Dynamics and Control of CubeSat Orbits for Distributed Space Missions

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Project Description: Research in Industrial Projects for Students (RIPS) Program - 2015

(Institute for Pure & Applied Mathematics – IPAM)

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Project Description:

The space industry is starting to realize the potential of small satellites. Indeed, the last decade has seen a substantial boom in their development, both domestically and internationally. Much of this growth can be attributed to the popularity of CubeSats, a well-known subclass of small satellites. Space missions in which the payload function is distributed among several satellites may benefit from the use of cluster orbits, where the satellites fly in a close formation with a relatively small Delta-V (ΔV) required to maintain the cluster. This concept was explored in the 1980s for geostationary communications satellites as a means for providing a collective payload capability greater than what could be carried on a single launch vehicle.

The purpose of this RIPS project is to select a mission (e.g., communications, remote sensing, or radiolocation) and determine a CubeSat cluster to meet the mission objectives. We anticipate the development of a general method for determining the cluster orbital elements, for predicting the disruption of the satellite formation due to the natural perturbing forces, and for estimating the maneuvering ΔV to counteract these forces. The formation-keeping strategy should be developed and tested with orbit perturbation and formation flying simulations in a near-circular orbit at 700-km altitude. The approach developed by the RIPS team should be applicable to a wide range of orbits and cluster configurations, although the formation keeping ΔV requirement may narrow the range of possibilities in a practical system.

To create a cluster constellation, the initial orbital elements must be chosen so that (1) each satellite occupies a node in an arbitrary spatial pattern and (2) the satellites undergo a cyclic motion that allows this formation to persist for several revolutions without maneuvering. Orbital elements are affected by natural perturbing forces such as the non-spherical geopotential, solar radiation pressure, and atmospheric drag, and hence maneuvers are required to counteract these forces. The two main challenges in developing a formation keeping algorithm are (1) achieving a tight tolerance for controlling each sub satellite and (2) minimizing the expenditure of propellant.

Work to be Done and Deliverables:

The proposed study for the summer of 2015 includes the following activities:

1. Survey and review domestic and international CubeSat Programs.
2. Select a mission (e.g., communications, remote sensing, or radiolocation) and determine CubeSat cluster to meet the mission objectives.
3. Determine cluster orbital elements and model/predict orbital motion due to perturbative forces (i.e., atmospheric drag, earth's geopotential).
4. Assess orbital stability of the CubeSat formation over time.
5. Determine performance drivers for supporting CubeSat formation flying (e.g., mission lifetime, minimum separation between sub satellites, satellite coverage, etc.).

Status:

.CubeSats derive their name from the so-called "1U" building block, which is a 10 × 10 × 10 centimeter cube, typically weighing around 1 kilogram. Larger CubeSats are built by stacking these units. Bob Twiggs (then at Stanford University) developed the initial concept in early 1999 after working with The Aerospace Corporation on his Orbiting Picosatellite Automated Launcher (OPAL) microsatellite.

The first CubeSat launched in June 2003; by the end of 2013, 155 had been placed in orbit, with 78 launched in 2013 alone. The United States, Russia, China, India, Japan, and the European Union all launched CubeSats in 2013. Almost 20 percent of the CubeSats launched that year were sponsored by the DOD. Aerospace has built and flown eight CubeSats since 2004 and is working on seven more.

CubeSats were originally conceived for education and flight tests of new technologies, but mission applications such as tactical communications, space weather measurement, and Earth observation are rapidly coming on line. The ability to design, build, test, fly, and redesign a spacecraft within one year is an obvious benefit for university students; but such fast development cycles also serve to spur the evolution of technologies and components for a wide range of future missions. These technologies can be applied to larger spacecraft to bring down launch and development costs. While the current launch architecture may not readily support the easy and timely launch of microsatellites in general, it does support the easy integration and launch of CubeSats.

Typical CubeSat missions in 2013 included flight-testing new technologies, hands-on education, store-and-forward communications, space science measurements, and Earth observation. Aerospace is helping the U.S. government develop several new mission areas. Some examples of government-sponsored Cubesats launched in 2013 include:

- AeroCube-5A and -5B. These 1.5U CubeSats were designed, built, and tested at Aerospace. They will demonstrate improved pointing capabilities needed for future missions and flight-test the CubeSat Terminator Tape Deorbit Module from Tethers Unlimited.
- SENSE-A and -B. These 3U CubeSats were sponsored by the Air Force Space and Missile Systems Center/Development Planning Directorate (SMC/XR) and built by Boeing. They will demonstrate collection of space weather data and timely integration of that data into ground-based ionospheric models for improved predictions.
- SMDC-ONE-2.3 and -2.4. Eight of these 3U CubeSats were developed by Miltec for the U.S. Army Space and Missile Defense Command to receive and forward data from unattended ground sensors and to provide voice and text message relay for field units.
- ORSES. This 3U CubeSat was developed by the Operationally Responsive Space office and the U.S. Army Space and Missile Defense Command to provide communications and data capabilities for underserved tactical users.
- STARE-B. This 3U CubeSat was developed by Lawrence Livermore National Laboratory to test the Space-based Telescopes for Actionable Refinement of Ephemeris (STARE) concept. STARE, in conjunction with ground-based assets, could provide improved accuracies for the orbital elements of space debris. Better orbital ephemerides should produce fewer false alarms during collision prediction routines, resulting in fewer collision-avoidance maneuvers for all LEO spacecraft.

References:

1. J.E. Pollard, C.C. Chao, and S.W. Janson, Populating and Maintaining Cluster Constellations in Low-Earth Orbit," Paper A99-31530, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 20-24 June 1999, Los Angeles, CA.
2. CC. Chao, J.E. Pollard, and S.W. Janson, "Dynamics and control of cluster orbits for distributed space missions," Paper AAS-99-126, Space Flight Mechanics Meeting, 7- 1 0-Feb 1999, Breckenridge, CO.

Prerequisites:

1. Advanced Calculus
2. Linear Algebra
3. Probability and Statistics
4. Advanced Physics
5. Numerical analysis
6. Introduction to Computer Science

Required: U.S. Citizenship

Keywords:
CubeSats, Satellite Clusters, Stationkeeping, Orbital Dynamics, Satellite Formation Flying

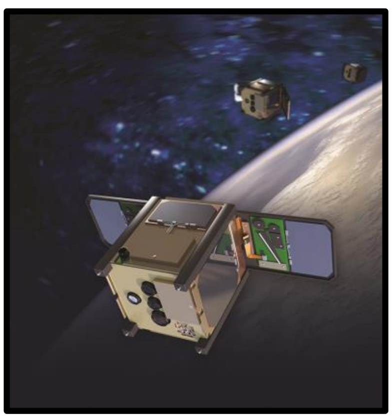

Figure 1. Artist depiction of CubeSat.

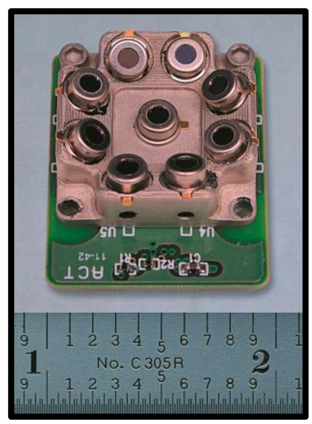

Figure 2. The CubeSat program has enabled Aerospace to design, build, and flight-test a number of satellite components. Shown here is the second generation Earth nadir sensor, which achieves a pointing accuracy of 1 degree.

Figure 3. Image of an almost completely frozen Lake Superior taken by AeroCube-4.

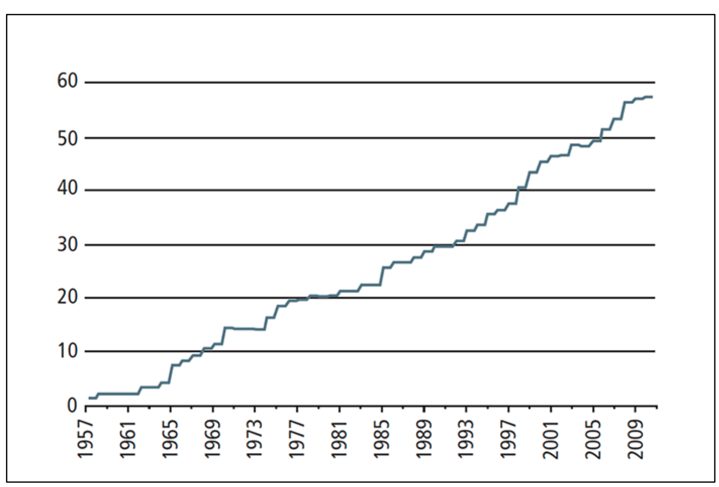

Figure 4. The number of nations and government consortia active in space has steadily increased over the last 50 years.