OPERATIONAL HUMAN-IN-THE-LOOP INTEGRATION OF 4D ARRIVAL GUIDANCE

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Abstract

A Human-Machine-Interface was developed to allow pilots to perform Continuous Descent Approaches following 4D (3D Position + time) guidance. This interface was then integrated into a complex Aircraft-Ground architecture to demonstrate the Trajectory generation, communication and execution process. For an evaluation of the developed system simulator are planned.

1 Introduction

Air Traffic is increasing worldwide due to population growth, globalization and increasing prosperity, among other reasons [1]. In already dense traffic regions this further increase is challenging the Air Traffic Systems (ATSs) to provide enough capacity for this increase in demand. In Europe the Eurocontrol Statistics and Forecast Service (STATFOR) predicts and average growth rate of 2.8% per annum for the 2010-2030 timeframe [2]. To cope with this increase in demand the legislatures in the U.S. and Europe have planned regional implementations of the International Civil Aviation Organization (ICAO) “Global Air Navigation Plan” [3]. These implementations, Single European Sky ATM Research (SESAR) [4] in Europe and the Next Generation Air Transportation System (NextGen) [5] in the U.S., are defining 4D (3D position + time) Trajectories and a System Wide Information Management (SWIM) as key enablers for an increase in capacity of the overall ATS.

In current operations 4D Trajectories are neither supported on the ground nor in the air. As the advantages of 4D trajectories can only be utilized when a large group of stakeholder supports these operations, mixed equipage and retrofit equipment of aircraft need to be taken into account. Studies have shown that a large group of participating aircraft is beneficial to the overall system performance [6] [7]. For a large number of aircraft participating, not only new aircraft should be equipped to support Trajectory Based Operations (TBO). Instead currently operating aircraft need to be retrofitted to support TBO.

To ensure the environmental sustainability of an increase of air traffic, highly efficient procedures need to be designed and utilized. Continuous Descent Approaches (CDAs) have shown the potential to decrease fuel burn and noise emissions on the ground of a descending aircraft [8]. The operational challenge is, for the air traffic controller, to maintain separation while keeping the capacity, of the arrival airport, on the same level as for standard stepped approach procedures (see Figure 1). 4D Trajectories can help to solve this challenge.

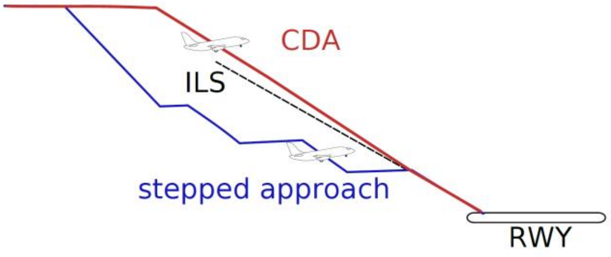

Figure 1: CDA vs. stepped approach [9]

This paper proposes a 4D CDA arrival guidance system, which can easily be integrated into any aircraft with basic Flight Management functionalities. The system will utilize an Electronic Flight Bag (EFB) as interface to the pilot to: plan, negotiate, brief and execute the 4D Trajectory. The pilot remains the decision maker on the flight deck. He reviews the information which the system provides and acts accordingly. This way, the pilot is always in the loop.

In the following, this 4D arrival guidance system is presented in detail. First, an overview of the system is presented, which consists of the airborne EFB part, and a ground part, which calculates the reference Trajectory. The guidance itself is discussed, which forms the basis of this system. To interact with the guidance, the information needs to be displayed to the pilot, through a Human Machine Interface (HMI). These parts form the core functionalities of the 4D arrival guidance system. To ensure its operational usability, and benefits, an evaluation has to be performed, which was done in multiple simulator trials, and is planned for integration into a 737 test aircraft in late 2012.

2 Architecture

The system consists of two components. The onboard component, that runs on the EFB, with which the pilot interacts. The guidance reference Trajectory is calculated on a ground component, to ensure that the planned Trajectory meets the needs of the overall traffic situation.

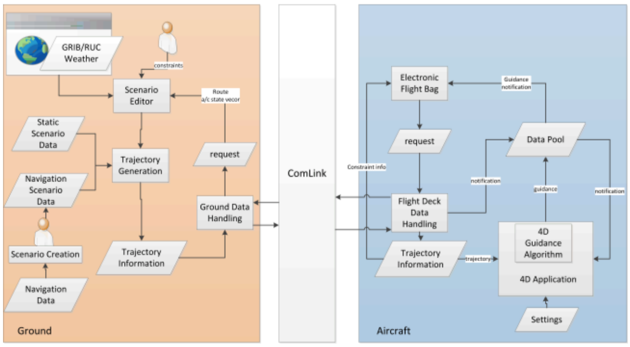

Figure 2: Architecture of 4D Guidance Integration

Figure 2 presents an overview of the subsystems, and functions, divided into the ground and the airborne segment, of the described solution. In the following each segment is described independently.

2.1 Ground Segment

The Ground Segment calculates the 4D reference Trajectory, which the aircraft attempts to follow. This Trajectory is a continuous description of the aircraft state vector over time. In addition, the Trajectory description consists of a discrete description of the aircraft intent, and constraints at waypoints.

To calculate the guidance reference Trajectory, the Trajectory calculation algorithm takes into account:

- 4D Weather information
- Aircraft State Vector
- Operator generated constraints
- Navigation Data

4D Weather information is retrieved from the online servers of the National Oceanic and Atmospheric Administration (NOAA). Depending on the location, either Rapid Refresh (RAP) or Global Forecast System (GFS) data is used to predict the 4D wind profile for the descent. As the Trajectory is defined as a ground referenced Trajectory, precise wind information is the key to defining an efficient approach Trajectory.

The negotiation of the Trajectory is initiated by the pilot. In the request downlinked from the aircraft to the ground, Aircraft State Vector information is included. These values are used, as initial conditions for the Trajectory calculation. In addition, the request includes the planned lateral route, which the pilot intents to fly.

To coordinate with other arriving aircraft, in the terminal area, constraints can be applied to any waypoint of the Trajectory. The constraints can include speed, time and altitude constraints.

Discrete constraint modifications to the Trajectory are easier to facilitate, either for a ground operator or automation, than a continuous modification of the Trajectory. This allows a coordination of arriving traffic, for example to merge arrival streams at the Final Approach Fix (FAF), by allocating a Required Time of Arrival (RTA) at this FAF to each aircraft.

All trajectories are based on published terminal area procedures. To allow an efficient Trajectory calculation, the used procedures must allow flexibility in the altitude over waypoints of the procedure as well as only few restricting speeds.

Various Integrations of the Ground Segment are feasible:

- Integration in Air Traffic Control Systems (ATC)
- Integration in Airline Operations Systems (AOC)
- Integration in Airborne Segment

The integration in ATC systems is described in this paper. In this case, ATC is responsible for the generation of constraints, to safely separate aircraft, and for the generation of the guidance reference Trajectory.

Integration in AOC systems would be identical but only feasible for airports where the carrier is the major operator, can influence most of the arriving aircraft, and has operational freedom from ATC. This situation would be similar to current operations in Louisville [8].

By integrating into the Airborne Segment, the aircraft would only receive constraints from ATC, and would calculate the guidance reference Trajectory onboard. This solution requires a broadband data link to retrieve the 4D weather information, for Trajectory calculation. Also a combination with an AOC solution could prove beneficial.

2.2 Airborne Segment

The Airborne Segment provides the following functionalities to the pilot:

- Trajectory Negotiation
- Briefing of Trajectory
- Guidance cues to follow the Trajectory

The Trajectory negotiation is initiated by the pilot. A data format has been defined that includes Aircraft State Vector information as well as the planned arrival and approach route. This Trajectory request message is sent to the Ground Segment where it is processed.

The Trajectory message format includes a discrete Trajectory description, to brief the pilot about planned constraints. Once the calculated Trajectory has been received, on-board the aircraft, the pilot can review the constraints in the chart, and decide if it is feasible to fly. If the pilot decides to fly the Trajectory, the pilot accepts the Trajectory and the guidance starts. If the pilot denies the proposed Trajectory, the approach is flown as in current operations, on a tactical basis, following instructions from the Air Traffic Controller.

The logic of guidance cues depicted to the pilot, when the Trajectory has been accepted, is described in the following section.

3 Guidance

The Guidance method used for the described system utilizes the Continuous Descent Approach for Maximum Predictability (CDA-MP) method developed by Boeing Research and Technology Europe (BR&TE) [10].

3.1 Guidance Logic

The CDA-MP guidance logic is based on total energy control. The idea is to minimize deviations in potential energy (altitude deviation) and kinetic energy (speed deviation) to a reference Trajectory. As altitude deviations, to the reference Trajectory, can be minimized easier, and speed deviations integrate to position deviations over time, the idea is to follow the reference speed (and thus time) profile very closely, and to allow deviations in altitude. To minimize throttle activity, and allow efficient CDA operations, the altitude deviation is only corrected once a certain deviation limit is exceeded.

This results in three different vertical guidance modes. The nominal setting is, in the current integration, an idle descent with the Autopilot in “LVL CHG” mode. If the aircraft reaches the upper limit, and is too high compared to the reference Trajectory, a speed brake usage is recommended by the system, to minimize the aircrafts total energy. If the aircraft reached the lower limit, and is too low, compared to the reference Trajectory, a vertical speed mode is recommended by the system. The recommended vertical speed is lower than the idle vertical speed, at this part of the reference Trajectory. Thus, it is the only mode that requires above idle thrust, to reacquire the Trajectory.

The guidance logic generates speed guidance cues, to minimize the 4D Trajectory time deviations. As the pilot cannot constantly change the speed setting in a manual integration, the output of the guidance function has been discretized, to enable a human-in-the-loop integration of CDA-MP.

3.2 Flaps Logic

As the CDA-MP guidance logic is aiming to minimize the total energy error to the reference Trajectory, the idea is also applied to the extension of flaps. As a change in aircraft configuration results in a change of total energy rate, it provides a mean to reduce the total energy error to a reference Trajectory. The developed process is called “Flexible Flaps Schedule” (FFS) and its calculation is described in the following.

The goal of the FFS is to calculate a time Δt by which the flaps deployment time has to be modified, to minimize the total energy error. The total energy rate is described by [11]:

$$\dot{E} = m \cdot V \cdot \frac{dV}{dt} + m \cdot g \cdot \frac{dh}{dt} = V(T - D)$$

With: E = total energy; m = aircraft mass; V = aircraft speed; g = gravitational acceleration; h = altitude; T = thrust; D = drag.

Assuming that there is no change in speed over time, a small flight path angle, constant thrust, small change in aircraft mass, a flat surface of the earth and a neglectable change in air density results in:

$$\int \frac{m \cdot g}{V(D_0 - D_1)} \Delta dh = \int \Delta dt$$

Where Δh equals the total energy equivalent altitude deviation and Δc_d equals the change in drag coefficient due to the change in configuration. After solving the integral the change in deployment time to the reference point Δt becomes:

$$\Delta t = \frac{2 \cdot \Delta h \cdot m \cdot g}{\rho \cdot S \cdot V^3 \cdot \Delta c_d}$$

Δt can have positive or negative values, which correspond to an earlier or later flaps extension, as was planned in the guidance reference Trajectory.

To account for the pilot reaction time, and the flaps extension time, the calculated Δt has to be preponed by an average factor. As Flaps can only be extended within a certain Indicated Airspeed (IAS) range, it has to be ensured the aircraft is within this range, when the cue is displayed to the pilot. To stay close to current airline operations, the shift to the reference deployment time should not be too large and be limited if the total energy deviation requires for a larger shift. A reasonable limit can be for example +/- 60s.

4 Interface

The interface for the Pilot is the Jeppesen “Gate-to-Gate” next-generation data driven charting application. This research application provides advanced functionalities such as: taxi-

routing, graphical NOTAM and Weather depiction with inflight updates and inflight optimized re-routing [12] [13].
Gate to Gate is enhanced by features allowing the pilot to fly a CDA, based on a 4D Trajectory. It serves the three purposes identified in Section 2.2.: Negotiation of Trajectory, Briefing of Trajectory and Guidance.

4.1 Negotiation of Trajectory

The negotiation of the Trajectory is initiated by the pilot, by selecting a CDA capable arrival procedure. This procedure was either communicated to the pilot via voice communication from the controller, or the pilot took the initiative to select it. This is shown exemplary in Figure 3 where the Pilot can select the "I10 D266W RW10" approach as CDA.

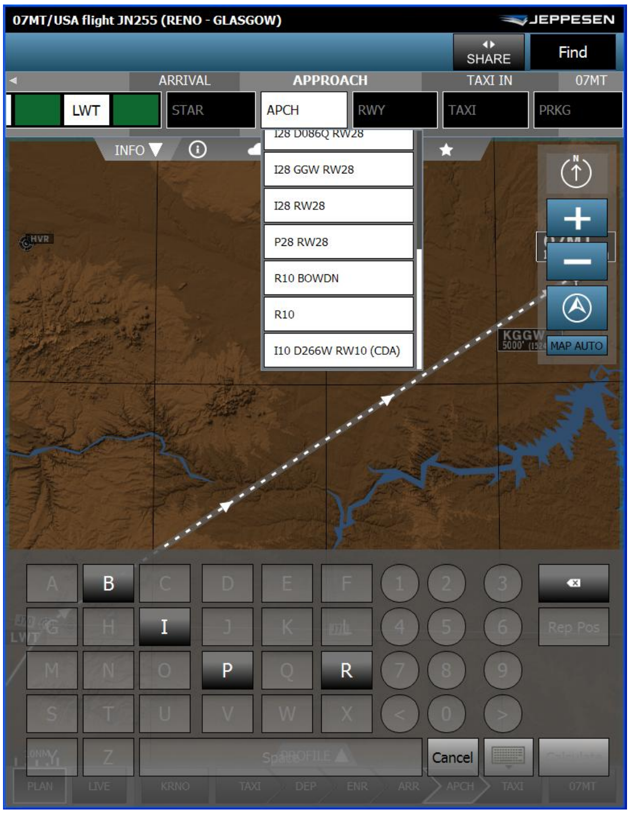

Figure 3 Selecting an Approach as CDA

In a next step, the pilot can review the procedure, and make a final decision, before downlinking the request to the ground operator. Figure 4 depicts this decision dialog for the pilot which appears after a CDA procedure has been selected.

After the request has been processed on ground, and a Trajectory has been created, it is uploaded to the aircraft. The pilot is informed that a new Trajectory has been received.

Figure 4 Confirm to send request to ground to perform a CDA

4.2 Briefing of Trajectory

The pilot is the decision maker, by choosing to follow the guidance cues or not. Thus, a detailed awareness of the Trajectory is needed. The pilot cannot comprehend a continuous Trajectory description, and extrapolate actions from it. This is why Trajectory information is discretized to navigational waypoints along the route and additional operational waypoints such as the Top of Descent (TOD). For these waypoints constraint information for altitude, speed and RTA as well estimate values are presented to the pilot. During the execution of the Trajectory the constraints at waypoints can be used, to confirm the aircraft is still performing within the Trajectory limits.

In integrations as depicted in Figure 5, the pilot also has the option to modify constraints set on the Trajectory, and to send those back to the ground for a renegotiation. Reasons for a modification can be: company preferences from the airline or personal safety preferences from the pilot, for example to insert an additional safety altitude in adverse weather conditions.

When no renegotiation is needed, the pilot can decide to accept the Trajectory, by a similar decision dialog as shown in Figure 4.

Figure 5 Briefing of Constraints on Trajectory [14]

4.3 Guidance

Once a Trajectory has been activated the CDA guidance bar on top of the application appears. This bar consists of 4 fields which have the following functions:

- "SPD CMD" - Speed Guidance
- "SPD BRK" Speed Brake activity
- Autopilot mode
- Flaps cue

These cues can be depicted in three different modes.

- Inactive
- Active
- Changed

The modes are used, to attract different levels of attention from the pilot. Inactive cues are depicted in gray as they don't require any Pilot input. Active cues are depicted in white and describe the current setting, which has already been set. Changed cues are depicted in blue and require the pilot to act and change the aircraft controls according to the cue.

The Speed Guidance is always active when the guidance is active. Below the Mach-CAS transition (depicted on the map as MCT) the guidance cue switches from a Mach cue to a CAS cue. The cue is discretized to 5 knots or Mach 0.01, to not overload the pilot with constantly updating speed cues. When a change in speed is required, the cue mode changes from active to changed, to attract pilot attention. The cue stays in the changed mode, either for a certain time such as 10 seconds, or until the pilot has entered the new speed on the Mode Control Panel (MCP).

The Speed Brake cue is either inactive or changed. When the cue is in inactive mode, the speed brake shall be retracted. When the cue is depicted as active, the Speed Brake shall be positioned in the flight detent position. This cue is always accompanied by the "LVL CHG idle"-cue for the autopilot mode.

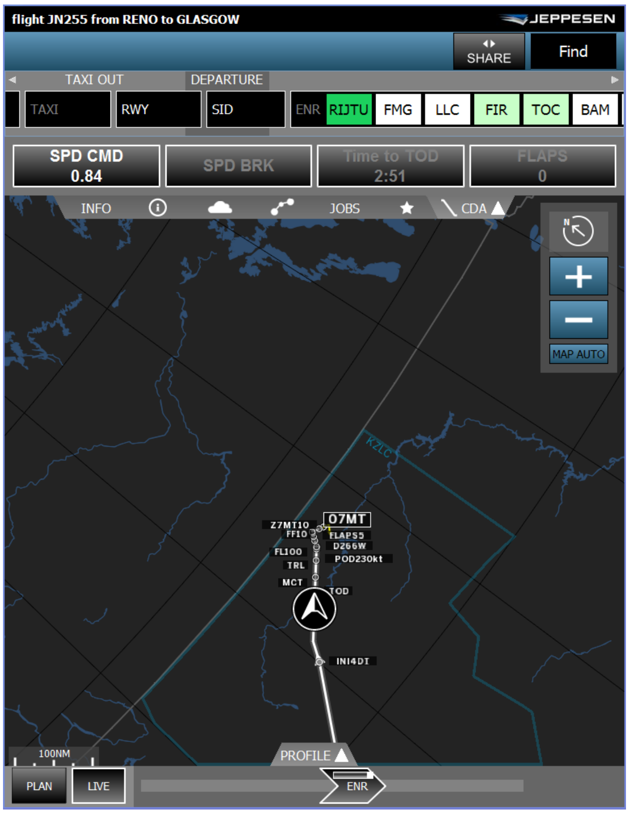

Figure 6 Guidance Bar indicates current speed setting and the time to the Top of Descent

The Autopilot mode cue has three functions. Before the TOD is reached, a countdown to TOD is shown as depicted in Figure 6. Once the TOD is reached, the nominal setting of “LVL CHG idle” is depicted as active. In Figure 7 a changed Vertical Speed (V/S) cues is depicted. This cue stays in the changed mode until the vertical deviation is minimized and a “LVL CHG idle”-cue is depicted as active. Auto throttle is always active, and actively reduced to idle position when the “LVL CHG idle”-cue is active.

The Flaps cue is inactive for most of the descent. The cue becomes changed, and after the cue has been followed active, near the flaps extension point of the reference Trajectory modified by the Flaps logic described in section 3.2. Only the first two Flaps settings will be displayed, as the CDA-MP guidance is only used down to 5000 ft. In case of a Boeing 737 aircraft these are Flaps 1 and Flaps 5.

Figure 7 Guidance requires a V/S of -500 ft/min to catch back the Trajectory

In addition to the direct guidance cues, operational waypoints are depicted in the approach chart. Figure 7 shows operational waypoints of expected decelerations (for example POD230kt with an expected deceleration to 230 knots), and the expected Flaps deployment points for Flaps 1 and Flaps 5.

5 Evaluation

Extensive evaluation and validation, has been planned and have already been carried out. Two challenges need to be overcome, for an operational system. One is, to have a pilot interface that enables the pilot to operate the system without increasing the workload. The other challenge is the system integration. To build an end-to-end solution requires extensive testing, for it to be operational in a real world scenario.

5.1 Previous Trials

First trials with a Human-in-the-Loop integration of CDA-MP have been carried out by BR&TE in 2009 [10], where the cues where depicted to the pilot below the Navigation Display. Extensive Fast-time simulations have been carried out to examine the benefit of CDA-MP operations from an ATM system perspective. A first integration of the current CDA-MP integration was evaluated in desktop, questionnaires and simulator trials as part of a Diploma Thesis [9]. New interface concepts have been designed as part of a Bachelor Thesis [14] to cover additional use-cases of the system. These concepts have been evaluated by questionnaires, and desktop evaluations with pilots.

These trials focused on the human machine interface. To negotiate, calculate and communicate a 4D Trajectory between ground and airborne systems requires an end-to-end integration.

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