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A Method for Solution of an Air Traffic Control Problem

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A METHOD FOR SOLUTION
OF AN
AIR TRAFFIC CONTROL PROBLEM

by

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Abstract: A method is given for computing flight plans for aircraft returning to the carrier after a mission. The basic goal is to minimize the total flight time for the landing aircraft, while maintaining various individual and interactive constraints on the aircraft.

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1. Introduction

The problem to be considered is that of computing flight plans for aircraft returning to a carrier after completion of a mission. The aircraft will be picked up at long range, say 100 n.m. or more, and a flight plan computed for each, to a point where an automatic landing device takes control of the aircraft. This point is called the four mile gate, and the aircraft must have, to within some tolerance, a specified location and velocity at that distance.

The object will be to minimize the total flight time of all aircraft to be landed. The flight plans are subject to various individual constraints, as well as constraints on the positions of the aircraft relative to each other.

We shall list constraints which might by typical of the kind required, and values for them.

I. Individual constraints

- (a) Velocity: between 110 n.m./hr. and 600 n.m./hr.
- (b) Rate of descent/ascent: between -4000 ft./min. and 1500 ft./min.
- (c) Turn rate: 3 degrees/sec. normal, 6 degrees/sec. emergency
- (d) Fuel: Maximum time to land, due to limited fuel supply
- (e) Aircraft performance: Some assumptions as to the acceleration/deceleration rates should probably be made. We assume these to be constant.

II. Interactive Constraints

- (a) Separation: at least 1000 ft. vertically and/or 2 n.m. horizontally
- (b) Time separation at gate: 1 minute

We note that it is desired to have the aircraft reach the gate at one minute intervals. Thus the aircraft must automatically approach at least a certain separation in the latter stages of the approach. With a speed at the gate $\geq$ 2n.m./min., this separation is $\geq$ 2n.m., as required.

As the aircraft are picked up at ranges of 100 n.m. or more, it is possible that one or more groups of aircraft may be returning in formation, thus not satisfying the separation requirements initially. It is felt that this should not cause undue concern, as long as the flight plans allow all or part of the formation to continue. As the aircraft pursue their individual flight plans it is necessary that the separation increase until the minimum is achieved, and then it is to be maintained.

A more difficult problem would seem to be the possibility (or necessity) of one or more aircraft "passing" others. In this instance it is clear that we must maintain the appropriate separation at all times.

The full solution of the overall problem requires the optimization of the flight paths in terms of order of landings, as well as individually, subject to the individual and interactive constraints. Certainly an analytical solution is impossible, and within the real-time constraint, a numerical solution is likely impossible also. Thus it is necessary to make some assumptions about the order of landing and/or the flight plans. It is felt that the most critical of the two is the type of flight plan to be assumed. The order of landing probably has a small affect as long as a "reasonable: order is assumed. Within the constraints of the problem, it is likely that there is not a unique landing order.

2. Assumed flight plan

As we noted above, it is felt that this part is the most important aspect of the optimization problem. If one makes as assumption of flight plan which does not contain enough flexibility, it may become impossible to solve the resulting problem; indeed, it may then have no solution. Even if there is a solution, it may be far from optimum because of artificial restrictions. On the other hand, it is desirable that one be able to describe the flight plan with a few parameters, for convenience in representation, and for checking and maintaining the interactive constraints. It is also important to be able to verify the individual constraints without difficulty. The individual constraints could be built into the assumed flight plan, thus automatically satisfying them. The flight plan we propose does just that.

The necessary time increment between arrivals at the gate assures one of the appropriate separation near the end of the flight plan. If that time interval is achieved at higher speeds, of course the separation criterion is sure to be satisfied. Thus it seems to be advantageous to continue at cruise speed (or maximum allowed speed, perhaps) until necessary to slow down to delay time of arrival at the gate to the desired time. This will tend to "naturally" achieve the desired separation between aircraft.

Our assumed flight plan will be broken into eight time intervals (some of which may be of zero length). The first six will be along a straight line (when projected into the x-y plans; altitude changes will be permitted), the seventh will be a circular turn onto the axis of the landing deck, and the eighth a short interval for final course corrections. The last will be the same for all aircraft, thus we need not consider it. In fact, for convenience we shall write as though the gate is reached at time t_7, although in practice it is not necessary that this be so. If separation requirements disallow the straight line path during the first six time intervals, a deviation can be incorporated. In some instances it may be necessary to lengthen the flight path (in distance) to allow an aircraft to be able to reach the gate under our assumed flight plan.

We are going to approximate the first six segments of the flight path by straight line segments. The corners are to be quite small, and the approximate circular transition can be computed. With only small changes in direction, the difference in the time required to traverse the circular arc and the theoretical time along the straight line segments is quite small, less than one percent. Since time in the turn is small, the total difference compared to total flight time is very small. We assume the aircraft is heading very nearly in the correct direction when picked up. If not, a correction could be required before they are placed in the landing "stack."

The horizontal projection of the flight path is given in Figure 1. All accelerations, decelerations, and descents are to be made at constant rates. Velocities are along the actual flight path; they are indicated at each of the times $t_o, t_1, \ldots, t_8$.

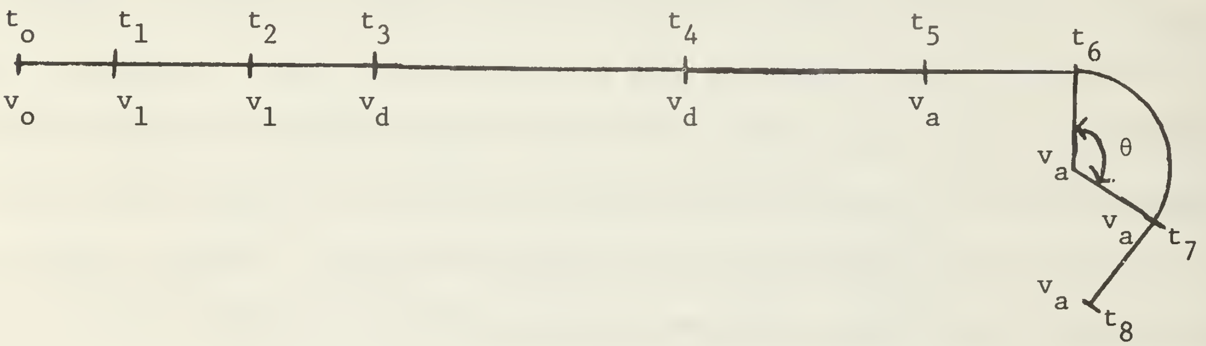

Figure 1

The action during each of the time intervals is as follows:

$[t_o, t_1]$ - accelerate from initial speed V_o to speed V_1 at the rate A_{max}, level flight

$[t_1, t_2]$ - constant speed V_{max} in level flight

If $V_1 < V_{max}$, $t_2 = t_1$.

$[t_2, t_3]$ - decelerate to speed V_d at constant rate, A_{min}.

$[t_3, t_4]$ - descend a vertical distance ΔZ at rate of descent $\dot{Z}_{min}$, constant speed V_d.

$[t_4, t_5]$ - decelerate to speed V_a at constant rate A_{min}, level flight

$[t_5, t_6]$ - constant speed V_a, level flight

$[t_6, t_7]$ - Circular approach to final direction, radius r, angle θ, constant speed V_a, level flight

$[t_7, t_8]$ - any final maneuvers required

The time intervals involved can be given in terms of other parameters for all but the level flight constant speed intervals. Thus we have the following relationships, where $\Delta t_i = t_{i+1} - t_i$.

$$\Delta t_o = \frac{V_1 - V_o}{A_{max}}$$

$$\Delta t_2 = \frac{V_d - V_1}{A_{min}}$$

$$\Delta t_3 = \frac{\Delta Z}{\dot{Z}_{min}}$$

$$\Delta t_4 = \frac{V_a - V_d}{A_{min}}$$

$$\Delta t_6 = \frac{r\theta}{V_a}$$

We will assume that deceleration rates are negative, and that ΔZ and $\dot{Z}_{min}$ are negative.

We note that if a flight path is required which is not a straight line (when projected into the x-y plane) through time t_6, the value of θ will need to be recomputed, as will Δt_6.

We assume that V_o and V_1 are bounded by V_{max}. The distance traveled horizontally during descent will be $\Delta t_3 \sqrt{V_d^2 - \dot{Z}_{min}^2}$. Let R_o be the length of the horizontal projection of the path, starting at time t_o, to time t_6. Then we need to select the various parameters to satisfy the equation

$$R_o = \frac{V_1 - V_o}{A_{max}} \cdot \frac{V_1 + V_o}{2} + V_{max} \Delta t_1 + \frac{V_d - V_1}{A_{min}} \cdot \frac{V_d + V_1}{2}$$

$$+ \Delta t_3 \sqrt{V_d^2 - \dot{Z}_{min}^2} + \frac{V_a - V_d}{A_{min}} \cdot \frac{V_a + V_d}{2} + V_a \Delta t_5 .$$

The total time to the gate is $T = t_7 - t_o$. We need to be able to compute the minimum value of T for a given path, as well as a flight plan which takes a given time.

In order to try to alleviate the separation problem, we follow the discussion given previously and seek to choose V_d as large, and Δt_5 as small as possible within the constraints of the problem. Likewise, we accelerate to as large a value for V_1 as permitted, or possible.

We first give a method for computing the minimum time, T_{min}. Let

$$D_1 = \frac{V_a - V_o}{A_{min}} \cdot \frac{V_a + V_o}{2} + \Delta t_3 \sqrt{V_a^2 - \dot{Z}_{min}^2} \ .$$

the minimum distance required to slow to speed V_a, and descend at that speed. If $R_o \geq D_1$, the flight path length must be D_1. The resulting T_{min} is $T_{min} = \frac{V_a - V_o}{A_{min}} + \Delta t_3 + \Delta t_6$.

Now assume $R_o \geq D_1$. Then we can descend at a higher speed than V_a. Let

$$D_2 = \Delta t_3 \sqrt{V_o^2 - \dot{Z}_{min}^2} + \frac{V_a - V_o}{A_{min}} \cdot \frac{V_a + V_o}{2}$$

the distance required to descend at speed V_o and decelerate to speed V_a. If $D_2 \geq R_o$, we descend at a rate of speed between V_a and V_o, V_d being given by the equation

$$R_o = \Delta t_3 \sqrt{V_d^2 - \dot{Z}_{min}^2} + \frac{V_a - V_o}{A_{min}} \cdot \frac{V_a + V_o}{2} \ .$$

T_{min} is given by

$$T_{min} = \frac{V_a - V_o}{A_{min}} + \Delta t_3 + \Delta t_6.$$

Now suppose thet $R_o \geq D_2$. Then we can accelerate to a higher speed than V_o, provided $V_o < V_{max}$. We make a tentative calculation for Δt_1, assuming we accelerate to speed V_{max} and descend at that speed. We obtain

$$\Delta t_1 = \frac{R_o - \left[\frac{V_{max}-V_o}{A_{max}} \cdot \frac{V_{max}+V_o}{2} + \Delta t_3\sqrt{V_{max}^2-\dot{Z}_{min}^2} + \frac{V_a-V_{max}}{A_{min}} \cdot \frac{V_a+V_{max}}{2}\right]}{V_{max}}$$

If $\Delta t_1 \geq 0$, we have completed the calculation, and we have

$$T_{min} = \frac{V_{max}-V_o}{A_{max}} + \Delta t_1 + \Delta t_3 + \frac{V_a-V_{max}}{A_{min}} + \Delta t_6$$

If $\Delta t_1 < 0$, we accelerate to speed V_1 and descend at that speed, V_1 being the solution of

$$R_o = \frac{V_1-V_o}{A_{max}} \cdot \frac{V_1+V_o}{2} + \Delta t_3\sqrt{V_1{}^2-\dot{Z}_{min}^2} + \frac{V_a-V_1}{A_{min}} \cdot \frac{V_a+V_1}{2} .$$

T_{min} is given by

$$T_{min} = \frac{V_1-V_o}{A_{max}} + \Delta t_3 + \frac{V_a-V_1}{A_{min}} + \Delta t_6 .$$

This completes all possibilities for the minimum time flight plan.

We must consider a flight plan to get an aircraft to the desired point in a specified time ($T \geq T_{min}$). As noted before, we desire to make Δt_5 as small as possible and V_d as large as possible.

Two times are of interest to us as aids in doing this computation. One is the maximum time to the gate without lengthening the flight path, the second is an intermediate time, assuming $\Delta t_5 = 0$ and $V_d = V_a$, reaching as rapidly as possible the point where descent is started.

T_{max} is easily computed. Recall that D_1 is the distance covered in slowing to speed V_a and then descending. Thus a distance $R_o - D_1$ is to be covered at speed V_a. Then

$$T_{max} = \frac{V_a - V_o}{A_{min}} + \Delta t_3 + \frac{R_o - D_1}{V_a} + \Delta t_6 .$$

We note that if $D_1 > R_o$ we have already discussed the situation.

For the intermediate time T^*, we travel a distance $R_o - D_1$ which is to be covered as rapidly as possible, starting and ending at V_o. We calculate a tentative value of Δt_1 by

$$R_o - D_1 = \frac{V_{max} - V_o}{A_{max}} \cdot \frac{V_{max} + V_o}{2} + \Delta t_1 \cdot V_{max} + \frac{V_o - V_{max}}{A_{min}} \cdot \frac{V_{max} + V_o}{2}$$

If $\Delta t_1 \geq 0$, we have completed the computation, and

$$T^* = \frac{V_{max} - V_o}{A_{max}} + \Delta t_1 + \frac{V_a - V_{max}}{A_{min}} + \Delta t_3 + \Delta t_6 .$$

If $\Delta t_1 < 0$, we do not have sufficient distance to accelerate to speed V_{max}, thus we compute V_1 from

$$R_o - D_1 = \frac{V_1 - V_o}{A_{max}} \cdot \frac{V_1 + V_o}{2} + \frac{V_o - V_1}{A_{min}} \cdot \frac{V_o + V_1}{2}$$

$$\text{and} \quad T^* = \frac{V_1 - V_o}{A_{max}} + \frac{V_a - V_1}{A_{min}} + \Delta t_3 + \Delta t_6 .$$

The purpose of the intermediate calculation is to simplify the computation of a flight plan taking T seconds. If the desired time to the final correction leg is T, and $T_{min} < T < T^*$, then $V_d > V_a$, which we compute. If $T^* < T < T_{max}$, than $V_d = V_a$, and we must compute Δt_5.

First assume that $T_{min} < T < T^*$. We must satisfy the equations

$$(*)\quad R_o = \frac{V_1 - V_o}{A_{max}} \cdot \frac{V_1 + V_o}{2} + V \cdot \Delta t_1 + \frac{V_a - V_1}{A_{min}} \cdot \frac{V_a + V_1}{2}$$

$$+ \Delta t_3 \sqrt{V_d^2 - \dot{Z}^2_{min}}\,, \text{ and}$$

$$T = \frac{V_1 - V_o}{A_{max}} + \Delta t_1 + \frac{V_a - V_1}{A_{min}} + \Delta t_3 + \Delta t_6, \text{ with}$$

$$V_1 = V_{max}$$

We make a tentative calculation for Δt_1 by

$$\Delta t_1 = T - \left[\frac{V_{max} - V_o}{A\ min} + \frac{V_a - V_{max}}{A_{min}} + \Delta t_3 + \Delta t_o\right]$$

If $\Delta t_1 \geq 0$, then calculate V_d from (*), with $V_1 = V_{max}$. If $\Delta t_1 < 0$, we take $\Delta t_1 = 0$ and calculate V_1 from

$$T = \frac{V_1 - V_o}{A_{max}} + \Delta t_3 + \frac{V_a - V_1}{A_{min}} + \Delta t_6.$$

V_d is then calculated from (*).

Now, if $T^* < T < T_{max}$, we descend at speed V_a and need to determine Δt_1. Now we must satisfy

$$R_o = \frac{V_1 - V_o}{A_{max}} \cdot \frac{V_1 + V_o}{2} + V_1 \Delta t_1 + \frac{V_a - V_1}{A_{min}} \cdot \frac{V_a + V_1}{2}$$

$$(**)\quad + \Delta t_3 \sqrt{V_a^2 - \dot{Z}^2_{min}} + V_a \Delta t_5$$

$$T = \frac{V_1 - V_o}{A_{max}} + \Delta t_1 + \frac{V_a - V_1}{A_{min}} + \Delta t_3 + \Delta t_5 + \Delta t_6.$$

We now make a tentative calculation for Δt_1, and Δt_5, assuming $V_1 = V_{max}$, by solving (**). If $\Delta t_1 < 0$ or $\Delta t_5 < 0$, we do not have sufficient distance to accelerate to speed V_{max}, and must have $\Delta t_1 = 0$. With $\Delta t_1 = 0$, we can then solve (**) for V_1 and Δt_5. We then have the flight plan computed.

Example: We consider an example to illustrate the calculations and to show the flexibility available in a typical set of initial conditions. We assign the following values.

$$V_o = 8 \text{ n.m./min}$$

$$V_a = 2 \text{ n.m./min}$$

$$V_{max} = 10 \text{ n.m./min}$$

$$R_o = 100 \text{ n.m.}$$

$$A_{max} = 2 \text{ n.m./min}^2$$

$$A_{min} = -2 \text{ n.m./min}^2$$

$$\Delta Z = -4 \text{ n.m.}$$

$$\dot{Z}_{min} = -2/3 \text{ n.m./min}$$

We find that

$$D_1 = \frac{2-8}{-2} \cdot \frac{2+8}{2} + \frac{-4}{2/3} \sqrt{4-4/9} = 15 + 8\sqrt{2} \quad \text{, and}$$

$$D_2 = 6\sqrt{64-4/9} + \frac{2-8}{-2} \cdot \frac{2+8}{2} = 15 + 4\sqrt{143}$$

Since $R_o > D_2$, we make the tentative calculation for Δt_1, obtaining

$$\Delta t_1 = \frac{100 - [9+6\sqrt{100-4/9} + 24]}{10} = \frac{[67 - 16\sqrt{14}]}{10}$$

This value is positive, thus acceptable, and

$$T_{min} = 1 + \frac{[67 - 16\sqrt{14}]}{10} + 6 + 4 + \Delta t_6 = \frac{177 - 16\sqrt{14}}{10} + \Delta t_6 \simeq 11.7 + \Delta t_6$$

T_{max} is easily computed, and

$$T_{max} = 3 + 6\,\frac{100 - (15 + 8\sqrt{2})}{2} + \Delta t_6 = \frac{103 - 8\sqrt{2}}{2} + \Delta t_6 \simeq 45.7 + \Delta t_6$$

To compute T^*, we find a tentative value for Δt_1, by solving

$$100 - (15 + 8\sqrt{2}) = 9 + 10\Delta t_1 + 9, \quad \text{or} \quad \Delta t_1 = (1/10)[67 - 8\sqrt{2}].$$

Thus, we have

$$T^* = 1 + 1/10\,[67 - 8\sqrt{2}] + 6 + 4 + \Delta t_6$$

$$= \frac{177 - 8\sqrt{2}}{10} + \Delta t_6 \simeq 16.6 + \Delta t_6$$

We now consider two different times for the flight plan, giving the calculations for each. First consider $T = 13 + \Delta t_6$. We then calculate a tentative value of Δt_1 by

$\Delta t_1 = 13 + \Delta t_6 - [1 + 4 + 6 + \Delta t_6] = 2$. Thus we compute V_d from (*),

$$100 = 9 + 20 + 24 + 6 \sqrt{V_d^2 - 4/9}\ , \text{ or}$$

$$V_d^2 = 4/9 + (47/6)^2 = \frac{16 + (47)^2}{36}\ , \text{ giving } V_d \simeq 7.9$$

The pertinent details of the flight plan, along with others, is given in Table 1.

Now, consider $T = 20 + \Delta t_6$. We set $V_1 = V_{max}$, tentatively, and solve (**) for Δt_1 and Δt_5. We have

$$100 = 9 + 10\Delta t_1 + 24 + 8 \sqrt{2 + 2\Delta t_5}$$

$$20 + 2\Delta t_6 = 1 + \Delta t_1 + 4 + 6 + \Delta t_5 + \Delta t_6, \text{ or}$$

$$10\Delta t_1 + 2\Delta t_5 = 67 - 8\sqrt{2}$$

$$\Delta t_1 + \Delta t_5 = 9$$

This gives $\Delta t_1 = \dfrac{49 - 8\sqrt{2}}{8} \simeq 4.7$ and $\Delta t_5 = \dfrac{23 + 8\sqrt{2}}{8} \simeq 4.3$

The results are again tabulated in Table 1.

Table 1 gives the approximate flight plans for the above initial conditions for various flight times. If one considers several aircraft returning in formation, it is easily seen that the interactive constraints are satisfied (in the sense that the separation increases) once an aircraft leaves the formation. In each case $\Delta t_3 = 6$.

TABLE 1

$T-\Delta t_6$	Δt_o	Δt_1	Δt_2	Δt_4	Δt_5	V_d
12	1	1	.25	3.75	0	9.5
13	1	2	1	3.0	0	8
14	1	3	2	2.0	0	6
15	1	4	2.75	1.25	0	4.5
16	1	5	3.5	.50	0	3
17	1	5.44	4.0	0	.46	2
20	1	4.7	4.0	0	4.3	2
40	.8	0	3.8	0	29.4	2

3. Order of landing

We give a method for determining the order of landing. In connection with the assumed flight plan, it should tend to minimize the possibility of violation of the interactive constraints. The three pieces of information to be considered, in decreasing order of importance, are

(a) Maximum time due to fuel constraint

(b) Minimum time to gate

(c) Distance from gate (approximated by R_o)

We first determine the minimum time to the gate for each aircraft (individually, without regard to interactive constraints). The first aircraft in the landing sequence, A_1, will be the one which has the smallest minimum time to the gate, T_1. The ordering is completed in an inductive manner. Assume A_k has been chosen, and he will reach the gate at time T_k. We must look ahead to determine if any aircraft is fuel constrained to land before time $T_k + 2$. If so, he becomes A_{k+1}, with $T_{k+1} = \max(T_{min}, T_k + 1)$. If no fuel constrained aircraft enters, we consider the set of all remaining aircraft with minimum time to gate being $\leq T_k + 1$. If the set is not empty, take A_{k+1} to be the aircraft of the set with the smallest R_o. If the set is empty, take A_{k+1} to be the aircraft with the smallest T_{min}, then $T_{k+1} = T_{min}$. In the event that "ties" occur, such as for aircraft returning in formation, the ordering is a matter of convenience. Position in the formation should likely be considered.

As a position is determined for an aircraft, its flight plan should be calculated and any correction due to interactive constraints should be made. It is possible that A_{k+1} could not satisfy the interactive constraints and still reach the gate by time T_{k+1}. It is felt this would be unlikely, however, since the ordering and flight plans are designed to minimize this sort of interference. The exception might occur in the case of a fuel constrained aircraft entering into the ordering. He would then "pass" some aircraft, perhaps, causing them to have to take some evasive action, since they would follow in the landing order.

When interactive constraints are violated, it is anticipated that a slight deviation in course away from the point of violation will correct it. This will slightly lengthen the flight path, and change Δt_o, thus new values for T_{min}, T^*, and T_{max} will have to be calculated, and the new flight plan tested for satisfaction of the interactive constraints. No major problem is anticipated for a "reasonable" number of aircraft.

4. Conclusions

As noted previously, we emphasize the idea that the most important factor in this problem is a realistic, but easily computed, flight plan. The more closely the assumed flight plan approximates the actual capabilities of the aircraft, the closer one can come to optimizing the operation.

It is felt that the above ideas can be programmed for a computer and shown to be feasible in a large number of cases. This should be done by making liberal use of subprograms so that various aspects of the overall calculation can be easily changed, and perhaps even improved. Some experience would likely lead to better assumed flight plans; more general ones would perhaps be needed. Experience might also lead to better methods of ordering the aircraft to help minimize the interactive constraint problem.

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13. ABSTRACT

A method is given for computing flight plans for aircraft returning to the carrier after a mission. The basic goal is to minimize the total flight time for the landing aircraft, while maintaining various individual and interactive constraints on the aircraft.

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