\mathbf{p}_i$ is the position vector of the i-th point in Cartesian coordinates: $\mathbf{p}_i = (x_i, y_i, z_i)^T$, which provides a reference frame for subsequent operations. Next, the current size of the formation was quantified by identifying the maximum euclidean distance between any two points. Using this value, a scaling factor was calculated by dividing a desired defined size by the current size. All points in the formation were subsequently multiplied by this factor, thereby uniformly stretching or compressing the formation while preserving its relative geometry. Finally, the formation was translated back to its original centroid, ensuring that the overall spatial positioning remained consistent while the formation size was adjusted (see Fig. 3). This procedure allows for controlled resizing of the small satellite formation without altering its internal configuration.

D. Simulation with the UAV platforms

The feasibility of using UAVs as testbeds for the assessment of small satellite formations is demonstrated by using simulated UAV platforms with the Gazebo simulator. The formation simulation with Gazebo was facilitated by the Aerostack2 framework. Aerostack2 is an open-source ROS2-based software framework designed to develop autonomous multi-robot aerial systems [30]. This framework was selected for this simulation as it provides an integrated interface for designing, monitoring, and executing command-and-control (C2) operations within a UAV swarm. Additionally, since it is platform-independent, the framework can be further used to operate a heterogeneous UAV swarm in the future, emulating different types of small satellite formations, both in simulations and experiments. For each formation scenario, two simple quadrotor models were initialized in Gazebo. The post-processed cartesian coordinates generated from the propagation of individual orbits were sampled and pre-configured into the respective platforms before the flight. The sampled coordinates were saved as mission waypoints for each UAV. To ensure the UAVs move along the sampled waypoints in a smooth and continuous manner, the trajectory path-following motion behavior was utilized in Aerostack2. This generated a smooth polynomial trajectory for the UAV connecting the desired waypoints, which was then tracked by the lower-level controllers. Following this pipeline, each UAV followed its assigned trajectory independently, maintaining the preset yaw and speed. During this study, the UAVs were configured to maintain heading along the direction of motion throughout the flight, i.e., tangential to the generated trajectory. The path traced by the two UAVs during sample formation flights is shown in Fig. 4.

V. Results

As seen in Fig. 4, each UAV formation begins by replicating the original geometry generated in MATLAB (Fig. 2), such as the spiral pattern illustrated in Fig. 4a. Although the agents initially conform to the intended configuration, the formation gradually degrades as the UAVs lose coherence and drift away from the prescribed pattern. This behavior arises from the absence of any control strategy to regulate their relative motion. The results clearly demonstrate that, without proper control, even well-defined geometric formations cannot be maintained, thereby emphasizing the critical need for robust control methods in analogous satellite missions.



(a) UAV Spiral Formation

(b) UAV Ellipse Formation

Fig. 4 UAV-replicated spiral and ellipse formation patterns used to validate relative-motion and tracking methodologies.

Moreover, as observed in Fig. 4b, the two UAVs approach each other closely at a specific point along the trajectory, highlighting a critical operational challenge: even small deviations in timing, velocity, or heading can lead to unintended proximity between agents following nominally coordinated paths. In an orbital context, such close approaches would be exacerbated by differential perturbations and would significantly increase the probability of collision if not actively managed. The UAV results therefore provide a compelling surrogate demonstration of the same phenomenon observed in multi-satellite formations, where locally unstable or weakly constrained trajectories can rapidly degrade without feedback control. These observations reaffirm that maintaining strict separation margins requires the implementation of active or passive formation-keeping strategies capable of mitigating drift, correcting accumulated errors, and ensuring safe geometric spacing throughout the mission. The UAV platform thus effectively emulates the sensitivity of small satellite formations to small dynamical inconsistencies, illustrating both the necessity and the complexity of robust control in close-proximity operations. These procedures were undertaken to illustrate how the experiments can be performed on a UAV-based platform. However, the current testbed has several limitations. Notably, due to the under-actuated nature of conventional multi-rotors, fully independent three-axis attitude control is not available. As the translational and rotational dynamics of such platforms are highly coupled, much attention is paid to the translational tracking of the desired coordinates. Thus, a conventional UAV platform that follows a set position trajectory is not capable of attaining arbitrary orientations or performing large-angle maneuvers. Consequently, the simulations primarily regulate the heading angle, with limited control over the remaining two axes. Despite these constraints, the platform successfully demonstrates the formation behaviors previously implemented in Simulink, including those accounting for space-environmental factors.

VI. Conclusion and Future work

UAVs can serve as effective surrogates for satellites flying in formation because they are capable of reproducing key relative motion behaviors, coordination strategies, and sensing patterns characteristic of formation-flying small satellite missions. In this work, we first compute the true orbital trajectories of multiple satellites using full inertial-frame propagation, then scale these trajectories to a size compatible with a terrestrial testbed, and finally command the resulting paths to UAVs in the Gazebo simulation environment.

A critical component of this workflow is the normalization and resizing of small satellite formations, which ensures that real orbital geometries can be safely reproduced within a constrained UAV flight area. This procedure preserves the internal geometry of the formation while resizing the configuration to a physically feasible scale for UAV experiments. The ability to accurately downscale orbital formations without distorting their structure is a substantial result of this research, as it provides a rigorous and repeatable pathway for reproducing realistic multi-satellite configurations in ground-based testbeds. Although UAVs initially follow the prescribed, scaled satellite trajectories, they gradually deviate (as shown in Fig. 4) from the commanded paths due to accumulated tracking errors and the absence of any formation keeping or feedback control mechanism. This deviation mirrors the natural drift and loss of coherence that occur in multi-satellite constellations when no active control is applied, reinforcing the idea that even accurately designed formation geometries cannot be maintained in practice without continuous control method.

These findings highlight the need to implement dedicated formation control strategies on the UAV platform to ensure precise trajectory tracking, stable relative geometry, and probably reliable collision avoidance. Consequently, future work will focus on integrating and comparing multiple control approaches to determine which methods most effectively preserve formation integrity and guaranty safe, collision-free operation in both simulated and real UAV-based testbeds.

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