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PLANNING AND NEGOTIATION OF OPTIMIZED 4D-TRAJECTORIES IN STRATEGIC AND TACTICAL RE-ROUTING OPERATIONS

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Abstract

This paper presents the development of 4-Dimensional Trajectory (4DT) Planning, Negotiation and Validation (4-PNV) functionalities based on multi-objective 4DT optimization algorithms. These novel 4DT management capabilities are conceived for integration in airborne and ground-based Decision Support System (DSS). The ground-based 4-PNV DSS interacts with Next Generation Flight Management Systems (NG-FMS) on board manned and unmanned aircraft, by means of data links. Suitable models are implemented for aircraft dynamics, engine thrust, fuel consumption and pollutant emissions. Sources of real-world aeronautical weather data are also adopted. These elements have been implemented and assessed in the multi-objective 4DT optimisation algorithms of ground-based 4-PNV DSS and NG-FMS.

1 Introduction

Major research and development initiatives around the globe are currently tackling the modernisation of air transport to meet the ambitious objectives set for safety, capacity, efficiency and environmental sustainability in a steadily growing air traffic context. Air traffic is subject to a substantial number of unpredicted events and perturbations, often leading to congestions and delays at airport or to large-scale re-routings. Both of these significantly deteriorate the economic and environmental performances of involved flights, and have the notable tendency of inducing spill-over effects for subsequent flights of the same airline and to interconnected airports. With the growth in demand, it is expected that these issues will be further exacerbated unless the introduced improvements will be successful in enhancing the levels of capacity, efficiency and operational flexibility. In the operational domain, the introduction of innovative avionics and Air Traffic Management (ATM) Decision Support Systems (DSS) featuring higher levels of automation and information exchange will relieve flight crews and ATM operators from low-level workload-intensive tasks while at the same time supporting an informed decision-making for their higher-level and more strategic responsibilities. The technological framework for the development of these innovative DSS is being laid down with the evolutions in Communication, Navigation and Surveillance (CNS) performance currently pursued. Four-dimensional trajectory (4DT) descriptors are a complementary enabler, allowing the exchange the future states of traffic in terms of position and overflight times. The adoption of 4DT descriptors in a Trajectory-Based Operations (TBO) framework is therefore a fundamental step for the enhanced exploitation of the available airspace resources, mitigating the effects of unpredicted disruptions.

Innovative avionics and ATM DSS require new automation-assisted functionalities specifically tailored for the online strategic and tactical TBO contexts, including algorithms for the planning, validation, execution and monitoring of 4DT intents. The dynamics of air traffic, airspace and atmosphere have to be fully considered and implemented in the avionics and ATM DSS algorithms in order to significantly enhance the predictability of future states and the resilience to perturbations, and consequently extend the validity and accuracy of 4DT planning, prediction and monitoring. Consequently, the TBO scenario will see the appearance of 4DT optimization algorithms that will allow integrating multiple operational, economic and environmental objectives. As such, the 4DT optimisation is a key topic of current research and development and a growing application in the ATM and avionics domain. Suitable Human-Machine Interfaces and Interactions (HMI[2]) formats and functions will allow human ATM operators and flight crews to monitor the automated 4DT planning and negotiation processes and amend as necessary the 4DT intents. Although the presented functionalities design mainly targets the TBO implementation stage, opportune arrangements can be adopted to implement high levels of retro-compatibility and this is briefly discussed in section 3. In our assumed datalink-based operational paradigm, the online processes are distributed across Next Generation Flight Management Systems (NG-FMS), the ground-based ATM infrastructure and Airline Operations Centres (AOC). The ATM infrastructure consists of one or multiple Area Control Centres (ACC), regional Air Traffic Flow Management (ATFM) centres and secondary facilities. Each centre/facility *i* is typically tasked with the tactical control of a number of airspace sectors *j*, as well as some level of strategic flow management and airspace management duties. The ground-based 4DT Planning, Negotiation and Validation (4-PNV) ATM system is designed as a distributed and decentralized computational DSS deployed in each centre *i* to assist the human operators while handling different strategic and tactical ATM/ATFM roles.

2 Trajectory planning

Current systems only consider direct operating costs related to fuel consumption and flight time and largely do not take into account the wind field and airspace blockage. The limited optimality set does not allow the mitigation of actual environmental impacts, since neither their dependencies on geographic location, such as in the case of perceived noise and contrails, nor throttle settings, such as in the case of soot, unburned hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NO_X), are captured by current algorithms. The occurrence of unfeasible constraints also requires the implementation of multi-objective techniques such as sequential goal programming. Therefore, the adoption of 4DT planning functionalities based on Multi-Objective 4DT Optimisation (MOTO-4D) algorithms represents an evolution from the conventional flight planning methodologies and their associated limitations. In order to pursue multiple optimality criteria and constraints, the MOTO-4D suite comprises a number of models including an aircraft dynamics model, an operational costs model, emissions models, an airspace model, a contrails model and a noise model. The databases used in conjunction with the noise model are the demographic distribution and digital terrain elevation databases. Traditionally, three degrees of freedom (3-DoF) point-mass flight dynamics models are employed for trajectory optimisation studies, as the improvements in accuracy offered by six degrees of freedom (6-DoF) models are counterbalanced by the presence of short-period instability modes that compromise numerical convergence performance [1]. A general formulation of 3-DoF flight dynamics used in most of our MOTO algorithms assumes variable aircraft mass, constant vertical gravity and the effects of winds and is therefore written as:

$$\begin{cases} \dot{v} = g\,(T/W\cos\epsilon - D/W - \sin\gamma) \\ \dot{\gamma} = \dfrac{g}{v}\cdot\left[\left(\dfrac{T}{W}\sin\epsilon + N\right)\cos\mu - \cos\gamma\right] \\ \dot{\chi} = \dfrac{g}{v}\cdot\dfrac{(T/W\sin\epsilon + N)\sin\mu}{\cos\gamma} \\ \dot{\phi} = \dfrac{v\cos\gamma\sin\chi + v_{w_\phi}}{R_E + z} \\ \dot{\lambda} = \dfrac{v\cos\gamma\cos\chi + v_{w_\lambda}}{(R_E + z)\cos\phi} \\ \dot{z} = v\sin\gamma + v_{w_z} \\ \dot{m} = -FF \end{cases} \quad (1)$$

where the state vector consists of: longitudinal velocity v [m s^{-1}], flight path angle γ [rad]; track angle χ [rad]; geographic latitude ϕ [rad]; geographic longitude λ [rad]; altitude z [m]; aircraft mass m [kg]; and the control vector includes: thrust force T [N]; load factor N [ ]; bank angle μ [rad]. Other variables and parameters include: aircraft weight $W = m\,g$

and aerodynamic drag D [N]; wind velocity v_w in its three scalar components [m s^{-1}]; gravitational acceleration g [m s^{-2}]; Earth radius R_E [m]; fuel flow FF [kg s^{-1}] and thrust angle of attack ϵ [rad]. The aerodynamic drag is modelled as:

$$D = \frac{1}{2}\rho v^2 S\,(C_{D0} + C_{D2}\,C_L^2) \tag{2}$$

where $\rho = \rho(\phi, \lambda, z, t)$ is the local air density retrieved from weather input data grid or a weather model, S is the reference wing surface, C_{D0} and C_{D2} are the parabolic drag coefficients typically available from aircraft performance databases such as Eurocontrol's Base of Aircraft Data (BADA). The lift coefficient C_L can be calculated from:

$$N\,W = \frac{1}{2}\,\rho\,v^2\,S\,C_L \tag{3}$$

The thrust force control variable is most frequently expressed as the product of the throttle coefficient τ (defined as dimensionless and ranging between 0 and 1) and the maximum thrust T_{MAX} as in:

$$T = \tau\,T_{MAX} \tag{4}$$

This allows a natural nondimensionalisation of the control variable. For turbofan aircraft, the following empirical expressions were adopted in the development of BADA, to determine the climb thrust and the fuel flow FF, which operationally equates to the maximum thrust T_{MAX} in all flight phases excluding take-off [2]:

$$T_{MAX} = C_{T1}\left(1 - \frac{H_P}{C_{T2}} + C_{T3}H_P^2\right)\cdot \cdot\left[1 - C_{T5}(\Delta T - C_{T4})\right] \tag{5}$$

$$FF = \max\begin{bmatrix} \tau\,T_{MAX}\,C_{f1}\left(1 + \dfrac{v_{TAS}}{C_{f2}}\right) \\ C_{f3}\left(1 - \dfrac{H_P}{C_{f4}}\right) \end{bmatrix} \tag{6}$$

where τ is the throttle control, H_P is the geopotential pressure altitude in feet, ΔT is the deviation from the standard atmosphere temperature in kelvin, v_{TAS} is the true airspeed. $C_{T1} \ldots C_{T5}$, $C_{f1} \ldots C_{f4}$ are the empirical thrust and fuel flow coefficients, which are also supplied as part of BADA for a considerable number of currently operating aircraft [2]. In order to calculate pollutant emissions as a function of the fuel flow, the emission index EI is introduced as per the following definition:

$$GP = \int_{t_0}^{t_F} FF(t)\,EI_{GP}\,dt \tag{7}$$

where the generic Gaseous Pollutant (GP) should be replaced by the specific one being investigated. While carbon dioxide (CO_2) emissions are characterised by an approximately constant emission index of $EI_{CO_2} = 3.16\,[Kg/Kg]$, an empirical model for carbon monoxide (CO) and unburned hydrocarbons (HC) emission indexes ($EI_{CO/HC}$) in [g/Kg] at mean sea level based on nonlinear fit of experimental data from the ICAO emissions databank is:

$$EI_{CO/HC}(\tau) = c_1 + \exp(-c_2\tau + c_3) \tag{8}$$

where the fitting parameters $c_{1,2,3}$ accounting for the emissions of 165 currently operated civil turbofan engines are $\boldsymbol{c} = \{0.556,\ 10.208,\ 4.068\}$ for CO and $\boldsymbol{c} = \{0.083,\ 13.202,\ 1.967\}$ for HC [3]. The nitrogen oxides (NO_X) emission index [g/Kg] based on the curve fitting of 177 currently operated civil aircraft engines is [3]:

$$EI_{NO_X}(\tau) = 7.32\,\tau^2 + 17.07\,\tau + 3.53 \tag{9}$$

In case the mitigation of radiative forcing associated with condensation trails (contrails) is one of the environmental objectives to be considered, the MOTO suite can include a model such as the one presented in [4].

Figure 1 represents the architecture of the MOTO-4D algorithm used for terminal area 4DT planning, which involves an optimal-control based formulation and exploits a weighted sum, a pseudospectral solution method an operational 4DT smoothing algorithm to translate the mathematically optimal trajectory in a flyable and concisely described one, as discussed in [5].

2.1 Weather input data

Accurate and continuously updated weather data are essential for advanced DSS such as the 4-PNV and NG-FMS. Meteorological data handled by ground-based ATM/ATFM systems

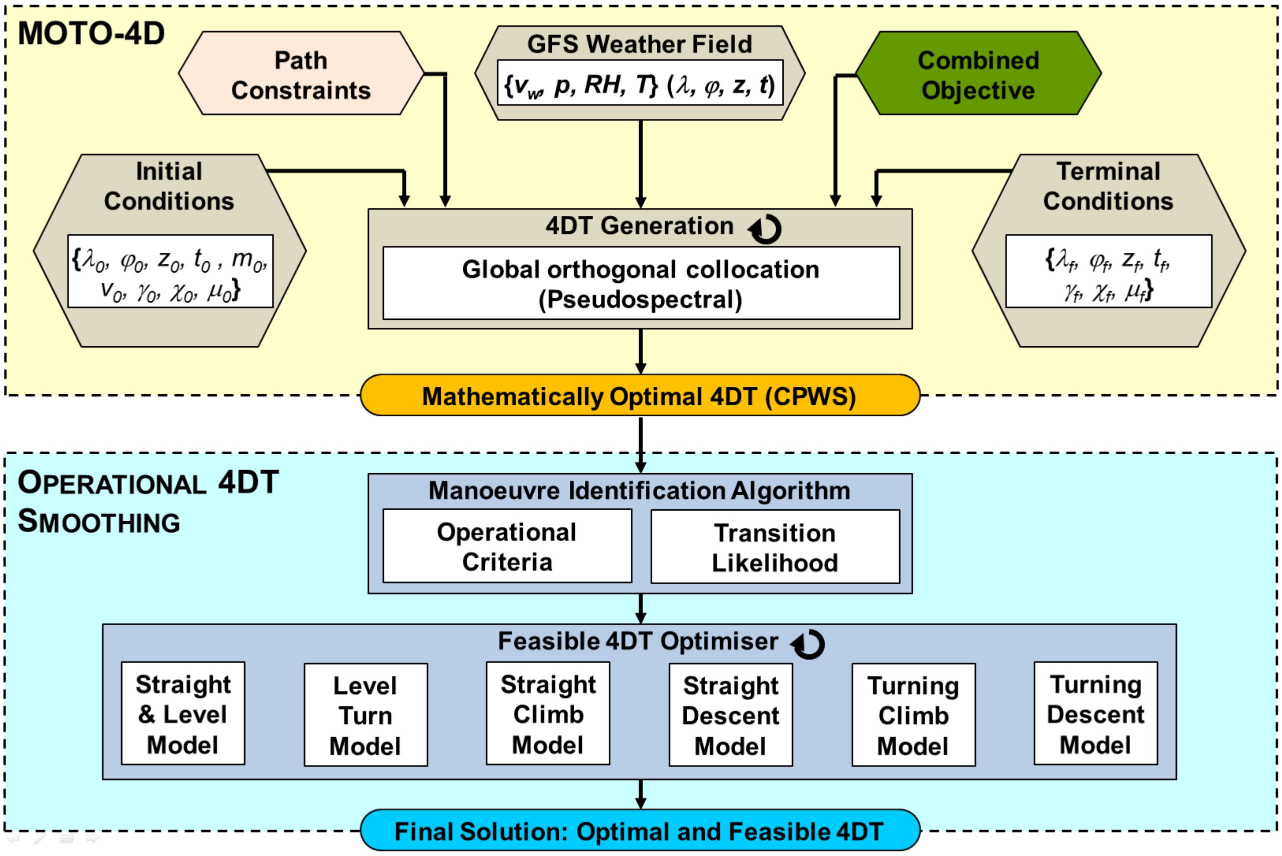

Fig. 1. Block diagram of the 4DT planning algorithm.

shall correspond to data handled by airborne avionics systems as far as practical. This ensures consistency in the 4DT planning and negotiation/validation processes and supports full interoperability, which is an essential aspect for the functional air/ground integration being implemented as part of the technological roadmap. It is therefore useful to consider the most recent standards and planned evolutions of weather data services for aviation and propose their implementation in the ground-based ATM DSS development.

RTCA DO-340 introduces an advanced concept of use for Meteorological (MET) data link services [6]. These are specified in terms of service category, method of delivery and of the weather information involved. The MET services are classified into 2 categories. Category 1 services are the primary means of delivering MET information and may be exclusively relied on to support decisions without questioning their validity, while Category 2 services are useful for making non-critical decisions but should not be relied upon as the sole source of information. Category 1 services comprise both MET and Aeronautical Information Service (AIS) data links. MET data links are used on-board aircraft to provide weather information for supporting flight crew decisions. There are three types of pilot decision support services which reflect the different planning and execution needs of the flight crew: a Weather Planning Decision Service (WPDS), a Weather Near-term Decision Service (WNDS) and a Weather Immediate Decision Service (WIDS). WPDS provides weather information for strategic planning such as in the case of changes in routing or cruise altitude due to ATFM initiatives or destination airport closures. In such scenarios, it is assumed that the flight crew has an advance time of 20 minutes or more to comprehensively evaluate the situation and plan/validate diversions or route amendments. WNDS provides weather information for tactical decision-making such as avoiding hazardous weather cells (including cumulonimbus, icing, turbulence, etc.) especially in terminal arrival/departure operations. In these cases, the flight crew has limited time for replanning and co-ordination with ATM operators, typically between 3 and 20 minutes. WIDS is conceived to provide weather information for freshly detected or quickly evolving weather hazards in order to allow the flight crew to initiate an emergency avoidance or abort take-off/landing. These decisions are assumed to require immediate action from within a few seconds to 3 minutes.

All the services are supported by three delivery modes: Broadcast, Demand and Contract. Broadcast data link delivery service issues continuous regular transmissions of MET information to all aircraft within range. Demand and Contract data links delivery services require two-way communication between the aircraft and ground station, where the flight crew initiates a request for specific MET information which the ground station then responds to. For the Demand service, the ground station only needs to respond to an initiated request, while for the Contract service, the information request is usually pre-coordinated and this requires the ground station to monitor the aircraft and provide the MET information at predefined time intervals or position.

RTCA DO-308 specifies four different categories for MET data formats [7]. These are: point data, area data, vector graphics and gridded data. Point and area data are given in alpha-numeric strings and, as their name suggest, provide weather information on either a single geospatially located point or over an area delimited by a polygonal line. Examples of point data include the conventional Meteorological Terminal Air Report (METAR) and Terminal Aerodrome Forecast (TAF), whereas examples of area data include Significant Meteorological Information (SIGMET). Vector graphic data are images, represented by vectors, points, lines or other geometric entities and can be used to mark out volumes of interest. Gridded data, typically in the form of General Regularly-distributed Information in Binary format (GRIB), consist in a 4-dimensional structured grid (latitude, longitude, altitude, time) of weather data with a forecast time dimension. The amount of MET information exchanged is also dependent on the delivery method. Broadcast services always transmit the full set of weather information, while demand and contract will usually transmit a subset of information based on the initiated request and thus have shorter transmission times. The nature of the decision service also affects the type of information provided. For example, Table 1 shows the information provided by the three pilot decision support services. As WPDS is used for route planning and optimisation, the information transmitted has a significantly longer time horizon than WNDS and WIDS. The geographic extent of WPDS MET data is also significantly larger as WPDS data is conceived for strategic large-scale replanning and diversions, whereas WNDS information is used for local tactical rerouting or altitude changes and might involve higher fidelity and resolution, while these tasks are not supported by WIDS. The profile grid-point data is mainly used for arrival and departure planning and involves MET information along the planned flight profile only. The information provided in WIDS is used for more tactical operations such as Airborne Separation Assurance Systems (ASAS). Hazardous weather information is similar across all the three services, while for airport weather, WPDS and WNDS provide more comprehensive information in the form of METAR, TAF and Runway Visual Range (RVR), while WIDS provides only visibility and wind shear weather data.

Table 1. MET information classified according to decision service [8].

MET Service	Weather Planning Decision Service (WPDS)	Weather Near-term Decision Service (WNDS)	Weather Immediate Decision Service (WIDS)
Time horizon	Greater than 20 mins	3 mins to 20 mins	Less than 3 mins
Profile grid-point data	Offline and strategic online operations	Tactical online operations	Emergency operations
Airport Equivalent	METAR (incl. RVR), TAF		RVR, gusts and wind shear

RTCA DO-324 specifies the Required Communication Performance (RCP) for the service delivery [8]. These are determined in terms of Transaction Time (TT) and can be either the RCP Transaction Time (TT_{RCP}) or the Normal Transaction Time (TT_{95}), both expressed in seconds. A transaction is defined as the basic unit of an interaction between peer parties which includes one or more operational messages that are transmitted from one party to the other. TT_{RCP} is the maximum time for completion of a transaction, while TT_{95} is the time before which 95% of all transactions should be completed. Different TT requirements are defined for airport, terminal and en-route domains. These are tabulated in Tables D7 to D15 of RTCA DO-324 [8].

The recommended quality of MET information is defined in ICAO Annex 3 [9], which lists the desirable accuracies of measurements forecasted data for a range of weather data. A partial list is provided in Table 2, which shows the desired quality of measured data and also the TAF data. The rest of the document also provides recommendations regarding forecast data for general trends, take-off and en-route cases. However, these are not operational requirements but rather desirable accuracy figures to fulfil typical operational needs. RTCA DO-308 also identifies a list of candidate MET products [7]. In particular the Global Forecast System (GFS) used for planning and offline/strategic online optimisation purposes falls under the World Area Forecast Centre group shown in Table 3. The WPDS data described above have been sufficient for flight planning and offline/strategic online trajectory optimisation applications within airborne avionics and ground-based ATM DSS, as the main factors driving the lateral/vertical planning are the 4D wind and temperature fields. Nevertheless, a significant gap is represented by the lack of information regarding weather cells and other adverse phenomena. Consequently, in terms of future CNS+A evolutions, ICAO's ASBU roadmap acknowledges that further improved meteorological services are required to implement advanced functionalities such as the ones involved in 4D-TBO.

Table 2. Recommended quality of MET information [9].

Weather data	**Accuracy of measurement**	**Accuracy of forecast**	
Wind direction	± 10°	± 20°	Minimum percentage within range
Mean surface wind	± 1 knot up to 10 knots ± 10% above 10 knots	± 10 5 knots	80% of cases
Visibility	± 50 m up to 600 m ± 10% between 600 m and 1500 m ± 20% above 1 500 m	± 200 m up to 800 m ± 30% between 800 m and 10 km	80% of cases
Cloud amount	± 1 okta	One okta below 1500 ft Occurrence of BKN or OVC between 1500 ft and 10 000 ft	80% of cases
Cloud height	± 33 ft up to 330 ft ± 10% above 330 ft	± 100 ft up to 1000 ft ± 30% between 1000 ft and 10000 ft	70% of cases
Air temperature	± 1°C	± 1°C	70% of cases

Table 3. Reference global forecast MET data for WPDS [7].

World Area Forecast Centre Information	Data Format	Refresh Rate	Validity (hours)
Wind (Latitudinal and Longitudinal)	Gridded	6 hr	36
Temperature	Gridded	6 hr	36
Humidity	Gridded	6 hr	36
Tropopause – Height, Temperature, Direction	Gridded	6 hr	36
Max Wind – Speed, Direction, Height	Gridded	6 hr	36
Sig. Weather Charts	Vector	6 hr	13

Long-range weather forecasts (such as GRIB and METAR) are already being supplemented by nowcasting techniques for the provision of ATM and ATFM services, particularly in the terminal area. Some of these advanced weather services are already acknowledged by RTCA in DO-308, as shown in Table 4. In particular, the US National Centre for Atmospheric Research's Thunderstorm Identification, Tracking, Analysis and Nowcasting (TITAN) system is an example of a nowcasting system belonging to the NCWF class and used by ANSPs in the US, Australia and South Africa.

Table 4. Advanced METLINK products for flight planning in the USA and Europe [7].

	Data Format	**Refresh Rate**	**Validity (hours)**
National Weather Service (NOAA)			
National Convective Weather Forecast (NCWF)	Gridded/ Vector	5 min	1
Graphical Turbulence Guidance (GTG)	Gridded	15 min	0.25
Current Icing Product (CIP)	Gridded	1 hr	N/A
Forecast Icing Potential (FIP)	Gridded	1 hr	3
WIMS (FLYSAFE)			
WIMS thunderstorm	Gridded/ Vector	5 min to 6 hr	0.2-1
WIMS turbulence	Gridded/ Vector	6 hr	36
WIMS icing	Gridded/ Vector	15 min to 12 hr	0.24-24
WIMS wake vortex	Gridded/ Vector	1 to 6 hr	2-12

Nowcasting provides detailed current weather information extrapolated up to 6 hours into the future, typically with sub-kilometre spatial resolution and a temporal resolution in the order of minutes. Nowcasting systems use sophisticated algorithms to track and extrapolate individual storm cells from weather radar information. Aviation weather service providers are increasingly supplementing this information with satellite imagery and ground-based sensors such as lightning detectors.

The ability to downlink weather data turns datalink-equipped aircraft into mobile weather sensors able to report on the weather in their vicinity. Current-generation ATM systems are capable of receiving this data and exporting it to aviation weather service providers. Such data can contribute to a "4D weather cube", supplementing weather data along major air routes and allowing those sections of the cube that are of the most interest to aviation users to be updated more frequently and more accurately. However, the availability of a near real-time, high-resolution full 4D Weather Cube is not far off. In 2015 SESAR successfully demonstrated a web-services-enabled SWIM implementation of the FAA NEXTGEN 4D Weather Cube concept in their "Optimising trajectories over the 4DWeatherCube" SWIM Masterclass. Further research and development is currently being carried out as part of SESAR's TOPMET project.

The weather model currently implemented in the 4-PNV system processes the global weather data available from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA) and selectively extrapolates the required information on a structured 4D grid. The data currently employed is extracted from the GFS, collected on a 0.25° latitude and longitude resolution grid, updated every 6 hours (4 times daily) and including projection of up to 180-hours in 3-hours intervals.

3 Manual revision by the ATM operator

To facilitate the transition towards progressively higher levels of automation (requiring significant HMI[2] evolutions), an attempt was made to accommodate some of the key features of the 4-PNV in more conventional ATM operator interfaces. The presented concept was developed based on the interactive Sector Package Demonstrator (SPD) prototype of the European ATM Validation Platform (EVP) available as part of EUROCONTROL's Early Demonstration and Evaluation Platform (eDEP) [10]. The SPD interactive prototype also considers non-data-link based negotiation scenarios. A conceptual representation of the ATM operator's tactical display in the instance of a manual review and amendment of the optimal 4DT is given in Fig. 2. The original (active) 4DT of fictitious flight QF005, shown in green and passing through waypoint APL, is no longer feasible due to the formation of a weather cell, represented as a shaded polygon. On ATM operator's request, the 4-PNV automatically computes an optimal avoidance trajectory, represented in pink. The segments of the amended trajectory are represented by different line-types based on their projected time into the future. These are grouped into different bands: a solid line represents segments which are projected 0 to 5 minutes from the present epoch; a dashed line represents segments with a projection of 5 to 10 minutes; a dot-dashed line represents segments with a projection of 10 to 20 minutes; and a dotted line represents segments projected more than 20 minutes from the present. This provides an additional visual cue for the time dimension in the interface. With this visual cue, the ATM operator is able to build an approximate mental image of each 4DT of an aircraft without making reference to the timestamps at each waypoint. Based on expert analysis, the human ATM operator judges that an increased spacing of the avoidance 4DT from the weather cell is required to account for weather forecast inaccuracies. As such, with the help of the Cursor Control Unit (CCU), the 4DT is manually dragged further away from the weather cell, as represented by the light-pink line. The 4-PNV attempts to snap the amended 4DT to the closest waypoint, represented by an empty triangle. The interface identifies a possible conflict in the amended trajectory, due to a crossing of fictitious flight EK141 (the original optimised avoidance trajectory is conflict-free) and flags the relevant segment in red to the operator. The ATM operator then has the option to discard the manually amended 4DT (CANCEL) or to resolve the conflict by making amendments to either flight. Until then, the options of storing the trajectory in the 4-PNV system (ACCEPT), and of uplinking it flight QF005 (UPLINK) are both greyed out.

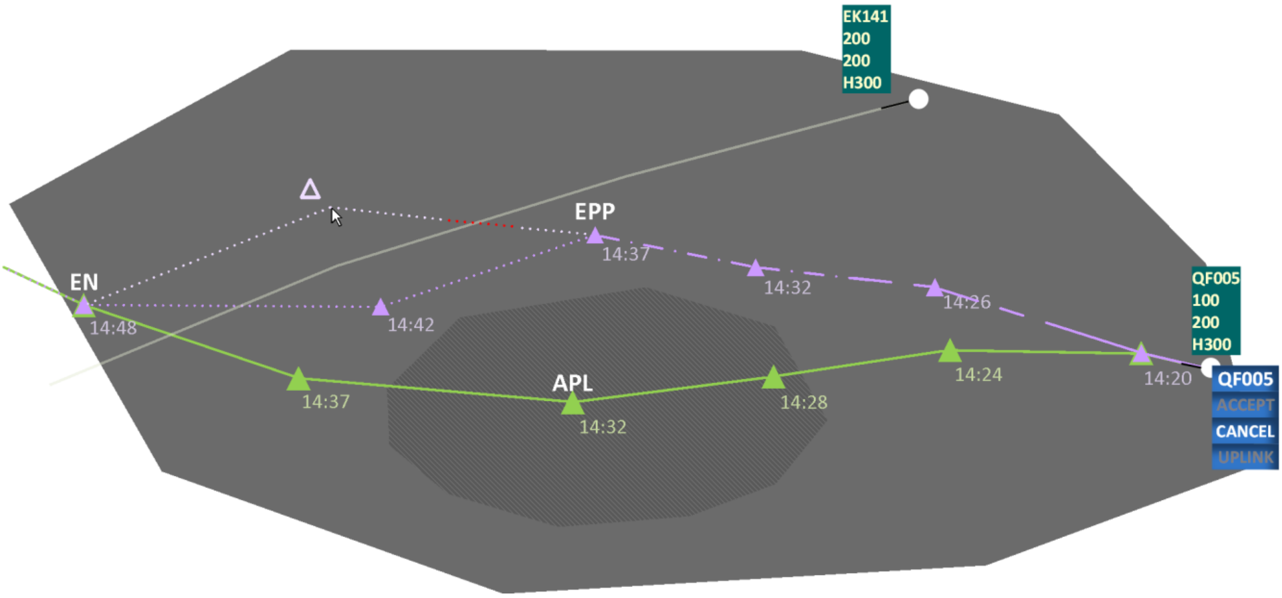

Fig. 2. Manual review and amendment of an optimal 4DT by the human ATM operator.

Once the conflict is resolved, the operator will have the option to either uplink the amended 4DT to the NG-FMS via NG-ADL (UPLINK), or, if data-link trajectory negotiation is not available or is not the active means of trajectory negotiation, he can accept and store the amended 4DT in the 4-PNV system (ACCEPT) and verbally instruct the flight crew of the changes via voice communication. The MOTO functionality can therefore enhance operations of aircraft not equipped with NG-FMS as well. This would limit the maximum number of waypoints (ideally up to 5) that the optimised 4DT can consist of, but ensure a significant retro-compatibility of the 4DT functionalities. A similar review and manual amendment process has been also introduced for 4DT time constraints and for the overall arrival sequence, by implementing similar interactive interfaces on the Arrival Manager (AMAN) display.

4 Simulation case study

The AMAN duty of sequencing and spacing dense arrival traffic towards a single final approach segment was extensively evaluated as a representative case study of online tactical terminal area operations [5]. In the AMAN scenario, the 4-PNV identifies the best arrival sequence among the available options. Longitudinal separation is enforced at the merge-point to ensure sufficient separation upon landing and to prevent separation infringements in the approach phase itself. The 4-PNV is capable of performing point-merge at any metering point. After the initial intents have been stored in the 4-PNV, the point-merge sequencing algorithm allocates the available time slots accordingly. The assumed minimum longitudinal separation is 4 nmi on the approach path for medium category aircraft approaching at 140 knots, therefore the generated time slots are characterized by a 90~160 seconds separation depending on the wake-turbulence categories of two consecutive aircraft. The results of one representative simulation run are depicted in Fig. 3. Fig. 4 depicts the computed 4DT in a distance-time AMAN schedule plot format. Waypoints and lines depicted in magenta represent the flyable and concisely-described 4DT consisting of a limited number of fly-by and overfly 4D waypoints, obtained through the smoothing algorithm presented in [5].

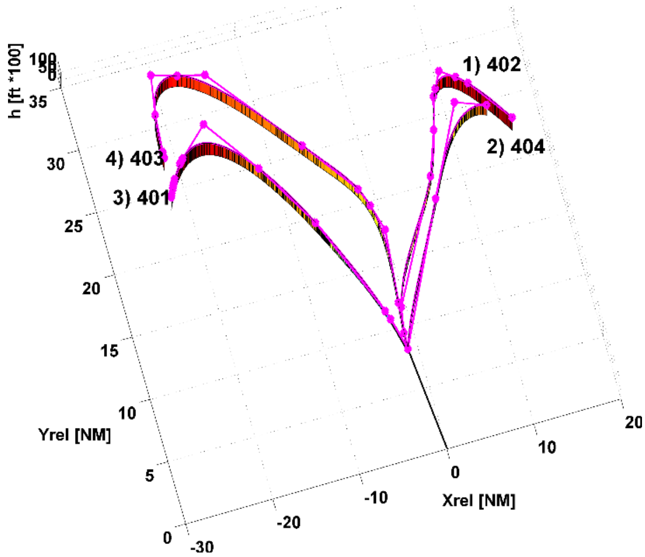

Fig. 3. Results of the 4-PNV in the AMAN scenario.

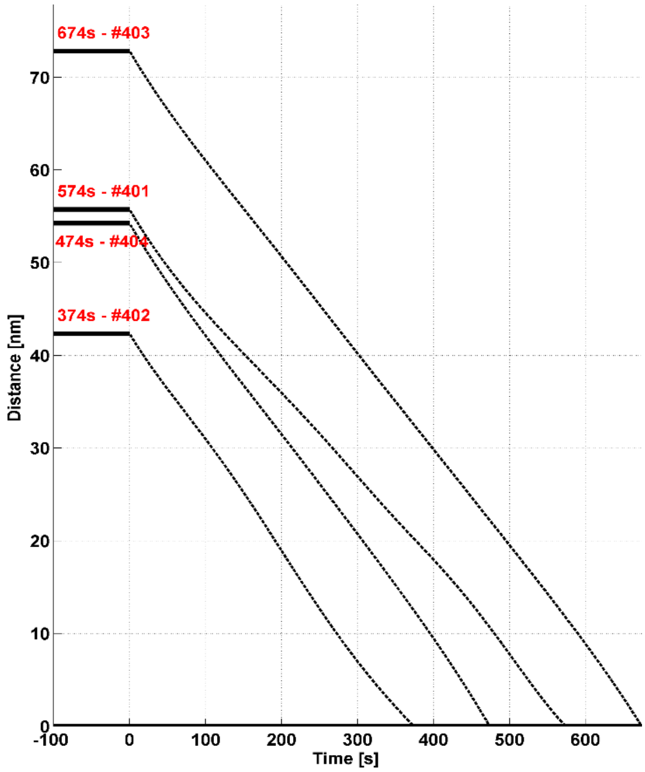

Fig. 4. AMAN Schedule plot of the resulting 4DT.

Monte Carlo simulations have been performed, resulting in an average of 21 seconds for single newly generated 4DT intents and consistently less than 60 seconds. The 4DT post-processing allowed reducing 4DT of 150 to 450 points into a number of fly-by and overflying 4D waypoints consistently below 20. These results meet the set design requirements for tactical online data-link negotiation of the 4DT.

5 Conclusions and future work

This paper presented 4-Dimensional Trajectory (4DT) functionalities designed for integration in novel avionics and ground-based 4DT Planning, Negotiation and Validation (4-PNV) Air Traffic Management (ATM) systems. The 4DT planning functionality is based on a Multi-Objective 4DT Optimisation (MOTO-4D) algorithm. Suitable flight dynamics, fuel flow, engine thrust and emission models and real-time aeronautical weather input data support the MOTO-4D algorithm in identifying optimal 4DT for en-route deconfliction and terminal sequencing and spacing duties fulfilling the requirements of online strategic and tactical ATM operations. Suitable integrity monitoring and augmentation strategies for both strategic and tactical online operations will be developed as part of future research activities [11, 12].

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