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GROUND BASED CONCEPT FOR TIME CONTROL OF AIRCRAFT ENTERING THE TERMINAL AREA

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Abstract

This paper summarizes current research for increasing the efficiency of traffic flow at hub airports by application of four dimensional (4D) guidance techniques. A method for generating 4D guidance commands to control the landing time of aircraft that are not equipped with on-board 4D guidance systems is described. In one possible implementation the commands are generated in an auxiliary processor linked to the ATC host computer and displayed on a controller's monitor in the form of profile descent advisories. Accurate time control is achieved by generating air traffic controller advisories in a ground-based algorithm that combines aerodynamic, thrust and atmospheric models with an efficient numerical integration method. The time accuracy and fuel efficiency achieved when the pilot responds to these advisories were evaluated in a piloted simulation of a transport aircraft.

Introduction

Recent years have seen a continued increase of congestion in the nation's air-traffic-control system, resulting in delays and fuel waste especially at those terminal areas designated by airlines as operation "hubs." This study investigates the use of 4-D or time-controlled approaches to handle traffic more effectively at congested hub airports. Although the technology exists to implement accurate 4D guidance systems on board aircraft, a crucial obstacle preventing the early introduction of 4D techniques is the lack of a method for accurately controlling the landing time of those aircraft that will not be 4D equipped for many years.

A concept for controlling the arrival times of such unequipped aircraft by issuing to them speed profile advisories has been developed to deal with this problem. An algorithm has been constructed to implement this concept on a ground-based micro-computer linked to the ATC host computer. By modeling how the typical pilot flies a descent profile, the algorithm predicts the arrival time based on the current aircraft altitude, position and speed. It then computes a range of possible arrival times based on operational limitations of the aircraft. A controller or automated scheduler selects a feasible arrival time and, in response, the algorithm computes clearances to issue to the pilot in order to meet that time. These clearances take into account type and weight of aircraft, wind profiles and atmospheric conditions, and are compatible with airline procedures and FAA regulations. The essential features of this algorithm were described in Ref. 1.

This paper briefly describes the selection of descent speed profiles, the profile generation algorithm, and the results of an experimental evaluation of the method conducted on an airline-training-quality simulator of a 727 aircraft.

Selection of Descent Speed Profiles

The touchdown time of the aircraft is controlled by appropriate choice of the airspeed profile during descent. All speed profiles generated by the descent algorithm conform to standard airline operating procedures for subsonic jet transport aircraft. In this procedure the pilot begins the descent from cruise altitude by reducing thrust to near flight idle and using pitch attitude to hold Mach number fixed at some constant value. Sufficient thrust is maintained to limit descent rate to a specified maximum, typically 2500 ft/min. As the aircraft descends at constant Mach number, the calibrated airspeed (CAS) increases steadily. When the pilot's speed indicator has climbed to a specified value, he initiates tracking of the target CAS. At 10,000 ft above ground level the pilot reduces the descent rate briefly in order to decelerate to 250 knots CAS as required by ATC regulation.

Control of arrival time is achieved by appropriate choice of descent Mach number and CAS within the speed boundaries of the aircraft. A single parameter is used to generate the complete family of profiles between the maximum and minimum speed boundaries. However, the dependence of the touchdown time on this parameter is extremely complex and non-linear, and therefore iterative procedures must be used to calculate the value of the parameter that gives a specified arrival time. Iteration is initiated by setting the parameter so the extremes of the speed envelope are generated, thereby determining the maximum and minimum arrival times. If the specified time falls within the permissible time interval, iteration continues by a directed trial and error technique until convergence is achieved. Otherwise, the controller is informed that the specified time is outside the allowable range. [Ref. 1].

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Equations of Motion

For each trial speed profile selected in the iteration, the corresponding descent trajectory and arrival times are calculated by integrating a simplified set of point mass equations of motion. This method achieves the highest possible time accuracy since it can fully account for the aircraft's aerodynamic and propulsion models, as well as the wind and atmospheric conditions.

It was assumed that throughout most of the descent, the pilot maintains either constant Mach number or constant CAS. This assumption can be used to simplify the equation of motion to two first order differential equations. Using an earth fixed coordinate system with x as the horizontal and z the vertical axis, the components of inertial velocity u and w that must be integrated are:

$$u \quad \frac{dx}{dt} = V_T \cos \gamma_a + u_w \qquad F_1 \qquad (1)$$

$$w \quad \frac{dz}{dt} = V_T \sin \gamma_a \qquad F_2 \qquad (2)$$

where V_T is the true airspeed, γ_a the aerodynamic flight path angle and u_w the horizontal component of wind. Because of the assumption on the speed profile, V_T can be written as an explicit function of the altitude z. The expression is too cumbersome to be developed here but can be found in Ref. 2.

The aerodynamic flight path angle, γ_a, is determined by choosing one of three commonly used flight path control techniques: (1) Constant thrust setting, (2) constant descent rate, and (3) constant inertial flight path angle. The algorithm implements all three techniques, but the controller must enter the choice actually used by a particular aircraft. Expressions for γ_a applicable to the constant Mach and constant CAS segments, respectively, are as follows:

$$\gamma_{a\ M\ constant} = \sin^{-1} \frac{(T - D)}{m} \left(g + V_T M \frac{da}{dz}\right)^{-1} \times \left(1 - V_T \frac{du_w}{dz} \frac{1}{g}\right) \qquad (3)$$

$$\gamma_{a\ CAS\ constant} = \sin^{-1} \frac{(T - D)}{m} \left(g + V_T \times \frac{dV_T(VCAS, z)}{dz}\right)^{-1} \left(1 + V_T \frac{du_w}{dz} \frac{1}{g}\right) \qquad (4)$$

In these expressions, T = thrust, g = acceleration of gravity, M = Mach number, m = aircraft mass, a = speed of sound, D = aircraft drag force, which is a function of the lift force L. Lift is calculated from $L = mg\cos\gamma_a$

In all expressions above the small angle approximation can be used to evaluate sine and cosine functions. The drag coefficient involved in calculating D is represented by polynominal functions in the lift coefficient and the Mach number. Such functions must be developed for all aircraft that are subject to time control using this method. In addition, maximum and idle thrust values covering the operational envelope of all participating aircraft must be supplied as input to the algorithm.

Attention is directed to the last factor in parentheses in equations (3) and (4). This factor corrects the flight path angle for the effect of wind shear, du_w/dz. The effect of windshear manifests itself in the descent trajectory as an expansion or contraction of the distance to descend from cruise altitude. For a wind shear of 2 knots per 1000 ft altitude, the end-of-descent point of an aircraft descending from 35,000 ft can shift more than 5 nautical miles (n.m.) from the nominal point.

If the descent is flown at a near-idle thrust setting, which is the most common procedure in airline flight, γ_a is obtained from equations (3) and (4) by setting T to its minimum or idle value.

Integration Algorithm

Equations (1) and (2) are integrated by a fourth order Runge Kutta scheme developed in [3]. It has the advantage of giving accurate results with large step sizes and of not requiring evaluation of derivatives. If Δt represents the time increment, then the states x_{i+1}, z_{i+1} at the $(i+1)^{st}$ time increment are determined from four sets of sequentially computed state increments as follows:

$$\Delta_1 X_i = \Delta t\ F_1(Z_i, t_i)$$

$$\Delta_1 Z_i = \Delta t\ F_2(Z_i, t_i)$$

$$\Delta_2 X_i = \Delta t\ F_1\left(Z_i + \frac{1}{2}\Delta_1 Z_i,\ t_i + \frac{1}{2}\Delta t\right)$$

$$\Delta_2 Z_i = \Delta t\ F_2\left(Z_i + \frac{1}{2}\Delta_1 Z_i,\ t_i + \frac{1}{2}\Delta t\right)$$

$$\Delta_3 X_i = \Delta t\ F_1\left(Z_i + \frac{1}{2}\Delta_2 Z_i,\ t_i + \frac{1}{2}\Delta t\right)$$

$$\Delta_3 Z_i = \Delta t\ F_2\left(Z_i + \frac{1}{2}\Delta_2 Z_i,\ t_i + \frac{1}{2}\Delta t\right)$$

$$\Delta_4 X_i = \Delta t\ F_1(Z_i + \Delta_3 Z_i,\ t_i + \Delta t)$$

$$\Delta_4 Z_i = \Delta t\ F_2(Z_i + \Delta_3 Z_i,\ t_i + \Delta t)$$

$$X_{i+1} = X_i + \frac{1}{6}(\Delta_1 X_i + 2\Delta_2 X_i + 2\Delta_3 X_i + \Delta_4 X_i) \qquad (5)$$

$$Z_{i+1} = Z_i + \frac{1}{6}(\Delta_1 Z_i + 2\Delta_2 Z_i + 2\Delta_3 Z_i + \Delta_4 Z_i) \qquad (6)$$

The integration time increment Δt was experimentally selected to be as large as possible for each segment of the trajectory. In the constant Mach and constant CAS segments a step size of 60 sec. has yielded accurate and numerically stable results.

At the top and bottom of the descents, there can occur short segments in the trajectory where neither Mach number nor calibrated airspeed is held constant. In such transition segments, an additional differential equation, which determines the rate of change of airspeed, must be integrated. The incremental equations above can be augmented in a straight forward way to generate the airspeed as a function of time in these segments of rapid deceleration or acceleration.

A program that generates time controlled trajectories using the techniques described above has been written in VAX FORTRAN. The program is constructed in a modular top down fashion, where the higher level routines direct the calling sequences and oversee the data flow, and the lower level routines perform the calculations and integrate the equations.

Example Descent Profile

This section gives an example of a complete descent profile, including all necessary transition segments, generated by the program. The aircraft model used is that of a narrow body aircraft weighing 140,000 lbs. Initially, the aircraft is cruising at Mach 0.8 and 35,000 ft and is 150 n.m. from touchdown. The controller clears the aircraft to descend to a point 30 n.m. from touchdown and 10,000 ft altitude. At this end point the aircraft must have completed its deceleration to 250 knots CAS. Furthermore, the controller has specified a descent time of 900 seconds, measured from the 150 n.m. starting point to the end of the deceleration.

The synthesized trajectory consists of a total of four segments which are summarized in Table 1. The first is a level flight segment leading from the starting point to the point of descent calculated to be 108 n.m. from touchdown. This segment is followed by a Mach 0.8 descent with engine pressure ratio (EPR), which controls thrust, set to a near idle value (approximately one). The target speed calculated by the algorithm is 320 knots CAS, reached at 27604 ft. At this point the third and constant CAS segment begins using idle thrust (EPR=1) until 10,000 ft. is reached. The fourth segment is a deceleration from 320 to 250 knots CAS flown at 10,000 ft. The last line of the table shows that the time and distance to touchdown at the end of the last segment closely match the specified values.

Various other parameters relating to the trajectory synthesis, including the number of integration steps for each segment and the fuel consumed are also shown in the table.

In addition to achieving the specified descent time the trajectory also exhibits excellent fuel efficiency, requiring only 954 lbs of fuel to fly all four segments. High fuel efficiency is achieved by the combined beneficial effect of an idle thrust descent and the choice of the point of descent so as to eliminate any fuel wasting loiter flight at the terminal altitude of 10,000 ft.

Simulation Evaluation

An evaluation of the method was conducted on a so-called Phase II 727-200 aircraft simulator installed in the recently completed Man-Vehicle Systems Research Facility at Ames Research Center.

This type of simulator is widely used by airlines for crew training. It is equipped with a six degree of freedom motion system and a computer-generated, night/dusk vision system. The computer-generated imagery is displayed in front of the cockpit windows by four projection systems, giving a wide, high resolution field of view to the pilot and copilot.

Test subjects were three current 727 pilots one each from three major airlines. A tail-wind of 70 knots at 35,000 ft, which decreased linearily to zero at ground level was simulated. There was light turbulence and the ceiling was at 1000 ft with tops at 10,000 ft. Pilots were briefed on wind and weather conditions prior to the simulation. Each simulated flight consisted of a straight-in approach beginning at 150 n.m. to the runway threshold and 35,000 ft altitude.

Initially each pilot flew a profile descent and approach using a procedure recommended by his airline. All three pilots used essentially the same procedure, consisting of a Mach 0.8/280 knots CAS descent profile. Each pilot also used a well known rule of thumb to select the DME range to touchdown at which to initiate the descent (top-of-descent). These base line profiles were flown without air traffic control advisories.

After completing the base line runs, pilots flew three types of profile descents referred to as nominal, slow and fast. The corresponding speed profiles were Mach 0.8/320 Knots, 230 Knots, and Mach 0.84/350 Knots. The slow and fast profiles represented the usable extremes of the aircraft's speed envelope. An experimenter located at the engineer's position in the cockpit issued simulated air traffic control clearances to the pilots. Pilots were briefed on the importance of exercising care in following the profile clearances. The clearances specified DME range for the top-of-descent point and the descent Mach number and calibrated airspeed. The clearances had been calculated off-line by the previously described computer program and were printed on a compact form convenient for use by a controller. Each profile except the fast descent was flown at least four times. These relatively few simulation runs for each profile type are thought to be sufficient to establish important trends but are insufficient to warrant calculation of standard deviations of various quantities of interest.

The results of the simulation runs, summarized in Table 2, show a striking reduction in the variability of arrival times for the profile descent cases compared to the base line case. The variability, which is defined as the difference between the earliest and latest arrival times for all profiles of a given type, is reduced from 196 seconds for the base line profiles to a maximum of 35 seconds for the nominal profile.

The variability of the slow profile has an extremely low value of only seven seconds. This result can be explained by its greater simplicity compared to the other two. The slow profile lacks a constant Mach segment and can be flown at idle thrust for the entire descent. The absence of a deceleration segment at the bottom of the descent further helps to reduce timing errors. Profile complexity is thus seen to have an important effect on time control accuracy and should be carefully considered in choosing 4D descent profiles for manual flight.

Comparison of times listed in the first and second columns shows that the average descent times for the three types of advisory-controlled profiles are also accurately predicted by the algorithm. The accuracy achieved is all the more remarkable considering that the descents were flown manually, and that the advisories were given only once before the start of the descents.

The columns in Table 2 that tabulate average fuel use show that the slow profile is the most fuel efficient and the fast profile the least fuel efficient. The nominal profile, though considerably faster than the base line profile, consumes only slightly more fuel than the base line does. Thus, the tradeoff between time and fuel, so important in airline operations, weighs in favor of choosing the nominal profile when there is no scheduling conflict.

The range of fuel consumption for the four types of descents, listed in the last column, shows characteristics similar to the time variability. The difference of 200 lbs for the base line descents is reduced to a maximum of only 34 lbs for the controlled descents.

In addition to evaluating the tailwind condition described above, time accuracy of profiles was also determined for headwinds and zero winds. These conditions yielded results basically similar to the ones described. Furthermore, the time variability of flying from the 30 n.m. point to touchdown was investigated for both a straight-in and a standard approach pattern, the latter consisting of downwind, base and final segments. Analysis of results for these tests is still in progress.

Pilots participating in the simulation generally reacted favorably toward the profile descent advisory concept. They cited as the primary benefit the accurate timing of the top-of-descent point in the presence of complex altitude-dependent wind profiles. Moreover, they considered the advisories as unobtrusive and all profiles as comfortable to fly.

The experience of this study suggests that the following four conditions are necessary for accurate time control of unequipped aircraft. First, descent procedures given in the advisories should correspond to widely used pilot procedures. Second, pilots must be carefully briefed on the purpose of the advisory and the importance of executing it accurately. Third, aircraft performance and trajectory dynamics must be accurately modeled in the algorithm. Fourth, an altitude-dependent wind model must be updated frequently to reflect current wind conditions.

The time accuracies achieved in the simulation would be adequate for a time-based air traffic control system if they could be duplicated in practice. However, uncertainty in the knowledge of the actual wind profile and inevitable lapses in pilot attention to the profile tracking task will result in larger errors than obtained in the simulation. One can attempt to estimate such time errors from analysis of ATC radar tracking returns during an aircraft's descent. They can then be reduced by the controller issuing an updated speed clearance near the midpoint in the descent. By this method it is considered feasible to control time errors at the 30 n.m. point within ± 20 seconds. A simulation test of the mid-descent correction clearance is planned for 1986 after an on-line implementation of the program has been completed.

Concluding Remarks

The descent profile advisory system described in the paper promises to be an accurate and flexible tool for assisting an air traffic controller in controlling the touchdown time of aircraft not equipped with 4D guidance systems. It can help to achieve the benefits of 4D guidance, such as increased capacity and fuel efficiency, without requiring a large fraction of the airline fleet to become 4D equipped. Accurate time control combined with good fuel efficiency is obtained by an efficient method for integrating simplified performance equations along standard airline descent profiles. A piloted simulation of the method has demonstrated its accuracy and consistancy in predicting the bottom-of-descent time of an unequipped transport aircraft. Current plans call for a more extensive simulation followed by an operational evaluation of the method at an enroute air traffic control center.

References

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2. Lee, Homer Q., Erzberger, H., "Time Controlled Descent Guidance Algorithm for Simulation of Advanced ATC Systems", NASA Technical Memorandum 84373 Aug. 1983, Ames Research Center, Moffett Field, CA.

3. Chuen-Yen Chow, An Introduction to Computational Fluid Mechanics, Wiley, 1979.

TABLE 1 - EXAMPLE OF SYNTHESIZED PROFILE

CRUISE SEGMENT
- Step size is 300.0000 sec
- Mach is held constant
- Vertical speed is held constant
- Capture -108.0001 n.mi total distance
- Allowable capture error of +- 1.0000000E-03

Time (sec)	Dist (n.mi)	Alt (ft)	Mach	V tr (kts)	V cal (kts)	Gamma (deg)	EPR	Thrst (lbs)	Fuel (lbs)
0.00	150.000	35000.0	0.80	461.1	272.0	0.00	1.95	9824.0	0.0
286.32	108.000	35000.0	0.80	461.1	272.0	0.00	1.95	9824.0	617.1

- 2 integration steps

CONSTANT MACH SEGMENT
- Step size is 60.00000 sec
- Mach is held constant
- Vertical speed is held constant
- Capture 320.0000 kts CAS
- Allowable capture error of +- 1.000000

Time (sec)	Dist (n.mi)	Alt (ft)	Mach	V tr (kts)	V cal (kts)	Gamma (deg)	EPR	Thrst (lbs)	Fuel (lbs)
286.32	108.000	35000.0	0.80	461.1	272.0	-3.21	1.00	900.3	617.1
346.32	99.195	32000.0	0.80	467.4	291.0	-3.21	1.05	2475.5	648.5
406.32	90.382	29000.0	0.80	473.5	310.6	-3.21	1.08	2246.4	689.9
434.25	86.278	27603.7	0.80	476.3	319.9	-3.21	1.09	2664.8	713.1

- 4 integration steps

CONSTANT CAS SEGMENT
- Step size is 60.00000 sec
- CAS is held constant
- EPR setting is held constant
- Capture 10000.00 feet altitude
- Allowable capture error of +- 2.000000

Time (sec)	Dist (n.mi)	Alt (ft)	Mach	V tr (kts)	V cal (kts)	Gamma (deg)	EPR	Thrst (lbs)	Fuel (lbs)
434.25	86.278	27603.7	0.80	476.4	319.9	-2.93	1.00	73.7	713.1
494.25	77.661	24895.8	0.76	457.4	319.9	-3.01	1.00	-135.3	740.1
554.25	69.437	22224.7	0.72	439.5	319.9	-3.11	1.00	-278.8	767.1
614.25	61.586	19594.3	0.69	422.8	319.9	-3.22	1.00	-383.2	794.8
674.25	54.090	16996.4	0.65	406.9	319.9	-3.32	1.00	-359.9	823.5
734.25	46.933	14439.0	0.62	392.0	319.9	-3.42	1.00	-334.5	854.6
794.25	40.096	11927.2	0.60	378.1	319.9	-3.51	1.00	-294.0	889.3
840.99	34.982	10000.1	0.58	367.8	319.9	-3.60	1.00	-299.1	918.8

- 9 integration steps

BOTTOM-OF-DESCENT DECELERATION SEGMENT
- Step size is 30.00000 sec
- Neither Mach nor CAS is held constant
- Vertical speed is held constant
-EPR setting is held constant
- Capture 250.0000 kts CAS
- Allowable capture error of +- 1.000000

Time (sec)	Dist (n.mi)	Alt (ft)	Mach	V tr (kts)	V cal (kts)	Gamma (deg)	EPR	Thrst (lbs)	Fuel (lbs)
840.99	34.982	10000.1	0.58	367.8	319.9	0.00	1.00	-299.3	918.8
870.99	31.943	10000.1	0.51	324.4	281.5	0.00	1.00	-125.9	937.8
899.17	29.397	10000.1	0.45	288.6	249.9	0.00	1.00	17.1	954.9

- 3 integration steps

TABLE 2 SUMMARY OF SIMULATION RESULTS*

	Time (Seconds) and Fuel (Pounds) to 30 n.m. to Touchdown Point				
Type of Profile	Time Predicted By Algorithm	Avg. Time; No. of Descents ( )	Range of Times; Time Diff. ( )	Avg. Fuel Use	Range of Fuel Use; Fuel Diff. ( )
Base Line					
M 0.8/280 KCAS Without Profile Advisories	-	973 (4)	890 - 1084 (196)	1065	945 - 1145 (200)
Nominal					
M 0.8/320 KCAS Top of Descent: 108 n.m.	893	895 (4)	880 - 915 (35)	1082	1064 - 1098 (34)
Slow 230 KCAS Top of Descent: 133 n.m.	1104	1100 (5)	1098 - 1104 (7)	771	764 - 778 (14)
Fast M 0.84/350 KCAS Top of Descent: 107 n.m.	863	860 (3)	854 - 871 (17)	1175	1169 - 1183 (14)

* Simulation runs started at 150 n.m. from touchdown, M = 0.8 and 35,000 ft. Aircraft weight at start was 140,000 lbs. All runs used a 70 knot tail wind at 35,000 ft., decreasing to zero at sea level.