A Review of Formation Flying and Constellation Missions using Nanosatellites

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I. Introduction

Small satellites are enabling multi-satellite missions that were not otherwise possible because of their small size and modular nature. 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, and synthetic apertures. 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). Small satellites that weigh less than 10 kg can be broadly classified into nanosatellites (mass between 1-10 kg), picosatellites (mass between 0.1-1 kg), and femtosatellites (mass less than 100 grams). A class of standardized nanosatellites, called CubeSats, range in sizes from 1U (10 × 10 × 10 cm) to 6U (30 × 20 × 10 cm), weigh between 1-8 kg, and are usually launched using the standardized CubeSat deployment system called Poly Picosatellite Orbital Deployer (P-POD). In this paper, we survey thirty-nine multi-satellite 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 sources.
The objectives of this paper 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.

Multi-satellite missions can be broadly divided into two categories, namely FF missions and constellation missions. The dynamic states of formation flying satellites are coupled through a common control law. In other words, in a 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. Multi-satellite 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 Global Positioning System (GPS) satellites constitute a constellation since their orbit corrections require only the individual satellite’s position and velocity (states).

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 either active propulsion systems or the ability to actively change their drag profiles. Multi-satellite missions without position control are categorized under uncontrolled constellation missions.

I.A. Challenges in Formation Flying 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. 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. 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. Because of these challenges, FF missions is an active area for research and development (for example, see Refs. and the references therein).

I.B. Categorization of Multi-Satellite Missions

In Fig. 1, we have categorized the thirty-nine small satellite missions into constellations missions (controlled or uncontrolled) and FF missions (with or without docking). These missions are also grouped into five mission
types, namely Earth science (Section II), astronomy and astrophysics (Section III), planetary science (Section IV), heliophysics (Section V), and technology demonstrations (Section VI). Based on Fig. 1, we conclude that Earth science missions (fourteen) are the most popular among science-driven missions (twenty-two). Moreover, twenty of these science-driven missions only require a constellation. Among the seventeen
Table 1: Key for Fig. 1 and Fig. 2

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Mission’s Name</th>
<th>Lead Institution</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DICE</td>
<td>Utah State University</td>
<td>II.A</td>
</tr>
<tr>
<td>2</td>
<td>FIREBIRD</td>
<td>Montana State University</td>
<td>II.B</td>
</tr>
<tr>
<td>3</td>
<td>Flock-1</td>
<td>Planet Labs</td>
<td>II.C</td>
</tr>
<tr>
<td>4</td>
<td>EDSN (25, 26, 27)</td>
<td>Ames Research Center, NASA</td>
<td>II.D</td>
</tr>
<tr>
<td>5</td>
<td>QB50 (28, 29, 30)</td>
<td>Von Karman Institute</td>
<td>II.E</td>
</tr>
<tr>
<td>6</td>
<td>GGC (31)</td>
<td>Jet Propulsion Laboratory, NASA</td>
<td>II.F</td>
</tr>
<tr>
<td>7</td>
<td>RocketCube (32)</td>
<td>Dartmouth College</td>
<td>II.G</td>
</tr>
<tr>
<td>8</td>
<td>Charybdis (33)</td>
<td>University of Strathclyde</td>
<td>II.H</td>
</tr>
<tr>
<td>9</td>
<td>Centinel (34)</td>
<td>Imperial College London</td>
<td>II.I</td>
</tr>
<tr>
<td>10</td>
<td>Temperature Humidity Sounding (35)</td>
<td>Jet Propulsion Laboratory, NASA</td>
<td>II.J</td>
</tr>
<tr>
<td>11</td>
<td>FTS CubeSat (36)</td>
<td>Exelis Geospatial Systems</td>
<td>II.K</td>
</tr>
<tr>
<td>12</td>
<td>Ionospheric Tomography (37)</td>
<td>SRI International</td>
<td>II.L</td>
</tr>
<tr>
<td>13</td>
<td>SSAsat (38)</td>
<td>University of Adelaide</td>
<td>II.M</td>
</tr>
<tr>
<td>14</td>
<td>Artemis (39)</td>
<td>Artemis Space</td>
<td>II.N</td>
</tr>
<tr>
<td>15</td>
<td>BRITE (40)</td>
<td>University of Vienna</td>
<td>III.A</td>
</tr>
<tr>
<td>16</td>
<td>AAReST (41, 42)</td>
<td>California Institute of Technology</td>
<td>III.B</td>
</tr>
<tr>
<td>17</td>
<td>OLFAR (43, 44)</td>
<td>Delft University of Technology</td>
<td>III.C</td>
</tr>
<tr>
<td>18</td>
<td>SULFRO (45)</td>
<td>Chinese Academy of Science</td>
<td>III.D</td>
</tr>
<tr>
<td>19</td>
<td>INSPIRE (46, 47)</td>
<td>JPL</td>
<td>IV.A</td>
</tr>
<tr>
<td>20</td>
<td>CubeSat Constellation at Mars (48)</td>
<td>Jet Propulsion Laboratory, NASA</td>
<td>IV.B</td>
</tr>
<tr>
<td>21</td>
<td>iROCC (49)</td>
<td>Massachusetts Institute of Technology</td>
<td>IV.C</td>
</tr>
<tr>
<td>22</td>
<td>Solar Polar Imager (50)</td>
<td>Jet Propulsion Laboratory, NASA</td>
<td>V.A</td>
</tr>
<tr>
<td>23</td>
<td>STARS (51)</td>
<td>Kagawa University</td>
<td>VI.A</td>
</tr>
<tr>
<td>24</td>
<td>AeroCube-4 (52, 53)</td>
<td>Aerospace Corporation</td>
<td>VI.B</td>
</tr>
<tr>
<td>25</td>
<td>Prometheus (54, 55)</td>
<td>Los Alamos National Laboratory</td>
<td>VI.C</td>
</tr>
<tr>
<td>26</td>
<td>KickSat (56, 57)</td>
<td>Cornell University</td>
<td>VI.D</td>
</tr>
<tr>
<td>27</td>
<td>VELOX-1 (58)</td>
<td>Nanyang Technological University</td>
<td>VI.E</td>
</tr>
<tr>
<td>28</td>
<td>CanX-4k (59, 60)</td>
<td>University of Toronto</td>
<td>VI.F</td>
</tr>
<tr>
<td>29</td>
<td>CPOD (61, 62)</td>
<td>Tyvak Nano-Satellite Systems</td>
<td>VI.G</td>
</tr>
<tr>
<td>30</td>
<td>AeroCube-OCSD (63, 64)</td>
<td>Aerospace Corporation</td>
<td>VI.H</td>
</tr>
<tr>
<td>31</td>
<td>TW-1 (65)</td>
<td>Chinese Academy of Science</td>
<td>VI.I</td>
</tr>
<tr>
<td>32</td>
<td>Rascal (66)</td>
<td>Saint Louis University</td>
<td>VI.I</td>
</tr>
<tr>
<td>33</td>
<td>SAMSON (67, 68)</td>
<td>Israel Institute of Technology</td>
<td>VI.K</td>
</tr>
<tr>
<td>34</td>
<td>SWIFT (69)</td>
<td>Jet Propulsion Laboratory, NASA</td>
<td>VI.L</td>
</tr>
<tr>
<td>35</td>
<td>QUEST (70)</td>
<td>Kyushu University</td>
<td>VI.M</td>
</tr>
<tr>
<td>36</td>
<td>HiMARC (70, 71)</td>
<td>Stanford University</td>
<td>VI.N</td>
</tr>
<tr>
<td>37</td>
<td>Real-Time Geolocation (72)</td>
<td>Israel Institute of Technology</td>
<td>VLO</td>
</tr>
<tr>
<td>38</td>
<td>HumSat (73, 74)</td>
<td>European Space Agency</td>
<td>VI.P</td>
</tr>
<tr>
<td>39</td>
<td>UIUC-JPL FF CubeSats (75)</td>
<td>University of Illinois at Urbana-Champaign</td>
<td>VI.Q</td>
</tr>
</tbody>
</table>

technology demonstration missions, ten 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
The categorization of the thirty-nine multi-satellite missions, based on their current mission status, leading organizations, and their funding sources, are shown in Fig. 2. The primary funding sources for multi-satellite missions are the National Aeronautics and Space Administration (NASA) and NASA centers like the Jet Propulsion Laboratory (JPL), the National Science Foundation (NSF), the US Department of Defense (DoD), non-US agencies like the European Space Agency (ESA), Canadian Space Agency (CSA), Chinese Academy of Sciences, and private companies. The various mission status categories are: (i) concept, where the mission concept has been proposed and preliminary design work is being carried out; (ii) in development, where the hardware for the satellites is being developed; (iii) 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; (iv) launched, where the mission has been launched into orbit and the satellites are currently operational; and (v) completed, where the satellites were previously launched and the mission successfully or unsuccessfully achieved its desired objectives. Based on Fig. 2, we conclude that twenty-one missions are being led by universities around the world. Among the fourteen FF missions, three have already been launched and five are set to be launched within the next two years.

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.81 A number of multi-satellite Earth science missions, involving conventional large satellites, have been launched including the Afternoon Train (A-train),82 Gravity Recovery And Climate Experiment (GRACE),83 Time History of Events and Macroscale Interactions during Substorms (THEMIS),84 Cluster II,85 Swarm,86 TerraSAR-X add-on for Digital Elevation Measurement (TanDEM-X),87 Magnetospheric MultiScale Constellation (MMS),88 and Skybox Imaging.89 Cyclone Global Navigation Satellite System (CYGNSS) is a constellation of eight microsatellites (weighing 17.6 kg each) which aims to improve extreme weather predictions and is scheduled for launch in 2016.90 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),91 Drag-free CubeSat,92,93 ExoCube,94 Pratham,95 while weather monitoring could be done by Microsized Microwave Atmospheric Satellite (MicroMAS),96 Weathernews Inc. Satellite (WNISAT),97 the Colorado Student Space Weather Experiment (CSSWE).98 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 multi-satellite 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.

II.A. Dynamic Ionosphere CubeSat Experiment (DICE)

DICE was a multi-university mission, led by Utah State University and supported by NSF and NASA’s ELaNa program, which launched two 1.5U CubeSats into an elliptical LEO (altitude of 410 – 820 km, inclination of 102°) in October 2011. As shown in Fig. 3(a), 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 Mbits per second. These CubeSats could determine their absolute attitude to within ±0.7° (1σ error) using GPS, magnetometer, and sun sensors. They could control their absolute attitude to within ±5° (1σ error) using torque coils.

II.B. Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics (FIREBIRD)

The 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. 3(b),
were launched into sun-synchronous LEO (altitude of 467 – 883 km, inclination of 120.5°) as secondary payloads on an Atlas-5-501 launch vehicle from Vandenberg Air Force Base (VAFB), CA in Dec. 6, 2013.\textsuperscript{21, 22} Two additional FIREBIRD-II 1.5U CubeSats were launched into sun-synchronous LEO (altitude of 685 km, inclination of 98°) as secondary payloads on a Delta-2 launch vehicle from VAFB, CA in Jan. 31, 2015. These CubeSats featured passive magnetic attitude control. Since these CubeSats cannot control their position, this mission belongs to the uncontrolled constellation category.

II.C. Flock-1 Imaging Constellation

The Flock-1 constellation, developed by Planet Labs Inc., consists of over a hundred 3U CubeSats that provide 3-5 m resolution images of Earth for environmental, humanitarian, and business applications. The twenty-eight Flock 1 CubeSats, shown in Fig. 4(a), were launched into LEO (altitude of 400 km, inclination of 52°) from the International Space Station using the NanoRacks CubeSat Deployer in mid-February 2014.\textsuperscript{23} Currently the company has launched 113 CubeSats into space.\textsuperscript{102} These CubeSats are capable of actively changing their drag profiles by changing their attitude with respect to the flight direction, hence this is a controlled constellation mission.\textsuperscript{24}

II.D. Edison Demonstration of Smallsat Networks (EDSN)

The primary scientific purpose of the 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 in order to characterize the radiation environment in LEO by measuring the location and intensity of energetic charged particles simultaneously over a geographically dispersed area.\textsuperscript{25, 26} Each CubeSat has

\begin{figure}
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\includegraphics[width=\textwidth]{figure4.png}
\caption{(a) Flock-1 nanosatellites prior to launch (image credit: Planet Labs\textsuperscript{23}). (b) Photograph of eight EDSN flight satellites and one spare unit (image credit: NASA Ames Research Center\textsuperscript{101}).}
\end{figure}
II.E. QB50

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

II.F. GNSS Geospace Constellation (GGC) Mission Concept

The 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. Here GNSS refers to the global navigation satellite system.
II.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 sub-orbital scientific missions. These RocketCubes can be launched by a sounding rocket and have no position control capability. The aim is to launch ten to twelve RocketCubes to observe the spatial and temporal variations in the ionosphere and aurora by conducting in situ observation. This mission is funded by JPL and NASA’s Experimental Program to Stimulate Competitive Research (EPSCoR) program.

II.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 multi-spectral 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 micro-propulsion systems) of 115 nanosatellites for bi-hourly global coverage or thirty nanosatellites for bi-hourly regional coverage over the UK mainland.

II.I. Centinel Mission Concept

The Centinel mission concept, led by Imperial College London and funded by UK 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.

II.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 fifteen 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. 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.
II.K. Fourier Transform Spectrometer (FTS) CubeSat Mission Concept

In this conceptual design, led by Exelis Geospatial Systems and the University of Michigan, three formation flying 6U CubeSats, carrying the FTS payload, would cooperatively measure the global wind field for compiling vertical profiles of the wind field and for long-term weather forecasts. The CubeSats will maintain revisit time of 12 hours.

II.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.

II.M. Space Situational Awareness (SSAsat) Mission Concept

The SSAsat 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. A similar space situational awareness mission, where the CubeSat constellation is launched to 500 km above GEO, has also been proposed by the Lockheed Martin Space Systems.

II.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 thirty-five 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.

III. Astronomy and Astrophysics Missions

The aim of astronomy and astrophysics missions is to understand the universe and our place in it. 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. A single CubeSat mission was proposed for performing observations in the 21-cm wavelength from the shielded zone behind the Moon. In this section, we present astronomy and astrophysics related missions which use or aim to
use two or more small satellites.

III.A. BRIght-star Target Explorer (BRITE) Constellation

The 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. 5(b), use the GNB (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 determine 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.40

III.B. Autonomous Assembly of a Reconfigurable Space Telescope (AAReST)

The AAReST mission, led by California Institute of Technology and Surrey Space Centre and funded by Keck Institute for Space Studies, aims to demonstrate autonomous assembly and reconfiguration of a space telescope by having two 3U CubeSats autonomously un-dock and re-dock with a central 9U nanosatellite core. The central nanosatellite houses two fixed mirrors and a boom-deployed focal plane assembly, while the two 3U CubeSats each carry an electrically actuated adaptive mirror.41, 42 These satellites aim to achieve attitude control to within ±1° in all axes, with 0.5°/s slew rate, using a GPS receiver, a 3-axis magnetometer, CMOSArray-based Sun and Earth sensors, a 3-axis magnetorquer, and three reaction wheels.42

III.C. Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) Mission Concept

The 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. Due to the opaqueness of the ionosphere to low frequency radio waves, the frequency band below 30 MHz is one of the last unexplored frequency range in radio astronomy. Each satellite will host an astronomical antenna of 5.0 m size, which will consists of three orthogonal dipoles.43, 44

III.D. Space Ultra-Low Frequency Radio Observatory (SULFRO) Mission Concept

The SULFRO mission concept, led by Chinese Academy of Science, aims to launch an uncontrolled constellation, consisting of a microsatellite mothership and twelve 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.45
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 Refs. 111,112,113,114. The requirements on position and attitude knowledge for state-of-the-art science missions are discussed in Ref. 115.

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. For example, NASA’s GRAIL mission, which used two 200 kg spacecraft at 175 – 225 km separation, obtained high-quality gravitational field maps of the Moon in order to determine its interior structure. Asteroid mapping and retrieval using a single 6U CubeSat has been proposed. Here we present some planetary science related missions that need two or more small satellites.

IV.A. Interplanetary NanoSpacecraft Pathfinder In a Relevant Environment (INSPIRE)

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 (1σ 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 2015.

IV.B. CubeSat Constellation at Mars Mission Concept

The aim of this mission concept, led by JPL, is to launch a constellation of sixty 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 on board, because of their proximity to Mars.

IV.C. Interplanetary Radio Occultation CubeSat Constellation (iROCC) Mission Concept

The iROCC mission concept, led by MIT, 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.

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. In this section, we present a heliophysics related mission
that aims to use multiple small satellites.

V.A. Solar Polar Imager Mission Concept

This conceptual mission, led by JPL and funded by NASA’s Innovative Advanced Concepts (NIAC), 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.

VI. Technology Demonstration Missions

Technology demonstration missions aim to demonstrate the application of state-of-the-art technology in space. Multi-satellite technology demonstration missions using conventional large satellites have been proposed like Technology Satellite of the 21st Century (TechSat-21), System F6, Project for On-Board Autonomy-3 (PROBA-3), Prototype Research Instruments and Space Mission technology Advancement (PRISMA), and Ultralarge Solar Sail System (UltraSail). Surrey Nanosatellite Applications Program (SNAP-1) was the first nanosatellite that demonstrated orbit control using onboard propulsion in June 2000. The Orbiting Picosatellite Automatic Launcher (OPAL) mission successfully ejected six picosatellites from a single microsatellite (weighing 25.5 kg) in January 2000. The Space Technology 5 (ST5) constellation mission launched three microsatellites (each weighing 25 kg) in March 2006 in order to map the intensity and direction of magnetic fields within the inner magnetosphere. The two AprizeSat-3&4 microsatellites (each weighing 13 kg) were launched in July 2009 and they demonstrated Automatic Identification System (AIS) instrument technology for detecting ships on the oceans. The Formation Autonomy Spacecraft with Thrust, Rehnav, Attitude and Crosslink (FASTRAC) mission launched two microsatellites (each weighing 27 kg) in November 2010 and they demonstrated enabling technologies for satellite formations like on-orbit micro-thrust capability, relative navigation, attitude determination, and satellite crosslink communications. The Japan Canada Joint Collaboration Satellites – Formation Flying (JC2Sat-FF) mission aims to demonstrate autonomous formation flight with aerodynamic drag control and GPS-based relative navigation using two microsatellites (each weighing 20 kg). In this section, we present technology demonstration missions which use or aim to use two or more small satellites whose masses are less than 10 kg.
VI.A. Space Tethered Autonomous Robotic Satellite (STARS)

The 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 a 10 m tether. The mother satellite of mass 4.2 kg and the daughter satellite of mass 3.8 kg are shown in Fig. 6(a). 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 January 23, 2009 on the H-IIA vehicle from the Tanegashima Space Center, Japan. The mission achieved most of its objectives but faced instability problems in space.

VI.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. 6(b). Each of these satellites could control its attitude to 1° absolute accuracy using Earth and sun sensors, high fidelity 3-axis rate gyroscope and an inertial measurement unit. 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°) as secondary payloads on an Atlas-5-411 vehicle of United Launch Alliance from Vandenberg Air Force Base, CA in September 13, 2012. 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.53

VI.C. Prometheus

The Los Alamos National Laboratory launched eight Prometheus 1.5U CubeSats, where each satellite weighed 2 kg as shown in Fig. 7(b), in order to demonstrate the capability of transferring audio, video, and data files from man-portable, low-profile, remote field units to deployable ground stations terminals using over-the-horizon satellite communications. The eight satellites were launched into circular LEO (altitude of 500 km, inclination of 40.5°) as secondary payloads on a Minotaur-1 rocket for Wallops Island, VA, in November 19, 2013.54, 55 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 & Missile Defense Command.134

VI.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 re-entry characteristics. This project was “crowd-funded” using Kickstarter.56 After launch, the central 3U CubeSat, shown in Fig. 7(a), would launch 104 small Sprite ChipSats, each of size 32 × 32 × 4 mm and weighing less than 7.5 gram. The mission was launched into LEO (altitude of 325 km, inclination of 51.6°) as secondary payloads on SpaceX’s Dragon launch vehicle from Cape Canaveral, FL in April 18, 2014. The ChipSats could not be deployed due to timer reset and the satellite reentered the Earth’s atmosphere on May 15, 2014.57
VI.E. VELOX-1

The VELOX-1 mission, led by the Nanyang Technological University, Singapore, comprised of a nanosatellite and a picosatellite that demonstrated inter-satellite communications in orbit. The 3U nanosatellite with deployable solar panels released a 70 × 60 × 30 mm picosatellite once in orbit, as shown in Fig. 8(a). The nanosatellite achieved 3-axis attitude stabilization using a GPS, two IMUs, one dual-FOV sun sensor, eight coarse sun sensors, three magnetic torquers, and three reaction wheels. The mission was launched as a secondary payload on June 30, 2014 on the PSLV-C23 vehicle from Satish Dhawan Space Center, Sriharikota, India and it successfully achieved its objectives.58

VI.F. Canadian Advanced Nanospace eXperiment-4&5 (CanX-4&5)

The 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 sub-meter tracking error accuracy and low change in velocity (ΔV) requirements. Each nanosatellite, weighing less than 7 kg as shown in Fig. 8(b), was capable of attitude control accuracy of 1° using six coarse/fine sun sensors, a 3-axis magnetometer, three rate gyroscopes, three magnetorquer coils, and three orthogonally-mounted reaction wheels. The satellites could achieve relative position determination accuracy of 10 cm using inter-satellite communication and differential GPS techniques. The satellites performed formation maneuvers, with relative position control accuracy of 1 m, using the 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°) as secondary payloads in June 30, 2014 on board the Indian PSLV-C23 launch vehicle from Sriharikota, India.59,60 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. This mission currently sets the bar for state-of-the-art FF missions.

VI.G. CubeSat Proximity Operations Demonstration (CPOD)

The 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 duplicate 3U CubeSats with deployable solar panels. The mission is scheduled for launch in 2016 through NASA’s ELaNa program.

VI.H. AeroCube - Optical Communication and Sensor Demonstration (AeroCube-OCSD)

The 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 and also 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 laser rangefinder and an inexpensive optical mouse sensor. These CubeSats can achieve absolute pointing accuracy of ±0.1° using 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.

VI.I. TW-1

The TW-1 project, led by Chinese Academy of Science, aims to demonstrate autonomous formation flying with two CubeSats and inter-satellite communication using software-defined radio. The project consists of one 3U CubeSat and two 2U CubeSats and is scheduled for launch into LEO in 2015.

VI.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, 6DOF propulsion, RF proximity sensing, and automated operations. Each of the two 3U CubeSats will determine relative positions and attitude using IR and visible cameras, maneuver using a cold-gas 6DOF propulsion unit and dock with the baseplate using Velcro. The mission is scheduled for launch in 2016.
VI.K. Space Autonomous Mission for Swarming and Geo-locating Nanosatellites (SAMSON)

The 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 inter-satellite 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.\textsuperscript{67,68}

VI.L. Swarms of Silicon Wafer Integrated Femtosatellites (SWIFT)

The SWIFT mission, led by JPL, UIUC, and Scientific Systems Company, Inc. and funded by DARPA, aims to launch a swarm (100s to 1000s) of 100-gram-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 grams as shown in Fig. 9(a,b), will house a communication system, 3-axis attitude and position sensors, a on-board computer and power unit, micro reaction wheels, and a propulsion unit based on either microthrusters or a miniaturized hydrazine system. The design study \textsuperscript{1} concludes that the success of SWIFT flight demonstration is predicated on successful miniaturization of the propulsion system and electronics for long-distance communication.

VI.M. Kyushu/US Experimental Satellite Tether (QUEST) Mission Concept

The 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 sub-satellite.\textsuperscript{69} A similar mission for generating artificial
VI.N. High-speed, Multispectral, Adaptive Resolution Stereographic CubeSat Imaging Constellation (HiMARC) Mission Concept

The 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. 70, 71

VI.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 in order to accurately determine the position of a terrestrial source emitting electromagnetic pulses. It is envisaged that space-borne 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. 72

VI.P. Humanitarian Satellite Constellation (HumSat) Mission Concept

The 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, and to monitor parameters related to climate change. Nineteen universities worldwide have expressed their interest in developing the satellites of the global constellation. 73, 74

VI.Q. UIUC-JPL Formation Flying CubeSats Mission Concept

This conceptual mission, 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 between multiple $J_2$ invariant relative orbits, 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 paper, we surveyed thirty-nine multi-satellite missions using small satellites. We conclude 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\textsuperscript{23}). Moreover, most science-driven missions (twenty out of twenty-two) 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\textsuperscript{1} and UIUC-JPL FF CubeSats.\textsuperscript{15} Currently, CanX-4&5 mission sets the bar for state-of-the-art FF missions.

Table 2: Best Accuracies of Control Parameters

<table>
<thead>
<tr>
<th>Control Parameter</th>
<th>Accuracy</th>
<th>Mission's Name</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Attitude Determination</td>
<td>10 arcsec (rms error)</td>
<td>BRITE</td>
<td>III.A</td>
</tr>
<tr>
<td>Absolute Attitude Control</td>
<td>1 arcmin (rms error)</td>
<td>BRITE</td>
<td>III.A</td>
</tr>
<tr>
<td>Absolute Position Determination</td>
<td>2 – 5 m (rms error)</td>
<td>CanX-4&amp;5</td>
<td>VI.F</td>
</tr>
<tr>
<td>Relative Position Determination</td>
<td>2 – 5 cm (rms error)</td>
<td>CanX-4&amp;5</td>
<td>VI.F</td>
</tr>
<tr>
<td>Relative Position Control</td>
<td>1 m (rms error)</td>
<td>CanX-4&amp;5</td>
<td>VI.F</td>
</tr>
</tbody>
</table>

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 Ref. 6. Inter-satellite communication is another important technology necessary for FF missions, but it is not regarded as a bottleneck.\textsuperscript{15} Finally, we conclude that there is a dearth of FF missions aiming to use four or more small satellites. We envisage that this paper will inspire FF missions in this area.

Acknowledgments

The authors would like to thank Dr. Tom Cwik at JPL for his guidance and constructive comments. The authors would also like to thank D. Morgan, D. Chen, S. Chan, Y. Taleb, D. Rogers, J. Kokkat, D. Hanley, J. Puig, and H.-B. Yoon for their valuable inputs. This work was supported by the Jet Propulsion Laboratory. Government sponsorship is acknowledged. This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.
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