A Survey of Formation Flying Guidance

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1. Introduction

Numerous formation flying missions have been proposed, both in deep space and in planetary orbits. NASA's Terrestrial Planet Finder (TPF), and its precursor mission, Starlight, are aimed at detecting exo-solar, Earth-sized planets; the Laser Interferometer Space Antenna (LISA) is a three spacecraft mission to detect gravity waves [12]; NASA's Auroral Lites is a four spacecraft mission to measure the Earth's magnetosphere in the polar regions [7]; the Air Force Research Laboratory's TechSat 21 program includes a microsatellite-based, synthetic aperture radar mission [4]; and Reference 2 lists 30-plus missions that will use spacecraft "flying in formation."

Authors have considered formation flying missions since the late 1970's [10]. However, due to the many missions mentioned above, there has been an explosion of work on formation flying in the last five years, with many conferences now including sessions on formation flying (for instance, the 2000 AAS/AIAA Spaceflight Mechanics Meeting) and the advent of the first entire conference dedicated to formation flying.

This rich body of research is unsurveyed. For mission designers who want an overview of current orbit design methods for formations or Δv estimation formulas to correct for the effect of an oblate Earth on the formation—or even to use relative orbits that are J_2-invariant—or for control engineers who want to know the fuel-optimal way to maneuver a formation as a whole or how to optimally reconfigure formation, there is presently no one document that provides a starting place.

The role of this comprehensive survey is to provide such a starting place for formation flying guidance (FFG), FFG being defined as any path planning that is involved in the design of spacecraft formations. This definition encompasses a broad area, and so the full survey includes 76 references covering FFG results from deep space formations through libration point formations to planet-orbiting formations. In fact, the literature naturally divides between deep space (DS) and planetary orbital environment (POE) formations, that latter including planetary and libration point orbits.

The organization of the survey is shown graphically in Figure 1, the figure including the section number of each category treated. In DS formations, which are characterized by assuming double integrator relative dynamics, the guidance aspects are primarily 1) fuel/time optimal formation rotations (the spacecraft maintain relative positions, but the formation as a whole rotates as if it were a rigid body), 2) formation reconfigurations (given a formation geometry, such as a tetrahedron, and spacecraft occupying specific positions within the geometry, a reconfiguration consists of spacecraft moving to new positions such that the same geometry exists after the move), 3) optimal u, v-plane sampling for multiple spacecraft interferometers (MSIs), and 4) collision avoidance.

This division in the literature between DS and POE applications is due in part to the tolerances of the formation flying missions proposed to date. On one end of the spectrum

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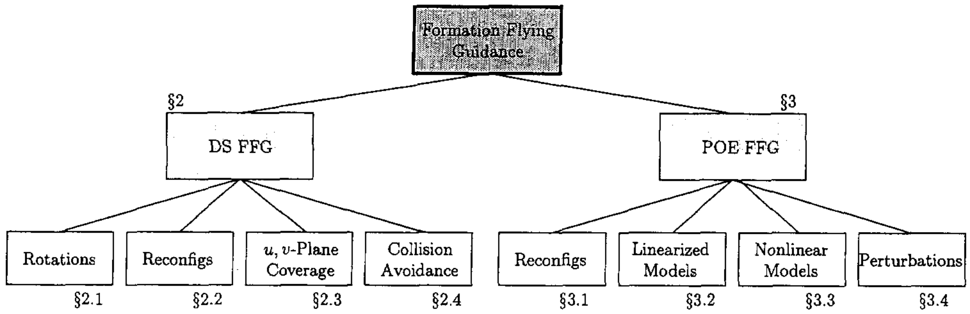

Figure 1: Organization of Survey

are Earth science missions and longer-wavelength MSIs with relative position tolerances from the tens of kilometers down to a few meters [6, 7], tolerances which can be met with realistic fuel expenditures in Earth orbit [5, 9, 13]. On the other end of the spectrum are optical wavelength MSIs that have relative position tolerances smaller than the centimeter level [1], and so require low-disturbance environments. The division is not absolute; optical-wavelength MSIs have been considered for GEO [8].

As the dynamics and disturbances are non-trivial in a POE (by definition), the primary thrust of POE FFG has been to find trajectories in which the natural dynamics provide or at least aid the desired formation motion and/or null or mitigate the effect of the main disturbances: an oblate Earth (J_2) and drag. Therefore, POE FFG is broken down by the model used in determining these trajectories—either a linearized model, for example, the well-known Hill-Clohessy-Wiltshire (HCW) equations, or a nonlinear model, such as the full, Keplerian, 2-Body equations. The Perturbations section then surveys papers in which linear and nonlinear models are modified and then analyzed to examine the effects of J_2 and drag. A number of formulas for calculating Δv's necessary to counteract the perturbations have also been derived in the literature and they are also covered in this section. Finally, there is some work on the reconfiguration problem in the context of POEs.

This survey does not cover formation flying/keeping technology such as thrusters or navigation sensors. The interested reader is directed to Refs. 2, 3 and 11.

2. Brief Survey

The deep space papers concentrate on fuel-optimal formation operations: rotating the formation as a whole, which Beard, his students and Hadaegh do using the virtual structure approach, both for fuel minimization and combined fuel minimization/fuel-equalization; reconfiguring the formation, which Wang and Hadaegh reduced to optimizing a sequence of permutation cycles in the configuration mapping, and for which a number of authors have developed fuel- and fuel/time-optimal and collision avoidance constrained path planning algorithms; and covering the u, v-plane—of particular note is McLain et al.'s result that, depending on the expansiveness of the u, v-set and the angular separation between targets, it can be more fuel efficient to move back and forth between targets rather than covering their respective u, v-planes sequentially.

The POE papers concentrate on designing passive apertures and determining the robustness of the designs when J_2 and drag effects are included. For circular reference orbits and linearized dynamics, Kong et al., among other authors, developed in detail the Circular Free Elliptical Trajectories (FETs) and Projected Circular FET trajectories of the HCW equations, in which the relative orbits rotate with the reference orbit, and DeCou developed elliptical relative orbits that remain in inertially fixed planes.

Using nonlinear models authors addressed existence conditions for relative orbits with elliptical reference orbits, designed relative orbits for circular reference orbits using performance metrics, the geometric approach of Sabol et al. and Schiff et al. or series expansions in the eccentricity of the spacecraft orbits, and studied the feasibility of L1-based formations.

Considering perturbations, Schaub and Alfriend and Hughes and Mailhe derive conditions for J_2-invariant relative orbits, and a number of authors derive Δv formulas for accounting J_2 effects in arbitrary and partially-invariant relative orbits. Some authors have considered drag. Sedwick et al. analyze drag, J_2 and solar pressure for polar orbits using the Buckingham Pi Theorem, and derive useful scaling results. They also explicitly break the perturbed motion into perturbed bulk motion of the formation and perturbed relative motion. There are also a number of papers on modifying the HCW equations to include perturbations and comparing HCW-derived, semi-J_2-invariant relative orbits with the actual, perturbed relative orbits.

Finally, Yang et al. derive a very general, dynamic-programming-styled algorithm for fuel-optimized reconfigurations that has the added benefit of being almost entirely computationally distributed: a genetic algorithm runs on one spacecraft and is used to select the best final configuration when multiple configurations satisfy the mission objectives, but the cost of each reconfiguration is calculated via a communication protocol and information exchange between spacecraft of locally calculated quantities. Though it is formulated in the context of FETs, it can equally be applied to deep space formations.

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