

On-Board Decoupled Vertical and Lateral Flight Planning for Minimum Emissions and Population Disturbance

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ABSTRACT

Trajectory optimization methods have been successfully used to minimize pollutant emissions during departure and arrivals, and noise over communities near the airports. This has led to the development, within the CleanSky European research project, of a trajectory optimization framework capable of finding optimal flight paths that minimize emissions, flight cost and noise impact on the population, while still taking into account aircraft limitations and operational restrictions. While this can be very useful when the next generation of trajectory-based air-traffic management systems arrives, as being proposed by SESAR and NextGen, it can still provide benefits in the current context, if implemented taking into account the air navigation rules. This paper describes the optimal control based framework for on-board optimal flight planning, providing an overview of its preliminary human-machine interface, and demonstrates the trade-off that can be obtained by using such a tool when planning a full flight plan for distinct cost criteria.

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INTRODUCTION

The interest in obtaining optimal flight trajectories has significantly increased in the last years, due to the extensive research within NextGen [3] in the United States and SESAR in the European Union, to implement 4D trajectory-based operations in the near future. The higher flexibility that the airliners and pilots will have to plan each flight is expected to allow the reduction in total flight cost, being it due to lower fuel consumption or reduced time-related operational costs such as crew cost and airport fees. Moreover, as the pressure to reduce the environmental impact of flying increases, there is the possibility that emissions will be also charged to the aircraft operators. This has already been investigated by a recent research coordinated by Eurocontrol [1], which suggests reference values for CO₂ and NO_x emission that can significantly increase operational costs. Another point that could lead to increase in costs is related to aircraft noise, which is expected to be taxed by airports that are located in the vicinity of highly populated communities.

Emissions and noise-abatement procedures are not always obvious to design in an efficient way, and when not correctly designed, can even have a negative impact on the targeted environmental criterion. For example, Koenig et al. [2] evaluated standard procedures such as ICAO-A and ICAO-B,

which are not optimal regarding noise, against carefully designed ones, showing a significant reduction in noise contours. Nevertheless, these designed procedures do not take into account the population distribution near a given airport, therefore still leaving room for improvements, as shown in recent studies [3], [4].

In the search for optimal flight trajectories, several methods have been studied in the past years and successfully demonstrated in specific scenarios, such as noise-optimal departure and arrivals. In the research performed by *Antoine & Kroo* [5], the use of an earlier thrust cutback was able to reduce noise on the standard ICAO noise measurement points by up to 3dB, while *Visser & Wijnen* [6, 7, 8] have shown that a combination of thrust cutback and lateral deviation can achieve an even more significant reduction of RNAV departure and arrival's noise (in this case, when accounting for sleep disturbance). Their work further developed into a trajectory optimization tool, as described by *Hartjes & Visser* [9, 10, 11], on which one is able to carefully implement and design departure, arrival and full flight trajectories. Also, improvements to noise optimal trajectories have been proposed by *Prats & Puig* [12], whose work took into account a time-of-the-day disturbance component based on fuzzy logic, leading to different optimal trajectories

$$\begin{aligned}
 t &\in [t_0, t_f] \\
 \dot{x}(t) &\equiv f[x(t), u(t), t] \\
 p[x(t), u(t), t] &\in [p_{\min} ; p_{\max}] \\
 \phi[t_0, x(t_0), t_f, x(t_f)] &= 0 \\
 x(t_0) &\in [x_{\min,0} ; x_{\max,0}] \\
 x(t_f) &\in [x_{\min,f} ; x_{\max,f}] \\
 x &\in [x_{\min} ; x_{\max}] \\
 u &\in [u_{\min} ; u_{\max}]
 \end{aligned}$$

This OCP problem is tackled using a direct approach (refer to *Betts* [14] for more information), in which the continuous problem is transcribed into a discrete optimization problem with algebraic constraints. This work uses the Radau pseudospectral method as implemented by the open-source MATLAB toolbox GPOPS [15, 16, 17, 18, 19, 20]. In this toolbox, states are interpolated using a basis of Lagrange polynomials collocated at the Legendre-Gauss-Radau nodes. The optimization problem is then solved numerically using a non-linear programming solver (both SNOPT [21] and WORHP [22, 23, 24] NLP solvers are used within this tool).

Flight Planning Formulation

Previous studies formulated aircraft flight plans by considering together waypoints, altitude and speed *gates* when implementing the multiple-phase optimal control problem. This leads to a very complex OCP setup, such as shown in [25], in which the operator has to decide beforehand what is the sequence of *gates/waypoints* that the aircraft has to fly through (in other words, should the aircraft climb to a target speed before or after reaching a target waypoint). Not only this brings extra complexity when defining the optimization problem, but also when solving it, as a large number of phases penalizes or even blocks the solver convergence. In that sense, following the already in use principles involved in LNAV and VNAV flight planning, the proposed approach in this work splits the optimization problem into two distinct ones, that is, to find the a lateral trajectory (as shown in Figure 3) that flies over each target waypoint, at the requested orientation - if any - while respecting the aircraft maximum turning rates and rolling limitations, and to find the optimal vertical climbing and descent schedule (as in Figure 7). This approach is explained in more details next.

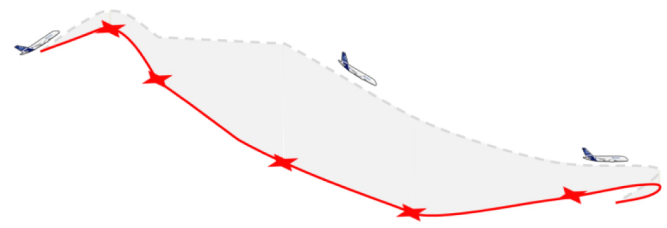


Figure 3. Lateral flight planning

Lateral Flight Planning

For the lateral trajectory optimization, a set of waypoints is required:

- Starting point at the departure runway (from the current database, approximated as the middle of the runway)
- Set of waypoints comprising the departure procedure (e.g. from the Standard Instrument Departure)
- Set of waypoints comprising the en-route flight planning (e.g. from En-Route charts, or the ATC)
- Set of waypoints comprising the arrival procedure (e.g. Standard Terminal Arrival Route charts)
- Set of waypoints comprising the approach procedure (e.g. approach charts for the destination airport)
- Final point at the selected destination runway (from the current database, approximated as the middle of the destination runway)

At each of these waypoints, a crossing tolerance and a heading angle (or range) can be specified beforehand.

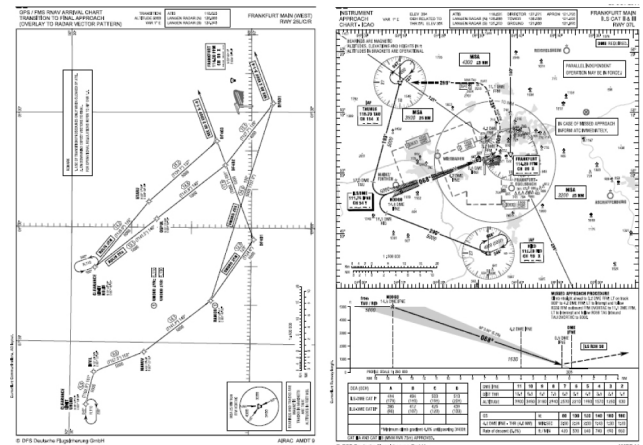


Figure 4. Sample navigation charts used for flight planning

For the lateral part of the flight, a simplified aircraft dynamic model that considers only the lateral flight dynamics on a longitude/latitude WGS84 coordinate system is used. States variables are:

- Latitude φ

- Longitude λ
- Yaw Angle ψ
- Roll Angle ϕ

The control variable used for the lateral trajectory is the rolling rate $\dot{\phi}_c$, selected to allow the use of control regularization to enforce minimum control rates and avoid bang-bang solutions.



$$\left\{ \begin{array}{l} \dot{\phi} = \frac{V \cdot \sin(\psi)}{R_0} \\ \dot{\lambda} = \frac{V \cdot \cos(\psi) \cdot \sec(\varphi)}{R_0} \\ \dot{\psi} = \frac{g}{V} \cdot \sin(\phi) \\ \dot{\phi} = \dot{\phi}_c \end{array} \right.$$

Figure 5. State equations for the lateral flight plan

No-fly zones

No-fly zones here are used to represent prohibited and restricted airspace regions over which the aircraft is required not to fly over - either due to security or other reasons. They are also used to represent weather hazards to be avoided during the flight. The flight planner presented in this work is capable of dealing with arbitrarily defined polygonal no-flying zones. For each zone, a new constraint is added to the OCP formulation that specifies that the signed distance between each node in the trajectory and the closest point in the polygon should be bigger than a given desired tolerance.

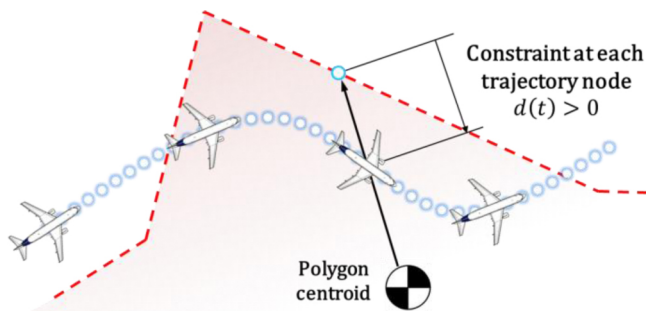


Figure 6. Arbitrary-shaped polygonal no-fly regions

Vertical Flight Planning

Once the lateral flight plan is obtained, the next step in calculating an optimal trajectory is to obtain the sequence of climbing and descent procedures representing the aircraft behavior in the vertical plan. This is normally composed of the initial climbing after take-off, the cruise, descent and approach, as shown in Figure 7. For the vertical plan, the framework provides a set of actions that are added to the flight plan, in the sequence desired by the operator:

- Climb to [...]
 - Descent to [...]
 - Accelerate to [...] TAS/CAS/Mach
 - Decelerate to [...] TAS/CAS/Mach
 - Cruise at [...] or between [...] and [...]
 - Extend flaps at [...]
 - Retract flaps at [...]
 - Keep below altitude [...]
 - Keep above altitude [...]
- These actions can be combined with one condition related to the original lateral flight plan, using one of the following:
- Before waypoint/distance
 - After waypoint/distance
 - At waypoint/distance

Also, rules can be specified for either climb or descent phases, such as “Keep below [...] TAS/CAS/Mach until [...] altitude”, or “Minimum Climb Gradient [...]”.

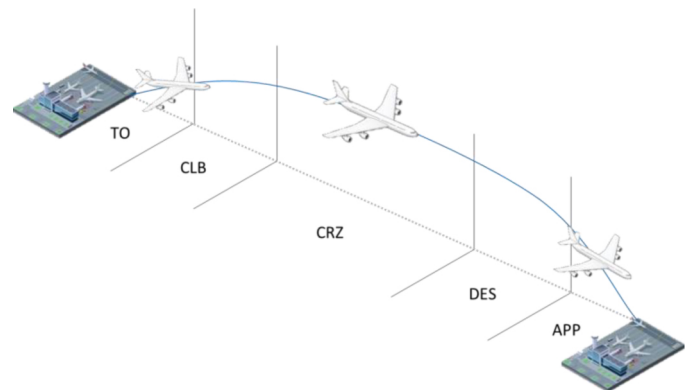


Figure 7. Phase composition for the vertical flight plan

Following this formulation, a typical flight plan represents an aircraft starting at the 35ft AGL screen height, V_2+5 knots, flaps set for take-off, and continues through the flap retraction schedule at VF and VS, then to the altitude(s) defined at the SID, continuing then to cruise altitude and speed. Next, the aircraft starts its descent, reaching the first fixed altitude from the STAR/Approach charts, and the following the arrival and approach procedures. The final flight segment represents crossing the -3° glideslope (see Figure 8), and this part of the flight is not considered for optimization, as there are no degrees of freedom available and the pilot follows a fixed procedure until landing. Therefore, the last action for the vertical flight plan optimization should be the crossing of the glideslope at the desired distance/altitude.

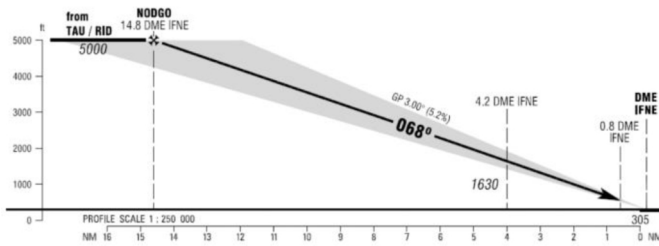


Figure 8. Sample of a final arrival segment, where the aircraft must cross the -3° glideslope short before landing

For the vertical part of the flight, a simplified aircraft dynamic model that considers only the vertical flight dynamics on a distance/altitude coordinate system is used. States variables are:

- Distance s
- Altitude h
- Speed V
- Flight Path Angle γ
- Throttle Γ
- Climb Rate CR

The control variable used for the lateral trajectory are the vertical acceleration $\dot{C}R$ and the throttle rate $\dot{\Gamma}$, selected as well to allow the use of control regularization to enforce minimum control rates and avoid bang-bang solutions. The control state is augmented with a speed-brake control variable that increases the aircraft drag by a specific factor and by a flap/slats configuration parameter fixed for each segment. Speed brake is constrained to be used only when descending in idle throttle.



$$\left\{ \begin{array}{l} \dot{s} = V \cdot \cos(\gamma) \\ \dot{h} = CR \\ \dot{V} = \frac{Thrust(\Gamma) - Drag(h, V, \phi)}{m} - g \cdot \sin(\gamma) \\ \dot{\Gamma} = \dot{\Gamma}_c \\ \dot{m} = -FuelFlow(Thrust, V, h) \end{array} \right.$$

Figure 9. State equations for the vertical flight plan

Standard Procedures Parsing

The current implementation of the framework includes a database of standard procedures, for which a parser between them and the internal representation of the flight plan have been developed and integrated. Although not fully compatible with all the possible flight plan fields, it is able to capture all waypoints specified in the sequence, and identify altitude and speed parameters. As an example, consider the following departure from the Munich Airport, taking off from runway 08R:

SID INPU1E

RNW 08R TRK 081 UNTIL 1900
FIX OVERFLY DM084
FIX DM076
FIX DM065 SPEED 250
FIX INPUD

This sequence specifies that the aircraft should take off from runway 08R, fly in a constant heading of 81° until reaching 1900 ft AGL, then overfly DM084, fly through DM076, keep under 250 knots until flying over DM065 and finally fly to INPUT. The procedure is shown in the chart depicted in Figure 10, while its parser interpretation is shown in Figure 11.

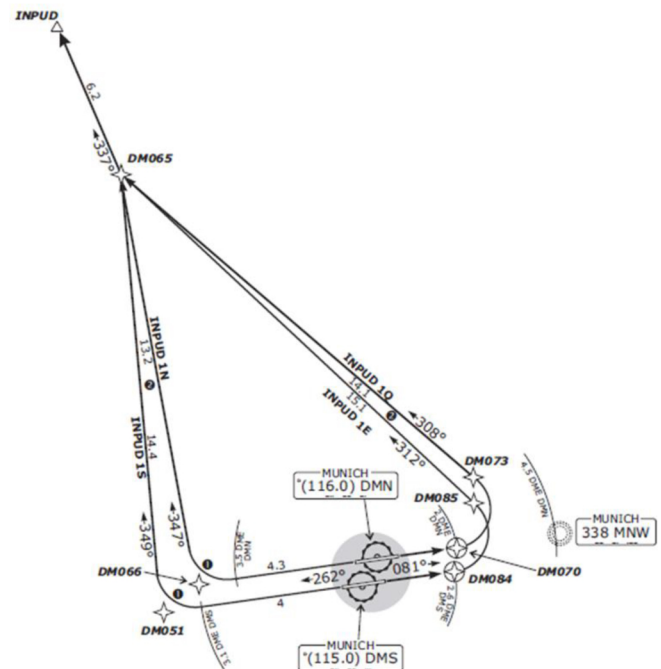


Figure 10. Chart representing the sample INPU1E SID