Arrival Time Control during Continuous Descent and Its Application to Air Traffic Control

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Arrival time control in a continuous descent operation (CDO) and its application to arrival traffic control are discussed. Through numerical simulations, the feasibility of the arrival time extension and reduction while maintaining the idle thrust during the continuous descent trajectory is presented. The extensible and reducible time of a CDO trajectory are also numerically analyzed. They are uniquely determined by the aircraft speed, altitude and distance from the runway. The CDO trajectory that potentially has the maximum extensible and reducible time is also proposed, which is expected to cancel the deviation of arrival time from that scheduled. A set of numerical traffic simulations proves the effectiveness of the proposed traffic control strategy. It is concluded that CDO using the proposed traffic control strategy is able to achieve delay-free air traffic with enhanced arrival time predictability. A noteworthy numerical result is also obtained showing that a slower trajectory for a larger reducible time can achieve a faster arrival time on average than the fastest trajectory with no reducible time.

Key Words: Air Traffic Management, Continuous Descent Operation, Flight Trajectory, Air Traffic Control

1. Introduction

Continuous descent operation (CDO) has been strongly focused on because it enables the reduction of the environmental load such as noise and fuel consumption. A trial of CDO has been demonstrated at some airports, and it has been recognized as one of the most promising operational concepts in several future air traffic plans. In CDO, aircraft continuously descend during arrival and approach phases. Although this operation is expected to minimize the noise and fuel consumption, it is considered difficult to control the separation with other traffic while maintaining the idle thrust. Therefore, it is expected to be difficult to achieve CDO in a congested terminal area even though it indeed has a strong potential in this area. The tailored arrival (TA) is proposed to facilitate CDO in a congested terminal airspace. In TA operation each aircraft is provided with a specifically designed flight trajectory from the air traffic controller that facilitates conflict-free CDO.

There have been many strategies presented for the CDO. Although these concepts differ in detail, their basic strategies can be summarized as follows: an aircraft descends from the top of descent (TOD) to reach the merging point at a required time, and maintains an appropriate interval with the preceding aircraft by airborne separation as shown in Fig. 1. The descent from TOD to the merging point is operated using a time-based strategic traffic control. This operation strategy is expected to enable every aircraft to reach the merging point at the required time while maintaining almost minimum thrust without any conflict. In a previous study, however, it was reported that time-based separation cannot always be achieved especially due to unexpected wind. To cope with such undesirable situations, the authors presented the “arrival time controllability” concept to evaluate how large arrival time difference could potentially be made at the TOD. The arrival time controllability is defined as the difference between the extensible and reducible time, and is uniquely determined for a CDO trajectory. It means how large arrival time error at the TOD could be compensated during continuous descent. For example, when an aircraft at the TOD has a time difference from its schedule, it can adjust the time to reach the merging point as scheduled by flying on a CDO trajectory with sufficient arrival time controllability. However, an aircraft on a CDO trajectory with no arrival time controllability can no longer keep the scheduled time. Generally, the flight time reduction is rarely performed because it requires high additional fuel consumption on the cruise route. In contrast, the CDO trajectory with sufficient arrival time controllability is expected to enable an aircraft to reduce its flight time while maintaining its idle thrust. This is expected to facilitate sophisticated air traffic control.

In this study, the arrival time controllability is analyzed using a practical flight condition, and its effectiveness is demonstrated through a descent air traffic control simulation. It is possible to determine the flight trajectory with the optimum arrival time controllability from the TOD. It is expected that many aircraft will become able to arrive at the airport on time by scheduling their flight time along this flight trajectory. It is also expected that it will be possible to find a flight trajectory that has a certain level of arrival time controllability during the CDO. Such a flight trajectory is expected to enable aircraft to keep the scheduled time of
arrival even against disturbances such as unexpected wind.
In the traffic control simulation, we aim to present a traffic
control strategy that utilizes the CDO trajectory with the
optimum arrival time controllability to achieve a delay-free
and precisely predictable arrival traffic.

2. Arrival Time Controllability Analysis

2.1. Arrival time analysis

The arrival time is defined as the time required for an
aircraft to reach the final boundary condition defined at
the altitude of 3000 [ft] from its TOD. It is obtained through
numerical analyses using the aircraft equations of motion
considering the flight constraints such as the Mach limit,
flight speed limits and flap configurations. Since the arrival
time basically depends on the descent ratio, only the aircraft
vertical motion is considered in this paper. It is also assumed
that the aircraft maintains the idle thrust during descent.
The numerical analyses are carried out using the B777-300
parameters and flight conditions. The aircraft equations
of motion are as follows.

$$m \frac{dv}{dt} = - \frac{1}{2} \rho v^2 S C_D - mg \sin \gamma + T_{des}$$

(1)

$$T_{des} = C_{Tdes} \cdot T_{max,climb}$$

(6)

$$T_{max,climb} = C_{Tc,1} \left( 1 - \frac{h}{C_{Tc,2}} + C_{Tc,3} \cdot h^2 \right) \left( 1 - C_{Tc,5}(\Delta T_{ISA})_{eff} \right)$$

(7)

$$\Delta T_{ISA}\_{eff} = \Delta T_{ISA} - C_{Tc,4}$$

(8)

The coefficients are provided as follows.

$$C_{Tdes} = 4.11 \times 10^{-2}, \quad C_{Tc,1} = 4.37 \times 10^5$$

$$C_{Tc,2} = 5.11 \times 10^4, \quad C_{Tc,3} = 5.80 \times 10^{-11}$$

$$C_{Tc,4} = 9.46, \quad C_{Tc,5} = 4.53 \times 10^{-3}$$

(9)

The flap configuration is defined by the $C_{D0}$ and $C_{Df}$ values. These values are determined according to the aircraft altitude and the calibrated air speed (CAS). The CAS is calculated as

$$v_{CAS} = \sqrt{\frac{2P_0}{\mu \rho_0} \left( 1 + \frac{P}{P_0} \left( 1 + \mu \frac{\rho}{\rho_0} \frac{v^2}{2} \right) \frac{v^2}{2} \right) - 1}$$

(10)

$$\mu = \frac{k - 1}{k} \approx \frac{1}{3.5}$$

(11)

Table 1. Aircraft configurations.

| Cruise          | $h \geq h_{max,AP}$                  | $C_{D0}$ (cruise) | $1.69 \times 10^{-3}$ |
|-----------------|--------------------------------------|-------------------|------------------------|
| Approach        | $h_{max,AP} > h \geq h_{max,LD}$ and $v_{CAS} \geq v_{min,CR} + 10$ [kt]$C_{D0}$ (approach) | $2.25 \times 10^{-2}$ |
| Landing         | $h < h_{max,LD}$ and $v_{CAS} < v_{min,AP} + 10$ [kt]$C_{D0}$ (landing) | $8.69 \times 10^{-2}$ |

Note: $h_{max,AP} = 8000$ [ft] and $h_{max,LD} = 3000$ [ft].

Table 2. Aircraft parameters.

| $m$ [kg]       | $2.38 \times 10^3$ |
|----------------|-------------------|
| $S$ [m$^2$]    | $4.28 \times 10^3$ |
| $v_{min,CR}$ [kt$C_{D0}$] | $2.08 \times 10^3$ |
| $v_{min,AP}$ [kt]$C_{D0}$ | $1.57 \times 10^2$ |
| $v_{min,LD}$ [kt]$C_{D0}$ | $1.44 \times 10^2$ |

where $C_D$ and $C_L$ are the drag and lift coefficients, $C_D$ is
given using the parasite and induced drag coefficients, $C_{D0}$
and $C_{Df}$, as the following equation.

$$C_D = C_{D0} + C_{Df} C_L^2$$

(5)

The idle thrust $T_{des}$ is given as follows.

The flight trajectories are analyzed numerically so that they satisfy both the following initial and final boundary conditions. The initial condition is given at the TOD as
\[
h_{\text{ini}} = 39000 \text{[ft]} = 11887.2 \text{[m]},
\]
\[
v_{\text{ini}} = 250 \text{[m/s]},
\]
The final boundary condition is given as
\[
h_{\text{fin}} = 3000 \text{[ft]} = 914.4 \text{[m]},
\]
\[
v_{\text{fin}} = 109 \text{[m/s]}, \quad x_{\text{fin}} = 0 \text{[m]}
\]
Disturbances such as wind and navigation error are not considered in this study for the sake of clarity. The analyses are carried out using MATLAB Optimization Toolbox.\(^{18}\)

### 2.2. Concept of arrival time controllability

The arrival time controllability is defined as the potentially achievable time difference between the minimum and maximum time to reach the final boundary condition. It is possible to compose many flight trajectories to satisfy the final boundary condition from an arbitrary point on a CDO trajectory. Among these flight trajectories, it is also possible to find ones that have the maximum and minimum flight time. The time difference between a flight time of a CDO trajectory and the maximum or minimum time can be regarded as the extensible or reducible time. These time differences are regarded as the arrival time controllability. Large arrival time controllability is expected to enhance the CDO feasibility. For example, if an aircraft is on a CDO trajectory with insufficient arrival time controllability, the aircraft can no longer continue CDO with an idle thrust or satisfy the required arrival time when it is subject to some unexpected wind. In contrast, if an aircraft is flying on the CDO trajectory with sufficient arrival time controllability, this aircraft is expected to be able to choose another CDO trajectory that satisfies the boundary conditions at the required arrival time.

### 2.3. Arrival time controllability at TOD

To obtain the arrival time controllability at the TOD, the flight trajectories with the maximum and minimum arrival times are analyzed. They are presented in Fig. 2, where the solid and broken lines show the flight trajectories with the maximum and the minimum flight times, respectively. Both trajectories are determined by the Mach number limit, the flight path angle limit and the speed limits. Hereinafter, these flight trajectories are called the maximum time trajectory and the minimum time trajectory. An aircraft on the minimum time trajectory begins descent from the TOD following the Mach number limit to accelerate up to the upper flight speed limit as soon as possible. It descends with the upper limit speed to minimize the flight time, and finally decelerates by a level flight to satisfy the final boundary conditions. In contrast, on the maximum time trajectory, an aircraft decelerates by a level flight at the cruise altitude to have the lower limit speed. This enables the aircraft to spend the maximum flight time to reach the final boundary condition.

To cancel the arrival time deviation from the scheduled one, a CDO trajectory should be capable of both arrival time extension and reduction. In this paper, therefore, the CDO trajectory with the optimum arrival time controllability is defined as the one that has the mean arrival time of the maximum and minimum time trajectories.

The optimum arrival time controllability \(\Delta T_{\text{opt}}\) is determined from the time difference between these flight trajectories including the cruise time difference as follows:
\[
\Delta T_{\text{opt}} = T_{\text{opt}} - \left( T_{\text{min}} + \frac{\Delta \text{TOD}}{v_{\text{ini}}} \right)
\]
where \(T_{\text{max}}\) and \(T_{\text{min}}\) are the maximum and minimum flight times, and \(\Delta \text{TOD}\) is the distance between the TOD of the maximum and minimum time trajectories. From the analyses, the optimum controllability is obtained as follows.
\[
\Delta T_{\text{opt}} = 1606.3 - (1160.8 + 28.3)
\]
\[
= 417.2 \text{[s]}
\]
The CDO trajectory that has \(\Delta T_{\text{opt}}\) should have the following flight time:
\[
T_{\text{opt}} = T_{\text{max}} - \frac{\Delta T_{\text{opt}}}{2}
\]
\[
= T_{\text{min}} + \frac{\Delta T_{\text{opt}}}{2}
\]
\[
= 1397.7 \text{[s]}
\]
This result should be understood to mean that an aircraft on a CDO trajectory with this flight time \(T_{\text{opt}}\) is capable of both arrival time reduction and extension up to \(\Delta T_{\text{opt}}\). It should be noted that the optimum CDO trajectory is intentionally composed to be \(\Delta T_{\text{opt}}/2\) longer than the minimum time trajectory. It is possible to compose many flight trajectories with \(T_{\text{opt}}\). Some example trajectories are shown in Fig. 3. In addition, the example trajectories for 100 and 50[s] reduction, and 100 and 50[s] extension trajectories are shown in Fig. 4. In this way, it is also possible to compose many flight trajectories to achieve a specific flight time difference. Therefore, it is considered possible to also compose a flight trajectory that maintains significant arrival time controllability even during continuous descent.

### 2.4. Arrival time controllability during descent

At the TOD, an aircraft is able to select a suitable CDO trajectory to satisfy the required time arrival at the merging
point. However, it is also subject to some disturbances during descent, and some deviation from the required time of arrival will be inevitable. For a more punctual arrival, therefore, it is desirable that an aircraft can control its arrival time during descent while maintaining the idle thrust. To investigate the feasibility of this, numerical analyses are carried out to find flight trajectories that simultaneously satisfy the boundary conditions and achieve the flight time control. In this case, the initial boundary condition additionally includes the position $x$ constraints. In this paper, as one example, the CDO trajectories from the altitude of 20000 [ft] ($=6096$ [m]) are analyzed. To analyze the optimum arrival time controllability from these altitudes, the flight trajectories that transfer to the maximum or minimum time trajectories with additional minimum numbers of legs are numerically sought. In this case, three additional legs are required to satisfy the three constraints of the altitude, velocity and position.

The maximum and minimum flight time from a specific altitude depends on the position and velocity. Through the optimization of the flight time, the maximum and minimum time flight trajectories from the altitude of 20000 [ft] are

![Fig. 2. Maximum and minimum arrival time trajectories: (a) CAS-altitude, (b) distance-altitude, (c) altitude time history, (d) velocity time history and (e) CAS time history (solid and broken lines: maximum and minimum arrival time trajectories from TOD).](image)

![Fig. 3. Example CDO trajectories with optimum arrival time controllability (CAS-altitude).](image)

![Fig. 4. Example CDO trajectories for arrival time control (CAS-altitude).](image)
numerically obtained. In this case, the initial condition to compose the optimum CDO trajectory from the altitude of 20000 [ft] is obtained as

\[
\begin{align*}
x &= 120.2 \text{ [km]} \\
v &= 209.1 \text{ [m/s]} = 305.0 \text{ [kt}_{\text{CAS}}] \\
h &= 6096 \text{ [m]} = 20000 \text{ [ft]} 
\end{align*}
\] (24)

The optimum CDO trajectory from the altitude of 20000 [ft] is shown in Fig. 5. The solid lines and dashed lines denote the maximum and minimum time trajectories, respectively. The optimum arrival time controllability is analyzed as follows.

\[
\Delta T^{20000}_{opt} = 208.0 \text{ [s]}, \quad T^{20000}_{opt} = 825.1 \text{ [s]} \quad (25)
\]

It is revealed that both reduction and extension of the arrival time is still possible by more than 100 [s] with the idle thrust from the altitude of 20000 [ft]. The optimum CDO trajectory that still has the optimum arrival time controllability at the altitude of 20000 [ft] is obtained by connecting the flight trajectories satisfying the constraints at the TOD and the altitude of 20000 [ft] and 3000 [ft]. One example trajectory with the optimum arrival controllability both at TOD and the altitude of 20000 [ft] is shown in Fig. 6. On this CDO trajectory, an aircraft can adjust its arrival time within ±208.6 [s] at the TOD and ±104.0 [s] at the altitude of 20000 [ft] while maintaining the idle thrust.

3. Effectiveness of Arrival Time Controllability in Traffic Control

It has been clarified through the CDO trajectory analyses that both flight time reduction and extension are potentially possible not only at the TOD but at arbitrary points during descent while maintaining idle thrust. It is expected that the flight time reduction enables schedule-based traffic control where all aircraft aim to follow their scheduled arrival time, and the time-based separation is achieved accordingly. The effectiveness of this flight time control is investigated through the traffic control simulations.

In the traffic control simulation, it is assumed that all aircraft are scheduled to arrive at the airport with a constant interval. Some disturbances are also considered on both cruise and descent trajectories that have aircraft deviate from the scheduled trajectory. The following two algorithms are investigated: A) interval based control: all aircraft are scheduled to fly on the minimum time trajectory, and aircraft intervals are achieved by delaying the following ones within the maximum extensible time range, and B) schedule-based control: all aircraft are scheduled to fly on the trajectory with the optimum arrival time controllability, and aircraft intervals are achieved by leading all aircraft to follow their schedule within the arrival time controllability. The interval-based control algorithm A is similar to the conventional one applied to today’s air traffic control. These algorithms are illustrated in Fig. 7. In both algorithms, the arrival time estimation and the flight trajectory determination for the arrival time control are carried out 1) at the
TOD only, and 2) at both the TOD and the altitude of 20000 [ft]. In addition, the half arrival time controllability cases are also considered to clarify the importance of the arrival time controllability. The combinations of the above traffic control strategies and conditions are summarized in Table 3, and they are indicated by symbols (e.g., A-1, B-2, etc.) in the following. The aircraft are scheduled to arrive at the airport every 90 [s] over 15 hours a day for 1 year, and they are subject to random disturbances on both cruise and descent routes, which result in random delay. It is assumed that the disturbances result in 60 [s] average delay with 60 [s] standard deviation following the normal distribution on the cruise route and 0 [s] average with 30 [s] standard deviation on the descent route, where 75% delay occurs from the TOD to the altitude of 20000 [ft].

The average and the standard deviation values of the delay from the schedule and the aircraft interval obtained through the traffic control simulation are summarized in Table 4. Through comparison between cases A-1 and B-1, it is clarified that the schedule-based control using flight time reduction has the effectiveness to achieve delay-free traffic. An example one-day delay history is shown in Fig. 8. While the average delay in the A-1 case gradually

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**Table 3. Traffic control algorithms, control altitude and controllability.**

| Algorithm     | Control altitude | Controllability [s] |
|---------------|------------------|---------------------|
| A-1 Interval-based | TOD only | 0 ~ +400 (TOD)     |
| B-1 Schedule-based | TOD only | −200 ~ +200 (TOD) |
| C-1 Schedule-based | TOD & 20000 [ft] | −100 ~ +100 (TOD) |
|               |                  | −100 ~ +100 (20000[ft]) |
| A-2 Interval-based | TOD only | 0 ~ +200 (TOD)     |
| B-2 Schedule-based | TOD only | −100 ~ +100 (TOD) |
| C-2 Schedule-based | TOD & 20000 [ft] | −50 ~ +50 (TOD)    |
|               |                  | −50 ~ +50 (20000[ft]) |

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**Fig. 6.** CDO trajectory with optimum arrival time controllability at TOD and 20000 [ft]: (a) CAS-altitude, (b) distance-altitude, (c) altitude time history, (d) TAS time history and (e) CAS time history (narrow lines: maximum and minimum arrival time trajectories from TOD).

**Fig. 7.** Traffic control concept: (a) interval-based algorithm and (b) schedule-based algorithm (gray lines: scheduled time; dashed black lines: disturbed arrival time; black lines: controlled arrival time).
increases, that of the B-1 case keeps a constant value around 0 [s]. The example histories of the estimated delay at the TOD in the A-1 case for five days are summarized in Fig. 9. As this figure shows, the estimated arrival time varies day by day. In contrast, it is possible to expect that all aircraft arrive at the airport at their scheduled time in the B-1 algorithm. Therefore, it is considered that the schedule-based arrival time control also achieves a better predictability of the arrival time in addition to delay-free traffic. From the B-1 and C-1 results, it is also derived that the arrival time control during descent improves the arrival time control precision, which is expected to improve the CDO operability. In the cases of the half arrival time controllability (A-2, B-2 and C-2) all the standard deviation values of the aircraft interval increase. This result means that some of the aircraft are unable to make sufficient arrival time control to follow the schedule or to make the required interval.

As Eq. (23) implies, to prepare the arrival time controllability, all aircraft need to be scheduled to fly intentionally more slowly than those scheduled to fly on the minimum time trajectory. In the B-1 algorithm, aircraft are scheduled to fly 200 [s] more slowly than the fastest trajectory in order to achieve both extensible and reducible time of 200 [s]. However, through the numerical simulation, it is clarified that the arrival time delay in the A-1 case becomes approximately 224.4 [s] larger than that in the B-1 case. This means that the air traffic controlled by the B-1 algorithm achieves 224.4 – 0.2 – 200 = 24.2 [s] faster arrival than that controlled by the A-1 algorithm. This arrival time reversal is also found between the A-2 and B-2 algorithms, where B-2 algorithm achieves 159.1 – 8.9 – 100 = 50.2 [s] faster arrival. This result implies the possibility that intentionally scheduled slow traffic achieves faster arrival.

4. Conclusion

In this paper, the possibility of controlling the arrival time while maintaining the idle thrust during CDO trajectories was numerically investigated. It was also clarified that it is possible to optimize the CDO trajectory in terms of the arrival time controllability, and to further optimize the CDO trajectories in order to facilitate the arrival time control even during the CDO trajectory. The effectiveness of the optimized CDO trajectories were demonstrated through the CDO traffic control simulations. It was shown that the schedule-based arrival time control proposed in this study can achieve delay-free air traffic, and that it improves the arrival time predictability. It was also shown that the schedule-based traffic control, that requires aircraft to fly intentionally slowly for traffic controllability, can achieve faster arrival of descent air traffic.

There are many future works required for the practical use of the proposed concept. The traffic controllability presented in this study was based on an assumption that aircraft are able to fly following the limit of the flight envelope. Indeed it is possible theoretically, but it is expected difficult to perform in actual operations. In addition, a concise scheme to derive a CDO trajectory that simultaneously achieves the required arrival time and its controllability is indispensable. A more detailed investigation and some interpretation must be made for the traffic simulation, especially on the reverse phenomenon: “traffic with slower schedule achieves faster arrival.” These investigations are expected to clarify the condition that leads the presented traffic control algorithm to bring many advantages. It may be possible to also apply the traffic control concept to general traffic such as highway road traffic.

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