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# Autonomous Formation Flight

The problem of formation flight has been a topic of research for many years and from different perspectives. D'Azzo and coworkers have contributed to the automated flight of a classical leader-wingman configuration and established conditions for which proportional-integral (PI) control can handle nonlinearities present in the formation dynamics [1]-[3]. Bloy investigated aerodynamic characteristics and directional stability properties in air-to-air refueling [4], [5]. Preliminary aerodynamic considerations as well as the potential use of decentralized linear quadratic regulator (LQR)-based control were described in [6], with reference to unmanned aerial formations. Applications to the civil sector, especially for handling projected increases in traffic around airports using formation flight, are described, for example, in [7]. More recently, at several levels, research efforts are underway and strategic priorities are being given to the use of multiple unmanned air vehicles (UAVs) for a large spectrum of platforms, from actual-size aircraft [8], to reduced-size UAVs [9], and to the implementation of microelectromechanical systems (MEMS) in flight [10].

This article focuses on the investigation of possible formation structures to be used in an operational environment, with an emphasis on optimization with respect to data information transfer among the elements (nodes) of the formation itself. The final objective is the capability of maintaining a formation in the presence of a failure of one of the nodes, such as the loss of an aircraft, with a high degree of autonomy and possibly without intervention from ground and/or command operators. Although the emphasis is on unmanned aircraft, the principles could be extended to automated manned formation flight as well.



## The Aircraft Model

The basic mathematical model for each aircraft's dynamic behavior was taken from [11]. In particular, we refer to a linearized set of equations about a trim condition of Mach = 0.4 and an altitude of 10,000 ft and described in a standard state-space form as

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \tag{1}$$

with $x \in \Re^n$, $y \in \Re^p$, $u \in \Re^m$ as state, output, and input vectors, respectively. The dynamics used in [11] include four inputs (symmetrical and differential taileron deflection, rudder deflection, and engine throttle) and 14 states inclusive of six body rates, Euler angles, center of mass position, and two engine states. The output equation in (1) is not very relevant at this point, since it depends on the number and types of sensors used. In a formation flight setting, the aircraft position and orientation are of primary interest so that some of the inner loops are assumed to be outside the system's bandwidth. In particular, the dynamics of actuators

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and sensors will be neglected, and longitudinal and lateral-directional modes will be considered decoupled.

With the above assumptions, the set of dynamic equations describing the longitudinal motion, linearized about the selected flight condition, can be written as

$$\dot{x}_{\text{long}} = A_{\text{long}} x_{\text{long}} + B_{\text{long}} u_{\text{long}} = A_{\text{long}} \begin{bmatrix} u \\ w \\ q \\ \theta \\ h \\ e_1 \\ e_2 \end{bmatrix} + B_{\text{long}} \begin{bmatrix} \delta_e \\ \delta_{th} \end{bmatrix} \tag{2}$$

where

$u$ = forward speed
$w$ = vertical velocity
$q$ = pitch rate
$\theta$ = pitch angle
$h$ = altitude
$e_1, e_2$ = engine states
$\delta_e$ = elevator deflection
$\delta_{th}$ = thrust position.

The lateral dynamics are similarly defined as

$$\dot{x}_{\text{lat}} = A_{\text{lat}} x_{\text{lat}} + B_{\text{lat}} u_{\text{lat}} = A_{\text{lat}} \begin{bmatrix} v \\ p \\ r \\ \phi \\ \psi \end{bmatrix} + B_{\text{lat}} \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix} \tag{3}$$

where

$v$ = lateral velocity
$p$ = roll rate
$r$ = yaw rate
$\phi$ = roll angle
$\psi$ = yaw angle (heading)
$\delta_a$ = aileron deflection
$\delta_r$ = rudder deflection.

## Formation Control

Formation flight control is implemented by a two-loop system. The main objective of the inner-loop controller is to allow tracking of commanded velocity, altitude, and heading $T_C = (V_C, H_C, \psi_C)$, and it actually operates as a preset autopilot for the formation management. In the present work, linear quadratic regulation techniques were used for synthesis of the inner loop. The choice of the methodology was dictated primarily by the relative speed with which suitable gains can be found and the fact that it is of general use in this context, as described in [1], [2], and [6]. In the outer loop, the formation controller (FC) generates a reference path command for the inner loop to follow the desired formation trajectory and to maintain the aircraft position inside the formation.

**Formation flight control is implemented by a two-loop system.**

### *Inner-Loop Synthesis*

The longitudinal inner-loop controller is based on (2) and must provide adequate tracking of commanded velocity and altitude. An LQ-servo controller was developed, and the $2 \times 5$ full state feedback gain matrix $K_{\text{long}}$ was obtained through minimization of a quadratic cost function of the form

$$\int_0^\infty \left( y^T Q y + u_{\text{long}}^T R u_{\text{long}} \right) \tag{4}$$

with

$$y = [I_5 \quad 0] \begin{bmatrix} x_{\text{longA}} \\ x_{\text{longE}} \end{bmatrix}$$

where $I_5$ is the $5 \times 5$ identity matrix, $x_{\text{longA}} = [\, u \;\; w \;\; q \;\; \theta \;\; h \,]^T$, and $x_{\text{longE}} = [\, e_1 \;\; e_2 \,]^T$.

The lateral-directional inner loop was synthesized in a fashion similar to the longitudinal one. The full state feedback controller is given by $u_{\text{lat}} = -K_{\text{lat}} x_{\text{lat}}$ and the $2 \times 5$ gain matrix is obtained with a minimization of a performance index such as in [4]. Tracking is achieved, and more detailed results can be found in [14].

### *Formation Modeling and Control*

In a typical formation flight, the Wingman follows the trajectory of the Leader, taking the other aircraft as reference to keep its own position inside the formation. In a large, rigidly flying formation, intra-aircraft distances must be kept constant. Then formation trajectory definition is usually the primary responsibility of the Leader.

Many important aerodynamic effects influence the specifications of the overall control system, such as the vortex leaving the trailing edge of the wing. To attain a more realistic simulation of a formation, a horseshoe vortex model of a wake was introduced, as described in [13]. To simplify the calculation of the induced velocities, the tail creates no vortices, under the assumption that the main wing lifting effect is much larger. The vortex produces an up-wash on the wing of the following aircraft. The main up-wash effect is the in-

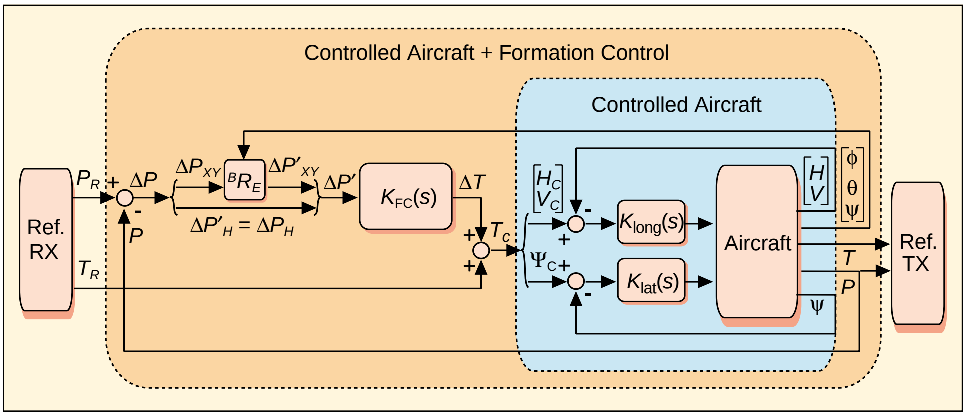


**Figure 1.** *The complete control scheme.*

crease of angle of attack with respect to the isolated flight condition; thus more lift is generated. The vortex-induced velocity decreases with distance; hence the left side of the wing will be more affected than the right side. This causes a rolling moment, so an attitude automatic control is necessary. Creation of a yawing moment has been neglected due to its weak contribution. A more accurate wake model is being tested.

The main objective of the FC, also based on LQR techniques, is to maintain the formation geometry. To compute the distance to its reference, each aircraft acquires its position $P = (X,Y,H)$ from a GPS-based position sensing system and receives, through appropriate communication channels, the other aircraft's positions $P_R = (X_R, Y_R, H_R)$.

The FC is also responsible for having each aircraft follow a prescribed path. The FC receives path information in terms of velocity, heading, and altitude $T_R = (V_R, H_R, \psi_R)$ from another Wingman, the Leader, or a ground station. Then the received data vector becomes $R_R = (X_R, Y_R, H_R, V_R, \psi_R)$.

The commanded trajectory for the inner-loop controller is $T_C = T_R + \Delta T$, where $\Delta T$ is the output of the FC. The position error inside the formation is $\Delta P = P_R - P$, and it is composed of the error in the formation plane $\Delta P_{XY} = [X_R - X, Y_R - Y]$ and the error in the vertical plane $\Delta P_H = [H_R - H]$: $\Delta P = [\Delta P_{XY}, \Delta P_H]$. These coordinates come from two GPS receivers and are expressed in an earth-fixed reference frame; they must be rotated into the aircraft body-fixed frame: $\Delta P' = [\Delta P'_{XY}, \Delta P'_H]$ using aircraft Euler angles $[\phi, \theta, \psi]$ to be used in the FC. In fact, only $\Delta P_{XY}$ must be rotated to keep the formation in the X-Y plane; otherwise $\Delta P'_H$ would depend on the roll ($\phi$) or pitch ($\theta$) angles; then $\Delta P'_H = \Delta P_H$ and

$$[\Delta P'_{XY}, 0] = {}^B R_E(\phi, \theta, \psi) \cdot [\Delta P_{XY}, 0] \tag{5}$$

where $^B R_E$ is the earth-to-body frame rotation matrix.

The effective FC was designed with linear quadratic techniques and takes $\Delta P'$ as input. Fig. 1 shows the complete control scheme. The resulting control law is

$$\Delta T = K_{FC}(s) \cdot \Delta P. \tag{6}$$

The FC applies the corrections $\Delta T$ to the reference trajectory $T_R$ to generate trajectory commands $T_C$ for the aircraft's autopilots. These corrections take into account the changes in velocity, heading, and altitude to the reference trajectory that are necessary to maintain the formation geometry.

Each aircraft can take more than one reference from the other elements of the formation. A convex combination $\Delta P_W$ of the distance errors $\Delta P_i$ from the $i$th aircraft taken as reference, can be used as a unique position error by the FC:

$$\Delta P_W = \sum_{i=1}^{m} k_i \Delta P_i \qquad \sum_{i=1}^{m} k_i = 1, \qquad k_i > 0 \quad \forall i. \tag{7}$$

Using $\Delta P_W$ in place of $\Delta P$ allows the formation to have a certain degree of "elasticity"; that is, the formation stretches in the direction of keeping the average position error to a minimum.

## Validation

To validate the overall control system performance, several computer simulations were performed with a three-aircraft diagonal formation as shown in Fig. 2. The relative nominal distances between each aircraft were set to be 15 and 10 m along the $x$- and $y$-axis, respectively, while the altitude was the same for all. With respect to the sequential references chain, two types of simulations were performed with two different strategies:

- **Leader Mode:** Both Wingman1 and Wingman2 take the trajectory references from the Leader of the formation.
- **Front Mode:** Each aircraft takes its reference from the preceding one. In this case, Wingman1 is referred to Leader and Wingman2 is referred to Wingman1.

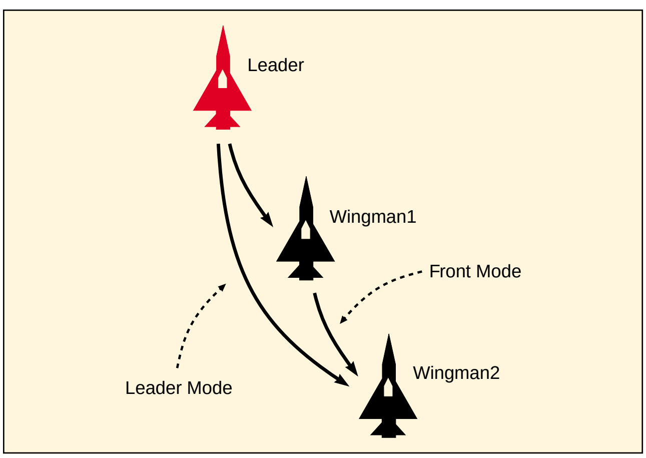


**Figure 2.** *Three-aircraft diagonal formation geometry.*

Figs. 3 and 4 show the responses of the Wingman2 to airspeed and altitude commands in Leader Mode and Front Mode. In the Front Mode structure, Wingman2 exhibits a poorer transient response due to error propagation. Although no optimization was performed in the computation of the control gains and each vehicle employs the same set of gains, on the basis of the preceding simulation results, an FC based on Leader Mode suggests better transient responses because of the absence of error propagation along the references chain. On the other hand, this type of formation structure may be more critical because, in this case, Wingman2, which is directly connected to the Leader, has no information about its distance to Wingman1, and therefore it would be not capable of avoiding a collision with Wingman1. Error propagation can be reduced by optimizing the autopilot, which is not the focus of the present work.

## Formation Flight Management

Management of the aircraft formation can be centralized or decentralized. In the former case, one formation manager acts as a supervisor for all the aircraft and manages the topology of the channels used to exchange information among them. This manager can be one of the aircraft or ground based. In both cases, the centralized scheme has several disadvantages:

- If ground based, the amount of communications required between the formation and the manager may be undesirable for some applications.
- Mission requirements may not allow continuous communications with the ground base.
- Formation failures must be detected and recovered from as rapidly as possible. Ground-based management can introduce delay in reacting to a failure.

The major advantage of ground-based management is the capability to react to and reach decisions from a possibly higher level of "intelligence" than that achievable by on-board computers. In fact, human decision could be added to the automatic system, but this surely introduces a delay in the reconfiguration progress. A prompt response is still needed to bring the formation into a safe configuration prior to a ground-based decision.

In a decentralized management scheme, on the other hand, each aircraft is given a certain level of decision capability, while the whole formation must be capable of reconfiguring, making decisions, and achieving mission goals. The problems with distributed management can be summarized as follows.

- The distributed decision-making algorithm must produce deterministic results on all the managed components; that is, on all the aircraft. Conflicting decisions must be avoided for formation safety.

The advantages of distributing the management are several:

- Only interaircraft information must be exchanged, except for possible mission updates that can be decided only at the ground control station.
- The same data channels used by formation-keeping control could be used to exchange management information.
- Very low power or, alternatively, non-radio-based communications such as optical sensors can be used because of the very small distances among aircraft. This could be very important for military applications.
- Reaction times can be minimized.

### *The Formation Communications Topology as a Graph*

Information exchange between aircraft can be point-to-point or broadcast. In the former case, not all the aircraft can receive dynamic and management data from all the others. In the latter case, every aircraft receives and sends data to the others. In both cases, graph theory can be used to describe interaircraft communication.

The aircraft can be thought of as the nodes of a graph. The physical communication channels create the arcs in the

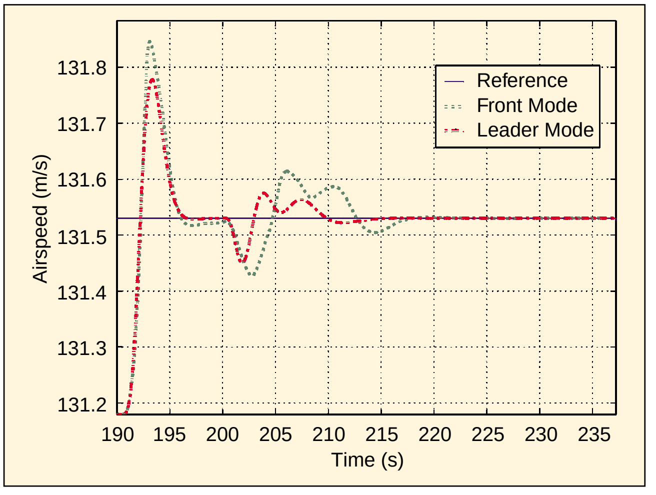


**Figure 3.** *Wingman2 response to speed command.*

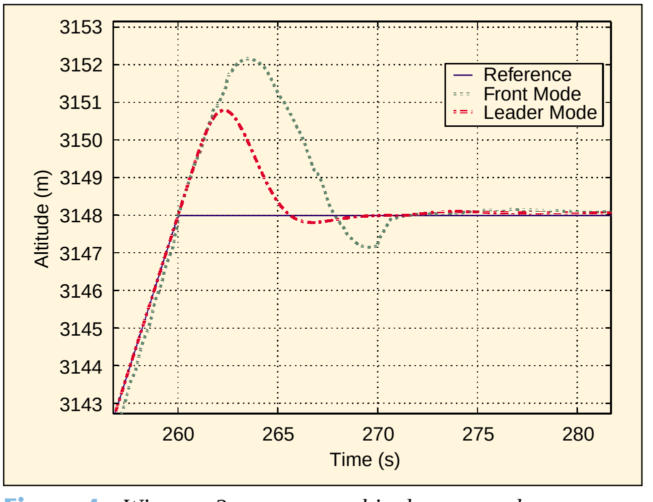


**Figure 4.** *Wingman2 response to altitude command.*

graph. These arcs are oriented because, in the most general case, channels are not bidirectional; this is not a limitation, because two nodes can be connected by two opposite direction arcs to model a bidirectional channel. The graph must also be connected—if two subgraphs exist without any arc connecting them, then the aircraft inside the two groups cannot behave like a formation and would, in fact, act as two separate formations.

**Management of the aircraft formation can be centralized or decentralized.**

The communications graph should be redundant from the standpoint of the capability of propagating information. In the event of failures, this redundancy leaves room for reconfiguration. Having the capability of using a channel, however, does not mean that it must be used at all times. Optimization of available channels under a cost function constraint can be achieved via graph programming techniques.

### Optimization of Communication Channels

To use an optimization technique, each arc must be given a weight. The cost function will minimize the total cost of the information paths throughout the formation using the arcs' weights to evaluate the cost of a connection. Weights can be chosen depending on various criteria:

- Capability of the formation control system to maintain constant interaircraft distances. In this case, a measure of control effort or closed-loop distance-keeping performance can be used to set the link weight.
- Formation safety: using distance references with adjacent aircraft might limit the risk of aircraft conflicts compared to using a common reference for all aircraft.
- If a non-radio-based or a non-omni directional communication channel is used, the geometry of the formation might influence the possibility of exchanging data between two airplanes that are not closely spaced or that are hidden by other vehicles.

In general, since the positioning error propagates and increases throughout the formation, the optimization algorithm should then consider optimizing the minimum error propagation path.

### Redundant Channels

Once an optimal nonredundant set of arcs has been found, lower priority suboptimal redundant arcs could be added to the active channels for two reasons: for mixing sensor information for control and as alternatives in emergency and failure conditions.

Using more aircraft data can benefit the formation-keeping control. In this case, more aircraft data are taken into account for the determination of the control action. Different weights can be given to the separate position errors to give higher priority to some reference data, with respect to the others. The disadvantage of this scheme is the use of more communications than those strictly needed, especially if communications are point-to-point.

Having ready-to-work suboptimal channels can be useful in fault-tolerance procedures relative to communication channel loss. The detection of channel loss can trigger an algorithm capable of re-optimizing the interaircraft connections. This algorithm must be decentralized for faster reconfiguration time, and information other than that strictly needed for the formation-keeping control system must be exchanged on the data channels. The reconfiguration process must arrive at the same result on all aircraft; that is, the local copy of the graph describing the formation communications must be identical in all aircraft at all times.

### Graph Theory Approach to Optimization

As noted above, the optimization problem is solved using graph search techniques under the following assumptions:

- The sender-receiver nature of communications leads to an oriented graph; the direction of arcs indicates the direction of data flow.
- The available communication channels can form cycles; with the broadcast communication scheme, all possible arcs exist among nodes.
- The arc's capacity is unlimited. There is no evident physical meaning of a communication channel with limited "capacity."
- The arc's weight can be set, without loss of generality, to values greater than zero.
- In the problem solution, each node has one incoming arc only; that is, each aircraft uses one reference only.
- The problem solution must be a connected graph.
- The problem solution must not present any cycles.

Under these assumptions, the problem can be configured as a shortest path problem.

How the last requirement can be fulfilled requires further explanation. Suppose that at least one of the aircraft knows the mission reference trajectory. This reference trajectory keeper can be seen as the effective formation leader and can be represented in the graph by a node called *Virtual Leader* (VL), so that each aircraft that knows the mission trajectory has one communication channel with the VL. If a cycle exists, since the graph must be connected, it must contain all nodes. Since at least one node has the VL as its only reference and the VL has no incoming arcs by definition, the VL and all nodes using the mission trajectory as reference cannot be part of a cycle. Thus the graph cannot have any cycle, and the VL will be the root of the solution tree.

To solve the shortest path problem, the Dijkstra algorithm [14] was used. It has polynomial complexity, guarantees optimality of the solution, and is deterministic; that is,

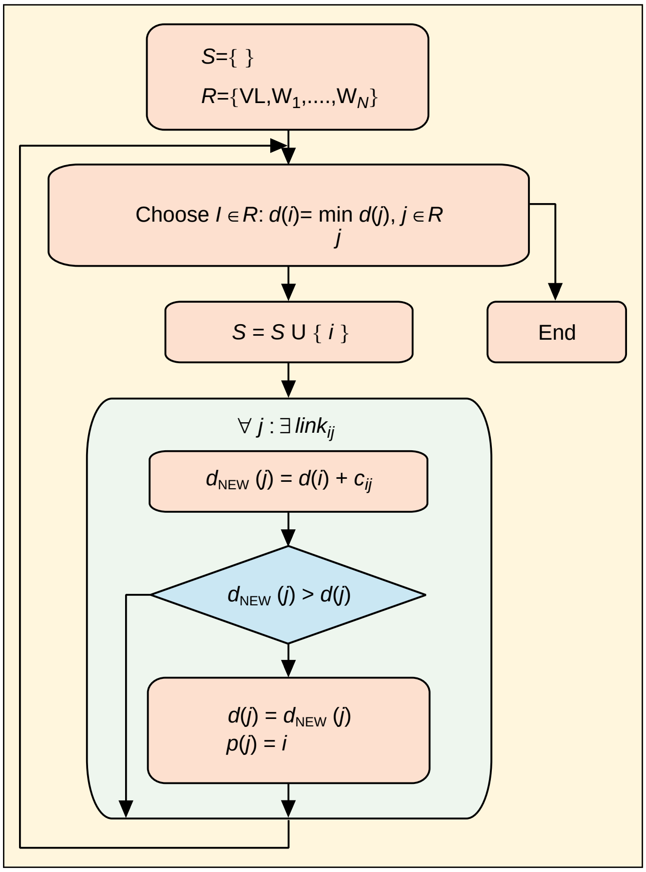


**Figure 5.** *The Dijkstra algorithm.*

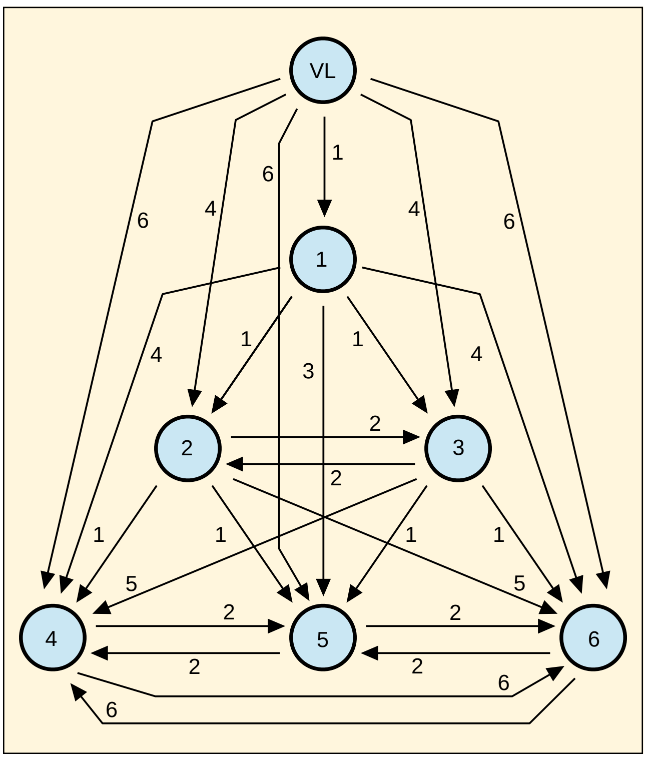


**Figure 6.** *Sample formation with Virtual Leader and six aircraft.*

starting from the same conditions, all runs lead to the same solution. The algorithm is summarized in Fig. 5. Each node in the graph represents a position in the formation, not necessarily an aircraft. Each node $i$ has a potential $d(i)$ and a preceding node $p(i)$. The potential is a temporary value used by the algorithm and is initialized to $+\infty$, except for the VL that has zero potential. For all the nodes, the initial value for the preceding node is the VL. The $S$ set is called the definitive-label set, and $R$ is called the temporary-label set. Each arc from node $i$ to node $j$ is assigned a weight $c_{ij}$.

The algorithm chooses, in the temporary-label set $R$, the node that has the minimum potential and moves it to the $S$ set until the $R$ set is empty. Then, for all outgoing arcs, the algorithm computes a tentative new potential for the arrival node. If this new potential is lower than the previous potential, it updates that node potential and sets its preceding node to itself. The algorithm runs until all nodes have been assigned a potential.

This solution provides the minimum noncyclic path connecting all nodes. No information is available at this point about possible redundant arcs.

## Extension to Redundant Channels

The Dijkstra algorithm can be modified to obtain the optimal redundant channels among those outside the optimal arcs set. Suppose we need $m$ total possible channels for each node; that is, $m-1$ redundant channels. The unmodified algorithm can still be used to find the optimal solution. At the end of the optimization procedure, the nodes' potentials are frozen. Then for all nodes $i$ in the $S$ set, select $m-1$ incoming arcs that have the minimum value of $d'(i) = d(j) + c_{ji}$, where $j$ is a possible redundant preceding node, and order for increasing values of $d'(i)$.

This modification computes suboptimal solutions. The arcs chosen with this technique can be considered suboptimal because they are the second-best choices; after removing the incoming arc of a node belonging to the optimal path, the new optimal incoming arc that a new run of the Dijkstra algorithm will produce is the first one from this redundant arcs list.

Fig. 6 shows the graph of a sample formation. While the VL is connected with all aircraft, not all possible inter-aircraft connections are present. An arc's weight is identified by a positive number.

Fig. 7 shows the result of the modified Dijkstra algorithm. The optimal path (the solid line) and each node potential are shown, together with the redundant channel. In this case, $m = 3$, but a node might not have the two required redundant channels because it has fewer than $m$ incoming arcs; this is the case for node 1.

When node $A$ switches reference and uses a suboptimal path, its potential increases, and a reconfiguration procedure must be run on all the nodes of the subtree that originates from that node. In fact, a new global optimization would be needed, but the potentials of nodes that do not have any incoming optimal path from $A$ cannot be affected, because these surely have a lower cost path to the VL.

Since the detected failure and the new node $A$ potential after reconfiguration must only be propagated to the nodes that belong to the optimal $A$ subtree path, the same communications channels used for formation-keeping data can also be used to exchange potential updates. Furthermore, after all nodes have completed the reconfiguration, the new graph is optimal, and this procedure can be repeated in case of successive faults without ever having to reconsider optimization of the whole graph. This means that any number or combination of successive faults can be managed with this subtree-based technique without compromising whole-graph optimality.

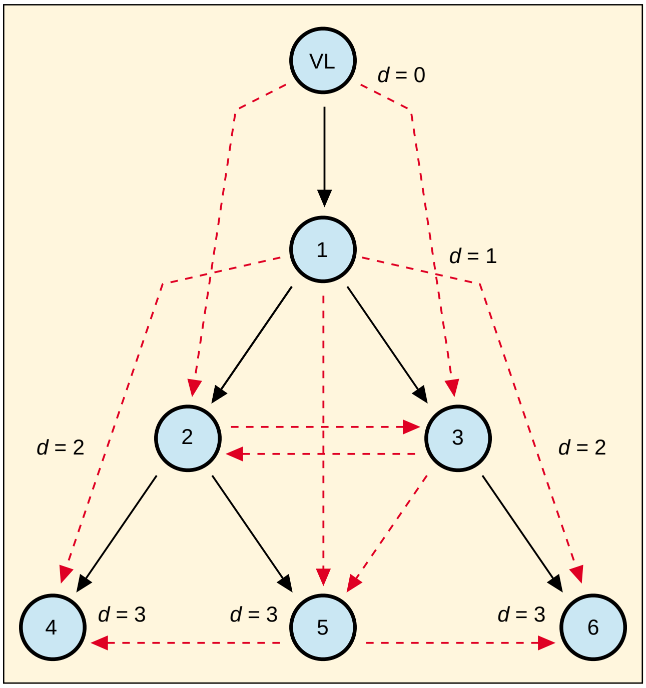


**Figure 7.** *Dijkstra optimal solution with a maximum of two redundant channels for each node.*

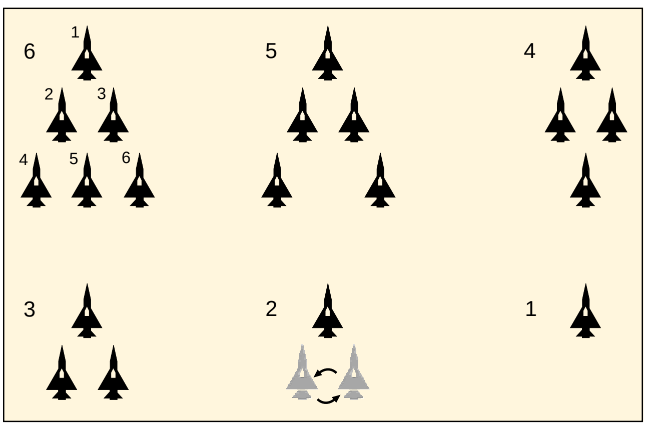


**Figure 8.** *Possible formation topologies for six or fewer aircraft.*

## Fault Analysis and Reconfiguration

Making no assumptions on the type of physical channel that transports information, each channel/arc can become faulty at any time independently of other channels functioning on the same node. Thus, in the most general case, any channel can become faulty at any time, even if a fault cannot be given a physical meaning at this point. For example, if a node experiences a fault in one of its outgoing channels, the cause could be a fault in its transmitter. If other outgoing channels keep working, however, the node must have more than one transmitter. It should be clear that the type of fault, and its influence on one or all channels of the same type/direction, depends on the physical implementation of such logical communication channels. Complete aircraft loss can be considered another possible type of "fault."

### *Aircraft Node Change*

After a generic fault, a fast reconfiguration procedure is run to restore formation keeping as quickly as possible. When the formation communications are in a safe configuration again, it may be necessary to switch aircraft positions or move an aircraft to an empty node to maximize the formation-keeping capability and safety of all aircraft. Since the node-changing decision is decentralized, the algorithm that makes the decision must be deterministic to avoid simultaneous conflicting decisions by more than one aircraft in response to the same post-fault-reconfiguration requirements.

The second problem to solve is the distribution of fault event information so that all aircraft can apply appropriate reconfiguration decisions. Even if the available communication channels used to exchange flight data for formation control are sufficient for optimal channel reconfiguration, it is possible that the best aircraft candidate for making the node change decision may not be informed of the fault event.

To keep all aircraft informed of active nodes, that is, nodes occupied by aircraft, an alternative broadcast communication channel can be set up that transmits data at low frequency. If the communication period on this broadcast channel is $T_{\text{active}}$ s, all aircraft are updated on active aircraft changes after at most $T_{\text{active}}$ s after fault. Each aircraft has a broadcast transmitter and receiver that are used periodically to inform on aircraft status and in the event of faults. Periodic communication is necessary in the event of aircraft loss to allow the remaining aircraft to detect the missing node. The information carried on this broadcast channel can be very limited. The aircraft has to notify the node it occupies if it is going to change its position inside the formation (e.g., after a fault). As an example, a formation of six aircraft will be used. Fig. 8 shows the possible formation topologies for six or fewer aircraft. The following sections describe three potential types of faults under the assumption that each aircraft has only one receiver and one transmitter.

## *Aircraft Loss*

In the case of aircraft loss, one of the graph nodes becomes free and, from the standpoint of the Dijkstra algorithm, all the incoming and outgoing arcs are deleted. A prompt optimal channel reconfiguration is needed to ensure formation keeping, and the same technique used to reconfigure after receiving channel loss can be applied in this case. After post-fault safety has been restored, aircraft positions could be changed. The empty node could be occupied by another aircraft capable of reconfiguring its transmitter and receiver. Then the optimization procedure could be run again to update the channels and the graph node potentials. Since the node potential is a measure of the formation-keeping and safety capability of the aircraft occupying a certain node, it is important to apply an aircraft node-changing procedure to minimize node potentials.

Fig. 9 shows the distributed Dijkstra reconfiguration scheme. Each aircraft has its own reconfiguration controller that, when it detects a change in the potential or a communication loss in the aircraft it is using as a reference, initiates the algorithm to obtain the new optimal channel. It suffices to select the first redundant arc given by the extended Dijkstra algorithm, compute its new potential, and propagate this information to its subtree through its outgoing reference data channel.

In the event of aircraft loss, after at most $T_{\text{active}}$ s, all remaining aircraft know that a particular node is empty. One and only one aircraft must decide to take the free position. Conflicting decisions can be avoided using unambiguous reconfiguration maps. Fig. 10 shows a set of possible reconfiguration maps (RMs) for the formations depicted in Fig. 8. In each map, the red aircraft represents the free node, and the arrows indicate which aircraft moves to take that postition. For example, the 5 to 4 RM states that if node 1 becomes free, then only the aircraft occupying node 2 can decide to take that position; if node 3 becomes free, only the aircraft in node 6 can take its place.

If the aircraft in node 2 decides to move to node 1, a simple procedure is necessary to achieve a safe transition. The aircraft in node 2 switches off its reference transmitter, and soon all aircraft that were using it as a reference for formation keeping have to reconfigure. This is necessary to avoid having the aircraft following it move rigidly with it inside the formation. After a quick transient, formation keeping is guaranteed again. At this point all aircraft behave as if node 2 has a broken transmitter, but they know it is active. The node 2 aircraft starts to move to the node 1 position, and when it has reached the new position, it changes its active signal to that of node 1. Thus all aircraft will be notified of a new aircraft occupying node 1 and of a free node 2. At this point, the node 1 aircraft switches on its reference transmitter and all aircraft can reconfigure to use it as reference. Now, following an identical procedure, the aircraft in node 4 decides to move to node 2 and, when it is there, signals its node change. Node 4 being free triggers the decision by the node 6 aircraft to move to node 5. The formation is now close and optimal again.

**The Dijkstra algorithm can be modified to obtain the optimal redundant channels among those outside the optimal arcs set.**

## *Transmitter Failure*

When its transmitter is not operational, an aircraft A can no longer be a reference for the others. The transmitter fault has the effect of "deleting" all outgoing channels. From the standpoint of the Dijkstra algorithm, the arcs going out from that node may be assigned a weight equal to infinity. These arcs will not be used in any optimal path where other possible connections exist, under the assumption that working arcs have positive finite weight. All the aircraft that use $A$ as a reference (i.e., all the appropriate subtree nodes) must reconfigure. These aircraft must have a safe reference signal loss detection procedure.

If a transmitter fault occurs in an aircraft that is not a leaf of the formation, but is a reference for some other aircraft, then the formation should be reconfigured to move the aircraft that has lost its transmitting capability to a leaf node. First, it must move behind the formation following a trajectory outside the formation plane. This is necessary to avoid any conflict with adjacent aircraft. When it has reached the rear, it signals its new position via the broadcast channel; all aircraft will know that an empty position exists, and the reconfiguration procedure can begin just as in the aircraft loss case. The faulty aircraft monitors other aircraft movements by listening to the broadcast channel, and when the formation is in one of the configurations of Fig. 8, with itself at the back, it may decide to take a leaf node. The aircraft knows exactly which nodes are free because, after any node change,

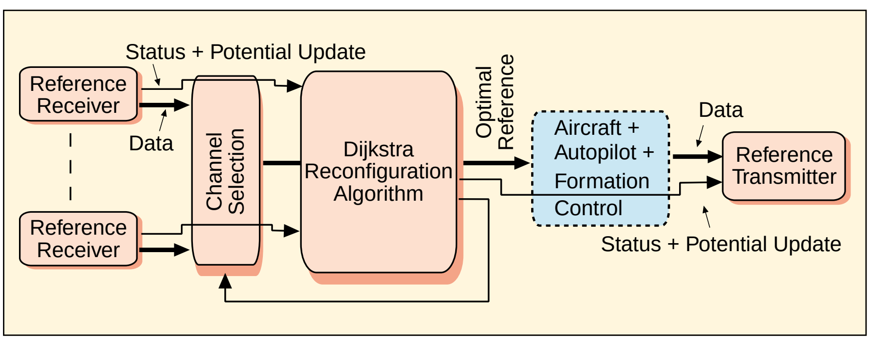


**Figure 9.** *Dijkstra on-line reconfiguration scheme.*

the aircraft that moved signals its new position. The 6 to 5, 4 to 3, and 3 to 2 RMs are invertible; that is, after an aircraft exits the formation, it may reenter without the need to reconfigure other aircraft positions again. As a matter of fact, going from five to six aircraft implies filling up node 5, just as going from three to four aircraft. Going from two to three aircraft implies filling up either node 2 or 3, depending on the free node. Going from four to five implies filling up either node 4 or 6, but to achieve the five-aircraft formation of Fig. 10, the aircraft in node 4 must move aside to get the remaining free position. Thus, additional information about reenter procedures must be added to RM 5 to 4. After complete reconfiguration, formation-keeping capability is optimal again.

**The possibility of an aircraft losing receiver capability is critical for the formation.**

### *Receiver Failure*

The possibility of an aircraft losing receiver capability is critical for the formation. That aircraft's formation-keeping capability will be severely affected because it will no longer have knowledge about adjacent vehicles. The aircraft can remain in the formation only if it has the channel link with the VL; that is, it knows the mission trajectory. If so, it can remain in the same position inside the formation or move to the front to lead it. If its transmitter is still working, the latter option becomes feasible. Connection to the VL has several meanings in this context:

- Mission trajectory has been stored inside the aircraft before departure and will not be modified.
- Mission trajectory is updated at very low frequency from the ground base, and the appropriate receiver is working.
- Mission trajectory is updated in real time from a ground-based virtual piloting station in a remote-presence fashion. The appropriate receiver, different from that used for interaircraft communications, is working.

If the faulty aircraft continues to occupy the same place inside the formation, formation-keeping capacity is altered because proximity information about other aircraft is not available. The faulty aircraft should then exit from the close formation and continue flying using VL data only. Due to the use of GPS for trajectory tracking, no drift should occur in the measurements; the aircraft may still be able to accomplish its own mission goals, but with no guarantee about those goals related to the close formation.

If the faulty aircraft becomes the new leader (i.e., the aircraft that follows the VL reference only), there is no formation-keeping capacity loss. In this case, the reconfiguration procedure must bring the actual leader outside the formation and allow the faulty aircraft to take its position. This result can be achieved by iteratively reconfiguring the formation just as in the case of aircraft loss, until the faulty aircraft reaches node 1. This can only be done by allowing richer information to be exchanged on the broadcast channel. The formation leader, in good working condition, must decide to leave its position, and this is possible only if the receiver failure is communicated to it by the faulty aircraft via the broadcast channel. When the leader moves, all aircraft must be notified that this movement is abnormal and that a particular reconfiguration is taking place. Additional information, other than a node change, must be sent via the broadcast channel because, when the leader moves to the back and signals its new position, the candidate replacement aircraft, specified by the RM, must hold its position and allow the faulty aircraft to reach node 1 safely. If the RM is not used, the faulty aircraft, which knows that the leader is leaving node 1 free for it, can move to node 1 with a safe trajectory outside the formation plane and then signal its new position. At this point, the leader can reenter the formation with the same procedure used in the case of transmitter failure.

Clearly, not all possible reconfiguration actions can take place effectively if the moving aircraft cannot activate the new communication channels required after taking the new node. Additional constraints must be placed inside the RMs to take into account the capability of a single aircraft to activate certain channels.

## Simulation Results

The first simulation presents the reconfiguration of the formation following a fault in the aircraft 3 transmitter (formation given in Fig. 8). The failure happens during a 180° turning maneuver. As shown in Fig. 7, aircraft 6 uses aircraft 3 as the reference for its formation-keeping control system. The first redundant channel for aircraft 6 is that coming

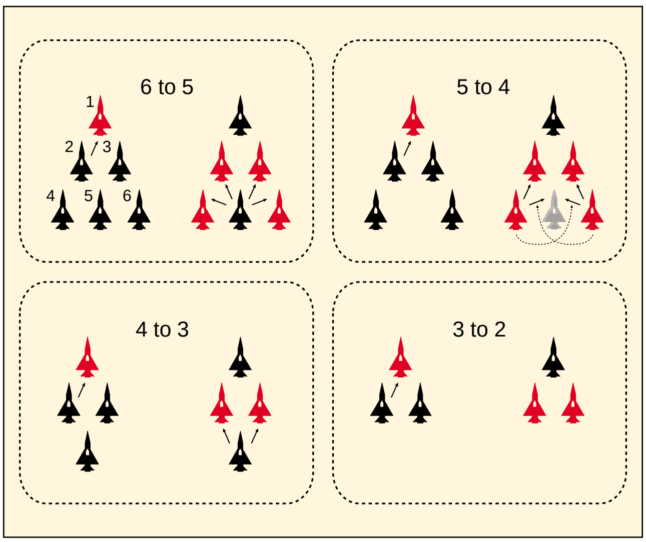


**Figure 10.** *Reconfiguration maps.*

from aircraft 5. When aircraft 6 detects a fault, it reconfigures itself to use aircraft 5 as reference. Fig. 11 shows the distance of aircraft 6 from its ideal trajectory compared to that of the same simulation without failure. The red line shows that, after the fault at $t = 50$ s, a fast transient is followed by a reconfiguration that brings the aircraft back into a stable position inside the formation. The two traces of distance error do not have to join, in this case, because the performance of the controller is different.

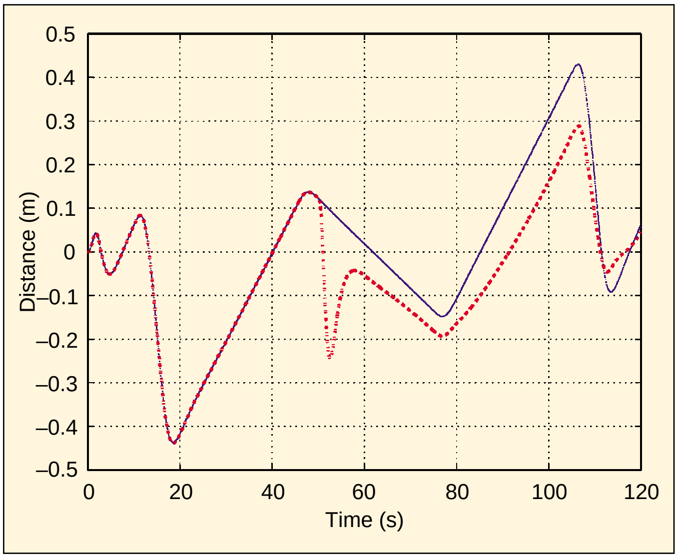


**Figure 11.** *Aircraft 6 reconfiguration after aircraft 3 transmitter fault.*

The second simulation shows the reconfiguration followed by a node change after a failure. The formation, shown in Fig. 12, is made up of ten aircraft and, at a certain time during a turning maneuver, the aircraft 5 receiver (node 5 is in the middle of the triangle) breaks down. The leader decides to move to the back of the formation, passing below it, to leave room for the failed aircraft. When the leader is approaching the final safe position behind the formation, aircraft 5 begins to move toward node 1, passing above the formation. When it has arrived at node 1, the reconfiguration is almost complete. Only two aircraft in the back must move to fill the void of node 5, leaving room for the previous leader to reenter the formation.

## Conclusions

This article has described an approach to close-formation flight of autonomous aircraft. A standard LQ-based structure was synthesized for each vehicle and for formation

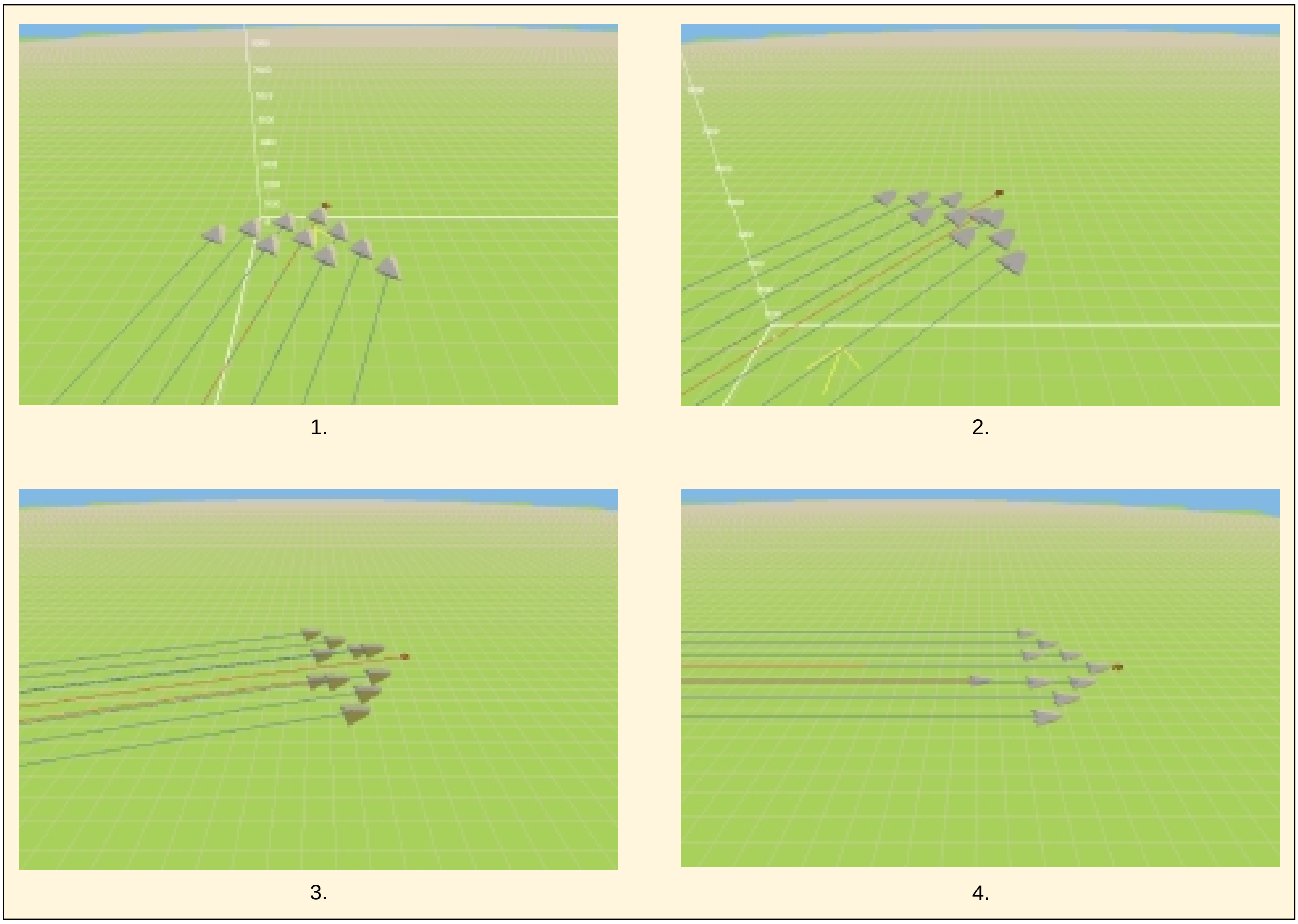


**Figure 12.** *Node change simulation: 1. The formation before fault; 2. The leader starts to move to the back; 3. The aircraft that must replace the leader starts to move to the front; 4. The new leader has arrived at node 1.*

position error control using linearized equations of motion and a lifting line model of the aircraft wake. We also considered the definition of a formation management structure, capable of dealing with a variety of generic transmission and communication failures among aircraft. The procedure was developed using a decentralized approach and relies on the Dijkstra algorithm. The algorithm provides optimal path information sequencing in the nominal case, as well as the redundancy needed to accommodate failures in data transmission and reception. Several simulations were carried out, and some of the results have been presented. The overall scheme appears to be a valuable starting point for further research, especially specializations to situations representing more detailed and operational failures.

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