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Management of Communication Failures in Formation Flight

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This paper addresses the problem of the management of unmanned air vehicles flying in formation, in the presence of failures in the communication system or aircraft loss. The problem is solved representing the formation as an oriented graph, and a procedure based on shortest path theory provides the optimal solution for the information flow within the formation. When a failure occurs, the procedure runs again providing a sub-optimal solution, and formation geometry is changed according to pre-set reconfiguration maps. Formal definitions, such as the novel definition of Virtual Leader, and simulation results validate the methodology.

Nomenclature

g = gravity acceleration
D = drag force
k_v,$k_□$$k_x$= controller gains
m = mass
n = load factor
T = engine thrust
V = speed
□ = flight path angle
□ = roll angle
□ = heading angle

I. Introduction

Coordination and management within a formation of multiple unmanned air vehicles (UAV) is a critical issue for utilizing their full potential in operational situations. While military and civilian mission scenarios would benefit from the addition of autonomous individual UAV, compared to nonautonomous or manned aircraft, it is clear that formation flight, with an effective coordination strategy, could lead to superior performance and resource utilization.

Coordinated control of multiple vehicles has been widely studied in the past. Kang[1] and co-workers addressed the problem of formation coordination and reconfiguration of multiple microsatellites, Meshabi and Hadaegh[2,3] approached the Leader/Wingmen structure for multiple spacecraft with graph theory and linear matrix inequalities (LMI) techniques, while Godbole[4] and others presented a communication protocol for the operation of an automated highway system in the presence of failures. Flight coordination of multiple UAVs was recently addressed by the

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present authors.[5,6] McLain and others presented results on the decentralized trajectory planning for coordinated rendezvous of multiple air vehicles.[7]

This paper focuses on the investigation of possible formation structures to be used in an operational environment, with emphasis on optimization with respect to data information transfer among the elements of the formation itself.

II. Formation Flight Management

The main issues involved in control and management of an aircraft formation are trajectory tracking and inter-aircraft relative distance regulation. In the case of decentralized management, each vehicle in the formation needs to exchange data, such as position and trajectory information. Many different configurations could be found for the communication flow within a formation, and not all of these configurations may provide good performance. Thus, the first step is to find an “optimal” one, among different configurations for information exchange.

Optimization of available communication channels based on a cost function figure of merit can be achieved using a variety of methods; here the problem is set up using graph-programming techniques. The formation is viewed as an oriented graph: the nodes represent the aircraft, while the physical communication channels between vehicles create the arcs. The graph is oriented because, in the most general case, channels are not bi-directional; this is not a limitation, because two nodes can be connected by two opposite direction arcs to model a bi-directional channel. The graph must also be connected because, if two sub-graphs exist without any arc connecting them, the aircraft in the two groups cannot behave as a single formation, but rather act as two separate formations.

In the optimization process, each arc must be given a weight. The optimization will minimize the total cost of the information paths throughout the formation using the arc weights to evaluate the cost of a connection. The weights for the arcs can be selected by taking into account general mission requirements related to the formation flight such as

1) Closed-loop performance: a measure of the capability of the formation control system to maintain the prescribed path and the nominal inter-aircraft distances, may be used to set the weight of the arc.

2) Formation safety: communications between neighborhood aircraft will have a lower cost. Using distance references with adjacent aircraft might limit the risk of aircraft conflicts compared to using a common reference for all aircraft.

3) Type of communication channel: in case 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, because the position error propagates and increases throughout the formation, the optimization algorithm should include the minimization of the minimum error propagation path. Once an optimal solution for the communication flow is found, the next step in the formation management design consists in giving the structure adequate robustness to communication failures. A failure in the communication occurs when one or more aircraft in the formation loses the information exchange capability (send or receive data). Obviously the loss of the aircraft itself is a communication failure: both receiving and sending information capabilities are lost. After a failure, there may be one or more connections lost and then a new channel configuration must be found. The resulting configuration will not be optimal, because of the loss of one or more channels, but it will be the optimal solution according to the new set of nodes and arcs. The algorithm for the re-optimization of the inter-aircraft connection is triggered by the fault detection, and it is 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 be the same for all aircraft; that is, the local copy of the graph describing the formation communications must be identical in all aircraft at all times.

There are cases in which, after a reconfiguration of the inter-aircraft connections, a geometrical reconfiguration of the formation is needed as well. Such cases are: aircraft loss, where the geometrical reconfiguration is related to aerodynamic efficiency effects, the data receiving capability loss for a 'leaf' aircraft of the graph, or the data sending capability loss by the root of the graph. In the latter cases, the geometrical reconfiguration is needed to keep the information flow (under the hypothesis that information flows from the front aircraft towards the rear aircraft). The geometrical reconfiguration of the formation is described by a set of heuristic rules that are implemented through several schemes, called reconfiguration maps (RM), presented in the next sections. Figure 1 shows the complete control and management architecture that will be used as reference in the rest of the paper.

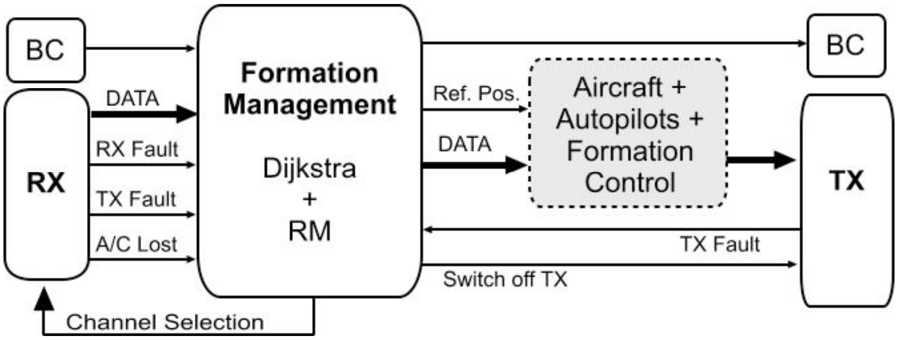

Fig. 1 Reference management and formation control architecture.

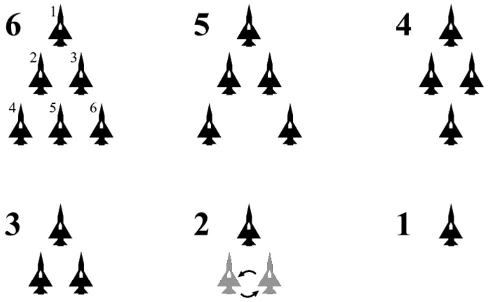

Fig. 2 Allowed formation geometries.

Where
BC = Broadcast Channel
RM = Reconfiguration Manager
RX = Receiver
TX = Transmitter

The gray block in the diagram represents the aircraft dynamics, the inner loop autopilots, and the formation flight control system. This single block is actually a two-loop system, with three inner loop autopilots for tracking of commanded speed, flight path and heading angles, and an outer loop (formation control) responsible for trajectory following and inter-aircraft distance control. For the purpose of the present work, a three-degree of freedom (3-DOF) point mass model was used. Using standard aerospace notation:

$$\begin{cases} \dot{V} = T\text{-}D/m - g \sin \gamma \\ \dot{\gamma} = g/V\,(n \cos \varphi - \cos \gamma) \\ \dot{\chi} = gn \sin \varphi / V \cos \gamma \end{cases} \tag{1}$$

Assuming perfect modeling, aircraft dynamics can be feedback linearized with the following control laws

$$\begin{cases} \mathrm{T} = k_v\,(V_d\text{-}V)\,m + mg \sin \gamma + D \\ n \cos \varphi = V/g\,[k_\gamma(\gamma_d - \gamma)] + \cos \gamma = c_1 \\ n \sin \varphi = V/g\, k_\chi\,(\chi_d - \chi) \cos \gamma = c_2 \end{cases} \tag{2}$$

the resulting linear system becomes

$$\begin{cases} \dot{V} = k_v(V_d\text{-}V) \\ \dot{\gamma} = k_\gamma(\gamma_d\text{-}\gamma) \\ \dot{\chi} = k_\chi(\chi_d\text{-}\chi) \end{cases} \tag{3}$$

To maintain the desired formation geometry, each aircraft must keep its relative position within the formation. The formation management is derived using Dijkstra's algorithm,[3] and reconfiguration maps give the reference position, according to the results of the optimization procedure. In the remainder, a formation of six aircraft will be used as an example (see Fig. 2).

III. Optimal Communications

As outlined in the previous section, an aircraft formation is described using graph theory. The presence of an outgoing arc in a node in the graph implies the capability of transmitting information, while an incoming arc is related to the capability of receiving information. Two virtual devices model such capabilities: a TX and an RX. These devices are "virtual" in the sense that failure implies the loss of the device capability, irrespectively of what subcomponent has actually failed (antennas, CPU, transmission bus, etc.). In the presence of TX and/or RX failure all the outgoing and/or incoming arcs are lost, while in case of aircraft loss, all incoming and outgoing arcs from the node representing the lost aircraft are neglected. It is important to notice that considering TX and RX separately, allows the extension of the present technique to non-radio-based communication devices.

A. The Virtual Leader

During the mission, the reference trajectory could be provided in two ways. It may be stored in one (or more) onboard computers, or it may be provided remotely from a ground station as well as from a manned aircraft. In both cases, not all the aircraft may be required to know the reference trajectory. However, according to the properties of the Leader/Wingman structure,[5] at least one aircraft in the formation knows the reference trajectory. The reference trajectory can be seen as the effective leader of the formation, by introducing an imaginary point moving in the space, tracking the path prescribed for the formation and rigidly followed by all the aircraft of the formation. Such an imaginary point is called a Virtual Leader (VL) and can be formalized through the following definitions:

Definition 1: The nodes representing the aircraft of the formation belong to the set:

$V = \left\{ v_1 \quad v_2, \ldots, v_n \right\}$, n = number of aircraft

Definition 2: The nodes representing the aircraft of the formation knowing the reference trajectory, belong to the subset of V: $L = \{ l_1 \quad l_2, \ldots, l_p \}, p \le n$

Definition 3: The graph $F = (V,E)$, where E is a finite set of arcs, is a formation graph (FG) if and only if:

$\forall v \in (V \backslash L) \; \exists l \in L$

Such that one of the following conditions hold:

1. $(l,v) \in E$
2. $\exists C = \{v_1 \quad ,\ldots, v_k\}, k \ge 1, C \subseteq (V \backslash L) : (l, v_1) \in E \wedge (\forall i = 1, \ldots, k\text{-}1, (v_i, v_{i+1}) \in E)$

Definition 4: Given a node n, the graph $F' = (V', E')$, where $V' = V \cup v'$, $E' = E \cup \tilde{E}$, and $\tilde{E}$ is a finite set of arcs, is an extended formation graph (EFG) if and only if:

1. $F = (V,E)$ is an (FG)
2. $\tilde{E}$ contains every arc outgoing from the node n to the nodes belonging to the set L

The node v' is called the VL.

Definition 5: An EFG is defined feasible if and only if it is connected and the nodes have at most one incoming arc.

Once the VL has been defined, the reference trajectory can be inserted in the optimal communication configuration procedure.

B. Graph Theory Approach

The send-receive nature of communications leads to an oriented graph; the direction of the arcs indicates the direction of data flow and the available communication channels can form cycles;[8] with a broadcast communication scheme, for instance, all possible arcs exist among nodes. Furthermore, the arcs capacity is unlimited; there is no evident physical meaning of a communication channel with limited "capacity." The arcs weight can be set, without loss of generality, to values greater than zero. The following propositions are useful in the optimization procedure.

Proposition 1: If an EFG contains a cycle, the cycle does not contain VL.

Proof: Suppose the VL is included in the cycle. From the definition of cycle node, the VL should have an outgoing arc and an incoming arc. This is in contrast with the condition 2 of Def. 4. Thus the VL is not included in the cycle.

Proposition 2: A feasible EFG contains no cycles.

Proof: Suppose that a cycle exists. VL is not included in the cycle (Prop. 1) but it must be connected to the cycle (Def. 5). The VL may not be connected directly to the cycle because both cycle and VL admit only outgoing arcs. If nodes were added to create a path between the cycle and the VL, they also could have at least one incoming arc (Def. 5) then there is no additional node that could receive the outgoing arc from the VL. Thus *EFG* does not contain any cycle, and the VL will be the root of the solution tree.

Under these assumptions, the problem can be configured as a shortest path problem (SPP), and Dijkstra's algorithm is used, as outlined in Fig. 3.

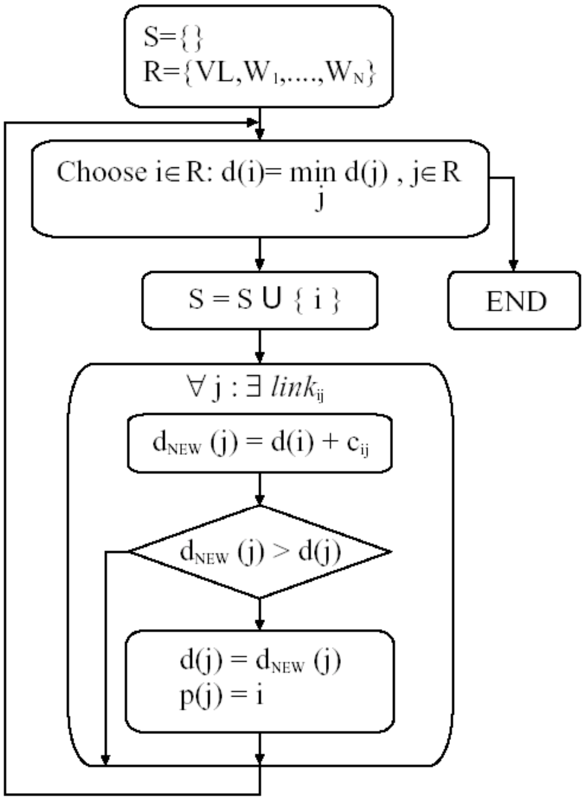

Fig. 3 Dijkstra's algorithm flow chart.

Each node in the graph represents a position in the formation, not necessarily an aircraft. 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 + infinity, 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 *V'* is called the temporary-label set. Each arc, going from node *i* to node *j* is assigned the weight C_{ij}.

The algorithm chooses, in the temporary-label set *V'*, the node that has the minimum potential and moves it to the *S* set until the *V'* set is empty. Then, for all outgoing arcs, the actual node 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 sub-optimal arc sets.

IV. Communication Failures

The communication system is modeled with a TX and an RX device on each aircraft. A TX or an RX can become faulty at any time, and a fast reconfiguration of the communication channels is needed. The activation of a new communication channel between two nodes in place of the broken one is determined by the presence of a working TX and a working RX on the aircraft occupying the nodes, therefore it depends on which communication terminal breaks down, and the history of past communication failures.

Each RX device must be able to reliably detect when a communication channel is lost. This means when the corresponding TX has become faulty, the reference aircraft has left the formation, or its own RX is not functioning. While the RX device is deciding whether the channel is definitively lost or the fault is temporary, it holds its output and notifies the formation controller. The formation controller must know that it is using held data because, although trajectory information can be held constant, absolute position (that is GPS data) can not, so it must interpolate position data using trajectory data.

The aircraft whose TX stops working must also be able to detect it because this is needed by the formation reconfiguration procedures. When, for any reason, one aircraft TX stops being operational, that aircraft can no longer be a reference for the others. The TX fault has the effect of "deleting" all outgoing channels. From the point of view of Dijkstra's algorithm, the arcs leaving 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 used the faulty one as reference must reconfigure. From the standpoint of communication reconfiguration, the case of an aircraft loss corresponds exactly to the broken TX case.

A. Communication Topology Reconfiguration

After a failure, a fast reconfiguration procedure must be run to restore formation-keeping as quickly as possible. When an aircraft detects that its own RX is faulty, it must reconfigure the formation controller to use the VL information, if no connection to the VL is available, the aircraft cannot remain in the formation. When an aircraft detects a TX fault in its reference that is it loses its present communication channel, it must use a different node as reference. Dijkstra's algorithm is run again to find the new optimal set. Changing an incoming channel node affects that node's potential and the aircraft using it as a reference should change their reference as well. The failure event must be propagated to every aircraft of the formation that must run the optimization algorithm even if their incoming channel is still functioning. A special communication channel, BC, is used to this end.

It is necessary to ensure that each run of the optimization algorithm leads to the same result in each aircraft. Because the implementation of Dijkstra's algorithm is deterministic, it is sufficient to ensure that each aircraft have the same information on the present nodes occupation and on working TXs and RXs to guarantee that each separate run of the algorithm in all aircraft leads to the same solution. This will be also achieved using the BC.

After all nodes have completed the reconfiguration, the new graph is optimal again, and this procedure can then be repeated in case of successive failures without having to reconsider optimization of the whole graph. The procedure must be the fastest possible, because between the fault detection and the reconfiguration, the aircraft does not receive any trajectory information and the risk of conflict with other aircraft increases dramatically. Due mainly to this motivation, the reference channel reconfiguration procedure is run locally on each aircraft.

If one aircraft does not find an alternative communication path, it must leave the formation following a prescribed escape maneuver, which brings it safely outside even if the formation is maneuvering. Before taking the escape path, it must switch off its TX to prevent the aircraft that were using it as a reference to follow on the escape path. The basic idea beneath the safe escape procedure is that the aircraft is first brought to fly at a different altitude, then driven away from the estimated formation direction, and then driven back home if possible. Three different altitude levels, z-1, z-2, and z-3, apply depending on position inside the formation. Figure 4 shows possible escape maneuvers.

B. The Broadcast Channel

To keep all aircraft informed of what is happening to a specific node, and which of the nodes are active (that is nodes occupied by a vehicle), an additional broadcast communication channel is introduced that transmits data at low frequency; this new channel is known as the BC. Communications on the BC are asynchronous because the formation must react to failure events with the shortest delay possible. At the same time, each aircraft notifies its presence in the formation with a periodic signal; if the communication period is T_{active} seconds, all aircraft are updated on active aircraft changes at the most T_{active} seconds after the fault. The information carried on the BC is in fact vital to the coordination of the formation as will be shown later. In particular, without the BC, it could not be possible to inform all aircraft when and how to re-optimize the communications, to move aircraft inside the formation without moving all the others using that one as reference and so on.

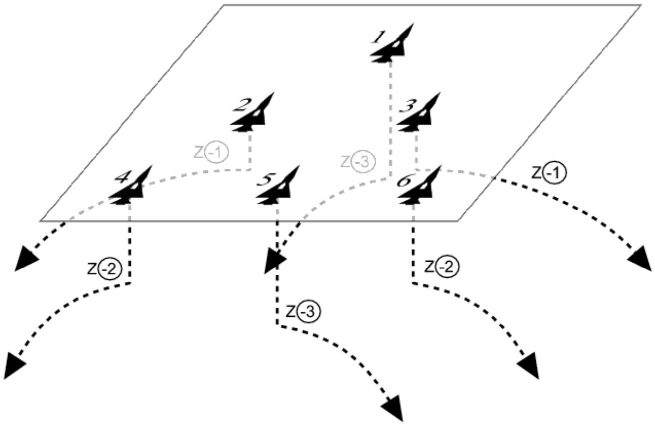

Fig. 4 Safe formation escape maneuvers

The use of BC communications is quite large during a post-fault recovery procedure but, BC communications are needed to coordinate the various aircraft and, although the carried information is very limited, it is vital for the propagation fault events and to avoid conflicting decisions. It must be stressed that no arbitration and no conflicting access may happen to the BC, unless two failures are simultaneous. While a fault is being serviced, other failures are kept in a priority queue and serviced sequentially. In this case, the aircraft subject to failure performs at least the communication channel re-optimization procedure to ensure safe, although suboptimal, channel usage. Failures in the BC transmitting and receiving devices were not considered in the present work.

V. Aircraft Position Reconfiguration

After the formation communications have been re-optimized, it may be necessary to move the aircraft inside the formation to fill holes left by a missing aircraft or to exchange two or more aircraft positions to reach desired formation geometry, and to maximize the formation-keeping capability and safety of all aircraft inside the formation.

Because formation safety and its precise control capability are measured by the total cost of the communication tree after a generic failure, the new communication cost is greater than or equal to the preceding one. By moving and exchanging two or more aircraft inside the formation, some arcs that were assigned a weight of infinity, as unusable arcs because of broken TXs or RXs, could regain their original weight or have a finite weight assigned; thus it is possible to decrease the total communication tree cost.

The introduction of heuristic rules embedded into the reconfiguration process in terms of reconfiguration maps, accommodate this situation. Because the node-changing decision must be decentralized too, 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-failure reconfiguration requirements. These rules constitute an expert system that decides, which is the best action to be taken after a failure:

1) An aircraft with a broken RX and without a link to the VL must leave the formation because it is unable to maintain the formation.

2) After the loss of an aircraft, the formation geometry must be brought to one of the desired geometries (see Fig. 6).

3) An aircraft with a broken RX has troubles keeping inter-aircraft distances because it has no knowledge of other aircraft positions, thus, the nearer to the leader it flies, the better it is.

4) The formation leader, that is the aircraft in position 1, can lead the formation even with a broken RX.

5) An aircraft with a broken RX can be brought to lead the formation if the present leader has a working RX.

6) An aircraft with a broken TX cannot be a reference for the others, and then its best position is at the back of the formation.

Based on the previous points, a number of reconfiguration maps were developed, which the reconfiguration manager in each aircraft applies in parallel to take post-fault decisions. The use of BC is vital in this case because it notifies each aircraft of the actions taken by the others.

A. Aircraft Loss

At the beginning of the formation mission, the communication optimization procedure is run to find the optimal communication scheme, but, when a node in the formation tree becomes free, the optimization procedure must be run again to find a new working communication channel set, just as in the case of TX or RX failures, but with the constraints given by the allowed geometries shown in Fig. 2. All the aircraft in the formation detect the event of an aircraft loss by listening to the BC. If after Tactive seconds one of the aircraft has not sent its "alive" signal through the BC, that aircraft is considered lost.

To describe the maneuvers needed to reach the new configuration, reconfiguration maps were used. The concept of RM was first introduced by the authors in Ref. 1. Here their use has been extended to cover all the possible cases of broken TXs and RXs in the formation. The RMs are grouped depending on the number of aircraft actually occupying the formation.

Figure 5 shows the RMs for the loss of one aircraft in a six aircraft formation. If position 1 (P1), the leader position, becomes empty, the aircraft in position 2 (P2) takes its place, unless its TX is not working. In this case, the aircraft in P3 moves to P1, but if its TX is not working the precedence to lead the formation goes to the aircraft in P2. If P2 becomes free, the aircraft in P5 takes its place, unless its TX is broken, in this case succeeds the aircraft in P4, only if its TX is working, otherwise the aircraft in P6 takes P2 and then the aircraft in P5 moves to fill the empty place. After this reconfiguration, if the aircraft in P1 has a nonfunctional TX, then the procedure in the next subsection is activated relative to the leader TX failure. The RMs for the free position in the third row are not shown because it is trivial: if P4 or P6 become free, the aircraft in P5 takes the free place. If the lost aircraft was in P5, no reconfiguration is necessary.

Figure 6 shows the RMs from 5 to 4 aircraft. If P1 is free the behavior is identical to the 6 to 5 RMs. If P2 becomes free, the aircraft in P4 or P6 are moved depending on which one has a working TX and with precedence to the aircraft in P4. The remaining aircraft completes the reconfiguration taking P5. If P3 becomes free, the RMs are specular. If P4 or P6 become free, the remaining aircraft in the last row takes P5.

The RMs from 4 to 3 aircraft are not shown but are very intuitive: if P1 is free the behavior is identical to the 6 to 5 RMs. If P2 or P3 become free, the aircraft in P5 takes the free position. If P5 becomes free no reconfiguration happens. If the formation has three or two aircraft, RMs are trivial as well and behave as already described in the previous cases.

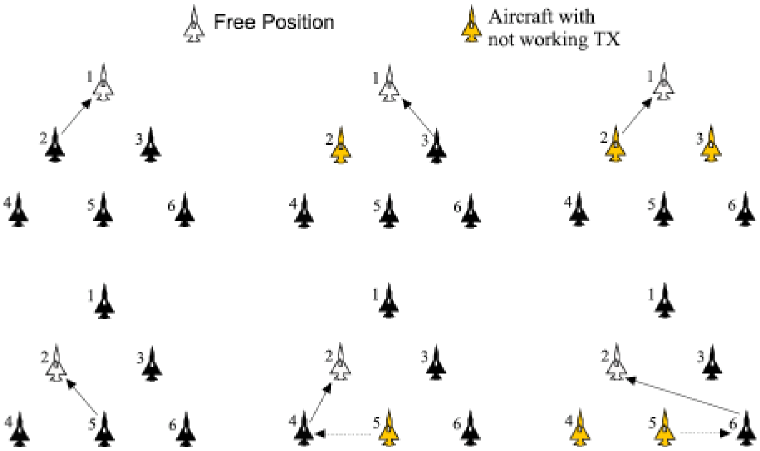

Fig. 5 Reconfiguration maps for 6 to 5 aircraft.

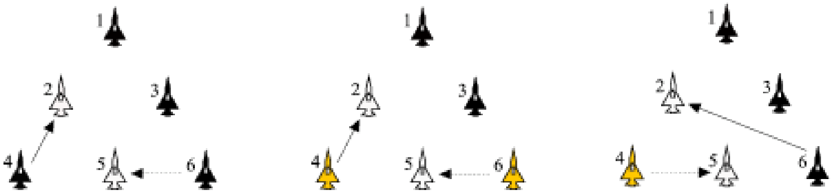

Fig. 6 Reconfiguration maps for 5 to 4 aircraft.

B. TX Failure

If a failure occurs in some aircraft TX, that aircraft is first moved inside the formation to become a leaf of the tree, where the TX capability is not needed. If the aircraft already occupies the last row or its RX is nonfunctional, no geometry reconfiguration is needed. If a reconfiguration is necessary, the faulty aircraft moves to a position outside the formation, just behind the last row, called position 7 (P7). The remaining aircraft reconfigure the geometry using the RMs as soon as P7 has been reached.

When reconfiguration is done, the aircraft in P7 re-enters the formation in P5 if the total number of aircraft is 6 or 4, in P4 or P6 depending on the free one if the aircraft are 5, in P2 or P3 if the aircraft are 3 or 2. During these phases coordination is essential and it is achieved via the BC. Figure 7 shows a high-level finite state machine description of this process. The BC communications are represented by arrows entering or coming out from the BC, depending whether the corresponding event is generated by the state transition or it generates the transition respectively. The scheme shows also how an aircraft behaves if the re-optimization process produces no sub-optimal channels in alternative to the broken one. The state marked as Aircraft Lost is not a real state and it was introduced only to complete the machine description.

Figure 8 shows an example of a six aircraft formation, with the aircraft in P4 and P5 having broken TXs. When the aircraft in P2 loses its TX, it moves to position P7, the aircraft in P6 takes its position, the aircraft in P5 should take P6 if this was a reconfiguration after a real aircraft loss but the Reconfiguration Manager knows that the aircraft in P7 is going to re-enter the formation, thus, to avoid useless position changes, leaves P6 free and drives the aircraft in P7 to move to P6.

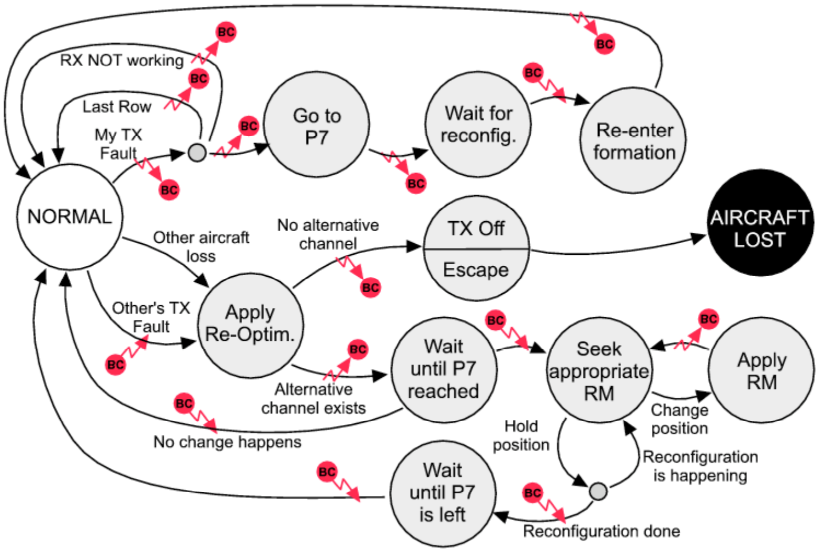

Fig. 7 TX failure management logic.

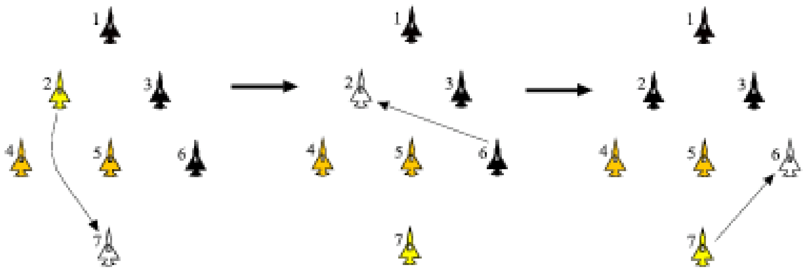

Fig. 8 Example of a reconfiguration after a TX failure.

C. RX Failure

After an aircraft detects a failure in its RX device, it either switches to use the VL trajectory, or it must leave the formation. As explained before, an aircraft with a faulty RX but with a virtual connection to the VL can lead the formation without affecting general performance. Thus, if the current leader has an operational RX, the two aircraft can change their position. First the leader moves to P7, the faulty aircraft takes P1, then the leader re-enters the formation in the place left free by the other. All other aircraft hold their positions during this phase. The finite state machine in Fig. 9 describes this logic.

The leader, before moving to P7 switches its TX off to avoid being followed by other aircraft. It will switch it on again after being in its new position inside the formation and back to the "Normal" state. The faulty aircraft, before moving to P1, switches its TX off for the same reason. It will turn it on again when it has started to lead the formation.

Figure 10 shows an example with a six aircraft formation. When the aircraft in P3 loses RX capability, the leader moves to P7, the aircraft in P3 moves to P1, then the former leader takes P3 and the reconfiguration is ended. In this case the formation keeping capability is unaltered and the communication optimal solution is the same as before failure. Note that in the case of a second RX failure (as shown in Fig. 9), the faulty aircraft remains in the same position, if connected to the VL, otherwise it must exit the formation.

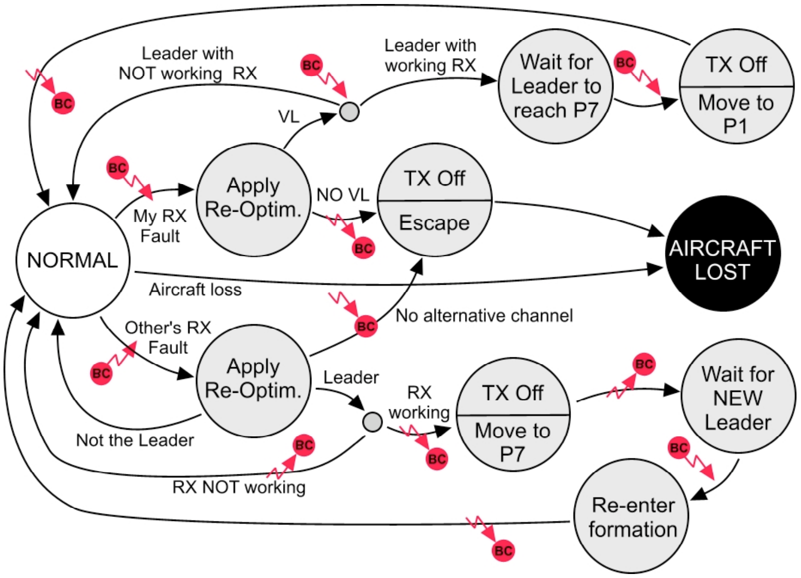

Fig. 9 RX failure management logic.

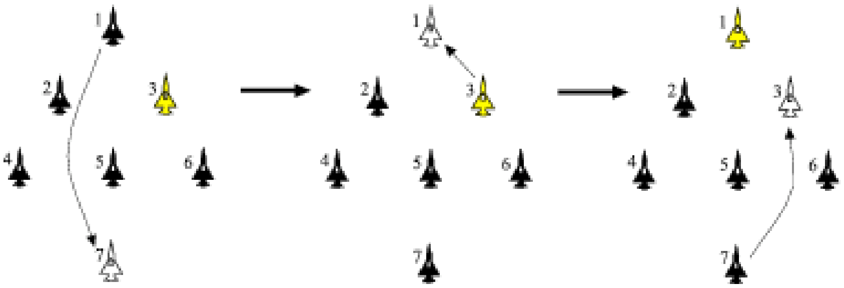

Fig. 10 Example of reconfiguration after RX failure.

VI. Example: Failure Management During Aircraft Loss

As an example of formation management procedure, we consider the case of loss of aircraft in a six-ship formation. As shown in Fig. 1, the manager is present in each aircraft and handles the commands to the autopilots based on the information received, transmitted, and communications from the broadcast channel. The schematic structure is shown in Fig. 11.

The status of the aircraft is processed by two Finite State Machines (FSM) defined as control's panel, and fault's manager. The control's panel has three parallel superstates, Receiver, Transmitter, Aircraft Status, it contains four events (one local and three as input), and has six datasets (two inputs and four outputs). Figure 12 shows the stateflow® implementation of the parts of Figs. 7 and 9 relative to the control panel's FSM.

Let us describe now the working procedure of the formation's manager during the loss of aircraft 3 in a formation of six, with aircraft 5 replacing it. Figure 14 shows the graph flow with node potentials and arc weights values, in the nominal situation.

The fault's manager FSM has a single superstate containing seven mutually exclusive states: Nothing Happens, Lost Aircraft, My RX Faulty, Leader, RM, My TX Faulty, and TX Faulty. The stateflow representation is shown in Fig. 13. When aircraft 3 is lost, each vehicle runs the algorithm again setting to infinity the weights of the arcs entering and exiting node 3. The result is shown in Fig. 15.

As far as aircraft 3 is concerned, its control's panel activates the state Aircraft Status Lost and the value of 1 is assigned to the output variable lost aircraft (L.A.). The latter causes the event Pos. A3 in all the other aircraft fault's managers, via the broadcast receivers, in addition of activating Dijkstra's algorithm. Event Pos. A3 forces the transition from state Nothing Happens to state Lost Aircraft in the Fault's Manager of aircraft 3, since L.A.=1 (see Fig. 16).

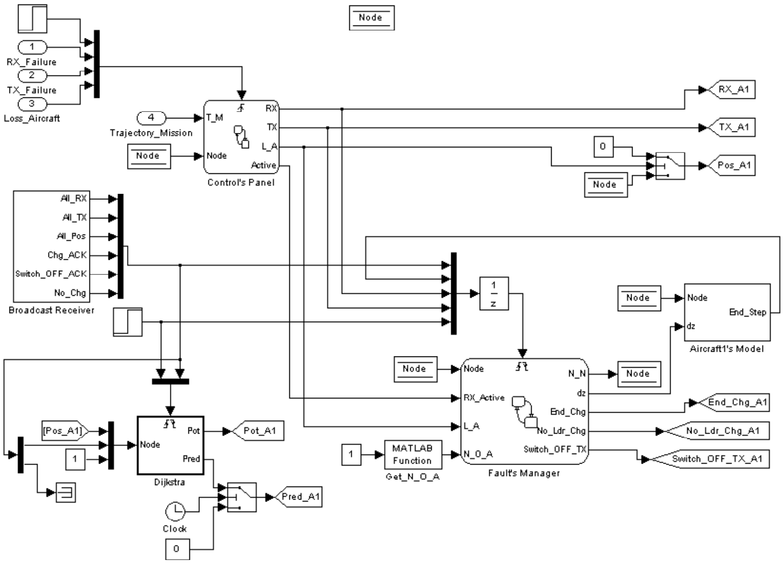

Fig. 11 Simulink diagram of a formation manager.

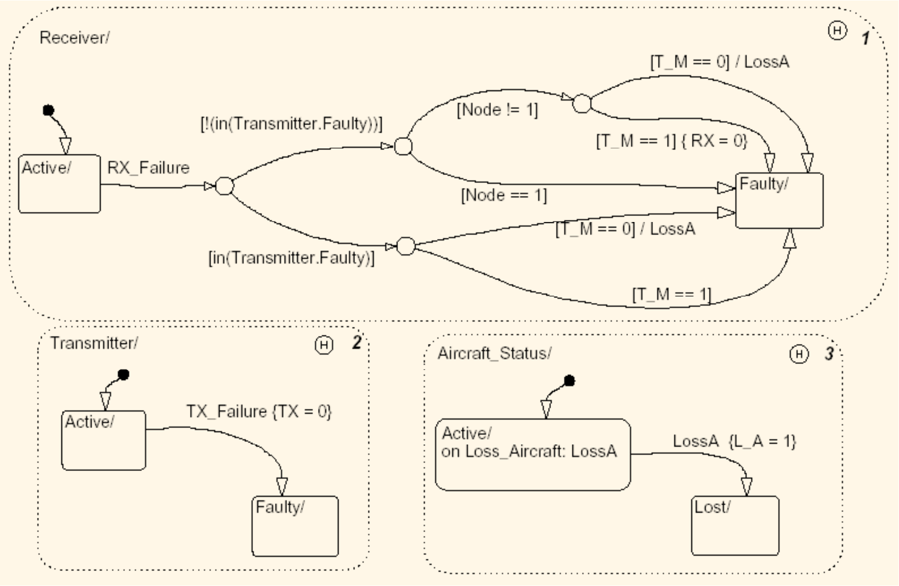

Fig. 12 Control panel diagram.

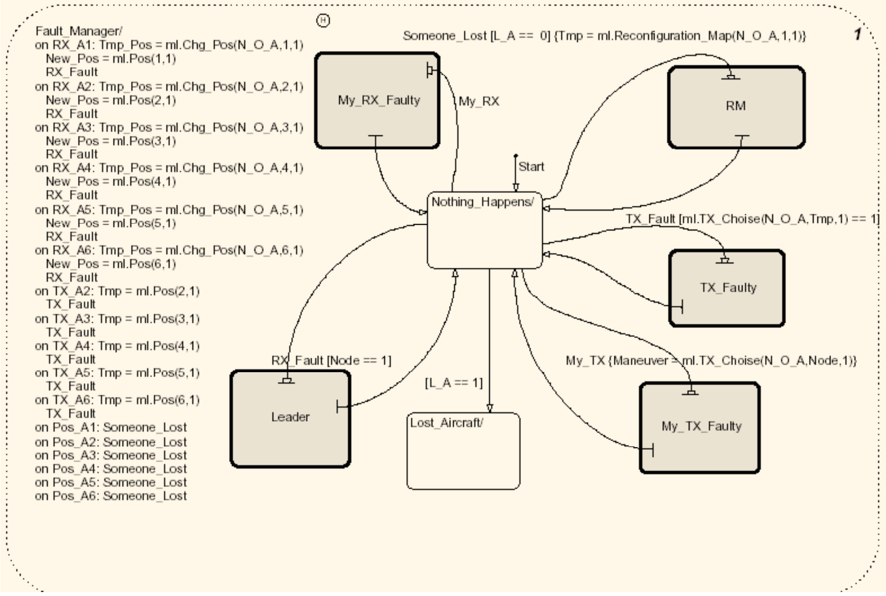

Fig. 13 Fault's manager diagram.

The other aircraft in the formation, receive event Pos. A3, and execute the reconfiguration maps, going to state RM (see top right block in Fig. 17). The Fault's Manager in aircraft 5, in particular, evaluates the function Reconfiguration Map obtaining the value 3 as new desired position in the formation, the transition is valid and the state RM is activated (see Fig. 17). Aircraft 5 understands that it must change position to node 3, shuts down the TX (see top left block in Fig. 18), waits for the others to perform channel reconfiguration (Switch OFF ACK), and then executes the maneuver to go to the final destination. In this case, two types of maneuvers are available as shown in Fig. 18, Maneuver 1 and Maneuver 2. The former is achieved with a change in altitude, the latter without. The choice is based on safety reasons. The complete sequence is described then by the sequence of Figs. 17, 18, and 19.

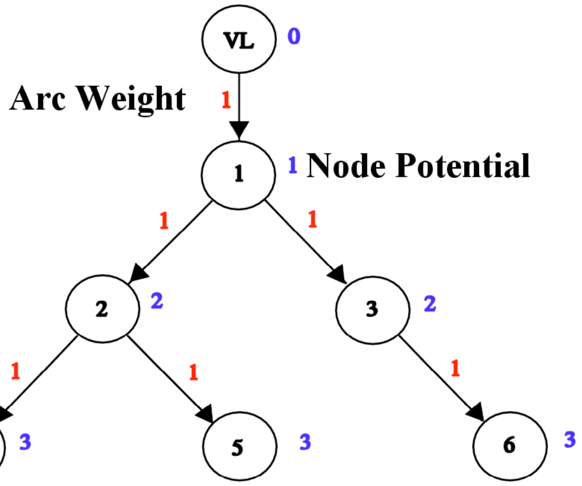

Fig. 14 Minimum cost graph from Dijkstra's algorithm, nominal.

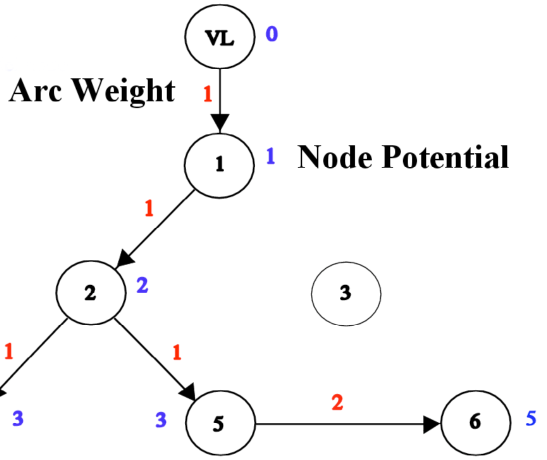

Fig. 15 Minimum cost graph from Dijkstra's algorithm, ignoring node 3.

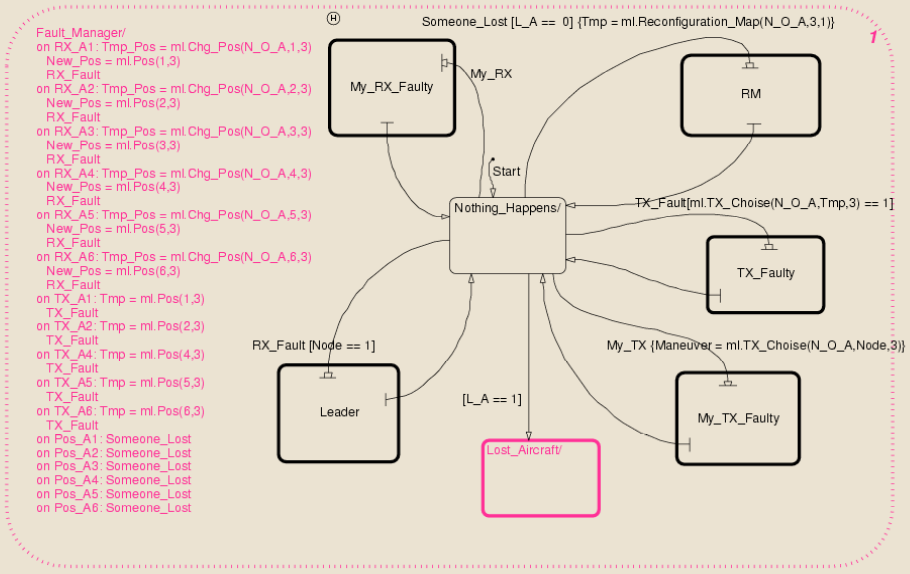

Fig. 16 Fault's manager aircraft 3 after its loss.

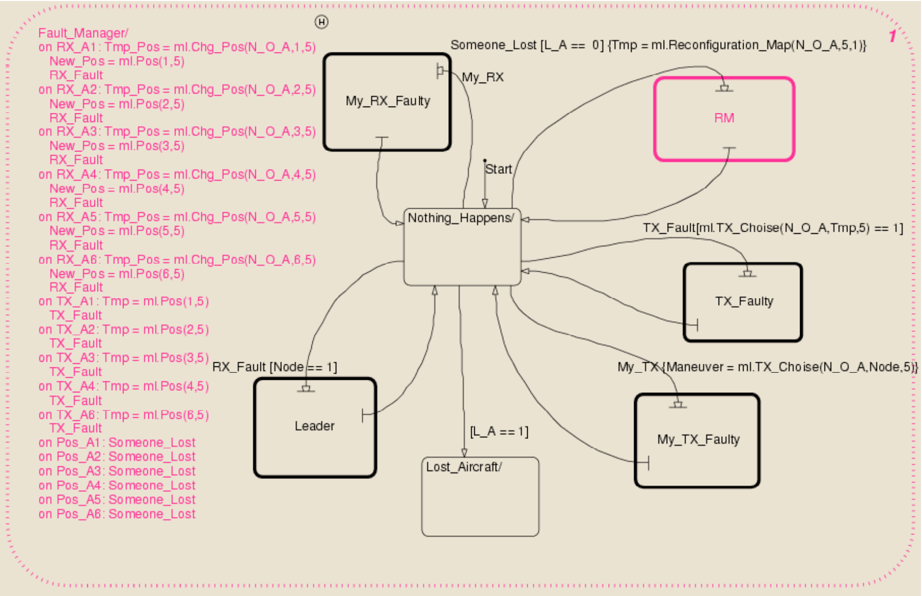

Fig. 17 Fault's manager aircraft 5 after loss of aircraft 3.

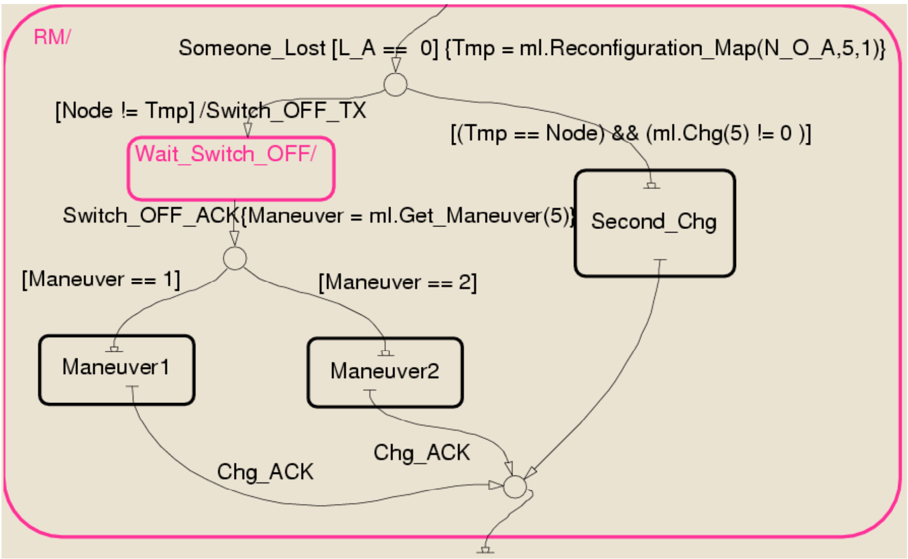

Fig. 18 RM aircraft 5 TX shutdown.

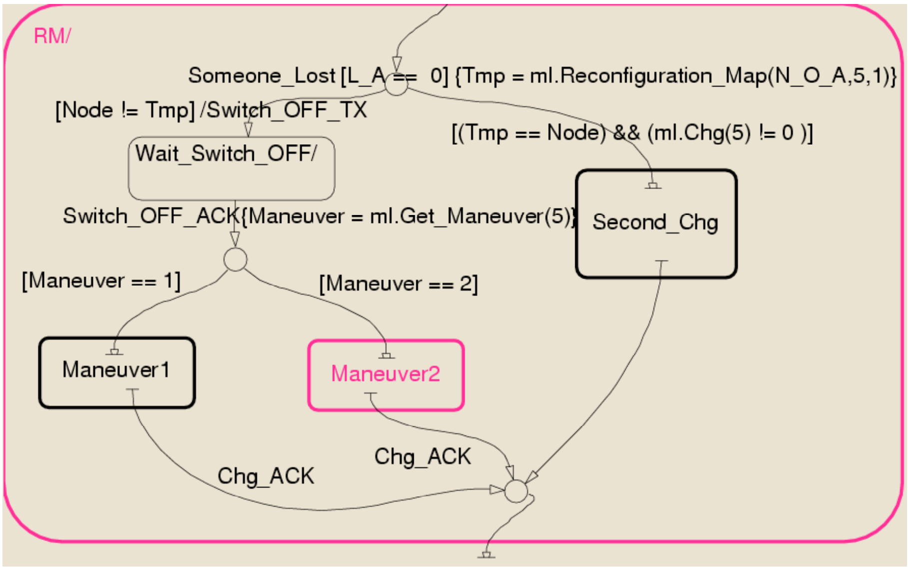

Fig. 19 RM aircraft 5 TX maneuver to node 3.

When aircraft 5 has decided to move to Node 3, the shutdown of its TX activates Dijkstra's algorithm, setting the weight to infinity for the arcs leaving Node 5 (this avoids other aircraft to follow 5 during the reconfiguration maneuver). The result is shown in Fig. 20. The new optimal graph, with aircraft 5 in the new position is computed, as in Fig. 21.

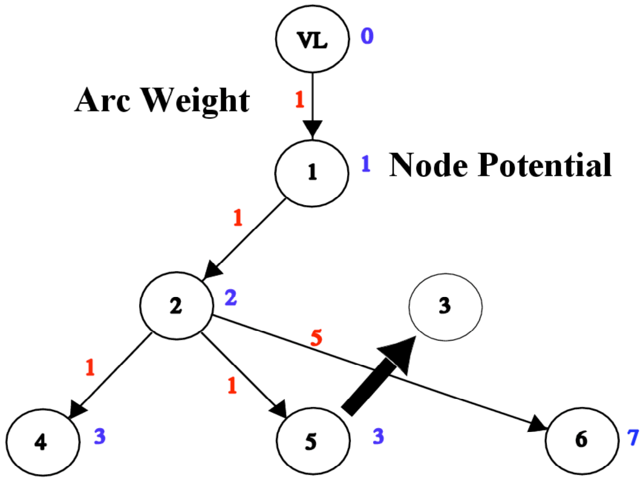

Fig. 20 Minimum cost graph ignoring node 3, and all arcs exiting node 5.

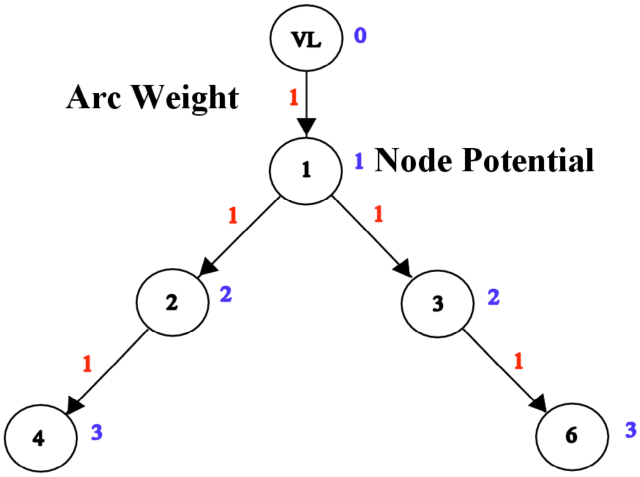

Fig. 21 Final minimum cost graph.

VII. Conclusion

The paper presented a finite state machine implementation of a deterministic approach to the problem of management of communication failures and aircraft loss inside a formation during autonomous flight. The aircraft formation is represented as an oriented graph and then a procedure, based on the shortest path theory, provides the optimal solution for the information flow within the formation. In case of failures, this procedure runs again providing with a suboptimal solution while a formation manager that uses Reconfiguration Maps and heuristic rules to find the new best placement for the aircraft in the formation changes the formation geometry. Theoretical development and numerical simulation results validating the fault management methodology were presented.

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