Chapter | one

Introduction

> The road became a channel running flocks
> Of glossy birds like ripples over rocks.
>
> **Robert Frost (1874–1963)**

In this chapter we introduce the readers to some of the fundamental questions, issues, and approaches related to spacecraft formation flying. In a sense, this chapter serves to provide a broad overview of the topics covered in this book. We also list some representative formation flying missions planned by NASA and ESA.

1.1 WHAT IS SPACECRAFT FORMATION FLYING?

The definition of *spacecraft formation flying* is not very precise or universally agreed upon. Most of the space community, however, would agree to the following definition, proposed by NASA's Goddard Space Flight Center (GSFC):

> The tracking or maintenance of a desired relative separation, orientation or position between or among spacecraft.

Formation flying spacecraft are therefore a particular case of a more general category, termed *distributed space systems*, defined by NASA GSFC as follows:

> An end-to-end system including two or more space vehicles and a cooperative infrastructure for science measurement, data acquisition, processing, analysis and distribution.

NASA GSFC proposed a number of other important distinctions: A *constellation* is a collection of space vehicles that constitutes the space element of a distributed space system; *virtual aperture* is an effective aperture generated by physically independent spacecraft; and *virtual platform* is a spatially distributed network of individual vehicles collaborating as a single functional unit, and exhibiting a common system-wide capability to accomplish a shared objective.

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1.2 COORDINATION APPROACHES

1.2.1 Orbit tracking

Single satellite missions are typically designed to occupy a particular orbit (as opposed to a particular location on the orbit) about which periodic stationkeeping maneuvers are conducted. This same approach can be extended to formations in which each satellite in the formation is controlled to a particular predetermined desired orbit. This approach is attractive from the perspective of allowing little or no cooperation or coordination between the spacecraft; however it is expected to require more maneuvers than methods that exploit the coupled nature of mission objectives.

1.2.2 Leader/Follower

In leader/follower coordination methods one *leader* spacecraft is controlled to a reference orbit and the other *follower* spacecraft in the formation control their relative states to that leader. This approach allows traditional periodic maneuvers to keep the leader in a desired orbit or ground-track while the remaining satellites in the formation control their relative state with respect to the leader. This approach has the advantage that it allows most satellites in the formation to follow the natural dynamics of the absolute orbit of the leader, while only performing regular automatic control on the relative states of the formation. The principal disadvantage of leader/follower is that the leader spacecraft is by definition at its correct state and will not require as much fuel use as the followers. Fuel use can be balanced among the satellites by periodically interchanging the designations of the leader and follower [5].

1.2.3 Virtual structure

Virtual structure [6] and virtual center [5] approaches fit a set of desired states to a formation in a way that minimizes the overall state error of the formation. The chief advantage of this approach over the leader/follower method is that state error will pertain to all the spacecraft in the formation. Adding fuel-weighting, as in Ref. [7], allows fuel use to be balanced methodically. The implementation of a virtual structure approach requires coordinated inter-spacecraft communication. An approach for coordination, formation maintenance and fuel balancing, developed from the fundamental astrodynamics principles of secular perturbations is presented in Ref. [156], and also discussed in Chapters 8 and 10 of this book.

1.2.4 Swarming

A number of researchers [8,9] have proposed simple heuristic control laws for arranging arbitrarily large numbers of vehicles into regular arrangements based on local information. These swarming methods have the advantage that they easily scale to large numbers of vehicles without incurring large communication or computation burdens. However, they are typically not fuel-optimal and rarely include provisions guaranteeing collision avoidance.

1.3 FUEL-USE DRIVERS

Minimizing fuel use is critical in any space mission, because fuel is expensive to launch into orbit and non-replenishable. Fuel use is expected to be a primary concern in the design of any spacecraft formation controller, because the task of keeping a formation from drifting apart and achieving science requirements is expected to require significantly more fuel than stationkeeping a single spacecraft. This section describes each of the expected drivers of fuel use in a spacecraft formation and details their expected impact on several types of control approaches.

1.3.1 Mission requirements

Several types of formation flying missions have been proposed: Interferometry, passive-aperture radar, and repeat ground-track observations. Each of these missions requires varying degrees of control to achieve observation objectives. Proposed interferometry missions require control of the spacecraft relative position with fine precision and to specific geometric templates. When the required geometry of a formation dictates that natural orbital perturbations be cancelled, significant amounts of fuel can be required to achieve mission objectives.

1.3.2 Initial conditions

The initial conditions (ICs), or the initial states, of the spacecraft in a formation dictate the future coasting behavior of the spacecraft formation. Choosing the ICs to make the future coasting behavior meet mission science requirements and minimize drift between spacecraft in the formation should minimize the need for future corrective maneuvering. In practice, it is rarely possible to choose initial conditions that completely eliminate inter-spacecraft drift, because of perturbations arising from Earth oblateness and drag. However, the ICs can be picked in such a way as to minimize the need for corrective action.

1.3.3 Navigation uncertainty

A significant source of fuel use is expected to be navigation uncertainty. In monolithic satellite systems, navigation would typically be handled by a series of ground-based observations from which a guidance maneuver would be designed. For a formation, control bandwidth is expected to be sufficiently high that on-orbit navigation will be required. Errors in navigation will lead to errors in state corrections, guaranteeing that some level of drift will always be present in the system, even if initial conditions are chosen that should completely eliminate drift. Correcting the drift in the system will require fuel.

1.3.4 Atmospheric drag

Although atmospheric drag can be considered in the dynamic models of the formation [10,11], in practice the effects of drag are partly stochastic. This is because the attitude estimation errors of each spacecraft in the formation will couple into the accelerations produced by drag for almost all spacecraft shapes. The drag equation [12]

$$\mathbf{a}_{\text{drag}} = -\frac{1}{2}\frac{c_D A}{m}\rho v^2 \hat{\mathbf{v}} = -\frac{1}{2}B^* \rho v^2 \hat{\mathbf{v}} \tag{1.1}$$

where m is the mass, c_D is the drag coefficient, ρ is the atmospheric density, $\hat{\mathbf{v}}$ is a unit vector lying along the velocity vector relative to the atmosphere and v is the magnitude of the velocity relative to the atmosphere, shows that the acceleration due to aerodynamic drag, $\mathbf{a}_{\text{drag}}$, is directly related to the cross-sectional area of the satellite A, which is determined by the attitude of the spacecraft, as well as to the *ballistic coefficient*, denoted by $B^* = c_D A/m$. An imperfect estimate of the attitude of the spacecraft will lead to errors in any trajectory predictions or corrections based on expected future drag effects.

1.3.5 Thrusting errors

Another source of uncertainty in any spacecraft mission is thrusting error. Thrusting errors arise from attitude estimation errors (i.e., thrusting in an unintended direction) and hardware design. A typical near-impulsive thruster can be modeled as a source of thrust within some percentage tolerance of a nominal force in a direction which is aimed correctly to within the knowledge of the attitude estimator. Both sources of thrusting errors couple to ensure that any attempt to cancel real drift resulting from system dynamics or perceived drift produced by navigation error will, in fact, also result in an additional source of drift, which will ultimately need to be corrected.

1.3.6 Dynamical process noise

In addition to thrusting errors, there will also be uncertainty in the dynamical model. This dynamical *process noise* will be a function of the fidelity of the dynamical model used for the controller implementation. Although the space environment is very well known, approximate linear models are often used because of their computational simplicity and ease of implementation. These models usually account for the effects of Earth's gravity modeled as a point mass, but may also take into account higher-order gravity terms (e.g., J_2). In addition, some linear models also include terms for drag [10]. However, in practice, dynamical models used for computing the control must always truncate or ignore some perturbations in order to be feasible. Typically, at least some of the higher-order gravitational terms, advanced atmospheric models, solar wind, and third-body effects of the Moon, the Sun and planets are excluded. These exclusions combine to form the dynamical model uncertainty.

1.4 CONTROL OF SPACECRAFT FORMATIONS

Formation flying spacecraft pose several control challenges beyond the problem of controlling a monolithic spacecraft or a constellation [13–16]. In a typical single-spacecraft mission, the term *control* would refer to maintaining and altering the attitude of the spacecraft, whereas *guidance* would encompass the maintenance and manipulation of the trajectory on the scale of an orbit. After launch and initial correcting maneuvers, adjusting a spacecraft's orbit would be an occasional activity planned from the ground. A constellation of spacecraft is operated in much the same way [17,18], because the constituent spacecraft operate in widely-spaced orbits (or spaced phase angles while in the same orbit), with short-term decoupled performance objectives. A formation of spacecraft is defined by the need for inter-satellite control cooperation [19]. The satellites in a formation are typically represented as sharing a common *reference orbit*, that is, being close enough in terms of their position and velocity in a central body frame that their long-term, large-scale motion can be modeled using the dynamics of a single orbit. This proximity, while typical for rendezvous missions, is uncommon for satellite missions where there is an expectation for long-term collision-free operation. Formation flying is expected to require a level of autonomous onboard guidance that in most applications would be classified as automatic control [19–22].

Many formation control approaches have been presented in the literature [6,14,19,23–30]. These papers cover a variety of approaches, including proportional-derivative (PD), linear quadratic regulation (LQR), linear matrix inequalities (LMI), nonlinear, Lyapunov, impulsive, rapidly exploring random trees (RRT), and model predictive. Typically, it is assumed that a formation is initialized to a stable orbit and deviations caused by perturbations such as differential drag and/or differential J_2 must be corrected. Some approaches, such as Lyapunov controllers and PD controllers [28,31], require that control be applied continuously, a strategy both prone to high fuel use and difficult to implement when thrusting requires attitude adjustment. Other approaches, such as the impulsive thrusting scheme introduced in Ref. [32], require spacecraft to thrust at previously-specified times and directions in the orbit, ensuring many potential maneuvers will not be fuel-optimal.

1.5 CONTROL APPROACHES

Many approaches for controlling formations exist in the formation flying literature. These approaches consider many different aspects of the formation flying spacecraft problem, including relative spacecraft control, coupled mission objectives, and global fuel minimization. The following subsections review some of the most commonly proposed methods of formation control.

1.5.1 State transition matrix inversion

One approach to spacecraft formation control is the use of a Battin matrix method [14,33]. This approach calculates the velocity change (Δv) required at the current time to achieve some desired state in the future. Similar approaches have been in the literature for decades [33] for use in correcting orbits for monolithic spacecraft.

1.5.2 Impulsive/Heuristic

Classic orbital maneuver Control for a formation of spacecraft can be treated as individual control of many individual spacecraft using traditional methods. Ref. [33] contains mathematical descriptions of the Lambert problem for finding an orbit connecting two states in a specified time, as well as methods for finding optimal one- and two-impulse burns to transfer orbits. These approaches have the advantage of low risk, because the methods have decades of established usage in the field. However, the methods will still need to be modified from their current usage to account for issues of collision avoidance and drift prevention.

Four-impulse method The algorithm in Ref. [34] can be summarized in four steps to be taken over the course of an orbit. When the argument of latitude, θ, is 0 or π radians, implement a velocity change (impulsive thrust), $\Delta v_{h_i} = [h/(r\cos\theta)]\delta i$, in the cross-track direction of an LVLH frame centered on the spacecraft to cancel the inclination error δi, with r being the orbital radius and h being the angular momentum. When the argument of latitude, θ, is $\pi/2$ radians, implement a velocity change, $\Delta v_{h\Omega} = [h\sin i/(r\sin\theta)]\delta\Omega$ in the cross-track direction to cancel the ascending node error, $\delta\Omega$. At perigee and apogee, implement Δv_{r_p} and Δv_{r_a}, respectively, in the radial direction to cancel the argument of perigee and mean anomaly errors, denoted by $\delta\omega$ and δM, respectively:

$$\Delta v_{r_p} = -\frac{na}{4}\left(\frac{(1+e)^2}{\eta}(\delta\omega + \delta\Omega\cos i) + \delta M\right) \tag{1.2}$$

$$\Delta v_{r_a} = \frac{na}{4}\left(\frac{(1-e)^2}{\eta}(\delta\omega + \delta\Omega\cos i) + \delta M\right) \tag{1.3}$$

where a is the semimajor axis and e is the eccentricity. Also at perigee implement Δv_{θ_p} and at apogee implement Δv_{θ_a} in the along-track direction, to cancel the semimajor axis and eccentricity:

$$\Delta v_{\theta_p} = \frac{na\eta}{4}\left(\frac{\delta a}{a} + \frac{\delta e}{1+e}\right) \tag{1.4}$$

$$\Delta v_{\theta_a} = \frac{na\eta}{4}\left(\frac{\delta a}{a} - \frac{\delta e}{1-e}\right) \tag{1.5}$$

where $\eta = \sqrt{1-e^2}$.

1.5.3 Continuous linear control

A straightforward approach to controlling the relative states of satellites in a formation when the dynamics of those states can be modeled linearly is to use a Linear Quadratic Regulator (LQR) [24]. This approach has the advantage that all the tools of linear control can be used to analyze stability and properties and should incur minimal risk. However, an LQR controller would be expected to fire continuously in response to system uncertainty, incurring a fuel penalty over maneuver-planning controllers. To prevent continuous firing, an LQR controller would likely be combined with a deadband.

1.5.4 Nonlinear control

Many formation control approaches have used nonlinear, continuous controllers [28–30,35–37] with stability guarantees based on Lyapunov proofs. Due to the use of Lyapunov-based control, these approaches give rise to Control Lyapunov Functions (CLFs), to be discussed in Chapters 3 and 10. Although these controllers eliminate concerns that nonlinearities in the dynamics could cause instability, they are still affected by many of the same issues which are expected to be problematic in continuous linear control. The form of the control input vector, $\mathbf{u}$, for an absolute state $\mathbf{x}$ and a state error $\boldsymbol{\zeta}$ is [29]

$$\mathbf{u} = -K(\mathbf{x})\boldsymbol{\zeta} \tag{1.6}$$

where K is some nonlinear function of the state. A specific form shown to be asymptotically stable under nominal conditions [29] is

$$\mathbf{u} = -[B(\mathbf{x})]^T P\boldsymbol{\zeta} \tag{1.7}$$

and P is a positive definite matrix and B is the matrix representation of Gauss' variational equations [33], to be discussed in Chapter 2.

1.5.5 Model predictive control

Model Predictive Control (MPC) can be used to generate optimized plans that satisfy performance constraints [26,38–40]. MPC using linear programming (LP) has a number of other advantages for spacecraft formation flying: It easily incorporates realistic constraints on thrusting and control performance; it generates plans that closely approximate fuel-optimal "bang-off-bang" solutions rather than the continuous thrusting plans that inevitably arise from LQR, H_∞, and Lyapunov controllers; and it allows for piecewise-linear cost functions, such as the 1-norm of fuel use.

1.6 SPACE NAVIGATION AND THE GLOBAL POSITIONING SYSTEM

The NAVSTAR Global Positioning System (GPS) is a space-based radio navigation system developed, owned, and operated by the United States Department of Defense. The GPS satellites transmit signals on two carrier frequencies. The civilian L1 frequency, 1575.42 MHz, carries a pseudo-random code for timing and contains a navigation message with ephemeris data [41]. GPS positioning is based on the principle of trilateration, which is the process of ranging off at least three objects with known position to determine a local position. The clocks that are used in the GPS ranging process are of low quality, so the time is added as a fourth dimension. Because of the time uncertainty, the four required ranges are not true measures of position, and are thus called pseudoranges.

The standard method of obtaining a pseudorange involves using the navigation information on the code message. Code-based pseudorange measurements typically produce differential accuracies of several meters, which are not sufficient for formation flying missions. Carrier techniques offer much higher accuracy by calculating pseudoranges from the phase measurement of the radio-frequency (RF) carrier wave. If carrier measurements from a mobile receiver and a base station are differenced, forming a carrier-phase differential GPS (CDGPS) measurement, the motion can be observed accurately. If the base is also moving, as in the case of chief and deputy vehicles in a satellite formation, the CDGPS observable leads to relative position and velocity [42]. CDGPS measurements will be used in Chapter 12 to provide highly accurate relative navigation.

In addition to the code and carrier pseudoranges, a Doppler measurement, which can be related to velocity, is available from the GPS receiver. The Doppler measurement is created inside the receiver by differencing carrier phase measurements. Because this is not a truly independent measurement, previous research has found that adding Doppler measurements does not significantly improve the state estimate [43].

1.7 FORMATION FLYING MISSIONS

Over the past decade, numerous formation flying missions have been conceived. These missions were driven by scientific and programmatic objectives ranging from sparse-aperture imaging of extra-solar planets to lunar gravitometry. In particular, the *TechSat-21* concept[1] was a revolutionary space architecture of collaborating clusters of similar, agile, capable microsatellites that could be adapted on-demand to perform a variety of missions. In addition, it was envisioned that system performance could be increased over time through "phased" deployment, or tailored to meet evolving mission needs. The advantage of such a system is that the loss of one or more satellites in the formation has only limited impact on the cluster's performance, as remaining satellites could "absorb" the lost satellite's responsibilities.

The increased scientific return and the potential adaptability of formation flying satellites to changing mission goals have created new opportunities for the scientific endeavor. However, the current control, measurement and modeling challenges of spacecraft formation flying have rendered some of the proposed missions too costly. Thus, recent years have seen many proposed formation flying missions cancelled or transformed into technology-demonstration missions.

Nevertheless, it is safe to say that operational formation flying satellites, performing tracking or maintenance of a desired relative state (cf. our definition of formation flying in Section 1.1), will be launched in the near future. While there are currently no formation flying satellites in orbit, some operational missions certainly implement technologies and methods required to maintain satellites in formation. Two such missions are ESA's CLUSTER mission and the ESA/NASA GRACE mission.

[1] See http://en.wikipedia.org/wiki/TechSat-21, accessed April 30, 2009.

CLUSTER[2] comprises four identical spacecraft launched into large, highly elliptical polar orbits around the Earth, with perigee and apogee altitudes of 19,000 km and 119,000 km, respectively. These satellites fly in pre-determined relative orbits designed so as to allow scientists to measure subtle changes in the interaction between the Earth and the Sun. The four spacecraft examine how particles from the Sun interact with the Earth's magnetic field. CLUSTER observes the magnetic and electrical interactions between the Earth and the Sun by making direct measurements of the three-dimensional fields. The CLUSTER satellites were launched in August 2000 for a nine-year (extended) mission.

Another mission that implements a formation flying technology – measurement of inter-spacecraft range – is the *GRACE* mission.[3] The GRACE mission features two identical satellites in a leader/follower formation (GRACE A and GRACE B) orbiting the Earth on the same orbital plane. The purpose of this mission is to generate high-fidelity modeling of Earth's gravitational field; it is expected to yield an improvement of several orders of magnitude in gravity measurements and allow much improved resolution of the broad to fine-scale features of Earth's gravitational field over both land and sea. A secondary experiment that GRACE performs is examining how the atmosphere affects GPS signals. The initial altitude of GRACE A and GRACE B above the Earth was close to 500 km. Due to atmospheric drag, it will decrease to about 300 km towards the end of the mission. The mean inter-satellite separation varies between 170 and 270 km. Originally funded for a five-year period (2002–2007), the mission has been further extended to 2009. As the orbit decay has been slower than initially thought and the satellites' current fuel supply is expected to last another few years at the very least, the mission is likely to continue past 2012.

Two ESA formation flying missions are currently in advanced development stages: PRISMA and PROBA-3.

PRISMA[4] is a Swedish-led satellite project with the objective to develop and qualify new technology necessary for future formation flying science missions. The PRISMA project is Europe's first step to demonstrate new formation flying technology – both hardware and software. The technology of PRISMA is developed mainly in Sweden, Germany, Denmark and France. PRISMA consists of two spacecraft, with a total mass of about 200 kg. It contains several new technologies within autonomous formation flying and rendezvous, small rocket engines and Micro Electro Mechanical Systems (MEMS). PRISMA is scheduled to be launched on a Dnepr launcher in early 2010.

PROBA-3 is the ESA formation flying demonstration mission[5] preparing for future formation flying missions, such as *XEUS*[6] and *DARWIN*.[7]

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[2] See http://sci.esa.int/science-e/www/area/index.cfm?fareaid=8, accessed March 26, 2009.

[3] See http://www.csr.utexas.edu/grace/, accessed March 26, 2009.

[4] See http://www.prismasatellites.se/?id=9033, accessed March 26, 2009.

[5] See http://www.ssc.se/?id=7613, accessed March 26, 2009.

[6] See http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=39306, accessed March 26, 2009.

[7] See http://www.esa.int/esaSC/120382_index_0_m.html, accessed March 26, 2009.

The PROBA-3 mission will demonstrate algorithms, sensors, propulsion systems and other technologies needed for formation flying.

An important joint NASA/ESA mission, implementing a number of critical formation flying technologies (very precise formation design and metrology, but no formation control), is the *Laser Interferometer Space Antenna* (LISA).[8] LISA is designed to detect "ripples" in space-time, as predicted by Einstein's general theory of relativity. LISA's three spacecraft will form an equilateral triangle with an arm length of about 5 million km. Each spacecraft houses two free-floating cubes made of a gold–platinum alloy inside the spacecraft, shielded from adverse effects of being in interplanetary space. The distance between the cubes in different spacecraft is monitored using highly accurate laser-based techniques.

NASA has proposed many formation flying missions. Some of these missions are currently under development, while others are in conceptual stages. One of NASA's main formation flying missions is the *Magnetospheric Multiscale Mission* (MMS).[9] MMS includes four identical spacecraft in a variably spaced tetrahedron (1 km to several Earth radii), with a planned two-year mission lifetime. The system includes inter-spacecraft ranging, communication and instrumentation, designed to measure magnetic and electric fields using electron and ion plasma spectrometers, providing high temporal and spatial resolution. MMS is currently in the preliminary design stage. Mission confirmation is targeted for July 2009; launch is planned for 2014.

Another interesting formation flying mission is the *New Worlds Observer* (NWO).[10] NWO consists of a large telescope and an occulter spacecraft in tandem at about 50,000 km apart. The purpose of NWO is to discover and analyze terrestrial extra-solar planets. The NWO concept features two spacecraft flying at the Earth–Sun L2 (Lagrangian) point or in a drift-away solar orbit. One craft carries a 4-meter aperture-diameter diffraction-limited telescope optimized to work in the visible band. The other occulter craft would each carry a starshade. Operating 70,000 kilometers from the telescope, one starshade would be maneuvered into the telescope's line-of-sight to a nearby star, blocking starlight while passing planet light. The NWO planned launch date is circa 2018.

Other future NASA formation flying missions are the *Stellar Imager* (SI),[11] *Milli-Arc-Second Structure Imager* (MASSIM),[12] and *Black Hole Imager*,[13] all planned for the third decade of the 21st century.

The SI mission is a space-based ultraviolet (UV)/optical interferometer with over 200 times the resolution of the Hubble space telescope. The purpose of this mission is to understand, by using high angular-resolution spectral imaging,

[8] See http://www.esa.int/esaSC/120376_index_0_m.html, accessed April 30, 2009.
[9] See http://stp.gsfc.nasa.gov/missions/mms/mms.htm, accessed March 26, 2009.
[10] See http://newworlds.colorado.edu/implementation/index.htm, accessed March 26, 2009.
[11] See http://hires.gsfc.nasa.gov/si/, accessed March 25, 2009.
[12] See http://asd.gsfc.nasa.gov/Gerald.Skinner/massim_proposal.pdf, accessed March 25, 2009.
[13] See http://bhi.gsfc.nasa.gov/, accessed March 25, 2009.

the details and dynamics of heretofore unresolved objects and processes: Solar/stellar magnetic activity and their impact on the climates and habitability of planets and life; and magnetic and accretion processes and their roles in the evolution of structure and transport of matter throughout the Universe. The mission consists of a 0.5-km diameter space-based UV-optical interferometer located near the Sun–Earth L2 point to enable precision formation flying. The interferometer consists of 30 primary mirror elements focusing on a beam-combining hub.

The proposed MASSIM mission will image in X-rays the structure of astrophysical objects with an angular resolution three orders of magnitude better than the present state of the art. An optics spacecraft carrying an array of diffractive/refractive lenses focuses X-rays onto detectors on a spacecraft 1000 km behind.