A 4D Trajectory Negotiation Protocol for Arrival and Approach Sequencing

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Abstract

Future 4D TBO will require effective air-ground data link communication and negotiation protocols. This issue is especially critical in Arrival and Approach flight phase due to the variability of conditions into a short space-time environment where multiple aircraft simultaneously converge. Besides, several subtasks are closely related with effective air-ground negotiation protocols for 4D TBO in Terminal Areas: predicting accurate arrivals 4D trajectories, performing well established 4D trajectory formats for an effective interoperability between airborne and ground systems, designing efficient real-time aircraft arrival sequencer and scheduler algorithms, etc.

In this paper we propose a 4D Trajectory Air-Ground Negotiation Protocol for Arrival and Approach Sequencing. The Negotiation Protocol has been implemented in an ad hoc multi-agent platform. Based on this proposal we summarize other relevant information that should be incorporated into the 4D trajectory information.

Introduction

Future Air Traffic Management (ATM) is demanding new systems and procedures based on the emergent technologies to increase current efficiency levels and to improve security while reducing the environmental impact of related Air Traffic Operations.

Several ongoing researches are exploring future ATM operations based on 4D trajectory possibilities. These procedures are based on three-dimensional flight plans plus additional temporal restrictions. However a fully transition from current 3D trajectory based procedures to 4D trajectory based operations (TBO) are still under studio, and related issues need also to be evaluated. One of these topics concern to the *Air-Ground Negotiation Protocols*. Designing 4D TBO and their associated air-ground negotiation processes probably presents more difficulties in arrival and approach flight phases due to the variability of the environmental conditions into a restricted airspace where several aircraft are simultaneously descending and converging to landing.

By other hand, obviously outstanding item in 4D TBO negotiation is the 4D trajectory concept itself. Besides a conventional definition of 4D trajectory, other issues must be taking into key aspects order to achieve effective 4D trajectory air-ground negotiation. Therefore, to achieve that main objective, should be considered the following topics:

- To develop a high and fast accurate trajectory synthesizer from both ground and on board systems. Trajectory precision strongly depends on the aircraft performance models as well as on the aerodynamic model, atmospheric and wind model, mainly. Therefore, there is also a need to improve such models.[1, 2]
- To define a standard framework to describe the 4D trajectory in an unique format in order to obtain similar prediction using on board and ground trajectory predictor. That must be accomplished taking into account the models used, aircraft intents, speeds and

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other flight parameters used in each flight sub-phase.[3, 4]

- To establish air-ground protocols to negotiate also considered to negotiate free of conflict user preferred 4D trajectories[5].The main argument into the negotiation process is the 4D trajectory, so it is necessary including a 4D trajectory instance properly formalized.
- Hence, obtaining free of conflict trajectories requires having efficient real-time aircraft arrival sequencing and scheduling systems.
- To design automatic 4D trajectory tracking system and procedures to check in-real-time new 4D trajectory to follow. It requires on board 4D trajectory guidance systems (Flight Management System with 4D guidance capabilities or 4D FMS) and 4D trajectory surveillance ground systems. 4D FMS system computes adequate aircraft control input to provide a 4D effective guidance and also both systems should be capable to detect critical parameters when a 4D guidance failure is produced and therefore a new re-negotiation is required. Also, those systems must detect critical aspects that could even lead to a possible renegotiation of the trajectory.[6, 7]
- To identify and easily extract from the defined 4D trajectory format, all the information needed to supervise it, generate it, negotiate it and track it according with the usual pilot and controllers' workload. The Air Crew and Air Controller need a simplified version of the trajectory properties to allow then identifying decisive aspect of the trajectory for an adequate comprehension and/or supervision on the above mentioned systems during the trajectory synthesis, negotiation, guidance and surveillance processes.[8, 9]

In this paper we present a preliminary scheme for 4D Trajectory air-ground negotiation protocol for arrival and approach sequencing. Besides, in this work we perform a revision of the related works to propose a basic architecture of a 4D Trajectory instance software to account for the above subtasks. 4D Trajectory object is defined as an embedded down-level object linked to an air-ground negotiation protocol to optimal (minimal delays) aircraft sequencing for a descent and terminal approach flight phase.

The negotiation protocol has been designed and implemented on an agent based air traffic simulator developed under a *Java Agent DEvelopment Framework (JADE)* Platform[10]. JADE simplifies the implementation of multi-agent systems through a middle-ware that complies with the *FIPA (Foundation for Intelligent physical Agents)* specifications[11]. The agent-based air traffic simulator has been developed in order to model situations with multiple aircraft executing their own 4D trajectory and following instructions from a traffic controller. JADE platform has been used due to its extended FIPA Interaction Protocols and Agent Communication Language (ACL) specifications that suits well for the problem under consideration.

The paper is organized as follows. First we provide a functional description of the operational scenario where the air-ground negotiation protocol is projected. Second, the proposed air ground negotiation is discussed. Later on, a review of the required technical supports for the above procedure is provided. Into this summary, special attention is paid on proposing a new formalized 4D trajectory with twofold features: to be used by different based ground and airborne systems and for extracting human compressible information during automatic negotiation processes. Then, implementation of above negotiation protocol in a JADE multi-agent platform is discussed and, finally conclusions and future work are presented.

Functional design of a 4D Arrival Trajectory Procedure

To provide a suitable description of a 4D Air-Ground Negotiation Protocol it is required a previous representation of the operational scenario where the procedure takes in place. Besides, it is necessary to define roles and responsibilities of the involved agent in the procedure: the ATC and the Flight Crew (FC).

We, also remark that the proposed negotiation process is an automatic procedure performed by both ground and airborne systems. In this way, ATC and FC human functions consist of supervision of their respective decision make systems and when it is required, they introduce new preferences and restrictions on them. However into the roles and responsibilities concept we include actions performed by both automatic systems and human decision activities.

Operational Scenario

The operational scenario provides an arrival route structure similar to the new Arrival RNAV Procedure [12, 13] where current Standard Terminal Arrival Routes (STARs) are extended until overlaying the airport traffic pattern (figure 1).

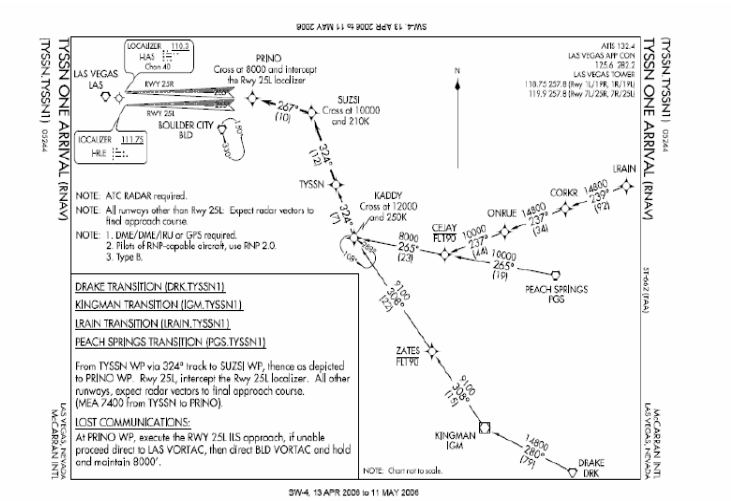

Figure 1: Arrival RNAV chart

The operational scenario is represented in Figure 2. Around this route structure we define the following operational airspaces:

- An inner airspace that is similar to the current *Approach Zone* (or NAS TRACON zone) where aircraft speeds are similar between different types. Radios of this area could be 35-50 NM around the airport. The altitude can be defined between Ground and 18000 feet.
- A second one is similar to the current *Arrival Area* (or NAS Center area), where aircraft usually start the descent phase and where inherent difference in speeds between jet and turboprop aircraft may cause overtakes. Then, in this area we provide descent routes for fastest and slowest aircraft while maintaining lateral separation. Usually this area radio is between 40-200 NM.
- Around the Arrival Area, other airspace has been defined as *Arrangement Area*. Lateral boundary of this area is defined in terms of the time to the outer meter fix to the arrival zone (i.e. 90 minutes before).

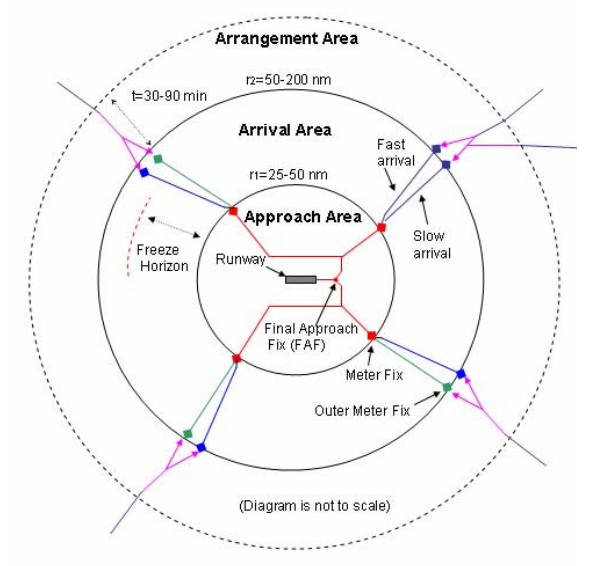

Figure 2: Operational scenario

This area is used to negotiate initial arrival trajectories. Arrangement area is, also, divided in several time-intervals (see figure 3). These intervals are delimitated by the following elements:

- *Limit Time to Request Trajectory (LTRT).* It represents the boundary of the Arrangement Area. All aircraft must send to the ATC its predicted 4D trajectory before reaching this point.
- *Negotiation segment (NS).* This segment represent the time-segment where the arrival air-ground negotiation is carried out. The initial point of NS *(NS-IP)* is used by the ATC as time-limit reference for the initial assignment of the trajectory to the aircraft. The end point of the segment *(NS-EP)* is the time limit where all negotiation must finish.
- *Adaptation Segment (AS)*. This segment is located after the NS and finalize when the aircraft reaches the outer meter fix to the arrival area. AS segment by the aircraft to

achieve the RTA to the outer meter fix, according with the 4D negotiated trajectory.

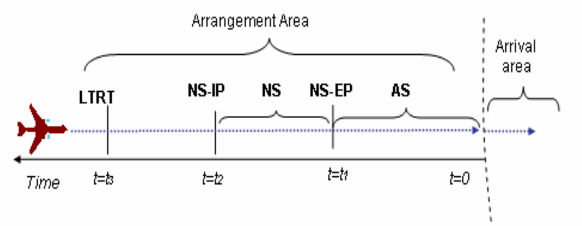

Figure 3: Arrangement area

Finally, due to variability of environmental conditions during the arrival phase (mainly weather conditions) it would be necessary later air traffic control actions in order to solve conflicts derived from unexpected changes along aircraft predicted 4D trajectory. Automatic decisions taking about those control actions are not an easy task to deal with and they are beyond of this paper goal. Some authors (i.e. [14]) have proposed tactical actions based on a fuzzy logic approach. However, in order to minimize tactical control in the Approach zone, it could be convenient to develop new strategic actions by means of a second negotiation process *(Approach Negotiation)* performed before aircraft arrival to the mentioned zone. According with previous work about aircraft scheduling in Approach zone it has been defined a new time boundary *(Freeze Horizon)* between the outer meter fix and the meter fix.[15] Freeze horizon is used as a new time limit into which the ATC control could initiate a new ground-air negotiation in order to alter aircraft Scheduled Times of Arrivals (STAs) to the meter fix and others merging points into Approach area.

Approach Negotiation could be also required when aircraft come from near airports that are placed after to the *LTRT*, so aircraft need to fly directly to the meter fix.

Fly Crew and ATC Roles and Responsibilities

During the mentioned procedure the Fly Crew (FC) uses on-board systems to compute the preferred 4D trajectory. This trajectory is computed taking into account updated meteorological conditions and active arrival routes. This information has been previously obtained from an Aeronautical Meteorological Service and from an Air Navigation Resort Service respectively.

Then, in order to obtain clearance to perform the arrival procedure, the FC requests clearance to the ATC before the *LTRT*. Into this application message, FC sends its preferred trajectory which includes a matrix indicating predicted aircraft position versus time, as well as other associated data (navigation data, aircraft performance constraints and preferences, etc.).

The ATC receives the above data broadcasted from aircraft in order to compute optimal aircraft sequencing to the airport. As a consequence of this task, several aircraft will have to modify their Estimated Time of Arrival (ETA) to the different waypoints in the routes in order to reach them at specific STAs. In such cases, the ATC proposes a new 4D trajectory for each aircraft under these new constraints. This information is communicated to each aircraft before reaching the *NS-IP*.

The new 4D trajectory proposed by ATC will be checked by on board systems in order to determine if they are operationally acceptable. If that is the case, the aircraft will follow previous instruction. In other case a new aircraft proposal will be re-negotiated. Also a re-negotiation will be performed if the airborne system finds a better 4D trajectory that the one previously proposed by the ATC. The trajectory proposed by the aircraft will be evaluated by ATC and if it matches all constraints – especially safety restrictions- it will be accepted.

Furthermore, ATC is responsible of initiating an Approach Negotiation to modify previous aircraft scheduling into to the Approach zone when new environmental conditions arise and they produce in-trail or merging aircraft conflicts.

Air-Ground Negotiation Protocol

As it was explained before, the proposed Air-Ground Negotiation Protocol consists of an Arrival Negotiation Protocol and, optionally, an Approach Negotiation Protocol. Both procedures are similar, so, for the sake of simplicity, only the Arrival Negotiation Protocol is described in this section.

As a result of the Arrival Negotiation Protocol performed into the Arrangement Area, 4D arrival and approach trajectories are assigned to aircraft. These 4D trajectories start in the outer meter fix and finalize on the runway threshold.

The overall air-ground arrival negotiation protocol is represented in figure 4. Communication process is shown in an AUML (Agent Unified Modelling Language) notation[16] between an Aircraft Agent and the ATC agent.

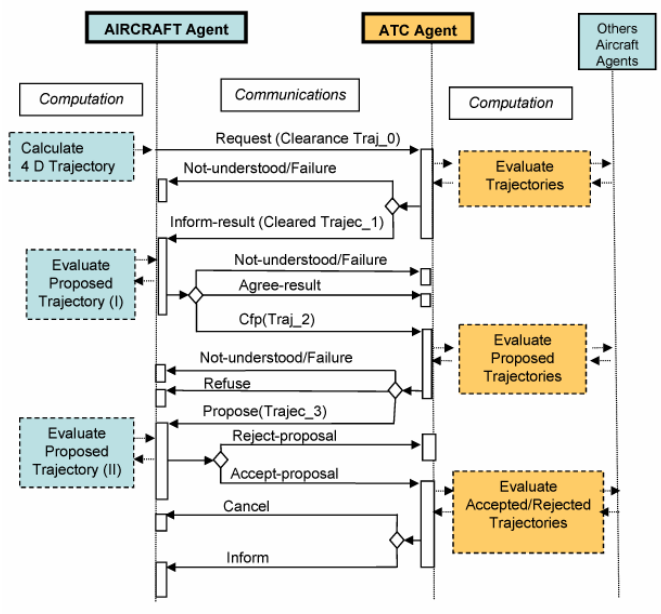

Figure 4: Arrival Negotiation Protocol

On board computation processes are represented on the left side of the aircraft agent *lifeline*. On the right side of ATC agent lifeline we can observe computation performed by ground systems. Moreover, on the right side of the Ground computation system, a new lifeline for others aircraft agents are shown.

The arrival negotiation protocol can be divided into two phases.

- Phase 1: Before reaching LTRT.

In this phase the aircraft calculates its preferred 4D Trajectory (Traj_0). To perform this computation, the aircraft agent uses available information about meteorological conditions and arrival routes. This information is obtained by means of a previous communication procedure (no represented in figure 4) with Meteorological Ground System (or Meteorological Agent) and Navigation Resource System (or Terrain Agent). Once the 4D trajectory is calculated, the aircraft requires clearance to the ATC to execute it. In our simulation agent platform, requesting clearance is performed by a normalized *FIPA Request Interaction Protocol*.[16] ATC agent receives Request messages from different aircraft, and they are periodically batch processed. The ATC Agent, after receiving the Request message, computes free of conflicts aircraft 4D trajectory. As a result, the ATC agent informs to each aircraft about the trajectory to be tracked (Trajec_1). This trajectory can coincide with the initially preferred by the aircraft or can be a new one. If the aircraft is agreed with previous information, it sends to the ATC a corresponding message and the communication process finalizes. But if the aircraft wish to flight an alternative trajectory (i.e. a faster one), the negotiation protocols continues in a second phase by means a *FIPA Contract Net Protocol* which is initiated with Call For Proposal *(cfp)* message.

- Phase 2: Call For Proposal

In this phase, the aircraft makes a proposal and tries to obtain a better trajectory that the one offered previously. This proposal consists of a specific new 4D trajectory or a set of preferences defined as faster and slower trajectories. This proposal (Traj_2) will be evaluated by the ATC. If Traj_2 proposal alters any trajectory that has been accepted by others aircraft in the previous phase, it will be refused. In other case, a new trajectory will be proposed to the aircraft (Traj_3). In such a situation, Traj_3 proposal is evaluated by the aircraft and as a result, a rejecting or accepting air-ground message is sent. Finally, accepted and rejected proposal groups are analyzed to evaluate whether they are free of conflict or not.

ATC Agent decision process

ATC decisions processes performed by the ATC agent during the above negotiation protocol are represented in figures 5-7.

Figure 5 shows a flow chart of the ATC *Evaluate Trajectory* Process. According to it, initial aircraft proposal are accepted if there are no conflicts. When conflicts arise, a Trajectory Synthesizer computes new free of conflict trajectories, taking into account previous outputs provided by Aircraft Scheduler. Aircraft Scheduler provides Scheduled Time of Arrival (STA) to different point of the arrival and approach route (mainly STAs to the outer meter fix, meter fix, merging fixes, final approach point and runway threshold).

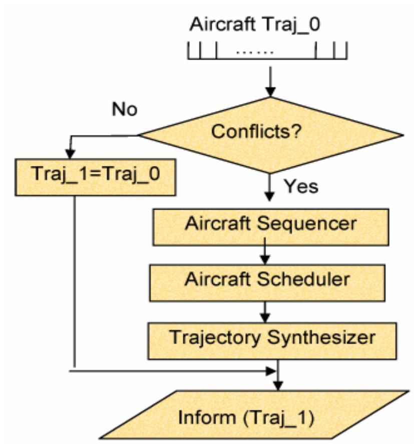

Figure 5: Evaluate Trajectory

Figure 6 illustrates the main tasks carried out by the *Evaluate Aircraft Proposed Trajectory* module, when a call for proposal is performed. In this schema, aircraft proposed trajectories are initially compared with trajectories accepted by others aircraft in phase number 1. If there are no conflicts between them, Traj_2 will be accepted. By other side, Traj_2 will be refused when proposed trajectories or possible solutions for solving conflicts between them, affect to previously accepted trajectories. In other case ATC proposes a new solution.

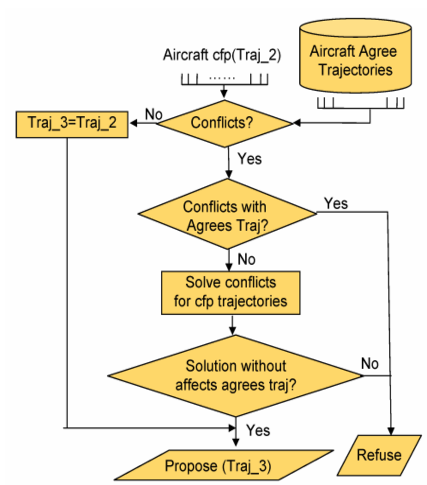

Figure 6: Evaluate Proposed Trajectory

The above ATC proposal will be evaluated by the aircraft by means of the *Evaluate Proposed Trajectory (I)* module. This module, that will be explained later, produces a rejection or acceptation according with aircraft operational priorities. Therefore, aircraft rejecting their respective proposal will execute Traj_1 as it is deduced from Negotiation Protocol. Additionally, aircraft accepted trajectories need a new ATC evaluation to confirm if there exists any incompatibility between them and rejected trajectories. This evaluation is shown in figure 7. In this scheme, accepted and rejected trajectories are treated into two different groups to find possible conflicts between them. If there isn't any conflict, then the ATC confirms Traj_3 to respective aircrafts (Inform-result). But if any conflict exists between one of these and some of the trajectories assumed by aircraft that rejected last ATC proposal (trajectories type Traj_1), then, initial ATC proposal will be cancelled and the aircraft assumes Traj_1. Otherwise, ATC confirms Traj_3 to aircraft.

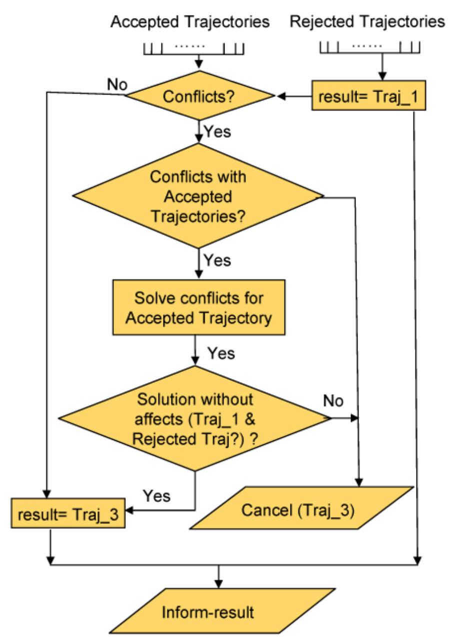

Figure 7: Evaluate Accepted/Rejected Trajectory

Aircraft Agent decision process

Additionally, schemes used by the aircraft to evaluate ATC proposal represented in two separated modules. The first one (figure 8) is responsible for evaluating Traj_1 (phase 1 of the negotiation protocol). The second one is responsible for evaluating proposal carried out by the ATC in the second phase of the negotiation protocol (figure 9).

Evaluation represented in figure 8, consists of determining if ATC proposed trajectory, Traj_1, is in agreement with initial trajectory, Traj_0, or with on board operational priorities (i.e. Cost Index or others factor as punctuality, etc.). If that is the case the aircraft accepts Traj_1. In other case, it computes a new preferred trajectory to initiate the call for proposal.

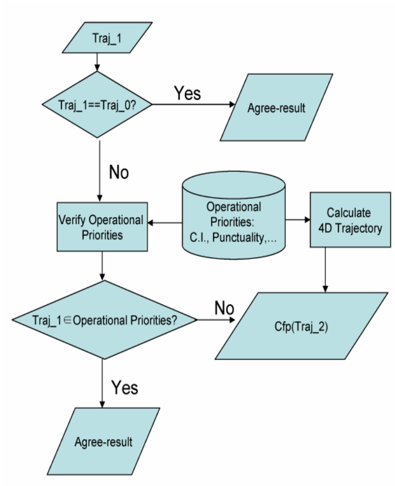

Figure 8: Evaluate Proposed Trajectory (I)

As it can be seen in figure 9, an ATC proposal is either accepted or rejected by comparing it with the initial ATC proposal and operational priorities.

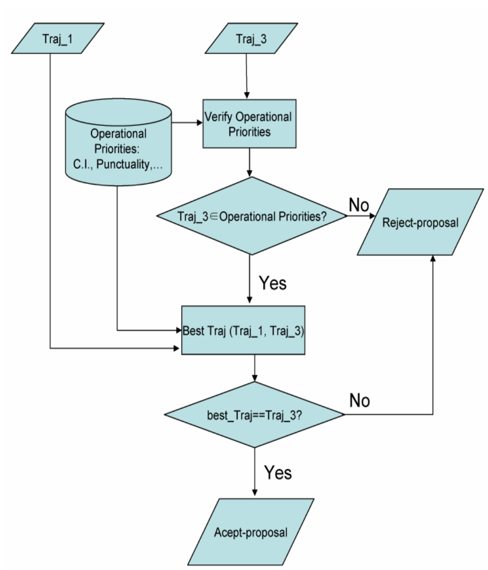

Figure 9: Evaluate Proposed Trajectory (II)

4D Trajectory Based Operations Supports

Both, on board and ground decision making systems for 4D Trajectory Based Operations described in the above section require an underlying technical support. Nowadays, there are several extended tools and sound algorithms normally applied to deal with these technical recourses. However, future researches are pointed out to achieve a fully automatic 4D TBO. In what follows, a complete description of a 4D Trajectory format implemented as a down-level software object linked to the previous negotiation protocol is discussed.

4D Trajectory: synthesis and associated parameters

The most extended procedure to trajectory synthesizing consists of integrating equations that describe the aircraft dynamic. Aircraft dynamic is described throw a flight dynamics model (FDM) and an Aircraft Performance Model (APM).

The flight dynamic of an aircraft can be represented by means of a full 6 degree-of-freedom model[17]. However, to achieve an accurate trajectory at a low computational cost a simplified Point Mass Model (PMM) can be used.[18-20]

By integrating the mass point model –and considering the restrictions given by aircraft performance parameters, operational speed as altitude functions and coordinates of way point routes - the trajectory is calculated. Then trajectory computation under the above constraints can be modelled by three main ways:

a) Defining several restrictions to be captured by the integration process. This procedure, suggested by [20] on a trajectory synthesizer in a ground system, uses a basic point mass equations where several parameters like variable accelerations, mass time-variations, etc. are neglected

b) Using the theory of Differential Algebraic Equations (DAEs), where flight conditions and constraints are modelled as algebraic equations.[4]

c) Identifying flight states by means of a Finite State Machine model. [21]

Models propose by [4] and [21] use the Aircraft Performance Model provided by the Base of Data of Eurocontrol (BADA).[18] BADA offers aircraft performance model that contains performance parameter as well as operational speed parameters for more than 295 different aircraft. Also accelerations, mass variation and navigation parameters are included in the point mass model.

As a result of the above operations a first solution provides information about 4 D Trajectory expressed as:

$$\{Traj\} = \bigcup_{i=1}^{N} \left[\chi(t_i), GS(t_i), RD(t_i) \right] \quad (1)$$

where, χ *(x(t),y(t),z(t),V(t),φ(t), m(t))* represents the state vector of the aircraft given by position *(x,y,z,)*, the true air speed *(V)*, magnetic heading *(φ)*, and aircraft mass *(m)*. In a 4D trajectory, also, others derivate parameters could be added for guidance o surveillance proposes: i.e. Ground Speed *(GS)*, Rate of Descent *(RD)*, etc.

Besides the above information, other relevant aspects must be considered in a realistic 4D trajectory software instance to give consistence to the above negotiation procedure. These issues are the following:

- 4D TBO will require a suitable coordination between both ground-based and on-board trajectory predictors. However, if they are supported under different models, they can produce inconsistent trajectories for the same flight. So it is necessary provide additional information about the PMM and APM used to synthesize the trajectory. Also, constrains used during the integration process must be shared between air and ground systems. Those restrictions can be modelled as aircraft flight discrete states.
- Also considering that human actors are behind of the above process it is necessary, to extract of above information those parameters that facilitate the intervention of the human element in 4D TBO. This information could be extracted from the above one.

To solve inconsistencies between results of different synthesizer models and constraints[4], proposes an Aircraft Intent Description Language (AIDL) that expresses constraints used by the model to compute the 4D Trajectory. These constraints represent information about how the aircraft will be operated within a certain time interval (aircraft intents). The AIDL express constrains for a DAE trajectory synthesizer in high level language. This language could be used to exchange information with others trajectory synthesizer models in order to solving possible inconsistencies between their respective results. Also, this language facilitates a human compression about the process followed by the trajectory synthesizer. This is particularly important into a human-centered paradigm where human actors must understand the process performed by decision-support tools that uses the reefed algorithms.

A similar approach is presented by[19] proposes an aircraft trajectory synthesizer developed as a hybrid dynamic systems. Constraints in the above system are introduced into a System Control that compares the aircraft state vector with a predefined flight plan and operational speeds set. As result of the mentioned comparison, several flight discrete states are modelled as finite states machine (FSM)

Then both, AIDL or FSM estates can be used to define aircraft states or intent into a 4D trajectory instance.

Aircraft Sequencing and Scheduling

Aircraft arrival sequencing and scheduling (ASS) is one of the main tasks that ATC needs to solve to optimize airborne and airport recourses. Currently, there several ATC decision support tools that provides strategic planning for arrivals.

Aircraft sequencer algorithm produces arrival and approach sequences taking into consideration aircraft ETA to the threshold, meter fix and outer meter fix, as well aircraft separation requirements. Then, a based First Came First Serve (FCFS) sequence is performed.[15] Starting from the previous sequence, an optimization process -in order to achieve minimal delays- is carried out by a scheduler module. Scheduler outputs consist of a set of Required Time of Arrival for deferments aircraft and on different fix point along the routes.

Future Air-Ground Negotiation Protocols require similar support tools in order to obtaining free of conflict 4D arrival and approaches trajectories. In this way, sequencer inputs (ETAs) can be obtained from predicted 4D trajectories. Then, RTAs produced by the scheduler can be used as new constraint to compute new free of conflict 4D trajectory.

The above algorithm assumes that number of different conditions (i.e. a determined number of aircraft) is fixed and previously known (static case)[22] .Static case is sufficient for planning purposes but it is limited to account with more tactical control when operational environment changes as time passes and new information becomes available (dynamic case)

On-line optimization considering the dynamic case hasn't been satisfactory solved and different approaches have been provided. However, a partial solution could come from the future airborne 4D guidance systems as it is explained next.

Airborne 4D Trajectory Guidance Systems and Ground 4D Trajectory Surveillance Systems

Future on board 4D trajectory guidance must provide suitable control inputs in order to allow that aircraft can achieve it predicted trajectory when several environmental conditions (mainly wind) changes respect to the predicted ones. In a previous work [7] we proposed a base model to supply 4D guidance capabilities to future Flight Management Systems (FMS). FMS with 4D guidance capacities (4D FMS) provides aircraft control inputs for maintaining aircraft position in such a way that for each instant, t_i, the predicted position and the actual ones remains inside a pre-defined tolerance interval. In this way, if environmental predicted conditions changes, severally and tracking assigned trajectory is unfeasible and the systems provides warnings in order to start a new 4D negotiation

By other hand, ATC surveillance system (i.e. Automatic Dependent Surveillance or ADS) can be used also to determine when an aircraft overloads its 4D trajectory tolerances. When it occurs, the ground systems will start to evaluate a possible conflict and, if it is the case, it will initiate a new negotiation ground-air with implied aircraft.

As it was remarked before trajectory re-negotiation processes required when warning arise from 4D FMS or from ground surveillance system is beyond of this paper target. However, the formalization of the current trajectory will keep in mind the possible parameters of the deviation of the trajectory with the purpose adding them up as arguments in this renegotiation.

4D Trajectory formalization

According with previous analysis a 4D trajectory software instance should be the following attributes in order to make compatible ground and airborne systems as well as extract human readable information during the negotiation process.

Trajectory Synthesizer

Models

- Aircraft Aerodynamic: PMM
- Aircraft Performance: i.e. BADA vers. X
- Flight Intent: i.e. AIDL, FSM, etc.

Inputs

- 3D flight plan
- Speed Segments
- RTAs

Outputs

- State Vector (components)
- Flight Discrete States
- Other Navigation parameter (GS, RD, Track, ETAs/STAs, etc...)

Airborne 4D Guidance System

Inputs

- Predicted 4D trajectory
- Longitudinal Deviation
- Vertical Deviation

Outputs

- Longitudinal Deviation Status (on track, tracking, tracking_out, etc…)
- Vertical Deviation Status (on track, tracking, tracking_out, etc…)

Ground Surveillance Systems
Inputs: longitudinal deviation (distance/time), vertical deviation (altitude)

Outputs

- Predicted 4D trajectory
- Longitudinal Deviation Status (on track, tracking, tracking_out, etc…)
- Vertical Deviation Status (on track, tracking, tracking_out, etc…)

Implementation status

The proposed negotiation protocol has been executed on an ad hoc agent-based air traffic simulator. The simulator has been implemented on a JADE multi-agent platform. JADE is one of the most extended multi-agent development tools and its library recourse provides a set of communication protocols templates that suits in a natural way to the problem under consideration. A more detailed description of this experimental air traffic simulator has been provided in a previous paper. [22] Two main agents have been defined: one for the Aircraft and the other for the ATC.

The overall aircraft behaviour is modelled as a hybrid dynamic system composed of to main modules: one of them represents the aircraft dynamic behaviour and the second ones is a control system. The aircraft dynamic module is represented by means of mass point model (PMM) *(Glover and Lygeros 2004).* The aircraft performance model (APM) used into the PMM has been obtained from Aircraft Database of EUROCONTROL –BADA. The system control module computes suitable control inputs to the PMM according pilot requirements or on board predefined 3D flight plans and operational speeds.

The aircraft is provided by the following capabilities: *(i)* On board trajectory synthesizer, *(ii)* Flight Management System with 4D capabilities (4DFMS), *(iii)* A basic set of flight priorities, *(vi)* Air-ground communication.

Airborne trajectory synthesizer algorithm is based on a simplified version of the PMM where accelerations and progressive turns are neglected. It computes 4D trajectories under two main types of restrictions: *(a)* a 3D flight plan plus predefined operational speed, *(b)* a 3D flight plan plus required time of arrival (RTA) to different points into its 3D flight.

The 4DFMS has been described in a previous work[7]. It consists of an entire hybrid dynamic control system that compares the aircraft state vector with the reference trajectory and calculates the necessary control entrances to fit the actual response to the previously estimated one. The methodology first controls the longitudinal deviation. If as a consequence of a longitudinal control, an altitude deviation occurs, this one is also modified either but acting on thrust (to reduce the descent regime) or by using speed-brakes (to increase the descent regime). If this is not enough to fit the trajectory to the reference one, a smooth lateral deviation of the trajectory from the original is accomplished (according to allowed altitudes and other restrictions to consider).

Flight priorities are, at the moment, model as a simple set of random options in order to select trajectories faster and slower than a nominal or a proposed one. Those priorities cover initial proposes to model onboard trajectories preferences in order to prove the negotiation protocol. Obviously airborne priorities would be extended in a more realistic way in future versions.

Air-ground communication is constituted by a set of air-ground messages. Those messages are grouped into several JADE behaviours. As it is known, agents JADE implement their predefined task (behaviours) associated to events. Details about JADE behaviour are provided in.[10]

According with[10], air-ground messages are grouped into the follows type of behaviour:

- Aircraft state messages, where Aircraft State Vector, Navigation Parameters, and Flight State, are sending to the ATC under a JADE *TickerBehaviour* which are executed according with a pre-defined simulation speed value.
- Air-ground negotiation messages contained into the previously described negotiation protocol. Negotiation protocol implemented into event-driven JADE *OneShotBehaviours* which is executed in a single time that starts when aircrafts are going to reach the LRLT point of the Arrangement Area (see figure 6).

- Receiving ATC messages are also implemented, as it is usual on JADE agent programming tasks, by means of *CyclicBehaviour* which is executed continuously.

By other side, ATC agent is provided by the following capabilities: *(i)* An arrival and approach scheduler algorithm, *(ii)* A 4D trajectory synthesizer, *(iii)* Ground-air negotiation communication recourses.

In this work, we will consider the static case, where ATC provides both arrival aircraft scheduling based on the FCFS scheme. Optimization methods are necessary for reducing and achieving efficient arrival and approach sequences. However in this work, delays' minimizing it is not essential task to evaluate the proposed negotiation protocol and its associated 4D trajectory.

The ATC 4D trajectory synthesizer algorithm has identical properties to the airborne one.

Ground-air communication is implemented under the following JADE behaviours:

- Replay messages to air-ground negotiation messages are included into One-Shot behaviours which are initialized every time than an incoming *Request(Traj_0)* or a *cfp(Traj_2)* message is received (see figures 4).
- Incoming messages are captured by two cyclic behaviours. One of them is used to receive aircraft state information. The second one is oriented to receive Aircraft Request o Call For Proposal messages. Both of the previous behaviours are executed concurrently by means of a more complex behaviour, also defined in JADE library: a *ParallelBehabiour*.
- As it was explained, ATC initiates a second negotiation when new corrections in the aircraft scheduling are necessary into the Approach area. Those events are detected by means of a new trajectory synthesis process carried out in an automatic way when algorithms receive air-ground negotiation messages as it was explained before. Both cyclic behaviours are executed in a concurrent way under a *ParallelBehaviou*r.

Finally we remark that described air-traffic is constituted by other two agents not mentioned yet. One of them is the agent Terrain that provides information to the arrival routes characteristics and restrictions according the defined operational scenario (see figures 3 and 4). The second agent is the Agent Meteorology that provides information about the wind and temperature to be used into an atmosphere model contained on the respective aircraft and ATC trajectory synthesizers.

Conclusions and future work

In this work we have presented a scheme for an automatic 4D trajectory air-ground negotiation protocol. The negotiation protocol has been implemented according to FIPA Interaction Protocol Specifications. An agent-based air traffic simulator has been developed under a JADE platform. The proposed negation protocol suggests a base schema for a 4D Trajectory formulation that provides information in order to achieve two main goals: avoiding inconsistent trajectories supplies by airborne and ground trajectory synthesizers and as a second objective, to extract human-readable information from the proposed 4D trajectory in order to allow an on board and on ground compressible monitoring of the negotiation protocol.

In future work, new decisions schemes must be added in both aircraft agent and ATC agent in order to prevent in-trail and merging conflict mainly in Approach Area when real conditions differs from predicted one. As a consequence of those decision processes, the proposed Air-Ground Protocol Negotiation could be extended to include tactical negotiation (mainly in approach and pre-landing flight phases).

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