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."

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].

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.

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[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.

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

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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