Review of Formation Flying and Constellation Missions Using Nanosatellites

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I. Introduction

Small satellites are enabling multisatellite missions that were not otherwise possible because of their small size and modular nature [1]. Multiple small satellites can be flown instead of a much bigger and costlier conventional satellite for distributed sensing applications such as atmospheric sampling, distributed antennas [2], and synthetic apertures [3,4]. Missions with multiple small satellites can deliver a comparable or greater mission capability than a monolithic satellite, but with significantly enhanced flexibility (adaptability, scalability, evolvability, and maintainability) and robustness (reliability, survivability, and fault tolerance) [1,5]. Small satellites that weigh less than 10 kg can be broadly classified into nanosatellites (mass between 1 and 10 kg), picosatellites (mass between 0.1 and 1 kg), and femtosatellites (mass less than 100 g) [1,6]. A class of standardized nanosatellites, called CubeSats [7], range in size from 1U (10 × 10 × 1 cm) to 6U (30 × 20 × 10 cm), weigh between 1 and 8 kg, and are usually launched using the standardized CubeSat deployment system called Poly Picosatellite Orbital Deployer (P-POD) [8]. In this Note, we survey 39 multisatellite missions in various stages of development, where each satellite’s mass is less than 10 kg. We categorize them based on their mission type and status, number of satellites (see Fig. 1), lead institution, and funding source (see Fig. 2). The objectives of this Note are to recognize state-of-the-art small satellite formation-flying (FF) missions, inspired by many enabling science applications, and to suggest future research directions.

Multisatellite missions can be broadly divided into two categories, namely FF missions and constellation missions. The dynamic states of formation flying satellites [9–11] are coupled through a common control law. In other words, in an FF mission, at least one satellite must track a desired state relative to another satellite, and its tracking control law must, at the minimum, depend upon the states of this satellite. FF missions are further subdivided into two categories, namely FF missions that involve rendezvous and docking and FF missions without docking. Multisatellite missions that do not satisfy the definition of FF missions are called constellation missions. For example, even though specific relative positions are actively maintained, the GPS satellites constitute a constellation because their orbit corrections require only the individual satellite’s position and velocity (states) [9,10]. Furthermore, constellation missions are subdivided into controlled constellation missions, where each satellite actively maintains its position (e.g., GPS), and uncontrolled constellation missions, where satellites have no active control over their position. As per these definitions, satellites in FF missions and controlled constellation missions must have active propulsion systems. Multisatellite missions without position control are categorized under uncontrolled constellation missions.

In contrast with constellation missions, the main challenges of FF missions stem from dynamic couplings between satellites and the environment. If FF satellites are launched into LEO, they face environmental disturbances, such as air drag, solar pressure, and J2 perturbations [12]. These disturbances can cause the satellites to rapidly drift away from each other unless they are correctly accounted for. Therefore, the satellites have to counter these disturbances while maintaining their orbits and relative distances and attitudes. If the desired positions are not in the same altitude, then the satellites have to expend additional control effort to synchronize their orbital periods and relative distances [13,14]. Also, the nonlinear nature of the dynamics of the satellites, with coupled formation flying control laws and environmental disturbances, makes formation flying challenging. This challenge is exacerbated by the limited capabilities of the current sensor and actuator technologies for small satellites [6,15]. Because of these challenges, FF missions are an active area for research and development (for example, see [1,9–12,16–18] and the references therein).

In Fig. 1, we have categorized the 39 small satellite missions into constellation missions (controlled or uncontrolled) and FF missions (with or without docking). The key for these missions is given in Table 1 [9–71]. These missions are also grouped into five mission types, namely Earth science [72] (Sec. II), astronomy and astrophysics [73] (Sec. III), planetary science [74] (Sec. IV), heliophysics [75] (Sec. V), and technology demonstrations (Sec. VI). Based on Fig. 1, we conclude that Earth science missions (14) are the most popular among science-driven missions (22). Moreover, 20 of these science-driven missions only require a constellation. Among the 17 technology demonstration missions, 10 missions aim to demonstrate formation flying capability in space using two to three small satellites. Only two FF missions are currently planning to use four or more small satellites.

The categorization of the 39 multisatellite missions, based on their current mission status, leading organizations, and their funding sources, is shown in Fig. 2. The primary funding sources for multisatellite missions are NASA and NASA centers like the Jet Propulsion Laboratory (JPL), the National Science Foundation (NSF), the U.S. Department of Defense (DoD), non-U.S. agencies like the European Space Agency (ESA), Canadian Space Agency (CSA), Chinese Academy of Sciences, and private companies. The various mission status categories are 1) concept, where the mission concept
has been proposed and preliminary design work is being carried out; 2) in development, where the hardware for the satellites is being developed; 3) launch date set, where the launch date has been fixed or the mission has been selected for launch by NASA’s Educational Launch of Nanosatellites (ELaNa) program [76,77]; 4) launched, where the mission has been launched into orbit and the satellites are currently operational; and 5) completed, where the satellites were previously launched and the mission successfully or unsuccessfully achieved its desired objectives. Based on Fig. 2, we conclude that 21 missions are being led by universities around the world. Among the 14 FF missions, three have already been launched, and five are set to be launched within the next two years. The state-of-the-art missions with the best accuracies for different control parameters are listed in Table 2.

II. Earth Science Missions

The aim of Earth science missions is to develop a scientific understanding of the Earth system and its response to natural and human-induced changes to enable improved prediction of climate, weather,
and natural hazards for present and future generations [78]. A number of multisatellite Earth science missions, involving conventional large satellites, have been launched including the Afternoon Train (A-train) [79], Gravity Recovery and Climate Experiment (GRACE) [80], Time History of Events and Macroscale Interactions During Substorms (THEMIS) [81], Cluster II [82], Swarm [83], TerraSAR-X add-on for Digital Elevation Measurement (TanDEM-X) [84], Magnetospheric Multiscale Constellation (MMS) [85], and Skybox Imaging [86]. The Cyclone Global Navigation Satellite System (CYGNSS) is a constellation of eight microsatellites (weighing 17.6 kg each) that aims to improve extreme weather predictions and is scheduled for launch in 2016 [87]. Earth science missions are also popular among missions employing single nanosatellites. For example, ionosphere monitoring is done by CubeSats investigating Atmospheric Density Response to Extreme driving (CADRE) [88], drag-free CubeSat [89,90], ExoCube [91], Pratham [92], whereas weather monitoring is done by Microsized Microwave Atmospheric Satellite (MicroMAS) [93], Weathernews Inc. Satellite (WNISAT) [94], and the Colorado Student Space Weather Experiment (CSSWE) [95]. Note that CADRE, Drag-Free CubeSat, and MicroMAS are precursors of some CubeSat constellation missions. We do not expand on these monolithic nanosatellite missions in this survey because we focus only on multisatellite missions. In this section, we present Earth science related missions, which use or aim to use two or more small satellites whose masses are less than 10 kg.

A. Dynamic Ionosphere CubeSat Experiment

The Dynamic Ionosphere CubeSat Experiment (DICE) was a multiuniversity mission, led by Utah State University and supported by NSF and NASA’s ELNa program, which launched two 1.5U CubeSats into an elliptical LEO (altitude of 410–820 km, inclination of 102 deg) in October 2011. As shown in Fig. 3a [96], each identical satellite carried two Langmuir probes to measure ionospheric in situ plasma densities, electric field probes to measure in situ DC and AC electric fields, and a magnetometer to measure DC and AC magnetic fields in situ, which facilitated accurate identification of geospace storm-time features like the geomagnetic-storm-enhanced density bulge and plume. These CubeSats did not have position control capability. In addition to successfully demonstrating an uncontrolled constellation in space, the DICE mission also pushed the envelope of downlink communication data rate to 3 M b/s [19,20]. These CubeSats could determine their absolute attitude to within ±0.7 deg (1σ error) using GPS, magnetometer, and sun sensors. They could control their absolute attitude to within ±5 deg (1σ error) using torque coils [96].

B. Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics

The Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics (FIREBIRD) mission, led by Montana State University and the University of New Hampshire and funded by NSF, aimed to assess the spatial scale and spatial temporal ambiguity of magnetospheric microbursts in the Van Allen radiation belts using two 1.5U CubeSats. The two FIREBIRD CubeSats, shown in Fig. 3b [97], were launched into sun-synchronous LEO (altitude of 467–883 km, inclination of 120.5 deg) as secondary payloads on an Atlas-5-501 launch vehicle from Vandenberg Air Force Base (VAFB), California, on 6 December 2013 [21,22]. Two additional FIREBIRD-
II 1.5U CubeSats were launched into sun-synchronous LEO (altitude of 685 km, inclination of 98 deg) as secondary payloads on a Delta-2 launch vehicle from VAFB on 31 January 2015. These CubeSats featured passive magnetic attitude control. Because these CubeSats cannot control their position, this mission belongs to the uncontrolled constellation category.

C. Flock-1 Imaging Constellation
The Flock-1 constellation, developed by Planet Labs Inc., consists of over 100 3U CubeSats that provide 3–5 m resolution images of Earth for environmental, humanitarian, and business applications. The 28 Flock 1 CubeSats, shown in Fig. 4a [23], were launched into LEO (altitude of 400 km, inclination of 52 deg) from the International Space Station using the NanoRacks CubeSat Deployer in mid-February 2014 [23]. Currently, the company has launched 113 CubeSats into space [98]. These CubeSats are capable of changing their cross-sectional area by opening or closing their solar panels; hence, this is a controlled constellation mission.

D. Edison Demonstration of Smallsat Networks
The primary scientific purpose of the Edison Demonstration of Smallsat Networks (EDSN) mission, led by NASA’s Ames Research Center and funded by NASA’s Space Technology Mission Directorate (STMD), is to demonstrate the capability of launching and deploying a fleet of eight satellites into an uncontrolled constellation approximately 500 km above Earth. Each of the eight 1.5U CubeSats carries the Energetic Particle Integrating Space Environment Monitor payload to characterize the radiation environment in LEO by measuring the location and intensity of energetic charged particles simultaneously over a geographically dispersed area [24,25]. Each CubeSat has a Nexus S smartphone onboard, for testing commercial off-the-shelf (COTS) software and hardware. The CubeSats determine their attitude using the smartphone gyroscope, GPS, and magnetometer sensor and control their attitude using three reaction wheels [99]. The EDSN satellites, shown in Fig. 4b [100], were launched as secondary payloads on a Super-Strypi launch vehicle from Kauai, Hawaii on 3 November 2015, but the launch vehicle failed during launch [26,100].

E. QB50
The QB50 project is a multiuniversity mission led by the Von Karman Institute, Belgium, and partially funded by the Research Executive Agency of the European Commission. It aims to launch a network of 50 CubeSats built by university-led teams all over the world to perform multipoint, in situ measurements in the lower thermosphere (90–350 km) and reentry research. Each 2U CubeSat carries a set of standardized sensors for lower thermosphere and reentry research in addition to standard instruments for providing the usual satellite functions, as shown in Fig. 5a [101]. These CubeSats are scheduled for launch in 2016 [27–29]. Most of the QB50 CubeSats will be placed into a near-circular LEO (altitude of 380 km, inclination of 98 deg). A smaller group of satellites will be deployed into an elliptical LEO (altitude of 380–700 km) [102]. Because most of these CubeSats cannot control their position, this mission belongs to the uncontrolled constellation category.

F. Global Navigation Satellite System Geospace Constellation (GGC) Mission Concept
The Global Navigation Satellite System (GNSS) Geospace Constellation (GGC) mission, led by JPL, is a space weather mission concept that proposes to use a CubeSat constellation with miniaturized GPS receivers for ionospheric remote sensing [30].

G. RocketCube Mission Concept
A team from Dartmouth College is developing a CubeSat-based platform called RocketCube to enable low-cost multipoint measurements for orbital and suborbital scientific missions. These RocketCubes can be launched by a sounding rocket and have no position control capability. The aim is to launch 10 to 12 RocketCubes to observe the spatial and temporal variations in the ionosphere and aurora by conducting in situ observation [31].

Fig. 5 Photographs of a) the first two QB50 satellites (image credit: Innovative Solutions In Space [101]), b) the two Canadian BRITE satellites called CanX-3 (image credit: University of Toronto Institute for Aerospace Studies [107]).
mission is funded by JPL and NASA’s Experimental Program to Stimulate Competitive Research (EPSCoR) program.

H. Charybdis Mission Concept
The aim of the Charybdis constellation project, led by the University of Strathclyde and funded by the Engineering and Physical Sciences Research Council, United Kingdom, is to obtain high spatial, high temporal resolution multispectral images of coastal and inland waterways. This information is necessary for understanding the evolution of ecological systems and sediment suspension in river estuaries, the effects of anthropogenic processes on water systems, and the effects of tidal forcing on ocean color. The project aims to maintain a controlled constellation (using micropropulsion systems) of 115 nanosatellites for bihourly global coverage or 30 nanosatellites for bihourly regional coverage over the U.K. mainland [32].

I. Centinel Mission Concept
The Centinel mission concept, led by Imperial College London and funded by the U.K. Space Agency, aims to launch an uncontrolled constellation of more than 100 CubeSats to study the magnetosphere. The satellites will perform in situ measurements to understand geomagnetic storm generation in the magnetosphere, especially in the magnetotail region, where these storms start [33].

J. Temperature and Humidity Sounding Mission Concept
The 6U CubeSat constellation concept for atmospheric temperature and humidity sounding, led by JPL, aims to launch four to 15 low-inclination satellites to image the key geophysical parameters that are needed to improve prediction of extreme weather events. Each 6U CubeSat will carry the 118 GHz temperature sounder instrument and the 183 GHz humidity sounder instrument and will maintain a controlled constellation in space [34]. A similar concept for measuring the bidirectional reflectance distribution function of the Earth’s surface (i.e., the directional and spectral variation of reflectance of the surface) using a constellation of nanosatellites has been proposed for precise determination of albedo [103].

K. Fourier Transform Spectrometer CubeSat Mission Concept
In this conceptual design, led by Exelis Geospatial Systems and the University of Michigan, three formation-flying 6U CubeSats, carrying the Fourier Transform Spectrometer (FTS) payload, would cooperatively measure the global wind field for compiling vertical profiles of the wind field and for long-term weather forecasts [35]. The CubeSats will maintain revisit time of 12 h.

L. Ionospheric Tomography Mission Concept
This conceptual mission, led by SRI International, aims to use a constellation of CubeSats with digital television (DTV) receivers for ionospheric tomography. Each satellite will establish links with DTV stations and measure the phase variations of the DTV signals, to understand the ionospheric response to solar, magnetospheric, and upper atmospheric forcing and perform tomographic measurements of ionospheric density [36].

M. Space Situational Awareness Mission Concept
The Space Situational Awareness (SSSats) conceptual mission, led by the University of Adelaide, Australia, aims to launch a small evenly distributed controlled constellation of five CubeSats to search for space debris in the medium Earth orbit and geostationary Earth orbit (GEO) belts [37]. A similar space situational awareness mission, where the CubeSat constellation is launched to 500 km above GEO, has also been proposed by Lockheed Martin Space Systems [104].

N. Artemis Mission Concept
The Artemis Earth mission concept, led by Artemis Space, is to launch a constellation of 200 nanosatellites that will be used for Earth observations and monitoring Earth’s local space environment. Artemis Space is also developing a lunar constellation of 35 small satellites and CubeSats, which will provide a range of services, like providing telecommunications links, mapping of the Lunar surface, and support future missions on the moon [38].

III. Astronomy and Astrophysics Missions
The aim of astronomy and astrophysics missions is to understand the universe and our place in it [105]. The readers are reminded of NASA’s Terrestrial Planet Finder (TPF) mission that proposed to construct a system of four highly sensitive telescopes for detecting extrasolar terrestrial planets [106]. A single CubeSat mission was proposed for performing observations in the 21 cm wavelength from the shielded zone behind the moon [49]. In this section, we present astronomy and astrophysics related missions that use or aim to use two or more small satellites.

A. Bright-Star Target Explorer Constellation
The Bright-Star Target Explorer (BRITE) constellation, led by the University of Vienna and funded by the Austrian Space Agency and CSA, aims to provide milli-magnitude (0.1% error) differential photometry of bright stars. The six nanosatellites, shown in Fig. 5b [107], use the Generic Nanosatellite Bus platform developed by the University of Toronto. All six satellites were launched during 2013–2014. They maintained an uncontrolled constellation in space, and the mission provided light curve data for multiple stars. The satellites could control their attitude to within ± 10 arcsec error using a GPS receiver, a three-axis magnetometer, six sun sensors, and a star tracker. The satellites could control their attitude to within ±1 arcmin rms error using three magnetorquers and three reaction wheels [39].

B. Autonomous Assembly of a Reconfigurable Space Telescope
The Autonomous Assembly of a Reconfigurable Space Telescope (AReST) mission, led by the California Institute of Technology and the Surrey Space Centre and funded by the Keck Institute for Space Studies, aims to demonstrate autonomous assembly and reconfiguration of a space telescope by having two 3U CubeSats autonomously undock and redock with a central 9U nanosatellite core. The central nanosatellite houses two fixed mirrors and a boom-deployed focal plane assembly, whereas the two 3U CubeSats each carry an electrically actuated adaptive mirror [40, 41]. These satellites aim to achieve attitude control to within ±1 deg in all axes, with 0.5 deg/s slews rate, using a GPS receiver, a three-axis magnetometer, complementary metal–oxide–semiconductor array-based sun and Earth sensors, a three-axis magnetorquer, and three reaction wheels [41].

C. Orbiting Low Frequency Antennas for Radio Astronomy Mission Concept
The Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) mission concept, led by Delft University of Technology, is to deploy a swarm constellation of 50–1000 identical nanosatellites for radio astronomy in the operational band of 0.3–30 MHz. Because of the opaqueness of the ionosphere to low-frequency radio waves, the frequency band below 30 MHz is one of the last unexplored radio astronomy bands. Each satellite will host an astronomical antenna of 5.0 m size, which will consist of three orthogonal dipoles [42, 43].

D. Space Ultra-Low Frequency Radio Observatory Mission Concept
The Space Ultra-Low Frequency Radio Observatory (SULFRO) mission concept, led by Chinese Academy of Science, aims to launch an uncontrolled constellation, consisting of a microsatellite mothership and 12 nanosatellite deputies, in a Lissajous or halo orbit around the second sun–Earth Lagrange point (L2). Each deputy satellite will have three dipole antennas that will enable observing “all the sky all the time” in the 1–100 MHz frequency range [44].

A summary of various astronomy and astrophysics related mission concepts that are possible using nanosatellites and the scientific and technological requirements for those missions are presented in
The requirements on position and attitude knowledge for state-of-the-art science missions are discussed in [112].

IV. Planetary Science Missions

The aim of planetary science missions is to understand the planets and small bodies that inhabit our solar system and the origins of life [113]. For example, NASA’s Gravity Recovery and Interior Laboratory (GRAIL) mission, which used two 200 kg spacecraft at 175–225 km separation, obtained high-quality gravitational field maps of the moon to determine its interior structure [114]. Asteroid mapping and retrieval using a single 6U CubeSat has been proposed [49,115]. Here, we present some planetary science related missions that need two or more small satellites.

A. Interplanetary Nanospacecraft Pathfinder In a Relevant Environment

The Interplanetary Nanospacecraft Pathfinder in a Relevant Environment (INSPIRE) is an interplanetary demonstration mission, led by JPL, where two nanosatellites are deployed beyond Earth orbit to evaluate communication, navigation, and payload-hosting technologies. Each of the two 3U CubeSats can determine their attitude to within ±7 arcsec (σ error) using a star tracker, gyroscopes, and photodiodes. The satellites can control their attitude using a four-thruster cold-gas system. The mission is scheduled for launch into an Earth-escape orbit in 2017 [45–46].

B. CubeSat Constellation at Mars Mission Concept

The aim of this mission concept, led by JPL, is to launch a constellation of 60 CubeSats around Mars to study the frequency, geographical distribution, and severity of electrical activity on Mars. It is envisioned that these orbiting sensors would be many orders of magnitude more sensitive than Earth-based sensors, even with less capable instruments onboard, because of their proximity to Mars [47].

C. Interplanetary Radio Occultation CubeSat Constellation Mission Concept

The Interplanetary Radio Occultation CubeSat Constellation (iROCC) mission concept, led by Massachusetts Institute of Technology, aims to send six 3U CubeSats as a secondary payload on a larger interplanetary spacecraft to another planet. The constellation will use radio occultation to measure the temperature, pressure, and electron density profiles of a planet’s atmosphere and ionosphere [48].

V. Heliophysics Missions

The aim of heliophysics missions is to explore the sun–Earth system to understand the sun and its interactions with Earth and the solar system [116]. In this section, we present a heliophysics related mission that aims to use multiple small satellites.

A. Solar Polar Imager Mission Concept

This conceptual mission, led by JPL and funded by NASA’s Innovative Advanced Concepts, proposes to launch a constellation of six 6U CubeSats for studying helioseismology and magnetic fields of polar regions. The constellation will be placed in a highly inclined out-of-ecliptic vertical orbit with semimajor axis of approximately 0.99 astronomical unit. The CubeSats, equipped with host of scientific instruments, will use solar sails to reach the high inclination [49].

VI. Technology Demonstration Missions

Technology demonstration missions aim to demonstrate the application of state-of-the-art technology in space. Multisatellite technology demonstration missions using conventional large satellites have been proposed like the Technology Satellite of the 21st Century (TechSat-21) [117], System F6 [118], Project for On-Board Autonomy-3 (PROBA-3) [119], Prototype Research Instruments and Space Mission Technology Advancement (PRISMA) [17,120], and Ultralarge Solar Sail System (UltraSail) [121]. The Surrey Nanosatellite Applications Demonstration missions that use or aim to use two or more small satellites whose masses are less than 10 kg.

A. Space Tethered Autonomous Robotic Satellite

The Space Tethered Autonomous Robotic Satellite (STARS) mission, led by Kagawa University and Takamatsu National College of Technology, Japan, demonstrated undocking and docking of a daughter satellite with a mother satellite using 10 m tether. The mother satellite of mass 4.2 kg and the daughter satellite of mass 3.8 kg are shown in Fig. 6a [128]. The mother satellite first deployed the daughter by injecting an initial velocity, and then it retrieved it using the tether, and the daughter finally docked with the mother satellite. The
mission was launched as a secondary payload on 23 January 2009 on the H-IIA vehicle from the Tanegashima Space Center, Japan. The mother satellite determined its attitude using GPS, magnetometers, and gyroscopes and controlled it using magnetorquers. The daughter satellite determined its attitude with respect to the mother satellite using a camera and then controlled it using its own arm link motion under tether tension. The mission achieved most of its objectives but faced instability problems in space [50].

B. AeroCube-4

Three AeroCube-4 satellites were built by the Aerospace Corporation, where each 1U CubeSat weighed 1.2 kg, as shown in Fig. 6b [129]. Each of these satellites could control its attitude to 1 deg absolute accuracy using Earth and sun sensors, a high-fidelity three-axis rate gyroscope, and an inertial measurement unit (IMU). These satellites could estimate its position with 20 m accuracy using a GPS receiver and control their position by varying their cross-sectional area using extendable wings. The satellites were launched into elliptical LEO (altitude of 480–780 km, inclination of 65 deg) as secondary payloads on an Atlas-5-411 vehicle of United Launch Alliance from VAFB on 13 September 2012 [51]. The satellites demonstrated formation flight by deliberately changing their drag profile and using different wing configurations, thereby reconfiguring themselves over the course of several weeks [52].

C. Prometheus

The Los Alamos National Laboratory launched eight Prometheus 1.5U CubeSats, where each satellite weighed 2 kg, as shown in Fig. 7a [53], to demonstrate the capability of transferring audio, video, and data files from man-portable, low-profile, remote field units to deployable ground station terminals using over-the-horizon satellite communications. The eight satellites were launched into circular LEO (altitude of 500 km, inclination of 40.5 deg) as secondary payloads on a Minotaur-1 rocket for Wallops Island, Virginia, on 19 November 2013 [53,54]. Each satellite features four deployable solar arrays, a deployable helix antenna, and a service life of three to five years. A similar mission is also being led by the U.S. Army Space and Missile Defense Command [130].

D. KickSat

The KickSat project, led by Cornell University, is a citizen space exploration project to dispense hundreds of small ChipSats into LEO, assess their in-orbit performance, and study their reentry characteristics. This project was “crowd-funded” using Kickstarter. After launch, the central 3U CubeSat, shown in Fig. 7b [131], would launch 104 small Sprite ChipSats, each of size $32 \times 32 \times 4$ mm and weighing less than 7.5 g. The mission was launched into LEO (altitude of 325 km, inclination of 51.6 deg) as secondary payloads on SpaceX’s Dragon launch vehicle from Cape Canaveral, Florida, on 18 April 2014. The ChipSats could not be deployed due to timer reset, and the satellite reentered the Earth’s atmosphere on 15 May 2014 [55].

E. VELOX-1

The VELOX-1 mission, led by the Nanyang Technological University, Singapore, comprised a nanosatellite and a picosatellite that demonstrated intersatellite communications in orbit. The 3U nanosatellite with deployable solar panels released a $70 \times 60 \times 30$ mm picosatellite once in orbit, as shown in Fig. 8a [132]. The nanosatellite achieved three-axis attitude stabilization using a GPS, two IMUs, one dual field of view sun sensor, eight coarse sun sensors, three magnetic torquers, and three reaction wheels. The mission was launched as a secondary payload on 30 June 2014 on the PSLV-C23
vehicle from Satish Dhawan Space Center, Sriharikota, India, and it successfully achieved its objectives [56].

F. Canadian Advanced Nanospace Experiments 4 and 5

The Canadian Advanced Nanospace Experiments 4 and 5 (CanX-4&5) mission, led by the University of Toronto and primarily supported by Canadian Space Agency, is a dual-nanosatellite mission that demonstrated satellite formation flying with submeter tracking error accuracy and low change in velocity (ΔV) requirements. Each nanosatellite, weighing less than 7 kg as shown in Fig. 8b [133], was capable of attitude control accuracy of 1 deg using six coarse/fine sun sensors, a three-axis magnetometer, three rate gyroscopes, three magnetorquer coils, and three orthogonal mounted reaction wheels. The satellites could achieve relative position determination accuracy of 10 cm using intersatellite communication and differential GPS techniques. The satellites performed formation maneuvers, with relative position control accuracy of 1 m, using the Canadian Advanced Nanospace Propulsion System (CNAPS) propulsion system that had a maximum thrust of 5 mN and total ΔV of 14 m/s. The CanX-4&5 nanosatellites were successfully launched into sun-synchronous LEO (altitude of 660 km, inclination of 98.2 deg) as secondary payloads on 30 June 2014 onboard the Indian PSLV-C23 launch vehicle from Sriharikota, India [57,58]. Using carrier-phase differential GPS techniques for extremely high-precision relative navigation, the two spacecraft were reconfigured to perform projected-circular orbit formations (in which one satellite appears to circle the other from a ground observer’s standpoint) at 100 m and then 50 m range. The satellites then executed a series of precise, controlled, autonomous formations, ranging from 1 km range down to 50 m separation [58]. This mission currently sets the bar for state-of-the-art FF missions.

G. CubeSat Proximity Operations Demonstration

The CubeSat Proximity Operations Demonstration (CPOD) mission, led by Tyvak Nano-Satellite Systems and funded by NASA STMD, aims to demonstrate rendezvous, proximity operations, formation flying, and docking in LEO using a pair of 3U CubeSats with deployable solar panels. The mission is scheduled for launch in 2016 through NASA’s ELaNa program [59,60].

H. AeroCube—Optical Communication and Sensor Demonstration

The AeroCube — Optical Communication and Sensor Demonstration (AeroCube-OCSD) project, developed by the Aerospace Corporation and supported by the NASA Small Spacecraft Technology Program (SSTP), aims to demonstrate optical communications from a CubeSat in LEO to a ground station terminal as well as demonstrate tracking of a nearby spacecraft using COTS sensors. The two 1.5U CubeSats will maneuver themselves within 200 m of each other using deployable wings and onboard cold gas thrusters, while avoiding collisions using a COTS automotive anticollision radar sensor and an inexpensive optical mouse sensor. These CubeSats can achieve absolute pointing accuracy of ±0.1 deg using GPS, sun and Earth horizon sensors, magnetometers, a star tracker, three magnetic torque rods, and three reaction wheels. This FF mission is scheduled for launch into a sun-synchronous LEO (expected altitude of 400–700 km) in 2016 [61].

I. Tianwang-1

The Tianwang-1 project, led by the Chinese Academy of Science, aims to demonstrate autonomous formation flying with two CubeSats and intersatellite communication using software-defined radio. The project consists of one 3U CubeSat and two 2U CubeSats and was launched into LEO on September 2015 from the Juquan Satellite Launch Center [62].

J. Rascal

The Rascal mission, led by the Saint Louis University and supported by NASA’s CubeSat Launch Initiative, aims to demonstrate key technologies for proximity operations and space situational awareness like infrared imaging, six-degree-of-freedom (DOF) propulsion, RF proximity sensing, and automated operations. Each of the two 3U CubeSats will determine relative positions and attitude using infrared and visible cameras, maneuver using a cold-gas 6-DOF propulsion unit, and dock with the base plate using Velcro. The mission is scheduled for launch in 2016 [63].

K. Space Autonomous Mission for Swarming and Geo-Locating Nanosatellites

The Space Autonomous Mission for Swarming and Geo-Locating Nanosatellites (SAMSON) mission, led by the Israel Institute of Technology and supported by the Israeli space industries, aims to demonstrate long-term autonomous formation flight of multiple satellites. Each of the three 3U CubeSats will carry a cold-gas propulsion system, an atomic clock, an intersatellite communication system, and deployable solar panels. The satellites will achieve formations with relative distances ranging from 100 m to 250 km. This mission is scheduled for launch in 2016 [64,65].

L. Swarms of Silicon Wafer Integrated Femtosatellites

The Swarms of Silicon Wafer Integrated Femtosatellites (SWIFT) mission, led by JPL, University of Illinois at Urbana-Champaign (UIUC), and Scientific Systems Company, Inc., and funded by the Defense Advanced Research Projects Agency, aims to launch a swarm (hundreds to thousands) of 100-g-class femtosatellites into LEO for applications like sparse aperture arrays and distributed sensor networks. The swarm will be capable of forming three-dimensional shapes and maintaining them in a fuel-efficient manner. Each femtosatellite, weighing 100 g as shown in Figs. 9a and 9b, will house a communication system, three-axis attitude and position sensors, an onboard computer and power unit, microreaction wheels, and a propulsion unit based on either microthrusters or a miniaturized hydrazine system. The design study [1] concludes that the success of the SWIFT flight demonstration is predicated on successful miniaturization of the propulsion system and electronics for long-distance communication.

![Fig. 9 Notional design of femtosatellite with a) digital microthruster system, and b) miniaturized warm gas hydrazine system. The size of the femtosatellite is $4 \times 4 \times 4.25 \text{ cm}$ (image credit: JPL [1]).](image)
M. Kyushu/U.S. Experimental Satellite Tether Mission Concept

The Kyushu/U.S. Experimental Satellite Tether (QUEST) mission, a joint project between Arizona State University, Santa Clara University, and Kyushu University in Japan, aims to first deploy a 2-km-long tether in space and then maintain a formation by cooperatively controlling the main satellite and the subsatellite [66]. A similar mission for generating artificial gravity has been proposed [134].

N. High-Speed, Multispectral, Adaptive Resolution Stereographic CubeSat Imaging Constellation Mission Concept

The High-Speed, Multispectral, Adaptive Resolution Stereographic CubeSat Imaging Constellation (HiMARC) mission concept, led by Stanford University, aims to launch an uncontrolled constellation of four 3U synthetic aperture optical telescopes for providing rapid, multispectral, high-resolution stereographic images of terrestrial, solar, lunar, and astronomical targets [67, 68].

O. Real-Time Geolocation Mission Concept

This conceptual project, led by Israel Institute of Technology, aims to use a formation of two or three LEO satellites for performing measurements of sequential time difference of arrival to accurately determine the position of a terrestrial source emitting electromagnetic pulses. It is envisaged that spaceborne geolocation with a small satellite formation could provide accurate tracking of a Mars rover, a redundant navigation system in a jammed GNSS environment, or a cost-effective system for autonomously locating distress signals [69].

P. Humanitarian Satellite Constellation Mission Concept

The Humanitarian Satellite Constellation (HumSat) mission concept, led by ESA, is an international educational initiative for building a constellation of nanosatellites for providing worldwide communication capabilities to areas without infrastructure. The aim is to deploy a worldwide constellation of CubeSats to support humanitarian and emergency applications as well as to monitor parameters related to climate change. Nineteen universities worldwide have expressed their interest in developing the satellites of the global constellation [70, 71].

Q. University of Illinois at Urbana–Champaign/JPL Formation Flying CubeSats Mission Concept

This conceptual mission [15], led by the University of Illinois at Urbana–Champaign (UIUC) and funded by JPL, aims to launch four or six CubeSats into LEO to demonstrate formation flying capabilities in space. The four CubeSats will maintain a tetrahedron formation in space. The six CubeSats will demonstrate optimal reconfiguration maneuvers using real-time sequential convex programming [33] between multiple $J_2$ invariant relative orbits [12], which are collision-free passive orbits that require minimal amounts of fuel for orbit maintenance. Extensive simulations showed that the four-CubeSat configuration could be maintained to a 5 m accuracy for up to 100 orbits, and the six-CubeSat configuration could perform up to 20 reconfigurations between $J_2$ invariant orbits using state-of-the-art COTS sensors and actuators [15].

VII. Conclusions

In this Note, 39 multisatellite missions using small satellites were surveyed. It is concluded that the technology for developing constellation missions using small satellites has matured. Therefore, private companies are launching missions with commercial interests in this area (e.g., Flock-1 [23]). Moreover, most science-driven missions (20 out of 22) only require a constellation. On the other hand, there is a lot of interest in demonstrating formation flying capabilities using two or three small satellites with or without docking capabilities for the purpose of enabling new science missions. Only two FF missions are currently planning to use four or more small satellites, namely SWIFT [1] and UIUC–JPL FF CubeSats [15]. Currently, the CanX-4&5 mission sets the bar for state-of-the-art FF missions.

Table 2 lists the missions, among launched and completed missions, that have the best accuracies for different control parameters. The CanX-4&5 satellites used differential GPS techniques to achieve such remarkable relative position determination accuracy. A survey of state-of-the-art technologies, sensors, and actuators for small satellites is presented in [6]. Intersatellite communication is another important technology necessary for FF missions, but it is not regarded as a bottleneck [15]. Finally, it is concluded that there is a dearth of FF missions aiming to use four or more small satellites. It is envisaged that this note will inspire FF missions in this area.

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