WINGMAN GUIDANCE IN TACTICAL FORMATION FLIGHT USING LEADER OBSERVATIONS

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1. INTRODUCTION

The problem of automating tactical aircraft formation flight concerns the determination of a reference wingman trajectory and of the ownship's relative position with respect to the trajectory and to its momentary reference point along the trajectory. From the reference trajectory and the ownship's position, feedforward and feedback signals are computed to drive an autopilot system. The determination of the wingman or ownship reference trajectory consists of two steps: the reconstruction of the leader aircraft trajectory, and the determination of the ownship trajectory as a derivative of the leader's trajectory using a preset wingman longitudinal and lateral offset.

During close formation flight or loose formation flight for fighter aircraft, the distance between the leader and the wingman aircraft typically does not exceed three to five wingspans. As a result, the dynamics of the wingman aircraft in terms of accelerations, velocities, and turn rates are approximately equal to those of the leader. In tactical formation flight, the lateral separation between the leader and the wingman typically ranges between zero and about 1000 ft or 300 m. Longitudinal separation, either expressed as a distance or as a time delay behind the leader, most often ranges between 5 seconds or 0.3 NM and 1 minute or 3 NM, but can theoretically go up to 100 NM. As a result, the dynamics of the wingman in tactical formation cannot be assumed equal to those of the leader. The increased lateral offsets require a speed change during turns to compensate for the increased or decreased trajectory length. This is illustrated in figure 1. The leader enters the turn while maintaining its initial speed. The right-hand wingman decelerates during the transition phase; the left-hand wingman accelerates. The projections of the wingmen's positions onto the leader trajectory move with constant speed.

Longitudinally and vertically, operational concepts distinguish between synchronous mode and tunnel mode. In synchronous mode, speed and altitude changes of the leader are immediately mirrored by the wingman. As such, the geometrical distance between the leader and the wingman is constant. In tunnel mode, speed and altitude changes by the leader are mirrored by the wingman when the wingman arrives at the same location – or abeam the same location, in case of a lateral offset – where the leader initiated the change. As such, the time interval between the leader and the wingman passing every point along the trajectory is constant. Thus, synchronous mode is related to specifying longitudinal separation in terms of a distance, and tunnel mode is related to specifying the longitudinal separation in terms of a time interval.

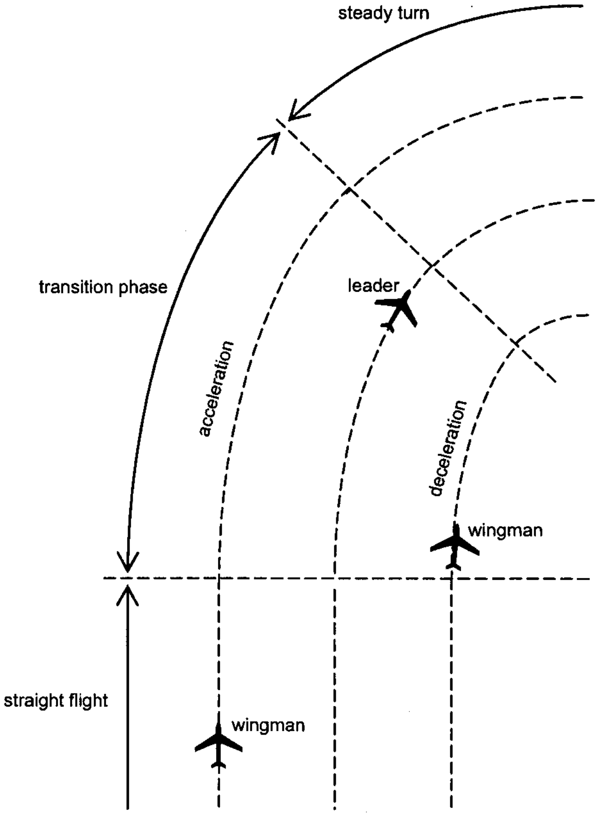


FIGURE 1. Transition between straight and turning flight of a tactical formation (not to scale)

1.1. Objectives of a tactical formation system

An automatic control system for tactical formation flight should support both synchronous and tunnel mode. As such, it should be able to relate geometrical locations along the trajectory to the time instants at which these points have been or shall be passed. At the same time, it should provide additional longitudinal acceleration or deceleration commands that adjust the wingman's ground speed to compensate for the difference trajectory length during a turn. For the lateral axis, the system should provide some parameter that specifies the nominal command to correctly fly the wingman turns. All of these are feedforward signals. Without disturbances, the wingman would follow the intended four-dimensional (three-dimensional space plus time) trajectory. To compensate for errors, additional feedback signals are required that relate the actual position of the wingman to its intended position for the applicable time.

In order to minimize the impact on aircraft flight control system design, an automatic system for tactical formation flight should be implementable as an outer loop to an existing autopilot system, providing alternative reference signals to those coming from the crew's control panel or the flight management system. However, a dedicated mode for automatic formation flight is expected to be necessary; it it deemed unlikely that an existing autopilot system can handle formation flight systems through one of its existing modes for automatic flight control. As the formation flight system is an alternative source of reference signals to the autopilot which is similar to the FMS, the system that is discussed in this paper is referred to as the *formation flight reference system* (FFRS) from now on.

The FFRS must ensure full axis decoupling through the reference signals it provides to the flight control system: A positional or temporal error in one axis must not lead to an error in one of the other axes. First, this allows the autopilot to control the axis with the initial error and use corrective feedforward information known from the aircraft's flight dynamics – for example the need to adjust power settings when an altitude change is to be performed at constant speed – without being disturbed by additional errors resulting from the initial offset. Second, axis decoupling allows the flight control system to put a selection of axes under automatic control and leave others to manual control by the flight crew.

Figure 2 depicts the context of the FFRS in a single aircraft. When the aircraft operates as a wingman, the FFRS receives the aircraft's own position from the navigation system and the position of the leader aircraft through a datalink; it delivers guidance reference signals to the flight control system. When the aircraft operates as a leader, a transmitter sends the aircraft's position from the navigation system to the wingman aircraft that follow. An aircraft that operates as a leader can have multiple wingmen. Aircraft can operate as a leader and as a wingman at the same time.

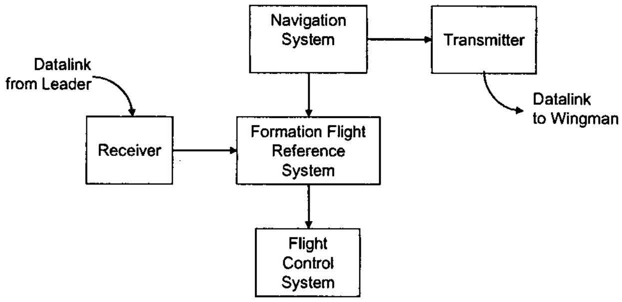


FIGURE 2. FFRS context.

1.2. Previous work

The problem of automatic formation flight has been addressed by several research projects and commercial programs, all within the perimeter of military aviation.

Giulietti e.a. (2005), like Hanson e.a. (2002) and Bever e.a. (2002), deal with the problem of close formation flight. Their research focuses on the aerodynamic advantages of benefiting from vortices of the lead aircraft, whereas a tactical formation intends to avoid wake penetration by selecting appropriate lateral and vertical offsets. During these projects, integrated automatic formation flight control systems have been developed that do not meet the requirements for a tactical formation flight control system as described in the previous section.

An existing product to automate tactical formation flight is the DRS (former Sierra Research) AN/APN-243(A) Station Keeping Equipment. It is based on cooperative exchange of radio transmissions between the participating aircraft. Directional antennae are used to determine the constellation of aircraft around the own ship. The system was originally developed to maintain formation during straight and level flight (US Patent 4674710, Rodriguez, 1987) and as such, is less suitable for highly dynamic flight maneuvers. The US Patent 4674710 introduces an operational procedure that offers an improvement to the SKE system for flying coordinated turns. However, it requires previous definition of the bank angle and roll rates of the leader aircraft.

The Honeywell Enhanced Traffic Alert and Collision Avoidance System (ETCAS) is an extension of the traffic collision avoidance system. It uses the navigational information that is exchanged by Mode-S TCAS ADS-B to create an aircraft constellation overview and provide a situation overview of both formation aircraft and other TCAS-equipped aircraft in the ownship's vicinity. (Honeywell, 2002).

1.3. Contribution of the current work

This document presents a new algorithm to derive a wingman trajectory in terms of discrete closely-spaced spatial time-tagged waypoints from observations of similar waypoints for the leader trajectory. The leader waypoints may be acquired from a pure datalink between the aircraft, as no more information is required than spatial, time-tagged position estimates that are readily available from the aircraft's navigation system, but can also be determined from range and bearing measurements as performed by the DRS SKE system. The new algorithm furthermore computes feedback and feedforward signals for the outer loop of a flight control system in a way that both synchronous and tunnel mode are supported, and that axes are fully decoupled to allow combined manual and automatic control modes. Finally, the algorithm puts no limits whatsoever upon the dynamics of the leader aircraft, thus allowing automatic formation flight in more demanding flight phases than existing systems do.

1.4. Assumptions

The algorithm that is presented in this paper is limited to the process of deriving a wingman trajectory and the corresponding feedback and feedforward signals from the leader waypoint observations and from the momentary ownship position. It addresses neither the process of acquiring the leader waypoint observations, nor the process of automatic flight control. The current algorithm assumes the leader waypoint observations to be plausible; hence, they are assumed to be preprocessed. To facilitate such a process, the current algorithm does not put fixed requirements on the availability or jitter of the observed leader waypoints. As the current algorithm is independent of a specific type of aircraft or an autopilot implementation, the autopilot signals are not checked for feasibility with respect to the dynamics or performance limits of the own ship.

2. FORMATION FLIGHT REFERENCE SYSTEM ALGORITHM

The formation flight reference system starts from a series of four-dimensional (time-tagged spatial) position samples from a leader aircraft, the sampled and time-tagged spatial ownship position, and crew settings for the desired longitudinal, lateral, and vertical offsets with respect to the leader aircraft. Its outputs are the real-time autopilot reference signals for formation flight, related to those instances in time for which the ownship navigation samples are received.

2.1. Definitions

Figure 3 depicts the concept of tactical formation flight for a leader aircraft and a single wingman in the horizontal plane. It shows the two aircraft, their respective trajectories as measured for the leader and computed for the wingman, and two virtual points along the wingman trajectory. The computed wingman trajectory is defined as the trajectory that is parallel to that of the leader, at a lateral (and vertical) offset equal to the current lateral (and vertical) offset of the wingman to the past leader trajectory. Hence, by definition the wingman trajectory goes through the wingman position. The *reference point* is the point on the wingman trajectory which is abeam the point on the leader trajectory that is longitudinally separated from the leader by the crew-commanded longitudinal separation value. The *anticipation point* is the point on the wingman trajectory which is ahead of the wingman by a preset separation.

The commanded longitudinal separation can be expressed either as a time interval or as a distance. As the leader trajectory is known in spatial coordinates plus time, time separation can be converted into distance separation and vice versa. Distance separation should be computed along the leader trajectory and not as a direct slant range. The preset anticipation separation can also be defined in terms of distance or time, although the former is deemed unpractical.

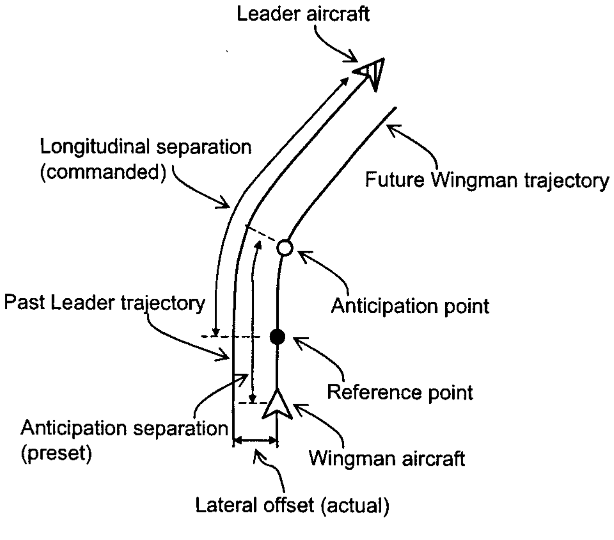


FIGURE 3. Definitions.

2.2. References for guidance

Guidance of the wingman aircraft along the intended wingman trajectory can be achieved along each of the three axes separately and independently. For each axis, guidance can be automatic by means of an autopilot and/or autothrottle system, or manual through involvement of the pilot flying.

In order to allow guidance, the following parameters have been identified as feedback and feedforward signals:

- for the longitudinal axis: the *longitudinal position error* (difference between the actual wingman position and the reference point, along the wingman trajectory), the *reference ground speed*, and the *reference acceleration*;
- for the lateral axis: the *lateral position error* (difference between the signed actual lateral offset and the commanded lateral separation), the *wingman trajectory curvature*, and the *reference ground track*;
- for the vertical axis: the *vertical position error* (in tunnel mode: difference between the wingman altitude and the past leader altitude abeam the wingman position plus the commanded vertical offset; in synchronous mode: difference between the wingman altitude and the current leader altitude plus the commanded vertical offset) and the *reference rate of climb*.

It is the combination of feedback and feedforward reference signals along each of the axes as defined here that allows for independent guidance for each axis, in combination with stable and zero steady-state error control.

To compensate for any equivalent time delay that is introduced by the dynamic response of the guided aircraft, for example for the response time of the aircraft's propulsion, anticipation signals may be added to the set of parameters that are sent from the formation flight reference system to the guidance system. As anticipation parameters, any of the feedforward signals listed above can be evaluated for the anticipation point as defined in figure 3 instead of the current wingman position. These are then referred to as the *anticipation ground speed*, *anticipation acceleration*, *anticipation curvature*, *anticipation ground track*, and/or *anticipation rate of climb*.

2.3. Wingman trajectory generation

As shown in figure 4, the leader trajectory is recorded through a series of spatial time-tagged positions. A local Carthesian three-dimensional reference frame with its origin at the wingman's position is used to transform the leader position observations into leader trajectory nodes that are relative to the current wingman position. The leader trajectory is defined as the series of straight line segments, each of which connects two consecutive nodes. In order for the simplification by straight line segments to be acceptable, leader position observations must be sufficiently closely spaced; for transport aircraft with moderate turn rates, the interval between consecutive observations should not exceed 0.5 sec.

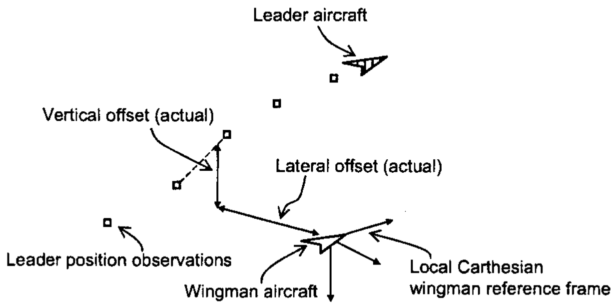


FIGURE 4. Leader observations.

Within the local Carthesian wingman reference frame, the actual lateral offset and vertical offsets of the wingman with respect to the leader trajectory are determined. To do so, two cases are distinguished.

If any line segment between two consecutive leader trajectory nodes exists from which a perpendicular towards the wingman position can be drawn, the lateral offset is the distance between the aforementioned line segment and the wingman position in the horizontal plane. When multiple line segments with a perpendicular to the wingman exist (concave leader trajectory), the lateral offset is computed from the smallest distance between a line segment and the wingman position. The optional vertical offset is computed as the distance between the horizontal plane through the point on the leader trajectory line segments that is closest to the wingman, and the wingman vertical position. This situation is shown in figure 5a. If no line segment exists from which a perpendicular towards the wingman position can be drawn (wingman abeam a node on a convex leader trajectory), the lateral and optional vertical offset are computed with respect to the single observed leader position that is closest to the wingman position. This case is depicted in figure 5b. The lateral offset is the distance between the leader observation and the wingman position in the horizontal plane; the vertical offset is always the distance between the two horizontal planes through each of the points.

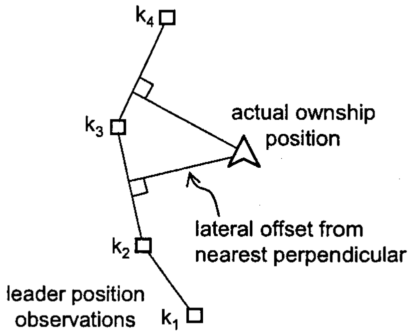
Both the lateral and the optional vertical offset are signed. The sign of the lateral offset indicates whether the wingman position is on the right-hand or the left-hand side of the leader trajectory, seen in the direction of leader flight. The sign of the optional vertical offset indicates whether the wingman is above or below the leader trajectory.

Using the lateral and optionally the vertical offset as described above, the wingman trajectory as shown in figure 3 is computed by adding the signed offset to each of the threedimensional time-tagged leader trajectory nodes. Like the leader trajectory, the wingman trajectory is defined as the series of straight line segments that connect consecutive wingman trajectory nodes. The time tag that is associated with each of the leader trajectory nodes is also applied to the corresponding wingman trajectory node.

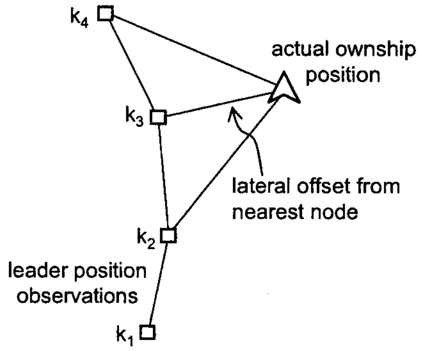
2.4. Longitudinal reference value computation

The longitudinal position error follows directly from the situation depicted in figure 3: It is the difference along the wingman trajectory between the actual wingman position and the reference point. When its value should be determined with the dimension of time, the time tag that corresponds to the actual wingman position along the time-tagged wingman trajectory is computed first from interpolation of the wingman position within the previously determined wingman trajectory nodes. The difference between the current time and this trajectory time that corresponds to the wingman position is the actual longitudinal separation. The difference between the actual and the commanded longitudinal separation is the longitudinal position error in units of time. In case the value should be determined with dimension of length, the planar or spatial reference point position is determined from the commanded longitudinal separation in distance or time and the time-tagged wingman trajectory. The longitudinal position error is then determined as the sum of the line segment lengths between the current wingman position and the reference point.

The reference ground speed and reference acceleration are computed from the observed time-tagged leader position samples as shown in figures 4 and 5. They can be determined directly from one or two pairs of nodes, from curve-fitting techniques, or by means of a filtering technique like a Kalman filter. The choice may depend on the expected accuracy and bandwidth of the reference signal, and thus on the dynamic requirements of the aircraft's guidance system.



a) concave case



b) convex case

FIGURE 5. Determination of lateral offset.

2.5. Lateral reference value computation

Because the lateral position error is the difference between the actual lateral offset and the commanded lateral separation, it follows directly from the wingman trajectory generation algorithm as described before.

The reference curvature is defined as the inverse of the momentary radius of the wingman trajectory in the horizontal plane at the current wingman position. The curvature is signed: A right turn (yaw vector pointing down) corresponds to a positive curvature, a left turn (yaw vector pointing up) corresponds to a negative curvature. A curvature of zero corresponds to straight flight. The curvature and reference track angle can be computed in closed form from three wingman trajectory nodes, or through curve-fitting or filtering techniques. As for the longitudinal reference values for ground speed and acceleration, the choice of technique may depend on the imposed requirements from the guidance system.

2.6. Vertical reference value computation

The vertical offset that is depicted in figure 4, which is the difference in altitude between the point on the leader trajectory that is closest to the current wingman position, is the basis for computing the vertical position error in tunnel mode. The difference between the actual vertical offset as shown in the figure and the commanded vertical separation yield directly the vertical position error. The reference rate of climb is computed from the time-tagged leader trajectory nodes. Similar to the computation of longitudinal and lateral reference values, the rate of climb may be computed directly from two nodes around the point closest to the current wingman position, or from curve-fitting or filtering techniques that take more points of the leader trajectory into account.

In synchronous mode, the vertical position error can be computed by extrapolating the leader altitude from the two or more most recent leader position observations, thus predicting the leader altitude for the time point at which the current wingman position is observed. The vertical position error then follows directly from the commanded vertical separation. The extrapolation inherently provides the leader rate of climb, which should be mirrored by the wingman in synchronous mode without delay.

3. AXIS DECOUPLING

Figure 6 defines the wingman target position as the desired position for the wingman based on the current leader position and the commanded longitudinal, lateral, and vertical separations. The reference point has been defined before: it lies on the trajectory that goes through the current wingman position, abeam the commanded longitudinal separation from the leader aircraft. The difference between the wingman target position and the reference point is the basis for axis decoupling.

The key to axis decoupling is the generation of the wingman reference trajectory through the current wingman position instead of the wingman target position. By computing the longitudinal position error, the reference ground speed, and the reference acceleration along the wingman trajectory at the actual lateral wingman offset, the longitudinal reference values are applicable both in feedback and feedforward to the reference position, instead of the wingman target position. As a result, a lateral position error – either intended in the case of single-axis guidance, or transient and unintended as the result of a lateral disturbance – automatically leads to adapted longitudinal reference values. For example, the lateral position error that is shown in figure 6 will lead to a reduced reference ground speed and the corresponding reference acceleration, which account for the reduced radius of the wingman's turn inside the curved leader trajectory. When longitudinal reference values are computed at the target position, too high a ground speed would be commanded, which would only be compensated by feedback with a steady-state error when the actual longitudinal wingman position is clearly ahead of the target position.

The computation of the reference curvature, track angle, and rate of climb at the actual longitudinal position of the wingman ensures correct following of the wingman trajectory that is parallel to the leader trajectory. The wingman guidance problem is thus separated in two parts: the lateral/vertical guidance problem, which keeps the aircraft at the correct distance from the leader trajectory, and the longitudinal guidance problem, which keeps the aircraft at the correct position along that trajectory. The separation of longitudinal and lateral/vertical guidance is reflected in the distinction between the wingman target position and the reference point; the latter isolates the longitudinal guidance problem.

The feedforward reference signals (reference ground speed, acceleration, curvature, track, and rate of climb) are therefore sufficient to keep the wingman at constant actual longitudinal, lateral, and vertical offsets from the leader aircraft, independent from the actual values of these offsets and whether they coincide with the wingman target position. The three feedback signals (longitudinal, lateral, and vertical position error) are then sufficient to eliminate the difference between the target position and the actual wingman position without introducing any steady-state error.

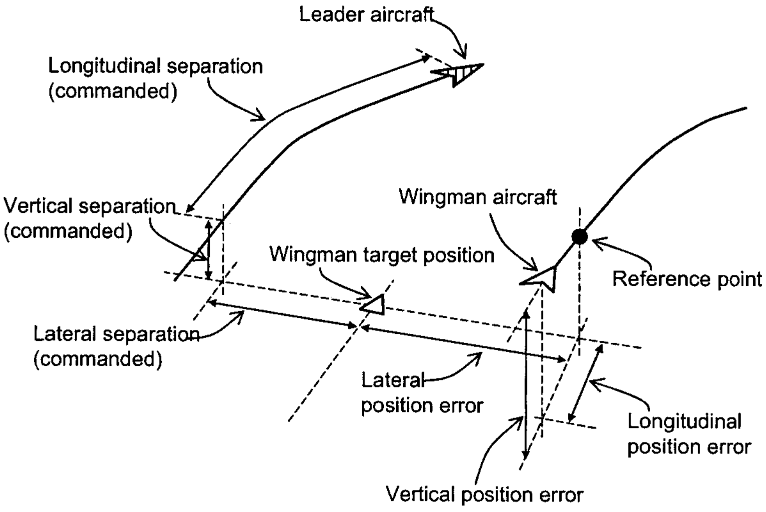


FIGURE 6. Wingman target position and reference point

4. CONCLUSIONS

The algorithm for deriving a wingman trajectory and three-axis flight guidance reference signals for tactical formation flight that is presented in this paper, only depends on time-tagged observations of the leader and the wingman aircraft positions. Named a *Formation Flight Reference System*, the algorithm can be used on-board a wingman aircraft to provide reference signals to an automatic flight control system (autopilot/autothrottle) or to a human pilot. The algorithm allows full decoupling of the three control axes and does not put any requirements to the dynamics or type of maneuvers that are flown by the leader aircraft, although wingman aircraft performance may prohibit accurate position keeping in case of highly dynamic leader maneuvers and/or too large separations.

The algorithm distinguishes between the wingman target position, which marks the intended position of the wingman given the separations with respect to the leader aircraft, and the reference point, which combines the commanded longitudinal separation with the actual lateral and optional vertical offsets. A reference trajectory is continuously computed through the momentary wingman position. For zero steady-state error flight guidance, the following reference signals are computed from the reference trajectory:

- the reference ground speed and acceleration at the reference point, as feedforward signals in the longitudinal axis,
- the reference curvature and track at the wingman position, as feedforward signals in the lateral axis,
- the reference rate of climb at the wingman position, as feedforward signal in the vertical axis, and
- the longitudinal, lateral, and vertical error between the wingman target position and the actual wingman position, as feedback signals.

The algorithm may be extended by the computation of equivalent guidance signals at an anticipation point that is located along the wingman trajectory, at a fixed distance or time ahead of the wingman aircraft. This way, the aforementioned feedback and feedforward signals can be enhanced by target references that allow to anticipate the trajectory dynamics and compensate for any delay in the aircraft flight control system, including aerodynamic and propulsion delays.

ACKNOWLEDGMENT AND CONTEXT OF THE WORK

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