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

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***Abstract*— Formation flying is defined as a set of more than one spacecraft whose states are coupled through a common control law. This paper provides a comprehensive survey of spacecraft formation flying control (FFC), which encompasses design techniques and stability results for these coupled-state control laws. We divide the FFC literature into five FFC architectures: (*i*) Multiple-Input Multiple-Output, in which the formation is treated as a single multiple-input, multiple-output plant, (*ii*) Leader/Follower, in which individual spacecraft controllers are connected hierarchically, (*iii*) Virtual Structure, in which spacecraft are treated as rigid bodies embedded in an overall virtual rigid body, (*iv*) Cyclic, in which individual spacecraft controllers are connected non-hierarchically, and (*v*) Behavioral, in which multiple controllers for achieving different (and possibly competing) objectives are combined. This survey significantly extends an overview of the FFC literature provided by Lawton, which discussed the L/F, Virtual Structure and Behavioral architectures. We also include a brief history of the formation flying literature, and discuss connections between spacecraft FFC and other multi-vehicle control problems in the robotics, UAV, underwater vehicle and Automated Highway System literatures.**

I. Introduction

In 1977, Sholomitsky, Prilutsky and Rodin studied a proposed infrared interferometer composed of multiple, free-flying telescopes [93]. Today, formation flying is a critical technology for planned and future missions of NASA [15], [109], the Department of Defense [16], [23], ESA [7], [38] and many other national space agencies.

In deep space, formation flying enables variable-baseline interferometers [54], [39] and large-scale distributed sensors [46] that can probe the origin and structure of stars and galaxies with high precision. In addition, synthetic aperture imaging formations will be used to search for Earth-like planets orbiting other stars and study their atmospheres for signs of life [14].

In Earth orbit, formation flying enables distributed sensing, sparse antenna arrays and contemporaneous spatial sampling for applications such as gravitational mapping, interferometric synthetic aperture radar (InSAR) and studying the Sun-Earth connection. Further, by allowing instruments on separate spacecraft to be combined into a *co-observatory*,[2] formation flying can replace an expensive multiple-payload platform with a large number of low cost spacecraft.

This survey of spacecraft formation flying control is the second part of a two-part survey on formation flying guidance and control. In the companion survey on formation flying guidance [87], we defined *formation flying* (FF) as a set of more than one spacecraft in which *any of the spacecraft dynamic states are coupled through a common control law*.[3] In particular, at least one member of the set must (*i*) track a desired state profile relative to another member, and (*ii*) the associated tracking control law must at the minimum depend upon the state of this other member. The second point is critical. For example, even though prescribed relative positions are actively maintained, GPS satellites constitute a *constellation*[4] since their orbit corrections only require an individual satellite's position and velocity.

A control law satisfying Condition (*ii*) above is called a *formation tracking control law*.[5] Based on the above definition of FF, we present a comprehensive survey of the spacecraft formation flying control (FFC) literature. Specifically, FFC refers to design techniques and associated stability results for formation tracking control laws.

A. A Brief History of Spacecraft Formation Flying

After the initial conceptual study of a multiple spacecraft interferometer (MSI) by Sholomitsky et al. in 1977, several MSI mission architectures were proposed and evaluated in the early 1980s (e.g. [98]). See Labeyrie, Savaria and Schumacher [51] and Stachnik and Gezari [99] for further references. These early FF mission designs considered Earth-orbiting MSIs and included preliminary analyses of possible orbits and corresponding fuel requirements.

In the late 1980s and early 1990s, research focused on developing aerodynamic drag compensation strategies (e.g. Matthews and Leszkiewicz [68] and Scolese, Folta and Borda [91]) and fuel-efficient relative trajectories for Earth-orbiting formations (e.g. DeCou [26]).[6]

Significant interest in formation flying started to develop in the late 1990s. The first general study of a spacecraft FFC architecture was by Wang and Hadaegh in 1996 [118], who analyzed the Leader/Follower architecture (previous papers considered specific controllers applied to two or three spacecraft formations). Also in that year, Folta, Newman and

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[2]A co-observatory is a planet-orbiting formation in which independent science instruments on separate spacecraft examine the same physical location closely enough in time that measurements may be considered contemporaneous. For example, the Cloudsat and Picasso-Cena satellites have been proposed as a co-observatory; CloudSat's radar and Picasso-Cena's lidar would observe the same groundtrack with less than 15 seconds of separation [50].

[3]This coupling can be in translational and/or rotational degrees of freedom and in position and/or velocity. For example, a formation may consist of ten spacecraft with synchronized angular velocities.

[4]A constellation is defined as a set of spacecraft whose states are not dynamically coupled in any way. As a result, there is no interaction between the constituent spacecraft (i.e., the change of state of one spacecraft does not impact the state of another). A *fleet* is defined as a collection of constellations and formations. The definitions provided here have not been used consistently throughout the literature.

[5]"Tracking" in this context includes regulation.

[6]These fuel-efficient trajectories are referred to as *passive relative orbits*, and they are discussed extensively in Part I of this survey [87].

Gardner defined classes of co-observatories and developed a Leader/Follower controller for enabling low Earth orbit (LEO) co-observatories [34].[7]

In 2000, Lawton overviewed the FFC literature up to that year [60]. As part of his overview, Lawton defined three main FFC architectures. In our current survey, we examine these architectures in more detail and add two new architectures. We also include the prolific research of the last few years and emphasize theoretical developments.

B. Formation Classification

In general, formations can be categorized based on (1) size (i.e., number of spacecraft), (2) precision (i.e., control performance requirements), and (3) ambient dynamic environment. These characteristics will in part determine which FFC algorithms are feasible for a formation. To define the size of a formation, let N be the number of spacecraft in a formation. If $N \leq 5$, then we consider the formation "small," and if $N \geq 20$, we consider the formation "large." These numbers are guidelines. Next, we consider the level of control precision required for formations: "high" precision (HP) formations require performance to the level of *centimeters/arcminutes* or smaller, whereas "low" precision (LP) formations have performance requirements greater than a *meter/degree*. Finally, we distinguish formations based on the ambient dynamic environment. Specifically, in deep space (DS) relative spacecraft translational dynamics are approximated by a double integrator (i.e., no state dependent forces are present in the open loop) [86], while in a planetary orbital environment (POE) spacecraft are subjected to significant gravitational dynamics and other environmental disturbances such as aerodynamic drag.

The size of a formation, however, has not been a primary concern in the FFC literature. This omission is due to the common assumption that a formation estimator is available to provide all the information required for control [101]. However, as N becomes large, the sensing and communication requirements imposed by an FFC algorithm can easily become impractical. An area for future research, discussed in the Conclusions, is reducing the amount of formation state information required by FFC algorithms.

Precision can generally be traded for control effort; that is, the precision achievable is limited by the amount of fuel on-board. As a result, when precision is considered, it is given as a function of the fuel required to achieve a specific precision level. However, non-ideal aspects of formation estimation, such as delayed measurements and asynchronous inter-spacecraft communication, have not been considered. Determining the achievable control precision in the presence of these practical constraints is an open area of research [126].

A formation's dynamic environment has two ramifications for FFC. First, in DS applications only relative spacecraft translational measurements are available to the necessary accuracy. Inertial spacecraft positions are known only to the level of kilometers. This aspect of DS formations requires that spacecraft measure their translational positions with respect to either (1) a non-maneuvering, "inertial" reference spacecraft or (2) to other spacecraft that are also maneuvering. In comparison, inertial positions can be measured and controlled in POE FFC algorithms (e.g. see [90]).[8]

The second ramification of the formation dynamic environment on FFC is that DS dynamics are more benign than POE dynamics, i.e., translational degrees of freedom (DOFs) approximately decouple into single-input, single-output double integrators. As a result, stability theorems for certain FFC algorithms have been developed for DS formations, but not for POE formations (e.g. see [73]).

C. Organization of Survey

In the companion survey on formation flying guidance [87], the dynamic environment of a formation was the primary distinction in the literature. While the formation size, precision and dynamic environment affect FFC development in the ways discussed above, they are not driving factors in FFC research to date. The primary distinction in the FFC literature is the type of *FFC architecture* used. An FFC architecture determines the overall design approach for a specific FFC algorithm; many different algorithms are possible within a given architecture. In this survey, we define five basic formation architectures: Multiple-Input, Multiple-Output (MIMO), Leader/Follower (L/F), Virtual Structure (VS), Cyclic and Behavioral. The L/F, VS and Behavioral architectures were originally described in Lawton's overview [60].

We organize the FFC literature by FFC architectures, with DS and POE specific algorithms noted. Each architecture is defined formally in its respective section. The advantages and disadvantages of each architecture are discussed in the Conclusions, as are directions for future research. Note that some control algorithms in the robotics, UAV and automated highway system (AHS) literatures are similar to spacecraft FFC algorithms. While we do not exhaustively survey these other areas, we include some representative references.

In designing FFC algorithms, formation stability must be addressed. Typically, authors only consider the stability of the *relative* dynamics of a formation. If the inertial position or attitude of a formation is relevant,[9] an additional controller is assumed for tracking an inertial state. reflect this usage, unless otherwise noted, by *stability* we mean the Lyapunov stability of the relative spacecraft dynamics, whether translational, rotational or both. In particular, the inertial position of a formation need not be controlled for a formation to be considered "stable."

While we have included rotational degrees of freedom in our definition of formation flying, the FFC literature focuses on translational control. Relative attitude control is as important.

[7] The co-observatory classes were first published in 1992 [33]. The purpose of this earlier paper was to analyze attitude pointing requirements for co-observatories.

[8] When inertial states are being controlled, one spacecraft's inertial reference trajectory must consist of another spacecraft's inertial state plus an offset. Otherwise, spacecraft states will not be coupled.

[9] For example, consider a synthetic aperture in Earth-trailing orbit. Displacing this formation hundreds of kilometers will not significantly affect the scientific performance of the formation.

For example, in rotating an MSI to fill the u,v-plane, attitudes must be synchronized with relative positions. However, accurate inertial attitude information is generally available, which simplifies the relative attitude control problem. Unless otherwise stated, translational control is discussed.

Finally, for brevity "architecture" is generally omitted from architecture names (e.g. L/F instead of the L/F architecture). Also, numerous acronyms are used throughout the paper. As a convenience, a table of acronyms is included in the appendix.

II. Multiple-Input, Multi-Output

In the Multiple-Input, Multiple-Output (MIMO) architecture, formation controllers are designed using a dynamic model of the entire formation. That is, the formation is treated as a multiple-input, multiple-output plant. Within this problem formulation, all the methods of modern control may be applied to formation control. For example, [41] formulates a minimal state space realization of the relative error states for a *rigid formation*[10] and designs an LQR controller.

Given a state space representation of the formation dynamics and a state feedback gain matrix for *relative* state control, [94] develops an algebraic method for deriving alternate control topologies based on linear dependencies in relative position specifications (e.g. feeding back the relative position $\mathbf{r}_{ij}$ is equivalent to feeding back $\mathbf{r}_{ik} + \mathbf{r}_{kj}$). It also examines using controls that affect only the unobservable states (i.e., the inertial position and velocity of the formation) to minimize fuel use or to ensure the net force on the formation is zero.

In [97], a decentralized LQG problem is considered. The resulting state feedback gain matrix is equivalent to a standard, centralized LQR controller. However, each spacecraft must optimally estimate the entire formation state using only a locally-optimal estimator (i.e., an estimator operating on a reduced set of measurements) and information communicated from other spacecraft. [97] reduces the information communicated between spacecraft by compressing local spacecraft measurements using an augmented local estimator. [37] applies this decentralized LQG algorithm to formations in Lagrange point orbits.

Directed graphs[11] (or digraphs) have been used in MIMO algorithms to both specify the desired formation geometry and to enforce specific spacecraft control interdependencies. Generally, multiple-input, multiple-output synthesis techniques may introduce arbitrary spacecraft control interdependencies (i.e., the resulting gain matrix is not sparse).

Ref. [112] uses a digraph to specify the geometry (not the interdependencies) of POE formations, where the spacecraft are placed in multiple circular orbits with identical radii. The digraph specifies constant angular offsets that are to be maintained between spacecraft (i.e., the reference trajectories). The digraph is then encoded into an LQR formulation.

In [73], rigid and unfoldable digraphs[12] are first used to specify the geometry of a formation. Algebraic constraints on vertex (spacecraft) locations resulting from the digraph are used to generate a potential function. The gradient of this potential function then forms the basis of a formation controller. Note that this approach enforces spacecraft control interdependencies, since only the spacecraft involved in a particular algebraic constraint enforce it. A general stability proof is also provided. This particular digraph approach is MIMO because a digraph specifying the entire formation is needed to design the formation controller. [75] discusses methods for constructing, merging and separating rigid and unfoldable digraphs.

Finally, model predictive control (MPC) has also been used within the MIMO architecture. [32] formulates and numerically solves a nonlinear, constrained MPC problem where the terminal state consists of a family of equilibria. Conditions for closed loop stability are also derived.

III. Leader/Follower

The Leader/Follower (L/F) architecture is the most studied FFC architecture.[13] L/F uses a hierarchical arrangement of individual spacecraft controllers that reduces formation control to individual tracking problems. We first define L/F, and then we discuss its stability properties. Finally, we summarize the L/F literature.

To formally define L/F, we introduce the *control dependency* directed graph,[11] which for brevity we refer to as the *dependency digraph*. The dependency digraph is similar to digraphs defined in [28], [30], [31] and [71], but it is less restrictive and does not depend on a particular control strategy. The vertices of the dependency graph represent the spacecraft in the formation. A directed edge (i, j) is added to the digraph if the control action of spacecraft j is a function of (i.e., depends on) the state of spacecraft i. This dependency can arise in at least three ways: (1) a function of the relative state between spacecraft i and j is being tracked by spacecraft j, (2) the reference trajectory for spacecraft j is a function of the state of spacecraft i, or (3) the feedback control action of spacecraft i is used in the controller of spacecraft j.[14]

Reviewing digraphs briefly, a *walk* is a sequence of vertices such that each sequential pair is a directed edge (e.g. ijk is a walk if (i, j) and (j, k) are edges), and the length of the walk is the number of vertices in it. A *cycle* is a walk of at least length three with no repeated vertices except that the first

[10] A formation is rigid if there exists a reference frame in which all relative spacecraft positions are constant.

[11] A directed graph consists of a set of vertices $\mathcal{V}$, a set of edges $\mathcal{E}$, and an optional set of weights $\mathcal{W}$. The edges are specified as ordered pairs (i, j), where $i, j \in \mathcal{V}$. The edge $(i, j) \in \mathcal{E}$ means that an arrow is drawn *from* vertex i *to* vertex j. One interpretation for an edge (i, j) is that the vertex (spacecraft) i is to maintain a desired position with respect to vertex (spacecraft) j. The weights typically represent the lengths of edges.

[12] The definitions of "rigid" and "unfoldable" ensure that given sets of vertices, edges and weights, there is only one embedding of the digraph in $\mathbb{R}^2$ or $\mathbb{R}^3$ modulo rigid body motions of the entire embedding. That is, if the vertices are considered particles and the weights the lengths of rods connecting the particles (according to the edge set), then the digraph represents a unique rigid body.

[13] Note that Leader/Follower has also been referred to as Chief/Deputy [90], Master/Slave [48] and, the traditional terminology from two-spacecraft rendezvous, Target/Chase.

[14] In the literature, the third type of dependency has only been used in conjunction with one of the first two.

vertex must equal the last (e.g. iji). A digraph without (resp. with) a cycle is called *acyclic* (resp. *cyclic*).

With these concepts, we define an L/F FFC algorithm to be an interconnection of individual spacecraft controllers that results in an *acyclic control dependency directed graph.*[15]

For an edge (i, j) in the dependency digraph, spacecraft j is called a *follower* and spacecraft i is called a *leader*. In any L/F algorithm, there is at least one spacecraft that does not follow another (see [27], pg. 230). This spacecraft is referred to as a *fleet leader* [118]. Note that a spacecraft can have multiple leaders, but care must be taken in this case to ensure that the tracking problem is well posed.[16] A special case of the L/F architecture is when each spacecraft is required to have only one leader. This special case is referred to as *single-leader L/F* [71].

In 1991, [117] presented a number of robotic formation control strategies, including a number of L/F algorithms. In 1996, the seminal paper [118] generalized L/F and adapted it to spacecraft formations in both DS and POEs. For single-leader L/F, [71], [117] and [118] prove the stability of directed tree dependency digraphs (i.e., the most general single-leader case) for particular control laws. In each case, if the individual tracking control laws used by each follower are stable, then the entire formation is stable. However, general sufficient conditions for L/F stability were not addressed.

General stability conditions are available for L/F, but they apply to a type of stability called *mesh stability*. Intuitively, a hierarchically connected system is mesh stable if it is asymptotically Lyapunov stable and perturbations to the top of the hierarchy (i.e., a leader) do not grow as they propagate through the system; specifically, if a leader is disturbed, then the peak tracking errors of its successive followers are uniformly bounded by the peak tracking error of the first follower. Mesh stability has its roots in the automated highway system (AHS) literature.[17]

Mesh stability is based on the earlier concept of string stability. Both mesh and string stability are more restrictive than Lyapunov stability. Since there are many types of string stability, we briefly discuss each, noting the differences. This discussion will lead naturally to the definition of mesh stability.

For the following discussion, we consider hierarchically connected systems (also called "look ahead") where the dynamics of each subsystem are given by

$$\dot{x}_i = f_i(x_i, x_{i-1}, \ldots, x_1),$$

where x_i is the state of the ith subsystem, $i \in \mathcal{I}$, where $\mathcal{I}$ is a possibly infinite subset of the natural numbers, and the state of the system is $x \triangleq [\ x_1^T\ x_2^T\ \ldots\ ]^T$. For L/F FFC, the state x_i should be thought of as the tracking error of a follower.

We begin with the *asymptotic string stability* of [106], which was defined for an infinite number of subsystems (i.e., $\mathcal{I}$ equals the set of natural numbers). Asymptotic string stability requires that for that for all $\epsilon > 0$, there exists $\delta > 0$ such that $\sup_i \|x_i(0)\| < \delta \Rightarrow \sup_i \sup_t \|x_i(t)\| < \epsilon$ (stability requirement) and that $\|x_i(t)\| \to 0$ for all i (attractiveness requirement). *The stability condition states that the the infinite chain of subsystems must be uniformly bounded.* In particular, the peak error cannot increase continually as you move from one subsystem to the next; with an infinite number of subsystems the state would become unbounded.

In [106], sufficient conditions are also derived for asymptotic string stability. The $f_i(\cdot)$ must be identical, but can be nonlinear and non-autonomous. Essentially, the subsystems (i.e., $\dot{x}_i = f(x_i, 0, \ldots, 0)$) must be exponentially stable, and the subsystem connections (i.e., how strongly $f_i(\cdot)$ depends on x_j, $j < i$) must be sufficiently weak.[18]

Ref. [22] studies *spatial asymptotic string stability* (s.a.s.s.). Similar to the stability requirement for asymptotic string stability, s.a.s.s. requires the subsystems to be uniformly bounded.[19] However, the attractiveness requirement is different. Rather than requiring each subsystem's error to go to zero in time, s.a.s.s. requires that $\lim_{i\to\infty} \|x_i(0)\| = 0 \Rightarrow \lim_{i\to\infty} \sup_t \|x_i(t)\| = 0$. That is, subsystem errors must go to zero as you move through the system *spatially*; the errors must decay (not just be uniformly bounded) through succeeding subsystems. [22] derives sufficient conditions for s.a.s.s. for systems with linear and identical $f_i(\cdot)$, again based on weak subsystem connections.

A third type of string stability is for hierarchically connected systems with a *finite* number of subsystems. For finite dimensional systems, there is always a uniform bound on the subsystem states *even if* the peak error increases from one subsystem to the next [92]. In [43], [79] and [92], string stability is defined as the property that a finite hierarchically connected system is Lyapunov stable and that $\sup_t \|x_i(t)\| \leq \sup_t \|x_{i-1}(t)\|$, that is, that peak errors decay *monotonically* as they propagate through the subsystems. We shall refer to this as *monotonic string stability* for ease of exposition. Recall s.a.s.s. only requires that the error goes to zero, not that the peak error is less in each subsequent subsystem. Also, the requirement for identical subsystem dynamics has been relaxed in monotonic string stability.

Monotonic string stability is based on the concept of a line of vehicles, each one following the preceding vehicle. Refs. [92] and [79] treat mesh systems: finite hierarchically connected systems where the subsystems are arranged in a two-dimensional grid. Subsystems in a mesh system are double-indexed to reflect this two-dimensional organization.

Mathematically, however, hierarchically connected systems

[15] Refs. [71] and [30] also use variations on acyclic digraphs to define more restricted forms of L/F.

[16] The L/F algorithm discussed in [43] considers a chain of vehicles maintaining constant offsets. Except for the fleet leader, each vehicle uses the velocity of the vehicle immediately in front of it, and the acceleration and velocity of the fleet leader. Each vehicle has two leaders.

[17] A common concept for automated highways is a platoon of vehicles, which is an L/F arrangement of vehicles such that each vehicle literally follows the one in front of it. Quoting [106], "tracking (spacing) errors should not amplify downstream from vehicle to vehicle for safety."

[18] "Weak" is defined in terms of the Lipschitz constants of $f_i(\cdot)$ and constants associated with a Lyapunov function.

[19] S.a.s.s. requires uniformity in an $\mathcal{L}_p$ norm, whereas asymptotic string stability only requires uniformity in the $\mathcal{L}_\infty$ norm.

and mesh systems are equivalent through a change of variables in the subsystem indices. With this observation, [78] formally defines a finite hierarchically connected system to be *mesh stable* if it is asymptotically Lyapunov stable and $\sup_t \|x_i(t)\| \leq \max_{k<i-1} \sup_t \|x_k(t)\|$. In monotonic string stability, the peak error of the current subsystem must be less than the preceding subsystem's peak error, whereas for mesh stability this condition has been relaxed to only requiring the peak error to be less than maximum peak error of *all* the preceding subsystems.[20]

With the exception of asymptotic string stability, all the subsystem dynamics are assumed time-invariant. Therefore, to represent closed-loop error dynamics, the reference trajectories in the L/F architecture must be *constant*. [43] has an excellent bibliography for those wishing to investigate L/F in the AHS context, and the bibliography of [106] provides a good starting place for those wishing to study connected system stability.

We now discuss the numerous L/F algorithms in the literature. Most authors consider a single-layer L/F architecture in which $N-1$ spacecraft all follow the same leader spacecraft. Also, though not formally proven, it is commonly assumed that if follower control laws are stabilizing, then an L/F connection of these controllers results in an asymptotically Lyapunov stable formation. As a result, the numerous contributions to the L/F literature differ primarily in the type of follower tracking control law designed.

The following papers consider DS formations. [120] simplifies the feedback linearized control laws of [118] and applies them to synchronized translational and rotational control of deep space MSIs. [79] uses sliding mode control. [70] and [71] combine feedback linearization and linear matrix inequalities (LMIs) to design robust and switched controllers for avoiding control saturation. [65] applies feedback linearization and model predictive control and also address saturation through controller switching. [84] and [85] develop and compare a variety of design techniques including proportional/derivative (PD), time optimal and mixed fuel-time optimal. [122] develops and experimentally demonstrates a rule-based controller for forming an equilateral triangle and aligning the orientation of three air-levitated robots. [83] develops a two-tier controller where the coarse loop is a phase-plane controller with a vernier PD loop. [121] develops a rule-based control law for synchronizing the rotations of multiple spinning spacecraft. Based on [121], [42] develops a rule-based controller for synchronizing thruster deadbands across multiple spacecraft. Impulsive thruster synchronization is necessary for MSIs since the vibrations from thruster firings can corrupt interferometric measurements. [64] also designs a thruster synchronized L/F algorithm, but it addresses both translational and rotational control, and uses classical control theory with nonlinear dynamic compensation. [128] designs a combined translational/rotational controller using LQR and H_∞ methods.

[20]Since mesh stability is defined recursively, the peak tracking error of all subsystems must be bounded by the peak tracking error of the first subsystem. Note that the first subsystem, which corresponds to the error dynamics of a vehicle following only fleet leaders, is not uniquely defined.

Similar to [120], [130] considers simultaneous translational and rotational control of a formation. However, the desired positions of the followers with respect to the leader are specified not in an inertial frame, as is generally done, but in the leader's *body* frame. The advantage of this approach is that the entire formation can be rotated by simply changing the attitude of the leader.

Ref. [74] builds a planar DS formation through *node augmentation*: spacecraft are added sequentially to a formation by specifying desired distances to any two existing formation spacecraft. This specification is such that the augmented formation remains rigid and unfoldable.[21] The two existing spacecraft "anchor" the new spacecraft to the formation. A similar approach is used in [30]. In [74], each new spacecraft uses a feedback-linearized controller to maintain the two specified distances. This controller only depends on the relative states of the anchoring spacecraft (i.e., the anchors are the two leaders for the new spacecraft).

Turning to the POE literature (which in many cases also applies to DS formations), the following papers develop variations on linear quadratic (LQ) control for design of the follower tracking control laws. All of these papers use variations of the Hill-Clohessy-Wiltshire (HCW) equations [20], [44], although a few authors modify them slightly. [49] develops a discrete-time LQ controller using pulse-based actuators. [131] extends this controller to include a periodic gain. [115] designs separate discrete-time LQ controllers for the in-plane (orbital plane) motion and the out-of-plane motion. [19] develops a similar, decoupled controller for GEO orbits. [96] also designs a decoupled LQ controller, but the angular velocity of the reference frame in the HCW equations is modified to include the effects of the J_2 zonal harmonic. [82] designs a discrete LQ controller for disturbance rejection and a feedforward controller that plans trajectories and provides non-equilibrium point control offsets. [18] uses an LQ controller with the decentralized estimation scheme of [97].[22] [95] designs an LQ controller and studies the frequency of thruster firings versus the total Δv needed to reject realistic disturbances. [104], [103] and [19] design LQ controllers without using radial thrusting. [127] designs an LQG controller using GPS and includes many practical considerations.

A variant on model predictive control (MPC) using linear time-varying models is developed in [45], [47], [111] and references therein. Followers are first placed in error boxes relative to the leader. When a follower approaches the edge of its relative error box, an optimal, feedforward control problem is solved to return the follower to the center of its error box. The optimal, predictive portion of the controller includes differential disturbances and sensor noise effects.

A variant on model predictive control (MPC) is developed in Refs. [8], [34], [35] and [36]. Followers are first placed in error boxes relative to the leader. When a follower approaches

[21]See the MIMO section for definitions of graph theoretic terms.

[22]While the overall state is estimated using the MIMO method of [97], the control design is localized—each spacecraft uses an LQ controller to track a trajectory with respect to the origin of the HCW frame. Hence, the FFC algorithm is L/F.

the edge of its relative error box, a trajectory is planned to return the spacecraft to a desired position within the error box. The trajectory planning algorithm is based on Battin's C^* matrix (see [6], pg. 461), which is a convenient reformulation of the orbital state transition matrix. This MPC controller is applied to libration point formations in [37]. A similar MPC algorithm using linear time-varying models is developed in [45], [47], [111] and references therein. The trajectory planning algorithm in this case uses optimal control theory and includes differential disturbances and sensor noise effects.

Considering nonlinear control, [25] and [132] design position feedback and output feedback nonlinear controllers, respectively, for the *full*, nonlinear Keplerian relative orbital dynamics. These controllers are globally uniform ultimate bounded (GUUB)[23] in position and velocity tracking errors. [118] develops feedback-linearized controllers for simultaneous translational/rotational control. [102] also considers simultaneous 6 DOF control and uses a state-dependent Riccati equation to design a full state feedback, nonlinear controller.

Adaptive control has also been used to design the follower tracking control laws. [123] develops a GUUB adaptive controller where the disturbance is assumed bounded by a known nonlinear function scaled by an unknown constant. [24] assumes that a single leader is in a circular orbit, but otherwise retains Keplerian relative orbital dynamics. Further, assuming that both the spacecraft masses and disturbance forces are unknown but constant, [24] develops a globally convergent,[24] full state feedback adaptive controller. [133] extends this controller to the case where the leader is in an unperturbed, elliptical orbit. [125] then extends the controller of [133] to include an unknown, but periodic disturbance force with a known upper bound. [124] departs from these previous papers and develops a locally convergent adaptive controller for constant disturbances that uses only position feedback. [77] develops a convergent 6 DOF adaptive controller that allows for unknown but constant masses and moments of inertia. [107] includes a number of references for adaptive L/F design in the AHS literature.

Rather than using Cartesian reference trajectories, some authors use orbital elements ("orbital" omitted hereafter). [108] considers a formation of spacecraft in elliptical orbits where spacecraft distances are kept nearly constant via small element differences. For this formation, [108] develops a feedback controller that controls the osculating[25] element *difference* of a follower and leader. In contrast, [90] develops a control law for mean[25] elements. Note that *inertial* states are being controlled (i.e., elements as opposed to differential elements), but the reference trajectory of the follower is the leader's elements (state) plus an offset. [90] also compares the mean element controller to a controller that uses the inertial state represented in Cartesian coordinates (i.e., position and velocity), where again the reference trajectory is the leader's position and velocity plus an offset.

[89] considers a control law where the reference trajectory for the follower is specified as an osculating element difference (similar to [108]) that is then mapped via a linearized transformation to desired Cartesian *relative* position and velocity vectors. The authors then compare this "hybrid" control law to a control law using mean elements. They show via example that a $20\,m$ increase in tracking accuracy results from using mean instead of osculating elements. Based on insights gained from Gauss' variational equations, [88] develops an impulsive osculating element controller such that individual elements are changed without affecting others. This controller is not FFC unless the trajectory the controller tracks depends upon the state of another spacecraft. This comment also applies to the fuel-optimal impulsive and low-thrust osculating element controllers of [113].

Finally, we present some papers that do not fall into any of the previous control L/F design methodologies. [134] applies hybrid stability analysis to full state feedback controllers. [61] uses binary drag panels (i.e., deployed/not-deployed) to move a spacecraft to and maintain it at the position of a leader (rendezvous). Whether their controller can be extended to maintaining offsets with respect to a leader is an open issue. For more on H_∞ L/F control, see references in [128]. Lastly, while [112] uses a MIMO controller to keep spacecraft phased within circular orbits, [72] estimates the mean motion and orbit-averaged, along-track offset (average phase) and develops two control schemes to maintain a desired offset.

IV. Virtual Structure

In the Virtual Structure (VS) architecture, the spacecraft behave as rigid bodies (or particles) embedded in a larger, virtual structure (or body). Motions of the virtual structure and the constant, specified positions and orientations of spacecraft within the virtual structure are used to generate reference trajectories for the spacecraft to follow. The motions of the virtual structure include rigid body motions and contractions/expansions. Individual spacecraft controllers are used to track the generated reference trajectories.

We identify two types of VS: Iterated VS (IVS) and Guidance VS (GVS). In IVS, a formation template (i.e., structure) is fit to the current spacecraft positions *at each time step*. The spacecraft then track desired states with respect to the fitted template. Spacecraft states are coupled through the template fitting step. [52] considers Earth-orbiting formations

[23] A state space system is GUUB if for all initial conditions $x(t_0) = x_0$ (globally), there exists a compact set X and a time $0 < T(x_0) < \infty$ independent of t_0 (uniform) such that $x(t) \in X$ for all $t \geq t_0 + T$ (ultimate bounded). See [5].

[24] In adaptive control, asymptotic stability of the error dynamics (position and velocity tracking errors and parameter estimate errors) is generally extremely difficult to prove. A more common goal is to show that all the errors are uniformly bounded and go to zero asymptotically. These two properties are what we mean by "convergent."

[25] To the standard Keplerian elements, perturbations can cause secular variations (unbounded growth proportional to a power of time), short period variations (on the order of the orbital period) and long period variations (longer than short period—there is a considerable range of long periods depending on the perturbation considered and the specific orbit, but long period variations due to zonal (latitude dependent) harmonics are on the order of 10's of days for near-Earth satellites). Osculating (instantaneous) elements include all variations. Mean elements have either the short period or the short and long period variations averaged out. See [114]).

and uses a time-invariant Walker constellation template (see [53]). Different fitting algorithms are discussed in [40] and [76]. [63] considers non-holonomically constrained robots and, in addition to fitting a template each time step, incrementally perturbs the fitted template to eventually achieve a formation goal state. Similarly, [110] finds the *virtual center* of a formation through a least-squares fit. This center may be thought of as the location of a virtual "leader" spacecraft that minimizes the tracking errors of all the "followers." However, since all the spacecraft states are coupled through the fitting step, this algorithm is not L/F.

The second type of VS, called Guidance VS (GVS), is proposed in [10]. GVS consists of an initial structure (i.e. template) fitting step, followed by prescribed motion of the structure to generate desired spacecraft trajectories. In [55], an adaptive controller that includes saturation constraints is designed to track GVS trajectories. GVS has also been used to plan optimal formation rotations; see [11] and [12]. The pattern matching methodology of [3] is a GVS algorithm.

By itself GVS is not FFC because spacecraft states are not coupled. However, if the virtual structure is referenced to a real spacecraft, then GVS becomes a type of L/F FFC algorithm with reference trajectories provided by the virtual structure. GVS also forms the basis for a Cyclic FFC algorithm. IVS, however, is FFC, and we advocate making it a type of Cyclic FFC.

V. Cyclic

Similar to L/F, a formation controller in the Cyclic architecture is formed by connecting individual spacecraft controllers. However, Cyclic differs from L/F in that the controller connections are *not* hierarchical. We define a Cyclic FFC algorithm to be an interconnection of individual spacecraft controllers that results in a *cyclic control dependency directed graph*.[26]

The stability analysis of Cyclic algorithms is difficult because cycles in the dependency digraph add higher levels of feedback to the individual spacecraft feedback controllers. As a result, many Cyclic algorithms are studied through simulation only [1], [117]. However, potential field-based cyclic algorithms often have an associated stability proof since the potential function itself serves as the basis for a Lyapunov function.

Ref. [117] introduces *multineighbor strategies*, where each spacecraft controls itself with respect to the center-of-mass (COM) of a subset of neighboring spacecraft. A cycle arises in the dependency digraph if two spacecraft are neighbors of each other (e.g. spacecraft i and j each control themselves with respect to the COM of spacecraft i and j). [1] and [4] use similar approaches. In particular, [4] studies a *unit-centered* strategy in which robots control themselves with respect to the COM of the entire formation. We refer to these algorithms as *centroid strategies*, and they have only been studied through simulation.

[26]See the beginning of the L/F section for the definitions of cyclic and control dependency directed graphs.

There also exist Cyclic algorithms for forming regular geometric patterns from arbitrary distributions of spacecraft/robots.[105] uses rule-based controllers to generate lines, circles, polygons and distributions of robots within convex polygons. [137] extends [105] by modifying the algorithms to better handle realistic actuators, sensors, and collision avoidance algorithms.

The basic rules for forming a circle in [105] are (1) first move towards or away from the farthest robot until it is a prescribed distance D_o away, and then (2) move away from the closest robot.[27] [119] develops two Cyclic algorithms, one of which is a rule-based approach similar to [105]. In the second algorithm of [119], potential fields are constructed that mimic rules similar to the two discussed above. That is, if a spacecraft is more than a distance D_o away from another spacecraft, then an attractive force results, and if less, then a repulsive force results. In [119], a stability proof for the potential field approach is provided, and the resulting formation equilibria are analytically characterized for up to four spacecraft.

Ref. [69] also uses a potential field approach (every spacecraft is repulsed by its neighbors) to evenly distribute spacecraft in a circular orbit, and proves the stability of the algorithm. [76] starts with the work of [69] and considers different potential function forms and spacecraft arrangements. [129] consider a potential field strategy where robots are attracted to two preassigned neighbors. In addition, *formation vectors* are applied to specific robots. Formation vectors are additional velocity commands used to shape the formation.[28] The stability of the algorithm is proven and conditions are imposed on the formation vectors for the formation to be stationary. Essentially, if the formation vectors are not selected properly, then the sum of their effects can lead to a fixed shape formation that translates as a rigid body.

Refs. [135] and [136] introduce a Cyclic algorithm based on the GVS architecture. However, there are two important differences. First, the motion of the virtual structure is no longer prescribed, but is generated by specifying a goal state and a controller *for the virtual structure*. The spacecraft still have their own local controllers to track the reference trajectories generated by the motion of the virtual structure. The second difference is to make the feedback gain for the virtual structure's control law dependent on the tracking errors of the spacecraft control laws. As a result, if the spacecraft begin to fall out of formation, the virtual structure's control gain decreases, slowing down the virtual structure. This slowing of the virtual structure allows the spacecraft to reduce their tracking errors, thereby reestablishing the formation. The stability of this algorithm is proven in [136].

[27]It is theorized that flocking or schooling (i.e., formation maintenance) in animals is achieved by each animal: (1) being attracted to distant neighbors, (2) being repulsed by close neighbors, and (3) aligning its velocity with the velocities of neighbors [62].

[28]A simple analogy is to imagine beads (robots) placed along a length of rubber band. The rubber band represents the effect of the potential fields and the formation vectors specify a pull on each bead. For example, pulling on the two end beads in directions 90 degrees apart and pulling on the center bead with the proper magnitude and in a direction opposite the bisector of the 90 degree angle generates a stationary "⊔" formation.

Lastly, the dependency graph for IVS is completely connected (i.e., every spacecraft depends on every other spacecraft through the virtual structure fitting step), and so it is Cyclic.

VI. Behavioral

As discussed in [4] and [13], the Behavioral architecture combines the outputs of multiple controllers designed for achieving different and possibly competing behaviors (i.e., objectives). According to Arkin [2], to whom formal behavior-based robotics is due, there is no universally accepted definition of a "primitive behavior." Drawing a consensus from the papers surveyed and [2], we consider a behavior to be an objective such as collision-avoidance or move-to-goal, functions that the spacecraft must individually or collectively perform.

For formations the maintain-formation behavior is required [1], [4]. For example, an L/F algorithm plus a repulsive potential field centered on each spacecraft is a Behavioral algorithm consisting of maintain-formation and collision-avoidance behaviors. Note that the maintain-formation behavior may itself be a composition of lower-level actions,[27] but we still consider it to be a single behavior. Note also that control laws for individual behaviors can be FFC algorithms in their own right, and are classifiable independent of the Behavioral aspect of the overall controller. Many of the FFC algorithms for the maintain-formation behavior were discussed more fully in the Cyclic section (e.g. centroid strategies).

Ref. [1] provides an excellent example of a Behavioral FFC algorithm. They consider velocity-commanded aircraft with collision-avoidance, obstacle-avoidance, *move-to-goal*[29] and formation-maintenance behaviors. Each of the behaviors has an associated velocity vector and weighting, and the velocity of each aircraft is set to the summed value of its behavioral velocities.

Ref. [4] develops a rule-based behavioral controller for platoons of robotic jeeps. For the maintain-formation behavior they consider L/F and two Cyclic strategies similar to the centroid strategies of [117]. To this behavior they add collision/obstacle-avoidance and move-to-goal behaviors. [105] considers arbitrary groupings of robots and develops simple, rule-based Cyclic algorithms for forming them into regular geometric shapes. To these maintain-formation rules, a "left-swerve" collision avoidance algorithm is added. [137], however, performs an exhaustive simulation study of the algorithm in [105] and identifies many cases where the collision-avoidance behavior "blocks" the maintain-formation behavior.[30]

Behavioral control is based upon the idea that by adding control actions for individual behaviors, one obtains a part of each behavior. However, as illustrated in [137], it is possible for the behaviors to destructively interfere. Generally, simulation is the only tool for verifying that the combination of behaviors functions as desired.

The previous Behavioral FFC algorithms do not have any theoretical guarantees or stability proofs. In contrast, the following series of papers proves the stability of its Behavioral algorithm.

Ref. [59] introduces the concept of *coupled dynamics*. There are two behaviors in this concept: maintain-formation and move-to-goal. The underlying idea is that the maintain-formation behavior is implemented by coupling goal-state tracking errors: if all the robots have the same tracking error with respect to their goal states, then the robots are in formation. Feedback linearized controllers are used by each robot to track its goal state (move-to-goal) and to track the average goal state tracking error of two neighboring robots (maintain-formation). Note that by itself the maintain-formation behavior (i.e., tracking the error of two neighbors) is a Cyclic centroid strategy, for which a general stability proof does not exist. However, in this case the Cyclic algorithm is stabilized by coupling it to the move-to-goal behavior.

Ref. [58] extends the concept of coupled dynamics to rotational motion using rate feedback and passivity based controllers. [56] compares L/F and the coupled dynamics approach in terms of control effort and tracking errors. Considering synchronized attitude maneuvers, [57] decomposes an individual spacecraft's current attitude into eigenaxis and off-eigenaxis components. The eigenaxis rotations are coordinated through coupled dynamics, and the off-axis deviations are damped using a PD controller. Unabridged stability proofs of the coupled dynamics Behavioral algorithm can be found in [60].

Finally, note that we did not find any papers applying Behavioral FFC to a POE formation.

VII. Conclusions and Future Directions

Formation flying control algorithms have been divided into five architectures: (i) Multiple-Input Multiple-Output, in which the formation is treated as a single multiple-input, multiple-output plant, (ii) Leader/Follower, in which individual spacecraft controllers are connected hierarchically, (iii) Virtual Structure, in which spacecraft are treated as rigid bodies embedded in an overall virtual structure, (iv) Cyclic, in which individual spacecraft controllers are connected non-hierarchically, and (v) Behavioral, in which multiple controllers for achieving different (and possibly competing) objectives are combined.

A. Comparison of FFC Architectures

When discussing the advantages and disadvantages of the various FFC architectures, we need only consider MIMO, L/F and Cyclic. As was argued in the VS section, VS FFC algorithms are either L/F or Cyclic depending on implementation. Also, Behavioral algorithms are combinations of MIMO, L/F and Cyclic algorithms. As part of the architecture comparison,

[29] For spacecraft using an L/F architecture a goal might be specified as a position with respect to another spacecraft, thus conflating the move-to-goal and maintain-formation behaviors. To avoid confusion, a goal is defined as a target state that is meaningful in the absence of other spacecraft.

[30] In particular, the collision-avoidance algorithm (1) can give rise to limit-cycle-like behavior where the robots almost form the proper shape but then spread apart, only to almost form the proper shape again, etc., or (2) can result in deadlock, where all the robots stop, waiting for the other robots to move.

information requirements will be discussed. Information requirements are the inter-spacecraft sensing and communication links necessary to support an FFC algorithm.

The primary advantages of the MIMO architecture are that optimality can be guaranteed and that stability follows directly from multiple-input, multiple-output synthesis techniques. Optimality can be guaranteed since the entire formation state is available for controller synthesis. However, for this reason, MIMO algorithms also have the highest information requirements. Typically, each spacecraft must know the entire formation state. Also, MIMO algorithms are not robust to local failures. For example, it can be shown that if a thruster fails on a single spacecraft, then the entire controller can go unstable, driving *all* the spacecraft apart. That is, *a local failure can have a global effect.*

The L/F architecture addresses both of these concerns, information requirements and robustness, at the expense of global optimality. Since L/F reduces formation control to individual tracking problems, each spacecraft only needs information about its leaders. This fact also simplifies formation coordination. For example, only a locally stabilizing controller and a leader assignment are needed to add a spacecraft to an L/F formation. In contrast, to join a spacecraft to a MIMO formation, the entire controller must be redesigned. Also, by commanding the fleet leaders, overall formation motion is easily specified in L/F formations. Regarding L/F robustness, if a spacecraft fails, then only its followers are affected. By reassigning the followers, the immediate effects of a failure can be minimized. However, all the advantages of L/F discussed above are traded for optimality. *Connecting individual, locally-optimal tracking controllers does not guarantee a globally optimal formation controller.* Also, if an L/F formation is required to be mesh stable, information requirements can approach those of a MIMO formation.

The Cyclic architecture lies between the MIMO and L/F architectures. By allowing non-hierarchical connections between individual spacecraft controllers, Cyclic algorithms can perform better than L/F algorithms (e.g. see [4] and the discussion of "formation feedback" in [136]) and distribute control effort more evenly [56]. Cyclic algorithms can also be completely decentralized [69] in the sense that there is neither a coordinating agent nor instability resulting from single point failures. The formation geometry "emerges" from the interactions of the individual controllers.[31]

The two primary drawbacks of Cyclic algorithms are that the stability of these algorithms is poorly understood and that in many cases the information requirements are as great as for MIMO algorithms. For example, in the rule-based Cyclic algorithms for forming regular polygons, each spacecraft needs to know the entire formation state. However, Cyclic algorithms are generally still more robust than MIMO algorithms. In the polygon algorithm, even if multiple spacecraft are removed or added, the formation adjusts without controller redesign.

[31] Emergent behavior is also a property of Behavioral algorithms. Note that Behavioral formations exhibit more complex behavior than seen in a Cyclic formation (e.g. a colony of ants foraging).

B. Future Research Directions

The advantages and disadvantages of these architectures highlight three main areas for future research: (1) rigorous stability conditions for Cyclic and Behavioral architectures, (2) reduced algorithmic information requirements, and (3) increased robustness/autonomy.

1) Stability Conditions

First, rigorous stability conditions must be developed for general Cyclic and Behavioral algorithms. To this end, the cooperative robotics literature may prove helpful; see the bibliography of [17]. Stability conditions would enable general design techniques and better comparisons between the different architectures. In addition, the stability of *hybrid* FFC architectures should also be studied. For example, sub-formations may be controlled via full-information, optimal MIMO algorithms, with the sub-formations being coordinated through a lower-information L/F algorithm.

2) Reduced Information Requirements

Next, for all FFC algorithms, information requirements must first be made explicit. Then techniques must be developed for reducing these requirements.[32] For example, one approach for reducing information requirements is to add interdependency constraints to MIMO formation control synthesis [73]. Similarly, Cyclic algorithms can be designed that use *only* local information [62], [69]. A significant challenge in this case is to determine the local actions that give rise to the desired global formation behavior [67], [80]. However, to achieve certain global behaviors, it is likely that formation-wide coordinating information will still need to be passed between local spacecraft controllers [13], [116]. Another approach to reducing information requirements is to develop control algorithms robust to inter-spacecraft communication delays.[33] The theory of jump systems is promising in this respect [126]. [9] develops an algorithm that eliminates the need for communication altogether: probabilistic, internal models of the other spacecraft enable individual spacecraft to make robust decisions for formation coordination.

Information requirements also couple formation estimation and control. Techniques must be developed for designing integrated estimation/control algorithms with sensing and communication constraints. For example, during formation maneuvers, FFC algorithms should be able to reconfigure if sensing and communication links (i.e., the estimation topology) change [94].

3) Autonomy and Robustness

The third main area for future research is the autonomy and robustness of FFC algorithms. It is cost prohibitive to

[32] Ref. [137] states, "One of the biggest challenges in implementing existing formation algorithms is the inability to sense the location (or even just the presence) of all other robots. . . ."

[33] A related field is designing inter-spacecraft communication systems robust to spacecraft/transmitter/receiver failures. See for example [81] and [100].

have a ground-based control center for each spacecraft in a formation (e.g. consider the thirty-plus spacecraft formation proposed for MAXIM [39]). Further, it is not uncommon for a spacecraft to enter "safe mode," in which case it ceases to participate in the formation [21]. Clearly, formations must function autonomously, particularly in the presence of such faults.

To varying degrees, Cyclic algorithms have an innate robustness, i.e., failed spacecraft do not affect the stability of the formation [69], [119]. However, MIMO and L/F algorithms must take immediate action to prevent the loss of further spacecraft from the formation. For L/F, when a leader fails, the followers must be reassigned. Refs. [48], [71], [29] and [31] consider leader switching. A related topic is deciding who should be a new leader. Network theory is applicable in this case; see [66] for references on leader election protocols.

Considering MIMO robustness, synthesis techniques have been developed that are robust to parameter variations and actuator saturation (e.g. [71]). An additional constraint that must be addressed is robustness to actuator (i.e., spacecraft) failures.

Finally, FFC algorithms should ultimately be scalable. One concept for the Terrestrial Planet Imager [14], the follow-on mission to Terrestrial Planet Finder, is a twenty-five spacecraft formation operating over a 350 km baseline that will image Earth-like planets at ten parsecs well enough to resolve continents. And that is a truly exciting and challenging goal.

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APPENDIX

Table of Acronyms and Abbreviations

AHS	Automated Highway Systems
CA	Collision Avoidance
COM	Center of Mass
Digraph	Directed Graph
DOF	Degree of Freedom
DS	Deep Space
FFC	Formation Flying Control
FOV	Field-of-View
GEO	Geosynchronous Earth Orbit
GPS	Global Positioning System
GUUB	Globally Uniform Ultimate Boundedness
GVS	Guidance VS
HCW	Hill-Clohessy-Wiltshire
HP	High Precision
IVS	Iterated VS
LEO	Low Earth Orbit
L/F	Leader/Follower
LMI	Linear Matrix Inequality

Table of Acronyms and Abbreviations (Continued)

LP	Low Precision
LQ	Linear Quadratic
LQG	Linear Quadratic Gaussian
LQR	Linear Quadratic Regulator
MIMO	Multiple-Input, Multiple-Output FFC Architecture
MSI	Multiple Spacecraft Interferometer
PD	Proportional/Derivative
POE	Planetary Orbital Environment
S.A.S.S.	Spatial Asymptotic String Stability
UAV	Uninhabited Aerial Vehicle
VS	Virtual Structure

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