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Flight Control Systems for Aircraft Engaged in Air Wake Surfing for Efficiency

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This paper gives an overview of a flight control architecture developed during studies for a trail aircraft flying in formation with a leading aircraft in order to save fuel, commonly referred to as air wake surfing for efficiency (AWSE). The paper starts with an overview of the motivation for formation flight followed by a generic flight control architecture and accompanying algorithms that achieve formation flight. Finally, a summary of some of the results from simulation of a formation of turboprop transport aircraft and formations of a tanker or high-speed transport aircraft with fourth generation fighters is presented.

I. Nomenclature

α	= Aircraft angle of attack, rad
β	= Aircraft sideslip angle, rad
θ	= Aircraft pitch angle, rad
τ_{Roll}	= Roll mode time constant, sec
ω_{Act}	= Actuator natural frequency, rad/sec
ω_{sp}	= Short period natural frequency, rad/sec
ω_{dr}	= Dutch roll natural frequency, rad/sec
ζ_{dr}	= Dutch roll damping ratio
ζ_{sp}	= Short period damping ratio
Alt	= Aircraft altitude, ft
A_y	= Body y-axis acceleration, ft/sec ²
b	= Reference wing span, ft
C_L	= Coefficient of lift
C_D	= Coefficient of drag
CR_{dy}	= Incremental change in roll rate due to lateral motion in the flow field, rad/sec
g	= Acceleration due to gravity, ft/sec ²
I_{xx}	= Body axis roll moment of inertia, slug-ft ²
K_p	= Controller gain on the error signal, proportional gain
K_d	= Controller gain on the first derivative of the error signal, derivative gain
K_{dd}	= Controller gain on the second derivative of the error signal, double derivative gain

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K_i	=	Controller gain on the integral of the error signal, integral gain
K_{ff}	=	Controller gain on the flow field
$Mass$	=	Aircraft mass, slug
$\dot{P}$	=	Angular roll acceleration, rad/sec ²
$\dot{Q}$	=	Angular pitch acceleration, rad/sec ²
$\dot{R}$	=	Angular yaw acceleration, rad/sec ²
P_{cmd}	=	Commanded roll rate, rad/sec
$P_{Cmd_{RCG}}$	=	Roll rate command due to lateral offset error, rad/sec
$P_{Cmd_{FFRA}}$	=	Roll rate command augmentation, rad/sec
$\dot{P}_{des}$	=	Desired roll acceleration, rad/sec ²
Q_{cmd}	=	Commanded pitch rate, rad/sec
$\dot{Q}_{des}$	=	Desired pitch acceleration, rad/sec ²
$\dot{R}_{des}$	=	Desired yaw acceleration, rad/sec ²
$\bar{q}$	=	Dynamic pressure, lb/ft ²
p	=	Roll rate, rad/sec
q	=	Pitch rate, rad/sec
r	=	Yaw rate, rad/sec
S	=	Reference wing area, ft ²
$T_{\theta 2}$	=	Pitch attitude numerator zero, sec
T_{R1}	=	Yaw rate time constant, sec
TLA_{cmd}	=	Throttle lever angle command
$Thrust_{des}$	=	Thrust desired to maintain longitudinal separation, lbs
TLA_{trim}	=	Throttle lever angle at trimmed flight
u	=	Body x-axis velocity component, ft/sec
v	=	Body y-axis velocity component, ft/sec
w	=	Body z-axis velocity component, ft/sec
$\dot{U}$	=	X-axis linear acceleration, ft/sec ²
$\dot{U}_{cmd}$	=	Commanded x-axis acceleration, ft/sec ²
V_T	=	Aircraft true velocity, ft/sec
X_{err}	=	Error between actual follower location and desired distance from lead aircraft, ft
$\dot{X}_{err}$	=	Rate of change error between actual follower location and desired distance from lead aircraft, ft/sec
Y_{err}	=	Lateral position error, ft
$\dot{Y}_{err}$	=	Lateral position error first derivative, ft/sec
$\ddot{Y}_{err}$	=	Lateral position error second derivative, ft/sec ²
Z_{err}	=	Vertical position error, ft
$\dot{Z}_{err}$	=	Vertical position error first derivative, ft/sec
$\ddot{Z}_{err}$	=	Vertical position error second derivative, ft/sec ²

II. Introduction

In order to reduce the fuel consumption of an aircraft, fuel-saving formation flight has been studied for several decades. An overview about already conducted investigations including flight tests is for example given in [1]. The first manual flight tests have been conducted in 1984 by the Technical University of Braunschweig, Germany [2], the first ones with a modified autopilot in 1987/88 also by the Technical University of Braunschweig [3].

The basic principle is that a trailing aircraft flies within the outer section of the wake vortex flow field behind a leading aircraft where an updraft can be encountered like shown on Figure 1. This principle is commonly called “wake surfing”.

Figure 1 Fuel saving formation flight is achieved by the trail aircraft flying within the updraft section of the lead aircraft wingtip vortex, referred to as wake surfing [1].

The trailing aircraft must be flown within a very narrow section of the flow field where the upwind velocity leads to the best fuel savings. This position within the flow field is commonly called “sweet spot” and is typically slightly outside of the wake vortex core requiring some wingtip overlap of the two aircraft (in case that both aircraft are of the same type).

Figure 2 Possible fuel savings within the flow field for an A320 following another A320 [4].

Applying classical trim computations yields the sweet-spot location as shown on Figure 2 for an A320 following another A320. The corresponding rolling moment induced by the flow field is plotted on Figure 3. Fuel savings of more than 10% can be achieved in a practical area (deep blue) around the sweet spot. It is noticeable that the rolling moment is close to zero at the sweet spot but with a large gradient along the lateral direction.

The white area on the left side of these figures represents the region of the flow field where the induced roll moment and the downdraft cannot be countered by the ailerons and the elevators of the trailing aircraft. Therefore, a flight into this hazardous section of the wake vortex should be avoided.

The flight tests have illustrated that it is very tedious for pilots to track the sweet spot manually for a long time without encountering the hazardous area of the wake vortex. Therefore, an automatic flight control system on the trailing aircraft is needed for safe and effective operation. The next sections describe a candidate control architecture and present some simulation results.

Figure 3 Aileron deflection is necessary to compensate for the rolling moment induced by the flow field [4].

III. Wake Surfing Flight Control System Architecture

The wake surfing flight control system development began by researching existing formation control architectures and verifying/judging whether or not they made sense for complex nonlinear simulations that have been created for wake surfing, see for example [5], [6], [7].

Much of the current work in the field of wake surfing flight control systems is for “ideal” situations and does not take into account the nonlinear disturbances within the flow field. Numerous papers also ignored noisy position signals, signal lag, and atmospheric turbulence. Very simple aircraft models were used in some papers, in other cases the control algorithms were only demonstrated for two-dimensional tracking. It was necessary to test many different control algorithms to determine which control scheme or variation of control scheme offered the best tracking and robustness in the presence of the multiple realistic characteristics that were modeled in before-mentioned simulations considering position sensor noise, signal lag (especially concerning ADS-B signal), and light turbulence.

The flight control system in total is either developed for the wake surfing (as in this paper) or consists of some add-on functions coupled to the outer loop autopilots that were previously designed around a classical inner loop control system, as shown in references [8], [9], [4], and [3].

A successful wake surfing flight control architecture is discussed in the following sections. It consists of an inner loop control that uses dynamic inversion to achieve the desired dynamics of the aircraft. The outer loop formation flight control is a blend of various algorithms to achieve both zero steady-state error tracking and a reasonably rapid response to disturbances.

The control architecture and algorithms that follow were created for the generic turboprop transport 6DoF model GTTM [10] but can be applied to other aircraft by changing the desired dynamics, the outer loop gains, and the thrust controller.

A. Dynamic Inversion Inner Loop Control

An inner loop controller was designed using dynamic inversion with desired dynamics is shown in Figure 4. Desired roll rate and pitch rate commands from the outer loop controller are used to calculate desired roll rate, pitch rate, and yaw rate accelerations for a given set of desired dynamics (where the actuator dynamics ω_{Act} were also included). The effector blender calculates the aileron, elevator, and rudder commands from the difference of the desired angular rates and the current angular rates.

The desired roll rate acceleration $\dot{P}$ was tuned by adjusting the roll mode time constant, τ_{Roll} , as shown in Equation (1) to meet the handling qualities of the class of aircraft.

$$\dot{P}_{Des} = \frac{\omega_{Act}}{s + \omega_{Act}} \left[\frac{1}{\tau_{Roll}} (P_{Cmd} - P_s) \right] \quad (1)$$

The desired pitch rate acceleration $\dot{Q}$, as seen in Equation (2), was tuned by adjusting the short period natural frequency ω_{sp} , its damping ratio ζ_{sp} , and the desired pitch time constant $T_{\theta 2}$ to meet the longitudinal handling qualities of the class of aircraft.

$$\dot{Q}_{Des} = \frac{\omega_{Act}}{s + \omega_{Act}} \left[\frac{\omega_{sp}^2}{T_{\theta 2}} \frac{Q_{Cmd}}{V_T} + \frac{\omega_{sp}^2}{s} (Q_{Cmd} - Q_s) - Q_{Cmd} 2\zeta_{sp} \omega_{sp} \right] \quad (2)$$

Figure 4 Dynamic Inversion Inner Loop Controller.

The desired yaw rate acceleration $\dot{R}$, Equation (3), was tuned by adjusting the Dutch roll mode natural frequency ω_{dr} , its damping ratio ζ_{dr} , and the desired yaw rate time constant T_{R1} to meet the appropriate handling qualities metrics.

$$\dot{R}_{Des} = \frac{\omega_{Act}}{s + \omega_{Act}} \left[\omega_{dr}^2 (R_{Cmd} + \beta) + \left(R_s - \frac{A_y}{V_T} \right) \left(2\zeta_{dr} \omega_{dr} - \frac{1}{T_{R1}} \right) \right] \quad (3)$$

As shown in Equations (4) and (5), the thrust inner loop control calculates a desired thrust value $Thrust$ based on the outer loop commanded body x-axis acceleration $\dot{U}$ and the current flight condition. This desired thrust value is used in a reverse lookup on the engine table to find the required throttle input TLA_{Cmd} for the desired thrust and flight condition.

$$Thrust_{Des} = \frac{Mass}{\cos(2/57.3)} \left\{ \dot{U}_{Cmd} - \left[(rv - qw - g \sin \theta) - \frac{\bar{q}S}{Mass} (C_D \cos \alpha - C_L \sin \alpha) \right] \right\} \quad (4)$$

$$TLA_{Cmd} = f_{TLA}(Thrust_{Des}, Mach, Alt) - TLA_{Trim} \quad (5)$$

B. Vertical Outer Loop Control

Figure 5 Vertical Outer Loop Controller.

The vertical position outer loop control, as seen on Figure 5 and defined in Equation (6), is maintained by generating pitch rate commands Q_{Cmd} that are fed to the inner loop controller. The pitch rate command is generated by summing the vertical position error Z_{err} , the derivative of the vertical position error $\dot{Z}_{err}$, and the double derivative of the vertical position error $\ddot{Z}_{err}$ with gains K_p , K_d , K_{dd} applied to each value. An iterative approach was used to tune these gains. It was found that the double derivative term is the largest contributor to maintaining stability. The same control algorithms were used on both the leading and trailing aircraft. However, the gains on the trail aircraft were modified to allow faster response and better tracking. A slower response was desired for the leading aircraft since high frequency motion on the part of the lead can drive the trail aircraft to become unstable.

The vertical outer loop controller drives the vertical tracking error to zero by commanding a pitch rate Q_{Cmd} .

$$Q_{Cmd} = -(K_p Z_{err} + K_d \dot{Z}_{err} + K_{dd} \ddot{Z}_{err}) \quad (6)$$

C. Forward Outer Loop Control

Figure 6 Forward Outer Loop Controller.

The forward position outer loop control, as seen on Figure 6 and Equation (7), was done in a manner similar to the vertical controller. A desired body X acceleration command, $\ddot{U}_{Cmd}$, was generated by summing the forward position error X_{err} and the derivative of the forward position $\dot{X}_{err}$ with appropriate gains K_p and K_d applied to those values. Since there is not a forward motion control mode for desired dynamics, the dynamics of the engine with a thrust response transfer function was included in the acceleration command $\ddot{U}_{Cmd}$. For this aircraft, the same control algorithm was used for both the leader and followers; however, for other aircraft a velocity hold algorithm was used. Since either algorithm produces adequate performance, it is left to the designer to determine what works best for them given their aircraft dynamics.

The outer loop forward control maintains the forward position relative to the lead aircraft by commanding a forward acceleration $\ddot{U}_{Cmd}$.

$$\ddot{U}_{Cmd} = \frac{6.67}{s+6.67} \frac{2.04}{s^2+1.73s+2.04} (K_p X_{err} + K_d \dot{X}_{err}) \quad (7)$$

D. Lateral Outer Loop Control

Figure 7 Lateral Outer Loop Controller.

The lateral position tracking control, as seen on Figure 7 and Equations (8), (9), and (10) was the most difficult task during the control design since there are strong lateral-directional non-linearities in the flow field right at and near the sweet spot (see Figure 3) that the controller is trying to maintain. For this reason, extra control augmentation was necessary to achieve and maintain stable tracking in formation. The roll control command $P_{Cmd_{RCG}}$ was first generated using the same method of summing the lateral position error Y_{err} , with the lateral position error derivative $\dot{Y}_{err}$, and the lateral position error double derivative $\ddot{Y}_{err}$. Lag filters were added to the derivative signals to help limit the noise propagation and amplification. A lead filter was added to the controller to increase the error signal when the aircraft moved rapidly in the lateral direction, which helped to boost the control signal that drove the aircraft back to a stable position.

Open loop control that was dependent on the lateral movement in the flow field was added to the control command $P_{Cmd_{FFRA}}$. Basically, the open loop control command determined the incremental change in roll rate due to lateral motion in the flow field, CR_{dy} . This incremental roll rate value was then subtracted from the roll command that was generated. The removal of the roll command allowed the controller to use the rolling moment of the flow field to its advantage to maintain lateral control of the aircraft.

The outer loop lateral position control included a controller similar to the vertical controller $P_{Cmd_{RCG}}$, but also included extra roll command augmentation $P_{Cmd_{FFRA}}$ to account for the strong roll nonlinearities in the flow field. The outer loop lateral control maintains the lateral position relative to the sweet spot by commanding a roll rate P_{Cmd} .

$$P_{Cmd_{RCG}} = \left(K_p Y_{err} \left(1 + \frac{s}{s+2.5} \right) + K_d \frac{5}{s+5} \left(\frac{d}{dt} \left(Y_{err} \left(1 + \frac{s}{s+2.5} \right) \right) \right) + K_{dd} \frac{5}{s+5} \left(\frac{d^2}{dt^2} \left(Y_{err} \left(1 + \frac{s}{s+2.5} \right) \right) \right) \right) \quad (8)$$

$$P_{Cmd_{FFRA}} = K_{ff} \frac{10}{s+10} \left(\frac{\bar{q} b s}{I_{xx}} C_{Rdy} Y_{err} \right) \quad (9)$$

$$P_{Cmd} = P_{Cmd_{RCG}} - P_{Cmd_{FFRA}} \quad (10)$$

E. Input Signal Filtering

Figure 8 2nd Order Input Signal Filters.

An important part of the formation tracking task is applying adequate filters, as seen on Figure 8, to the GPS position signals since there will be some amount of noise in the signal. Since the derivatives of these signals are taken, it is especially important to filter the GPS position inputs. Second order transfer functions were used to filter the noisy position signals. The appropriate frequency and damping were found through iteration. A more advanced signal filtering method may be desired for future work.

The ADS-B position information from the leading aircraft can be received with significant delays or and may contain data dropouts. This also must be taken into account in the input signal filtering block of the overall control scheme.

IV. Results

Formation position controllers were developed for the generic turboprop transport model similar to a C130, generic high-speed mobility aircraft model similar to a C5, and a generic fourth generation fighter model similar to an F16. This section summarizes some of the results from simulations of the controllers implemented in MATLAB/Simulink for the trail aircraft along with lead aircraft dynamics and the flowfield disturbances caused by the lead aircraft wingtip vortices.

Table 1 shows simulation results of the turboprop transport aircraft alone and in various formations. The reference to system fuel saved or system lift/drag indicates those are the respective values of the aircraft taken as a group, so the fuel burn and savings includes that expended by the lead aircraft and all the trail aircraft. The ideal numbers are produced by looking at the theoretical savings when positioning the trail aircraft at the sweet spot. The simulated columns are results of the Simulink simulation over a period of time, including the effects of light turbulence on all the trail aircraft.

Table 1 Summary of simulation results for varying numbers of C130 aircraft in fuel efficient formation flight.

Aircraft	Formation		System L/D	% System Fuel Saved		Fuel Saved (pph)		Fuel Saved (\$) (assuming \$4/gal)	
	# Aircraft			Ideal	Simulated	Ideal	Simulated	Ideal	Simulated
C-130 (Baseline)	-	-	15.75	-	-	-	-		
C-130/C-130	2		16.9	5.6%	5.3%	536	520	\$315	\$306
C-130/C-130	3		17.3	7.4%	7%	1072	1020	\$630	\$600
C-130/C-130	5		17.7	8.9%	8.4%	2144	2032	\$1,260	\$1,195
C-130/C-130	7		17.8	9.5%	8.4%	3216	2840	\$1,890	\$1,670

Table 2 shows the results of simulations of the generic fourth generation fighter in formation with a high-speed mobility aircraft and generic tanker aircraft. Note the high-speed transport produces very strong vortices that can result in over 35% fuel savings on the fighter when flying at the theoretical sweet spot. With the vortex flow model for the respective lead aircraft and the type of controller described earlier but with the appropriate gains, simulation results show a fuel savings of just over 30% when in formation with the transport and approximately 12% when in formation with the tanker. Since the fighter is significantly smaller than the leaders and consume much less fuel, the fuel savings in this table are for the fighters themselves, not including the transport or tanker leads.

Table 2 Summary of simulation results for varying numbers of fourth generation fighter aircraft in fuel efficient formation flight with transport and tanker aircraft.

Aircraft	Formation		Trail AC L/D	% Trail AC Fuel Saved		Trail AC Fuel Saved (pph)	
	# Aircraft			Ideal	Simulated	Ideal	Simulated
C-5/F-16 (Baseline)	-	-	8.8	-	-	-	-
C-5/F-16	2		15.5	38%	31%	941	765
C-5/F-16	3		15.5	38%	31%	1882	1531
KC-135/F-16 (Baseline)	-	-	9	-	-	-	-
KC-135/F-16	2		11.3	12.1%	12%	361	356
KC-135/F-16	3		11.3	12.1%	11.9%	722	709

V. Conclusions and Perspectives

The benefits of wake surfing for fuel efficient operations was introduced and reasons for the need of an automatic flight control system on the trailing aircraft were highlighted. A candidate control architecture with an inner loop and complementary outer control loops was illustrated. Simulation results for various combinations of turboprop transports, high speed mobility aircraft, tankers, and fighters were presented. The results show that the candidate controllers are capable of accurate relative positioning, including sensor noise and delay, atmospheric turbulence, vortex wake, and aircraft dynamics.

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