A Survey of Spacecraft Formation Flying Guidance and Control (Part II): Control[1]

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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 and Automated Highway System literatures.**

I. INTRODUCTION

In 1977, Sholomitsky, Prilutsky and Rodin conceptually studied a proposed multiple spacecraft interferometer for infrared synthetic aperture imaging [91]. Today, formation flying is a critical technology for planned and future missions of NASA [15], [107], the Department of Defense [16], [23], ESA [7], [37] and other national space agencies.

In deep space, formation flying enables variable-baseline interferometers [52], [38] and large-scale distributed sensors [45] that can probe the origin and structure of stars and galaxies with high precision. In Earth orbit, formation flying enables distributed sensing and sparse antenna arrays for applications such as gravitational mapping and interferometric synthetic aperture radar (InSAR). Further, by allowing instruments on separate spacecraft to be combined into a *co-observatory*, 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 [85], 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*. This coupling can be in translational and/or rotational degrees of freedom and in position and/or velocity. 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* since their orbit corrections only require an individual satellite's position and velocity. A *constellation* is defined as a set of spacecraft whose states are not dynamically coupled in any way (i.e., the change of state of one spacecraft does not impact the state of another).

A control law satisfying Condition (ii) above is called a *formation tracking control law*. Tracking includes regulation. 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. [96]). See Labeyrie, Savaria and Schumacher [49] and Stachnik and Gezari [97] for further references. These early FF mission designs considered Earth-orbiting MSIs and included preliminary analyses of orbit-maintenance fuel requirements.

In the late 1980s and early 1990s, research focused on developing aerodynamic drag compensation strategies (e.g. Matthews and Leszkiewicz [66] and Scolese, Folta and Borda [89]) and fuel-efficient relative trajectories for Earth-orbiting formations (e.g. DeCou [26]). These fuel-efficient trajectories are referred to as *passive relative orbits*, and they are discussed extensively in Part I of this survey [85].

Significant interest in formation flying started to develop in the late 1990s. The first formal study of spacecraft FFC was by Wang and Hadaegh in 1996 [117], who analyzed the Leader/Follower architecture. Also in that year, Folta, Newman and Gardner defined three classes of co-observatories and developed a Leader/Follower algorithm for them [34]. These co-observatory classes were first published in 1992 [32], but the purpose of this earlier paper was to determine attitude pointing requirements for co-observatories, not FFC design.

In 2000, Lawton overviewed the FFC literature up to that year [58]. 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. Organization of Survey

In general, formation size, precision and dynamic environment all affect FFC development. However, due to the

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common assumption that a formation estimator provides all the information required for control [99], neither formation size nor precision have been primary considerations in the FFC literature. An exception is that a few authors have studied the control effort required to achieve a certain precision level based on the control design model [109].

In the companion survey on formation flying guidance [85], the dynamic environment of a formation was the primary distinction in the literature. The ambient dynamic environment of a formation was divided into two regimes. 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) [84], while in a planetary orbital environment (POE) spacecraft are subjected to significant gravitational dynamics and other environmental disturbances such as aerodynamic drag.

The formation dynamic environment is also not a primary distinction in the FFC literature, but it does have two ramifications. First, in DS, only relative translational state information is available to the necessary accuracy for control. Second, again in DS, the translational degrees of freedom decouple, thereby simplifying analysis.

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. An architecture may be broadly construed as a "coordination scheme." 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 [58].

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 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.

Addressing the stability of FFC algorithms, authors typically only consider the stability of the *relative* dynamics of a formation. If the inertial position or attitude of a formation is relevant, an additional controller is assumed for tracking such inertial states. To reflect this usage, unless otherwise noted, by *stability* we mean the Lyapunov stability of the relative spacecraft dynamics, whether translational, rotational or both.

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 also important. 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).

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, [40] formulates a minimal state space realization of formation relative error states and designs an LQR controller.

Given a state space representation of the formation dynamics and a state feedback gain matrix for *relative* state control, [92] 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 [95], a formation estimation problem is considered in which each spacecraft has a full-state LQG estimator that requires communicated information to function. [95] reduces the information communicated between spacecraft by compressing local spacecraft measurements using an augmented local estimator. [33] applies this decentralized LQG algorithm to formations in libration point orbits.

Directed graphs[3] (or digraphs) have been used in MIMO algorithms to both specify the desired formation geometry and to enforce specific spacecraft control interdependencies (i.e., requiring certain entries in a gain matrix to be zero).

Ref. [111] uses a digraph to specify the geometry of POE formations, where the spacecraft are placed in multiple circular orbits with identical radii. This geometry digraph is encoded into an LQR formulation.

In [71], rigid and unfoldable digraphs (i.e., those that a have unique embedding in Euclidean space modulo rigid body motions) 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 formation-wide potential function. The gradient of this potential then forms the basis of a formation controller. This approach enforces specific interdependencies, since only the spacecraft involved in a particular algebraic constraint enforce it. [73] discusses methods for constructing, merging and separating rigid and unfoldable digraphs.

Finally, nonlinear and constrained model predictive control (MPC) has also been used within the MIMO architecture [31].

III. LEADER/FOLLOWER

The Leader/Follower (L/F) architecture is the most studied FFC architecture. Note that Leader/Follower has also been referred to as Chief/Deputy [88], Master/Slave [47] and, the traditional terminology from two-spacecraft rendezvous,

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[3] 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 $i, j \in \mathcal{V}$. For an edge (i, j), an arrow is drawn from i to j.

Target/Chase. L/F uses a hierarchical arrangement of individual spacecraft controllers that reduces formation control to individual tracking problems.

To formally define L/F, we introduce the *control dependency* directed graph,^{3} which for brevity is referred to as the *dependency digraph*. The dependency digraph is similar to digraphs defined in [27], [29], [30] and [69] (which are used to define more constrained versions of L/F), 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.

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 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*.

For an edge (i, j) in the dependency digraph, spacecraft j is called a *follower* and spacecraft i is called a *leader*. Note that a spacecraft can have multiple leaders (e.g. see [42]), but care must be taken in this case to ensure that the tracking problem is well posed. We refer to the special case of the L/F architecture in which each spacecraft is required to have only one leader [69] as *single-leader L/F*.

In 1991, [116] presented a number of robotic formation control strategies, including a number of L/F algorithms. In 1996, the seminal paper [117] generalized L/F and adapted it to spacecraft formations in both DS and POEs. For single-leader L/F, [69], [116] and [117] prove the stability of directed tree dependency digraphs (i.e., the most general single-leader case) for particular control laws.

Sufficient conditions for stability are available for general L/F algorithms, but they apply to a type of stability called *mesh stability* [76]. Essentially, an L/F formation is asymptotically mesh stable if it is asymptotically Lyapunov stable and follower tracking errors are uniformly bounded not in time, but *spatially*. That is, a perturbation to a leader does not grow as it propagates through the followers.

Mesh stability has its roots in the automated highway system (AHS) literature, and is based on the earlier concept of string stability. There are at least three types of string stability [104], [22], [42], [77], [90] that differ in various technical details (e.g. the norms used and the constraints on individual vehicle dynamics). However, for both mesh and string stability, the sufficient conditions generally require: (i) individual subsystem (i.e., spacecraft) dynamics are exponentially stable, and (ii) the interconnections between the subsystems are sufficiently weak. “Weak” is defined via inequalities relating Lipschitz constants that characterize the subsystem interconnections and bounding constants of the Lyapunov functions for individual subsystems. See [42] and [104] for bibliographies on AHS L/F and string/connected system stability, respectively.

We now discuss the many L/F algorithms in the literature. Most authors consider a single-layer L/F architecture in which spacecraft all follow the same leader. The other common architecture considered is a string or chain, in which each spacecraft follows the preceding one. 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 a stable formation. As a result, the numerous contributions to the L/F literature differ primarily in the type of formation tracking control law designed for the followers.

The following papers consider DS formations. [119] simplifies the feedback linearized control laws of [117] and applies them to synchronized translational and rotational control of deep space MSIs. [77] uses sliding mode control. [68] and [69] combine feedback linearization and linear matrix inequalities (LMIs) to design robust and switched controllers for avoiding control saturation. [63] applies feedback linearization and model predictive control and also address saturation through controller switching. [82] and [83] develop and compare a variety of design techniques including proportional/derivative (PD), time optimal and mixed fuel-time optimal. [121] develops and experimentally demonstrates a rule-based controller for forming an equilateral triangle and aligning the orientation of three air-levitated robots. [81] develops a two-tier controller where the coarse loop is a phase-plane controller with a vernier PD loop. [120] develops a rule-based control law for synchronizing the rotations of multiple spinning spacecraft. Based on [120], [41] 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. [62] 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. [127] designs a combined translational/rotational controller using LQR and H_∞ methods.

Similar to [119], [129] considers simultaneous translational and rotational control of a formation. However, the desired positions of the followers are specified not in an inertial frame, as is generally done, but in a leader’s *body* frame. In this manner, the entire formation can be rotated by simply changing the attitude of the leader.

Ref. [72] builds a planar DS formation through *node augmentation*: spacecraft are added sequentially to a formation by specifying desired distances to two formation members. This specification is such that the new spacecraft is uniquely “anchored” to the formation (i.e., the corresponding digraph remains rigid and unfoldable). [29] uses a similar approach.

Turning to the POE literature (which in many cases also applies to DS), 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], [43], although a few authors modify them slightly. [48] develops a discrete-time controller using pulse-based actuators. [130] extends this controller to include a periodic gain. [114] designs separate discrete-time controllers for in-(orbital) plane motion and out-of-plane motion. [19] develops a similar, decoupled controller for GEO orbits. [94] also designs a decoupled 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. [80] designs a discrete-time LQ controller for disturbance rejection and a feedforward controller that provides non-equilibrium point control offsets. [18] implements a controller with the decentralized estimation scheme of [95]. [93] designs a controller and studies the frequency of thruster firings versus the total Δv needed to reject realistic disturbances. [102], [101] and [19] design controllers without using radial thrusting. [126] designs an LQG controller using GPS and includes many practical considerations.

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 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 [33]. A similar MPC algorithm using linear time-varying models is developed in [44], [46], [110] 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 [131] design position feedback and output feedback controllers, respectively, for Keplerian relative orbital dynamics. These controllers are globally uniform ultimate bounded (GUUB)[4] in position and velocity tracking errors. [117] and [100] develop controllers for simultaneous translational/rotational using feedback linearization and state-dependent Riccati equations, respectively.

Adaptive control has also been used to design follower formation tracking control laws. [122] 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 retains nonlinear Keplerian orbital dynamics. Further, assuming that both the spacecraft masses and disturbances are unknown but constant, [24] develops a globally convergent, full-state feedback adaptive controller. [132] extends this controller to the case where the leader is in an unperturbed, elliptical orbit. [124] then extends the controller of [132] to include an unknown, but periodic disturbance with a known upper bound. [123] departs from these previous papers and develops a position feedback, locally convergent adaptive controller for constant disturbances. [75] develops a convergent 6DOF adaptive controller that allows for unknown but constant masses and moments of inertia. See [105] for references on adaptive L/F design in the AHS literature.

Rather than using Cartesian reference trajectories, some authors use orbital elements ("orbital" omitted hereafter). [106] considers a formation of spacecraft in elliptical orbits where inter-spacecraft distances are kept nearly constant via small element differences, and develops a controller to regulate the osculating[5] element *difference* of a follower and leader. In contrast, [88] develops a control law for mean[5] elements. Note that *inertial* states are being controlled (i.e., elements, not differential elements), but the reference trajectory of the follower is the leader's elements (state) plus an offset. [88] also compares the mean element controller to one that uses a Cartesian representation of inertial states.

[87] considers a control law where the reference trajectory for the follower is specified as an osculating element difference (similar to [106]) 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, [86] 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 osculating element controllers of [112].

Finally, we present some papers that do not fall into any of the previous L/F design methodologies. [133] applies hybrid stability analysis to full state feedback controllers. [59] uses binary drag panels (i.e., deployed/not-deployed) to rendezvous with a leader. For H_∞ L/F control, see references in [127]. Lastly, while [111] uses a MIMO controller to keep spacecraft phased within circular orbits, [70] estimates the mean motion and orbit-averaged, along-track offset 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 embedded in a larger, virtual rigid body (or structure). In particular, the overall motion of the virtual structure and the constant, specified positions and orientations of spacecraft within it are used to generate reference trajectories for the spacecraft to track using individual spacecraft

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[4] 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].

[5] To the standard Keplerian elements, perturbations can cause secular variations (unbounded growth), short period variations (on the order of the orbital period) and long period variations (e.g. on the order of tens of days). Osculating (instantaneous) elements include all variations. Mean elements have either the short period or the short and long period variations averaged out. See [113]).

controllers. The overall motions of the virtual structure include rigid body motions and contractions/expansions.

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. [50] considers Earth-orbiting formations and uses a time-invariant Walker constellation template (see [51]). Different fitting algorithms are discussed in [39] and [74]. [61] considers non-holonomically constrained robots and, in addition to fitting a template each time step, incrementally perturbs the fitted template to eventually achieve an inertial formation goal state. Similarly, [108] 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 [53], 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.

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.

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*.

The stability analysis of Cyclic algorithms is difficult because cycles in the dependency digraph introduce additional feedback paths. As a result, many Cyclic algorithms are studied through simulation only [1], [116]. However, potential field-based cyclic algorithms do generally have a stability proof since the potential function itself serves as the basis for a Lyapunov function.

Ref. [116] 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 when 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. We refer these algorithms as *centroid strategies*. They have only been studied through simulation.

There also exist Cyclic algorithms for forming regular geometric patterns from arbitrary distributions of spacecraft/robots. [103] uses rule-based controllers to generate lines, circles, polygons and uniform distributions of robots within convex polygons. [136] extends [103] by modifying the algorithms to better handle realistic hardware constraints.

The basic rules for forming a circle in [103] are (1) first move towards or away from the farthest robot until it is a prescribed distance away, and then (2) move away from the closest robot. [118] develops two Cyclic algorithms, the first of which is a rule-based approach similar to [103]. In the second algorithm of [118], potential fields are constructed that mimic rules similar to the two discussed above.

Ref. [67] also uses a potential field approach (every spacecraft is repulsed by its neighbors) to evenly distribute spacecraft in a circular orbit. [74] starts with the work of [67] and considers different potential function forms and spacecraft arrangements. [128] consider a potential field strategy where robots are attracted to two preassigned neighbors. In addition, pre-calculated velocity commands are applied to specific robots to shape the formation.

Refs. [134] and [135] introduce a Cyclic algorithm based on the GVS architecture. There are two key aspects. 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 controlled motion of the virtual structure. The second key aspect is to make the feedback gain for the virtual structure's controller dependent upon the tracking errors of the individual spacecraft controllers. 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 (i.e., "catch up"), thereby reestablishing the formation. The stability of this algorithm is proven in [135].

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. 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 (e.g., move towards distant neighbors and align velocity with nearby neighbors) but we still consider it to be a single behavior. Note also that control laws for the maintain-formation behavior are FFC algorithms, 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 a clear example of a Behavioral FFC algorithm. They consider velocity-commanded aircraft with collision-avoidance, obstacle-avoidance, move-to-goal and maintain-formation behaviors. Note that a *goal* is defined as a pre-specified inertial state, hence move-to-goal and maintain-formation are distinct behaviors. Each of the behaviors in [1] has an associated velocity vector and weighting. The velocity of each aircraft is set to the weighted sum 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 [116]. To this behavior they add collision/obstacle-avoidance and move-to-goal behaviors. [103] 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. [136], however, performs an exhaustive simulation study of the algorithm in [103] and identifies many cases where the collision-avoidance behavior interferes with the maintain-formation behavior.

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 [136], it is possible for the behaviors to destructively interfere. Generally, simulation is currently the only tool for verifying that the combination of behaviors functions as desired.

An exception is the following series of papers, which prove the stability of their Behavioral algorithm. Ref. [57] 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 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. [56] extends the concept of coupled dynamics to rotational motion using rate feedback and passivity based controllers. [54] compares L/F and the coupled dynamics approach in terms of control effort and tracking errors. For synchronized attitude maneuvers, [55] decomposes an individual spacecraft’s current attitude into eigenaxis and off-eigenaxis components. The eigenaxis rotations are controlled via 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 [58].

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. Also, as part of the architecture comparison, *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 optimality (the entire formation state is available for controller synthesis) and stability (follows directly from MIMO synthesis techniques). However, since the entire state is used, 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; that is *a local failure can have a global effect*.

The L/F architecture addresses both of these concerns, viz., 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 a subset 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 formation tracking control laws 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 [135]) and distribute control effort more evenly [54]. Cyclic algorithms can also be completely decentralized [67] 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.

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.

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.

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.

Next, for all FFC algorithms, information requirements must first be made explicit [136]. Then techniques must be developed for reducing these requirements. For example, one approach for reducing information requirements is to add interdependency constraints to MIMO formation control synthesis [71]. Similarly, Cyclic algorithms can be designed that use *only* local information [60], [67], though formation-wide coordinating information may be needed to achieve certain global actions [13], [115]. A significant challenge in localizing information dependence is to determine what local actions give rise to the desired global actions [65], [78].

Another approach to reducing information requirements is to develop control algorithms robust to inter-spacecraft communication delays (or robust communication networks themselves; see [79], [98]). The theory of jump systems is promising in this respect [125]. [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 coordination.

Information requirements also couple formation estimation and control. Techniques must be developed for integrated estimation/control design. For example, during maneuvers, controllers should be able reconfigure if sensing/communication links (i.e., the estimation topology) change [92].

The third main area for future research is the autonomy and robustness of FFC algorithms. It is cost prohibitive to have a ground-based control center for each spacecraft in a formation (e.g. consider the thirty-plus spacecraft formation proposed for MAXIM [38]). Further, it is not uncommon for a spacecraft to enter "safe mode," in which case it ceases to participate in the formation [21]. 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 [67], [118]. 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. [47], [69], [28] and [30] consider leader switching. A related topic is deciding who should be a new leader. Network theory is applicable in this case; see [64] 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. [69]). An additional constraint that should be addressed is robustness to actuator 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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