A Survey of Spacecraft Formation Flying Guidance and Control (Part I): Guidance

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Abstract—**This paper provides a comprehensive survey of spacecraft formation flying guidance (FFG). Here by the term guidance we mean both path planning (i.e., reference trajectory generation) and optimal, open loop control design. FFG naturally divides into two areas: Deep Space (DS), in which relative spacecraft dynamics reduce to double integrator form, and Planetary Orbital Environments (POE), in which they do not (e.g. libration point formations). Both areas consider optimal formation reconfigurations. In addition, DS FFG addresses optimal u, v-coverages for multiple spacecraft interferometers and rest-to-rest rotations. The main focus of the POE literature, however, is "passive relative orbits" or PROs. PROs are thrust-free periodic relative spacecraft trajectories used to design fuel-efficient formations. Finally, we present a brief overview of robotic path planning and discuss some of the similarities between this field and formation flying guidance.**

I. Introduction

In 1969, data from US, Soviet, and European Space Research Organization satellites were correlated to study how large solar flares interacted with the Earth's magnetic- and ionospheres—thereby achieving the first contemporaneous spatial sampling by a group of separated spacecraft [83]. Less than a decade later, Labeyrie proposed forming a stellar interferometer from free-flying telescopes [70]. Today, there are dozens of missions either flying, under development or proposed [22] that use spacecraft flying in formation. For example: Terrestrial Planet Finder (TPF) will look for extra-solar, Earth-like planets [76]; XEUS and the Constellation X-Ray Mission will explore high-energy astrophysical sources with unequaled resolution [11]; and both EO-1/L-7 and CloudSat/Picasso-Cena will study the Earth [34], [62].

Previous definitions of formation flying have not clearly differentiated it from constellations. We define formation flying as a set of more than one spacecraft whose *dynamic states are coupled through a common control law*. In particular, at least one member of the set must 1) track a desired state relative to another member, and 2) the tracking control law must at the minimum depend upon the state of this other member. The second point is critical. For example, even though specific relative positions are actively maintained, the GPS satellites constitute a constellation since their orbit corrections only require an individual satellite's position and velocity (state).

This paper presents a comprehensive survey of the guidance aspects of spacecraft formation flying. Formation flying guidance (FFG) is defined as the generation of any reference trajectories used as an input for a formation member's relative state tracking control law. This FFG definition includes open-loop control design (i.e., an optimal control profile that only depends on time and initial conditions).

The FFG literature can be divided into two main categories based on the ambient dynamic environment. In Deep Space (DS) relative spacecraft dynamics reduce to double integrator form (i.e., no state dependent forces in open loop) [109]. The second main category is Planetary Orbital Environments (POE), where spacecraft are subjected to significant orbital dynamics and environmental disturbances.

Both DS and POE FFG consider optimal formation reconfigurations. The DS literature also addresses formation rotations and planning u, v-coverages[2] for multiple spacecraft interferometers (MSIs). In POE, the dynamics are the dominant consideration. Since tracking arbitrary trajectories requires prohibitive amounts of fuel,[3,4] the POE literature focuses on developing periodic, thrust-free relative spacecraft trajectories, which are referred to as passive relative orbits (or PROs).[5]

Due to the dynamical environment inherent in POE guidance, this area has a larger number of associated papers. This imbalance, however, is a matter of perspective; when one also considers the research in formation flying control, the literature is evenly divided between DS and POE. Due to its mission focus, JPL and its collaborators have been active contributors to the DS FFG area. For example, Wang and Hadaegh [138] first addressed formation reconfiguration, precisely defining it (see Section II) and reducing the problem to a study of permutation groups. Also, in a series of papers, Beard and Hadaegh [12]–[14] analyzed DS formation rotations and highlighted the need to *balance* fuel use across a formation.

We note that problems in spacecraft formation flying guidance are similar to those in robotic path planning as well as UAV and underwater vehicle guidance. The research in these related areas, however, remains largely unexploited in the spacecraft formation flying literature. To encourage exchange between these fields, we include a brief overview of robotic path planning after surveying DS and POE FFG.

Since formation flying is dependent upon state coupling in spacecraft control laws, the intended use of a reference trajectory determines whether it is formation flying or constellation guidance. A number of formation flying papers deal with PROs in the Hill-Clohessy-Wiltshire (HCW) equations; however,

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[2]In synthetic aperture imaging, spacecraft are generally restricted to a plane, and the critical variables are not the physical positions, (x_1, y_1) and (x_2, y_2), but relative positions. Scaling by the wavelength observed (λ) and the distance to the target (z) results in $(u, v) = (x_1 - x_2, y_1 - y_2)/(z\lambda)$. A u,v-set is then a set of ordered pairs representing planar relative spacecraft locations, and a u,v-coverage is an ordered u,v-set. See [92].

[3]For example, given a geostationary reference orbit, [68] shows that spacecraft placed in an arbitrarily oriented, 20 km diameter circular formation can each require a Δv of 7 m/s *per orbit* (assuming a five year lifetime).

[4]Exceptions are XEUS and the MSI described in [123]. Both missions would use space station refueling.

[5]A PRO is also commonly called a "passive aperture."

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these trajectories are equally applicable to the design of small constellations. Similarly, a traditional Walker constellation design [72] is considered FFG if used in conjunction with Mean Constellation Control (MCC) [71]. Despite its name, MCC is a formation flying algorithm.[6] Traditional constellation designs, however, have already been surveyed [40], [46], [72], [130].

Finally, spacecraft rendezvous guidance is also a subset of FFG, but this area has also been previously surveyed [56].

II. DEEP SPACE FFG

DS FFG is simplified by the fact that arbitrary rigid formations (i.e., those with constant inter-spacecraft distances) can be maintained with no fuel penalty. Optimal u,v-coverages and reconfigurations then reduce to a traveling salesmen problem. Since formation rotations can be used in u,v-coverages, optimal methods for rotating a rigid formation are also studied.

A MSI interferes the electromagnetic waves from an observational target collected by spacecraft at various relative positions (u,v-points). Given a desired u,v-set, algorithms for finding fuel-optimal u,v-coverages (i.e., relative spacecraft motions) have been developed [7], [66]. If two targets are "close" as compared to the effective diameters of their u,v-sets, then the optimal u,v-coverage repeatedly switches between targets. That is, target u,v-sets are interweaved [7]. [92] derives optimal MSI mission-fuel/mission-time trade-offs assuming each target's u,v-coverage is the same.

Another approach to covering the u,v-plane is to spiral one spacecraft about another [29], [123]. In [53], an optimal spiraling problem is posed and sub-optimal solutions are derived by considering the modulation transfer function[7] in the wave number plane (i.e., the two-dimensional space of spatial frequencies of the Fourier transform).

One method for sampling a u,v-set is to rotate the entire formation. Given an axis and angle of rotation, [12]–[14] and [15] find the optimal point about which to rotate a formation as a virtual rigid body under various constraints. The objective function weights total formation fuel consumption and *unbalanced* fuel consumption.

A reconfiguration is essentially a reassignment of spacecraft positions in a formation. In DS, reconfigurations can be used to retarget an MSI or as a fuel-balancing method in a rotating formation. Formally, from [138], let $\mathcal{I}$ be a set of spacecraft identifiers (e.g. $\{a, b\}$), and let $\mathcal{R}^d$ be a set of time-varying desired spacecraft trajectories (e.g. $\{d_1(t), d_2(t)\}$). A *configuration* is then a mapping $\mathcal{C} : \mathcal{I} \rightarrow \mathcal{R}^d$. A *reconfiguration* is a change of this mapping, including adding and deleting elements from either set (e.g. merging formations or changing $\mathcal{R}^d$ to retarget an MSI). *Reconfiguration trajectories* are used to move spacecraft from their current trajectories to new desired trajectories. These definitions apply to POE formations as well.

Under the assumption that each spacecraft in $\mathcal{I}$ may only be assigned a desired trajectory from a subset of $\mathcal{R}^d$ [138], an optimal reconfiguration algorithm then has two steps: (1) for each spacecraft in $\mathcal{I}$, calculate the optimal reconfiguration trajectories from the spacecraft's current trajectory to the allowed trajectories in $\mathcal{R}^d$, and (2) based on Step 1, select a new configuration mapping $\bar{\mathcal{C}}$. The new mapping must be optimal in the following sense: the reconfiguration trajectories that move the formation from configuration $\mathcal{C}$ to configuration $\bar{\mathcal{C}}$ minimize a formation resource metric (e.g. total fuel consumed).

In [138], reconfigurations of rigid formations are considered. In this case, the fuel-optimal reconfiguration trajectories (Step 1) are straight lines with a "bang-coast-bang" control law. For Step 2, the configuration is treated as an element in a permutation group, and $\bar{\mathcal{C}}$ is found by optimizing over transposition sequences. Collision avoidance is addressed by sequentially moving spacecraft. Given a new configuration, [77], [90] and [119] find optimal, collision avoidance-constrained reconfiguration trajectories assuming all spacecraft move at the same time.

III. PLANETARY ORBITAL ENVIRONMENT FFG

Since ignoring the dynamics in POE results in prohibitively large fuel consumption, POE FFG concentrates on finding passive relative orbits (PROs). The effectiveness of a PRO, however, depends on the fidelity of the model used for its design. For example, if a PRO is the solution of disturbance-free design model, then including Earth oblateness may ruin its periodicity. As a result, a formation using such a disturbance-free PRO would consume extra fuel to artificially maintain the periodicity of relative spacecraft trajectories [107]. In some cases, PROs have been found when disturbances are included in the design model. Otherwise, active relative orbits (AROs) are designed by posing an optimal control problem. AROs are periodic relative spacecraft trajectories that require open loop control to maintain their periodicity.

Recall from the discussion in Section II that there are two steps in a reconfiguration. The first step is to calculate the reconfiguration trajectories. In POE the dynamics are significantly more complicated, and as a result, there are correspondingly more methods for calculating reconfiguration trajectories. The following methods have been used: optimal control including linear programming and primer vector theory [24], [25], [30], [67], [80], [93], [96], [102], [105], [128], [129], [132], [143], Hohmann transfers [31], Lambert's solution [6], [81], Gauss' variation of parameters equations [35], [81], [111], [132] and multi-impulse, sub-optimal methods [79], [88], [133]. Only some of these methods have been incorporated into a full reconfiguration algorithm. Note that [102] includes collision avoidance and thruster plume impingement constraints, [128] studies model fidelity and sensor noise versus fuel consumed, and [93] uses nonlinear programming. Further, although we did not include it in this survey, the literature on optimal rendezvous and orbit transfers may be favorably applied to POE reconfiguration trajectory calculation [19], [56].

For the second step of a reconfiguration (i.e., selecting the new configuration mapping based upon the reconfiguration

[6] In MCC, a constellation template is repeatedly fit to spacecraft positions, and the spacecraft track their desired locations in the fitted template. Spacecraft states are coupled through the fitting step.

[7] The modulation transfer function is the ratio of the estimated image intensity to the true image intensity

trajectories) bidding algorithms [94], linear programming [24], [129] and dynamic programming [143] have been used. In particular, [143] and [129] contain in-depth studies of POE reconfiguration.

The most common linear PROs are solutions to the Hill-Clohessy-Wiltshire (HCW) Equations, referred to in [68] as *Free Elliptical Trajectories* (or FETs) [3], [65], [68], [107], [144] and [125]. Two particular types of FETs are emphasized: the circular FET (CFET), and the circular-projection FET (CPFET). The CPFET has elliptical *relative orbits*[8] that project circles onto a plane perpendicular to the *reference orbit*[8] plane. The *interferometric cartwheel* FET is useful for synthetic aperture radar applications [33], [84].

The FETs rotate with the local-vertical, local-horizontal frame and are useful for looking at the Earth. For astronomical targets there are also PROs that remain in inertially fixed planes [29], [57]. The relative orbit plane may be *arbitrarily oriented*, but the eccentricity of the relative orbit depends on the target direction. Also using a linear model, [55] and [9] derive constraints on relative states for a PRO to exist about an *eccentric* reference orbit.

Turning to nonlinear models, [142] derives a similar initial condition constraint for the existence of a PRO about an eccentric reference orbit, while [132] and [106] numerically search for PROs. The energy-matching condition is also used to design formations [27], [113]. First, a point in the reference orbit is selected and spacecraft are put in a desired configuration. Next, their velocities are directed parallel to the reference orbit's. Finally, their velocity magnitudes are selected to match the energy of the reference orbit. Tetrahedral formations have been designed in this manner. See [43] for further references on tetrahedral formations.[9]

Another common approach in nonlinear PRO design, pioneered in [32], is to expand the formation geometry parameters (e.g. angular extent of formation) in a series based on eccentricity and then select relative orbital elements to eliminate first order terms [28], [51], [136]. Using this approach the CFET is recovered with the addition of a second order term in the series that captures the variation from the exact circular HCW solution [32], [91].

Purely geometrical arguments can also be used to obtain a nonlinear model-based PRO. In particular, one dimensional MSIs based on inclination differences [124], two-dimensional MSIs with spacecraft in the same circular orbit [54], and planar formations with constant inter-spacecraft distances and eccentric reference orbits [126] have been developed. Still another approach to designing a PRO is to introduce a formation performance metric, such as the number of u, v-points sampled in one orbit, and numerically search for optimum spacecraft positions [6], [43], [50], [52], [82], [116].

[8]We adopt the following terminology to avoid confusing three types of "orbits." An *orbit* is the periodic motion of a spacecraft about a planetary center or libration point. A *relative orbit* is the periodic motion of one spacecraft with respect to a reference point tracing out an orbit. The *reference orbit* is the orbit of this reference point. A spacecraft may or may not occupy the reference orbit.

[9]To date, tetrahedral missions have only been designed as constellations.

Given a PRO, the next step is to study its robustness in the presence of disturbances [8], [41], [55], [107]. Electric forces due to spacecraft charges and luni-solar gravitational perturbations are studied in [64] and [141]. In [117], dimensional analysis is used to estimate the magnitudes of various disturbances with emphasis on the division of J_2-induced motion into bulk and differential parts. The bulk portion may be removed by carefully selecting the semi-major axis of the spacecraft orbits [65], [101], [117]. This strategy reduces the control cost for an ARO designed for removing the remaining differential motion. Two strategies that do yield a PRO when J_2 effects are included are (i) to set the J_2-induced secular drifts of two orbits equal and derive constraints on the orbital elements [1], [2], [52], [112], [132], and (ii) to use dynamical system theory to select appropriate initial conditions [69], [139]. In [42], the conditions for a PRO to exist in the presence of solar pressure are derived.

If PROs are too restrictive or are not known for a particular disturbance, then control can be used to maintain relative orbits that satisfy formation objectives. Both linear [73], [97] and nonlinear [93] programming have been used to find open loop control profiles that reject J_2 and aerodynamic drag. Formulas for the Δv needed to reject J_2 for various formations have also been derived [1], [2], [107]. Considering aerodynamic drag, an ARO has been developed that maximizes the drift time between control inputs for two spacecraft with different ballistic coefficients [35], [62], [85], [115]. The strategy places the spacecraft with the larger ballistic coefficient at a slightly higher altitude.

To improve the robustness of PROs designed using linear models, the HCW equations have been modified to include the effect of drag [26] and J_2 [89], [114], [117], [131]. However, [55] shows that for an eccentricity of 0.005, the error induced in the HCW equations due to ignoring eccentricity dominates the error due to ignoring J_2. Addressing eccentricity, [23] surveys exact and approximate solutions for the unperturbed motion of a spacecraft relative to an eccentric reference orbit.

The primary approach for incorporating both J_2 and reference orbit eccentricity is to express the relative motion in the local-vertical, local-horizontal frame as a function of the known solutions to the *differential mean orbital elements*; see [5], [36], [38] and references therein. Osculating solutions require an eccentricity series-based approximation.

In the disturbance free case, a similar approach using (non-differential) orbital elements and a circular reference orbit is developed in [42] and [147].[10] The advantage of this approach is that the solutions are not required to be "near" the reference orbit, as is the case for the HCW equations. A complementary approach for increasing the accuracy and range of applicability of the HCW equations is to augment the equations themselves with second and third order gravitational terms [60], [103], [134]. Note that [61] derives the full, nonlinear equations of motion of a spacecraft subjected to drag and J_2 with respect to an eccentric reference orbit.

[10]Ref. [8] uses a similar approach with an eccentric reference orbit, but does not obtain closed-form solutions.

Finally, libration points have been proposed as areas for low-disturbance parking orbits for an MSI[11] and as alternate locations for PROs. In the latter case, PROs have been designed where one relative orbit takes approximately 6 months [10]. Also, the open loop control effort required to maintain various formations (e.g. tetrahedral) with respect to libration point orbits (i.e., halo orbits) have been calculated [47], [58]. If the relative dynamics about a halo reference orbit are stabilized, then (i) constant approximations to the time-varying linearized dynamics are accurate over significant time periods (e.g. 40 days), and (ii) Linear Orbital Elements defined via these constant approximations are useful for visualizing and designing formations [48], [49]. Approximate analytic expressions for the motion relative to a halo reference orbit have also been derived using the Lindstedt-Poincaré method [118], and they are accurate over a few days.

IV. ROBOTIC PATH PLANNING

Although optimal trajectory generation for formation guidance is a relatively new area of investigation, extensive work has been done in the related area of optimal path planning for mobile robotic systems [74]. The thesis [145] provides a recent overview of the field of optimal motion planning for robotic and mechanical systems.[12] The close relationship between the planning of optimal paths for separated spacecraft formations and mobile robotic systems is due to the fact that both problems can be formulated as optimal path planning problems on the group of rigid body motions $SE(3)$.[13]

Motion planning on SE(3) involves the choice of a distance metric;[14] see for example [99], [78], and [146]. Given an initial and goal configuration for a single rigid body, the necessary conditions for shortest distance and minimum acceleration trajectories on $SE(3)$ are derived in [146]. The path planning problem for a single rigid body on $SE(3)$ is also discussed in [59] where cubic splines are utilized to construct trajectories that minimize angular acceleration. In [17] a more computationally efficient algorithm for interpolation on $SE(3)$ based on the singular value decomposition is presented.

The papers [16] and [18] extend the generation of optimal trajectories on $SE(3)$ from a single body to a formation of mobile robots using a measure of total system energy as the cost. In [16], minimum energy trajectories are developed to maneuver a formation of vehicles as a virtual rigid body.

Once a reference trajectory on $SE(3)$ has been generated by any of the above techniques, LQR tracking methods can be formulated and applied directly on $SE(3)$ [45]. Optimal path planning techniques on Lie groups have also been used to generate optimal airplane motion schedules near airports [137], and to generate attitude control laws for spacecraft [122].

The problem of collision avoidance between autonomous vehicles (in the presence of both static and dynamic constraints) has been the focus of extensive study in the area of robotics; see for example [75] and [121]. The use of potential functions for robot navigation and path planning is a very effective method for handling collision avoidance constraints and has become standard; see [63], [104], and [37]. However, in developing similar potential-based methods for formation flying collision avoidance, additional and more stringent requirements must be included; see for example [86] and [119]. similar potential based methods for formation be forced to operate under additional and more example [86] and [119]. Moreover, the entire formation path planning problem is a complicated *multi-objective* optimization problem where admissible solutions must balance conflicting goals such as collision avoidance, fuel depletion, fuel balancing, and maneuver time [15], [135].

V. CONCLUSIONS AND FUTURE DIRECTIONS

FFG was shown to divide naturally into Deep Space (DS) and Planetary Orbital Environments (POE).[15] The main emphasis of the DS literature pertains to algorithms for finding optimal u,v-coverages, formation rotations and reconfigurations. The POE literature's main emphasis is PROs (thrust-free trajectories that achieve formation objectives), AROs if PROs do not suffice, and reconfigurations.

The next fundamental step for both DS and POE reconfigurations is to include the following constraints in calculating reconfiguration trajectories prior to selecting new configurations:[16] collision avoidance, plume and glint avoidance (attitude dependent), bright-body avoidance (e.g. Sun-avoidance constraints), and fuel-balancing. The resulting algorithms must be computationally tractable.

Also for reconfigurations, a developing area is the exploitation of disturbances (e.g. J_2, aerodynamic drag, and solar pressure) for fuel-efficient reconfiguration trajectories [4], [20], [21], [98], [108], [127], [140].

An undeveloped area in FFG, however, is coupled attitude and translation planning [44]. The only 6-DOF guidance reference found uses a probabilistic search algorithm to plan rendezvous trajectories with plume impingement and collision

[11]Libration point dynamics do not affect the formation significantly over the time scales involved in formation maneuvers (e.g. 8 hours) [39].

[12]Here we define a mechanical system as any collection of bodies subjected to motion constraints. Under this broad definition, the motion planning problem for a system of bodies—robot vehicles, underwater vehicles, single or multiple spacecraft—can be formulated under a common framework.

[13]The set $SE(3)$ consists of 4×4 matrices of the form $\begin{bmatrix} \Theta & d \\ 0 & 1 \end{bmatrix}$ where Θ denotes a 3×3 rotation matrix and $d \in \Re^3$. It is well known that $SE(3)$ has the structure of both a group and a smooth manifold, and hence is a Lie group. Once an inertial frame of reference has been established, the configuration of a rigid body in free space can be described by an element of $SE(3)$. The rotation matrix Θ denotes the absolute attitude of the body and the displacement vector d locates the center-of-mass of the body relative to the inertial frame of reference. Physically, a curve on $SE(3)$ represents the motion of the rigid body. See [95] for an extensive discussion.

[14]Recall that a metric function is a real-valued function $d(\cdot,\cdot) : SE(3) \times SE(3) \to \Re$ that is symmetric, positive definite, and satisfies the triangle inequality.

[15]Other classifications for formations are possible. For example, formations can also be categorized as high precision or low precision and large or small—a control architecture suitable for five spacecraft may not be for twenty.

[16]Unconstrained reconfiguration trajectories are often used to select a new configuration. Then, after the new configuration is chosen, reconfiguration trajectories are replanned to include, for example, collision avoidance constraints. This replanning can introduce a total energy increase of 80% [119]. Therefore, constrained reconfiguration trajectories should be used directly in the selection of a new configuration.

avoidance constraints [100]. Another important 6-DOF application is *DS formation initialization* [110]. In deep space, positions are known at best to within tens of kilometers. Therefore, before formation control can take place, the formation spacecraft must search for each other with limited field-of-view (FOV) sensors subject to various constraints. Subsequently, spacecraft sensor FOV occultations should be avoided during formation maneuvers.

In regard to 6-DOF guidance, connections were drawn between robotic path planning and formation flying guidance. While spacecraft dynamics are generally simpler than robotic dynamics (e.g. robots often have non-holonomic constraints), spacecraft constraints are generally more difficult to include (e.g. dynamic collision avoidance as opposed to static obstacle avoidance). We believe that the UAV and underwater vehicle literatures can also provide valuable techniques for formation guidance [87], [120].

Finally, POE formations are built upon PROs. Since formation design for other than circular reference orbits is still largely an art, recently developed solutions for perturbed and unperturbed motion about eccentric reference orbits should be utilized for PRO design [38], [42].

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