TPAS: Test-bed Platform for ATM Studies

Sergio Ruiz Navarro, Miquel A. Piera and Jenaro Nosedal
Technical Innovation Cluster on Aeronautical Management
Universidad Autónoma de Barcelona
Sabadell (Barcelona), Spain
Sergio.ruiz@uab.es, miquelAngel.Piera@uab.es, jenaro.nosedal@e-campus.uab.cat

Abstract—To encourage the development of Air Traffic Management (ATM) tools that could consider the full complexity in the Decision making process and avoid the technological gap between research and ATM practical application, a test-bed based on a global “discrete event” view of the dynamic system has been developed, for a better understanding of the emerging dynamics that cannot be understood without a global 4D micro-scale perspective of the full ATM system. The platform has been evaluated in several European scenarios, providing with a natural framework for the evaluation of new ATM concepts developed by different research and practitioner teams.

Keywords-component; test-bed; Spatial Data Structures; discrete-event modelling approach; ATM; Emerging dynamics

I. INTRODUCTION

In this paper it is introduced the Test-bed Platform for ATM Studies (TPAS), a kernel with several functionalities given through an Application Programming Interface (API) which supports the construction of meaningful benchmark problems and relevant test-cases with an interactive environment simulating the full European ATM airspace (approximated by latitudes interval [30, 70], longitudes interval [-20, 30] and Flight Levels interval [FL100, FL460]).

The idea is to offer to the scientific community a simulation platform with several tools that are integrated in a single modeling framework in order to facilitate the fast prototyping of new ATM concepts and the test of new Decision Support Tools through a modular application approach in which the different ATM research teams can test their algorithms (by means of TPAS’s API functionalities) and check the shortages and benefits with respect to other approaches through the use of some implemented and available metrics.

TPAS has been designed to provide a computer-based test-ben environment for the development and evaluation of new ATM tools as well as the verification of new ATM concepts that may contribute to a better understanding of the ATM system. TPAS can efficiently manage, represent and store ATM information of micro-level objects (such as 4D trajectories either in SBT or RBT format, airspace data and weather information) with a global and n-dimensional view (thus potentially extending the simplified 4D ATM model assumed in this paper). This can represent a key contribution for ATM researchers and users since this framework shall enable the observation and management of the potential emergent dynamics appeared in the network as a consequence of the decision-making processes that are based on a narrowed local-level perspective. One example can be found in some conflict resolution procedures of Air Traffic Control (ATC) that do not consider the effects of a trajectory resolution maneuver downstream in other sectors [4, 14].

It is well accepted by the ATM research community that there is a strong need for the design and development of realistic, relevant and common test framework [1, 6]. This paper intends to provide the ATM research and practitioner community with a clear motivation through the illustration of relevant benchmarking issues using a test bed platform that can consider the impact of the local decisions at global/network level.

In Section II an overview of the TPAS system is presented, while in Section III a detailed description of the system core and extra modular functionalities is given. Section IV presents a set of case-studies in which TPAS has shown its utility, and finally Section V summarizes the conclusions and next steps of the paper.

II. OVERVIEW OF TPAS

To facilitate the creation and verification of new ATM concepts and tools, TPAS has been designed with a modular approach that supports the integration of external tools, through a set of APIs that include several primitive functionalities (e.g. create and parameterize aircraft/flight, create routes/flight-plans and assign them to aircraft/flights, generate a 4D trajectory from a route/flight-plan, load a 4D trajectory from a file and assign it to an aircraft/flight, compute geodesic or loxodromic distances between waypoints, etc.) and different already integrated tools that may help to perform several kinds of ATM studies (e.g. conflict detection tool, clusterizer tool, temporal looseness calculator).

TPAS can be used as a standalone tool to facilitate the development process of new ATM tools, but also as a benchmarking platform supporting pre-loaded real traffic scenarios (e.g. European and/or US traffic patterns) to compare homologous ATM tools developed under different approaches.

TPAS has been programmed in C++ and it is multiplatform (i.e. it can be run under Windows, Mac, Unix, etc.). It supports 32bit and 64bit CPU architectures, and thus it can be configured to manage large amount of data that is stored (for efficiency purposes) in main/RAM memory.
III. TPAS ARCHITECTURE AND FUNCTIONALITIES

The system architecture developed is illustrated in Fig. 1.

A. TPAS core

1) Spatial Data Structure and State-Space storage

A Spatial Data Structure (SDS) is a database that represents a spatial region (i.e. an airspace or air sector) by using individual memory positions to represent each of the discrete (3D) coordinates of the sector. Such memory positions are sorted in a way that, given a certain coordinate, the information stored inside the SDS (associated with such a coordinate) is easily recoverable by applying simple mathematical formulas \[8, 10, 11\].

The use of SDS allows the storage of the entire State-Space (SS) description of the traffic and other ATM variables (e.g. a 4D trajectory, or the weather), including its evolution over the time. Therefore, the use of SDS contributes to have a precise 4D micro-scale representation of the current and future ATM states (probabilistic/stochastic future states are also supported to manage uncertainty). Such a representation is stored in the computer memory (main memory for efficiency purposes) like a “4D snapshot” which is a key contribution since it provides with a global discrete event (4D) view of the dynamic system.

Another key aspect of the SDS is its highly efficient updating/refreshing frequency, which is an important factor to tackle some aspects of the ATM uncertainty, specifically when considering the ATM at strategic/pre-tactical levels where the prediction uncertainty is bigger. The capability of the algorithms based on SDS to run in real-time (i.e. with an updating rate fast enough for practical ATM purposes), allows a continuous rolling process that may contribute to reduce the negative impacts of uncertainty during the ATM planning activities, by updating the SS with the most accurate information available for the decision-making process. For instance, consider any kind of individual perturbation (e.g. trajectory deviations) or network-level perturbations (e.g. convective weather, volcanic ash…) that cannot be predicted with precision beforehand: then, the sooner the current/actual states of those events are updated and known the better the re-planning decisions can be made.

The SDS (although implemented as a big one-dimensional array stored in RAM main memory, for efficiency purposes) can be conceptually drawn as a table containing as many rows as coordinates are in the modeled airspace, and as many columns as aircraft/trajectories will be processed. Fig. 2 illustrates an example of SDS content.

Different Geodesic models are allowed in TPAS, including UTM (Cartesian coordinate system), FAI (sphere) and WGS84 (ellipsoid).

2) Information Manager

The Information Manager (IM) is in charge of the efficient management of the objects Aircraft, Routes, Trajectories, and any other ATM information required in the models under consideration. Specifically, the IM module is in charge of the:

- Management of aircraft/flight information
- Management of original trajectories/flight plans
- Management of alternate trajectories/flight plans
- Calculate 4D trajectories from the routes/flight plans
- Add ATM information to the SDS (e.g. 4D trajectories)
- Delete ATM information from the SDS (e.g. 4D trajectories)
- Extract ATM SS information from SDS (e.g. conflicts, temporal looseness, complexity map…)
- Management and classification of ATM SS information (e.g. temporal sorting of conflicts, computation of basic metrics…)
- Coordination of modules functionalities

A flight can have different alternate planned trajectories to be considered during the ATM network planning. Therefore, the IM and the other TPAS modules (e.g. the CD, CR…) require a method of identification for the trajectories associated
to the same aircraft/flight. TPAS provides with efficient methods for such trajectory identification [8].

![Figure 3. RTSDS-based CD runtime performance](image)

### B. TPAS modules and functionalities

The basic functionalities of the TPAS core can be used to implement extra modules with high-level functionalities. The following useful modules are delivered in the default version of TPAS.

#### a) Conflict Detection module

Taking advantage of the SS stored in the SDS, the conflict detection (CD) process can be run with linear or near-linear temporal complexity, O(n), thus having the ability of processing thousands of trajectories in a few seconds [8, 9, 11].

A linear temporal complexity is especially desirable during the Strategic De-confliction of a large number of 4D trajectories (e.g. thousands) during large look-ahead times (e.g. 2 or more hours). Fig. 3 illustrates the performance measured using a version of this CD module (i.e., RTSDS-based CD) and is compared with a simple (i.e. without any kind of trajectory filtering) pairwise CD algorithm.

Note that the rapid SDS updating frequency makes possible a rapid CD algorithm, which can contribute to tackle the prediction uncertainty of future states that are not known with precision, e.g. trajectory deviations.

Two different ways of performing conflict detection with a SDS have been implemented in TPAS: (i) using discrete 4D tubes as safety envelopes for aircraft in order to check overlaps among them [11] and (ii) clustering the airspace in order to filter trajectories and thus performing pairwise distance comparisons among a reduced set of 4D trajectories [10]

Using “4D tubes” is often better for detecting conflicts with time-based distance separations whereas the “4D clustered pairwise” is often better for scenarios in which spatial-distance separations are required, but in both cases the intent is to keep the characters (i.e. point-mass positions or discrete surface-tube coordinates) “pre-sorted” in the SDS, based on their location in space, in order to rapidly identify which of them are in a given neighborhood at a given time-step, and perform CD without having to examine the entire population (see Fig. 4).

#### b) Clustering

Conflict Resolution with global optimization is a kind of Non-Polynomial (NP) problem whose complexity (and whose state space size) increases exponentially with the amount of trajectories to be analyzed.

A very efficient way to reduce the size of the solution space is by clustering, i.e. reduce the general problem scenario to several sets of independent (not connected) scenarios that are called clusters. In this way, each cluster has a much more reduced solution space and even the sum of each independent cluster solution space is also smaller than the solution space of the problem if considered as a whole (i.e., without clustering).

Fig. 5 illustrates a graphical representation of the concept in which the general problem is partitioned into several unconnected sets of trajectories.

The clustering method is explained in reference [3] and [8].

#### c) Pairwise Conflict Resolution

TPAS provides with a conflict resolution functionality that works pairwise, i.e. each resolution maneuver is calculated by considering only two aircraft, the ownship and the intruder. The generation of these resolution trajectories is based on Geometric Optimization Approach (GOA) [2]. This technique allows resolving the conflicts by applying different kind of maneuvers such as Heading Angle Changes (HAC), Speed Changes (SC), Flight Level Changes (FLC) or a combination of them (both cooperative and non-cooperative modes are possible).

The mathematical expressions of this model minimize deviations from the nominal trajectory (SBT/RBT), thus the obtained resolution trajectories can be considered “locally optimal” in certain simplified scenarios. However, the global optimality of those trajectories can only be determined after having considered the potential emergent dynamics (i.e. domino effects) of those trajectories from a global network perspective.

As a contribution of TPAS, the GOA algorithms has been adapted for working at large scale distances, considering the curvature of the Earth, which may be of interest for strategic conflict resolution (e.g. dynamic route allocation) [8].

![Figure 4. Neighborhood Search](image)
d) Interaction analysis and domino effects

A resolution trajectory generated for solving a conflict between 2 trajectories could generate new interactions (i.e. upstream or downstream conflicts) that previously did not exist in the network. Also a resolution maneuver could solve original upstream/downstream conflicts that existed before in the original trajectory. These new interactions appearing in the network (or the elimination of pre-existing interactions) are called “domino effects” [4, 14]. When a trial resolution trajectory generates new network interactions it is referred as a destabilizing effect (i.e. negative domino effects), and when they indirectly solve downstream conflicts it is referred as stabilizing effect (i.e. positive domino effects).

These complex ATM emergent dynamics require a global network perspective in order to optimize the air traffic management [3, 4]. These network interactions have been classified within the TPAS context as follows (see Fig. 6):

- **Primary conflict**: a conflict between 2 original SBTs/RBTs
- **Secondary conflict**: a conflict that emerges between a resolution maneuver proposed by CR to solve a primary conflict and a surrounding original SBT/RBT.
- **Tertiary conflict**: a conflict that emerges between 2 resolution maneuvers belonging to any surrounding aircraft.

e) I/O functionalities

TPAS include a module to ease the introduction of data to the core module and the output of the results and any SS information of interest:

- Different input formats: including txt, csv, AIDL designed by Boeing, so6 and All_FT from EUROCONTROL, and also any customized format.
- Input from SWIM: TPAS can be integrated (valid certificate required) with the SWIM communication platform through SOAP protocols, obtaining in real-time the airspace demand (i.e. flight plans) and network state (i.e. weather, availability of sectors…).
- Coordinates in UTM or Geodesic format
- ETD Perturbation Generator: Input trajectories can be longitudinally modified by applying randomly distributed delays/advances to the Expected Time of Departure (ETD), which may be useful to perform Monte Carlo analysis (e.g. to test robustness of a network planning).
- Several ways of introducing a trajectory: the 4D trajectories to feed the SDS can be obtained by loading flight plans and call the trajectory generator TPAS functionality or by directly loading the 4D trajectories in any allowed or customized format.
- Flexible trajectory sampling rate: user can parameterize the temporal resolution of the 4D trajectories (i.e. time-steps between trajectory waypoints of 1sec, 10 sec…).
- Graphical User Interface (GUI): TPAS can be integrated with customized GUIs, for example programmed in C#, while maintaining the general TPAS code in C++ for efficiency and multi-platform compatibility purposes.
- Different output formats: Output to GNUPlot, FACET, GEarth, txt, AIDL

f) Pre-loaded traffic scenarios for benchmarking

One important contribution of TPAS is that it can be distributed with one or several pre-loaded traffic scenarios and a common framework to obtain objective data about the test-bed results obtained during the verification of new ATM concepts and tools. Nowadays, there is a lack of such a common framework to allow benchmarking comparisons of the ATM tools generated by different scientific and practitioners research teams. For instance, in [4] it was noticed that CR algorithms are very sensitive to the scenarios under consideration thus confirming the necessity of having a benchmarking tool. Also a set of common metrics would be necessary for test-bed and benchmarking purposes.
g) Metrics computation (some of them based on BADA model)

TPAS includes a module in charge of measuring different metrics of different nature and in a flexible way. For instance, it can be applied some fuel consumption and other aircraft performance metrics (models from BADA), total and average delays, etc. More information can be found in [7].

h) Temporal looseness calculator (to study and improve robustness)

The concept of temporal (or longitudinal) looseness has been introduced in [8, 12] as a way to understand and control the de-synchronization network effects caused by delays. By properly configuring and analyzing the content of the SDS after processing the planned trajectories it is possible to quickly obtain the information about the temporal/longitudinal looseness, λ, for each trajectory, i.e. how much time a trajectory can be advanced or delayed without entering in conflict with another trajectory (whilst preserving the speed profile of the flight plan).

Fig. 7 illustrates the concept of temporal looseness: for a given trajectory (SBT or RBT), it is possible to find how many units of time can be advanced or delayed without causing interactions (i.e. conflicts) in the network. In the example of the figure the current SBT/RBT could be advanced 3 units of time or delayed 5 units of time without causing any conflict in the network.

Perturbations in the Expected Time of Departure (ETD), i.e. delays, is one of the main concerns of SESAR/NextGen, since they have strong de-synchronization network effects and thus also have a direct impact on the ATM capacity.

Delays are a kind of uncertainty that can be modeled through statistical distributions (also referred as structured uncertainty). See Fig. 8. TPAS can automatically configure a SDS with the proper configuration to compute and deliver temporal looseness information for a given set of trajectories. See Fig. 9.

IV. TPAS UTILIZATION CASE-STUDIES

The following examples aim at showing the potential benefits of the different configurations and capabilities of TPAS.

A. Time-based separation / wake vortex encounters avoidance

TPAS was configured for working with a simplified wake vortex model (i.e. 4D tubes enveloping the worst-case wake vortexes position and duration) in order to detect time-based conflicts (defined in this case as potential wake encounters) between descent/approach/landing aircraft and the wake vortexes generated by prior aircraft.
This research was successfully conducted under the ATLANTIDA project, and more information can be found in [8] and in [11]. Fig. 11 shows a snapshot of one of the resulting scenario simulations.

Figure 11: Time-based separation applied to heavy traffic patterns converging to Gran Canaria TMA

B. Real time flight data obtained from SWIM communication platform

TPAS has been adapted to obtain information from SWIM platform through the official APIs provided by EUROCONTROL. A prototype application was presented during the 1st SWIM Master Class [15] in which real flight data and airspace demand was taken from SWIM in real time. Fig. 12 shows a GUI for TPAS with the proper commands to select the traffic patterns from airport to airport using direct routes while respecting the real ETD, FL and cruise speed demand, data that was retrieved from SWIM. The traffic obtained (i.e., thousands of flight plans in a two-hour time-window) was de-conflicted at pre-tactical level in a few seconds, which might contribute to alleviate the workload of tactical ATC while obtaining more efficient traffic patterns through the use of direct routing across the European airspace.

Figure 12: SWIM demo presented during the 1st SWIM Master Class

C. Strategic de-confliction

TPAS functionalities have been used in the SESAR WP-E project STREAM, which aims at developing Strategic De-confliction algorithms that de-conflict in real-time all the trajectories flying over Europe in a 2 hour time-window [8, 9].

Several scenarios have been tested, using different functionalities of TPAS:

1) Scenario with 25 trajectories and 12 conflicts:

This scenario concentrates 25 concurrent trajectories of 30 minutes duration over a relatively small airspace (400x400Km2). The scenario was useful to study the emerging domino effects (positive and negative) among highly interactive trajectories in a controlled scenario. Fig. 13a shows the 12 interactions among the 25 trajectories and Fig. 13b the best solution found by a causal model [9, 12] after applying Geometric Optimization Approach [2] to 8 trajectories in order to obtain solution for the 12 conflicts. The causal model used in STREAM provided an optimized global solution that naturally favored those scenarios with greater positive domino effects.

Figure 13: 25-trajectories scenario illustrated in GNUPlot (a) (b)
2) European scale scenarios with up to 9000trs

Algorithms of STREAM and TPAS functionalities have been scaled to support the full en-route European ATM system. Several scenarios based on real traffic data provided by EUROCONTROL allowed to perform several CD&R simulations with up to 9000 trajectories in order to test the run-time of the algorithms.

A 4000-trajectory scenario based on real demand and direct routing has been tested, detecting 325 conflicts that were solved in less than 2 minutes by slightly changing (only) 286 trajectories (8% of the total traffic), mainly using HAC maneuvers (11 aircraft were required to maneuver with FL steps to avoid conflict regions). Fig. 14a illustrates the 4000 direct-route trajectories with the conflicts (in red) and Fig. 14b shows the best solution found (resolution trajectories in green).

3) Comparison of robustness and sensitivity to delay between structured and direct routes over Europe was also conducted.

Preliminary tests have been conducted in order to compare a real traffic scenario sample (more than 2000 concurrent aircraft whose original flight plans follow the structured routes network) with a synthetic traffic scenario in which the same airspace demand is satisfied through direct routing (flights simulated with a Trajectory Predictor developed by Boeing R&TE). Preliminary results indicated that the duration and distance of the trajectories can be reduced by a 6% if using direct routes, while the amount of conflicts was considerably lowered, i.e. 145 conflicts detected in the structured route scenario and 98 in the direct routing scenario. Random perturbations in the ETD within the interval of [-1', +15'] were stochastically applied to the trajectories population in order to quantify the robustness/sensitivity to delays of both scenarios. Early results have shown a reduction of conflicts in both scenarios, around 15-20% reduction, and no meaningful differences in the robustness/sensitivity to delays of the two scenarios were identified.

4) Sensitivity of applied strategic CD buffers

In order to tackle uncertainty it is common practice to add “uncertainty buffers” to the nominal safety distances in order to obtain more robust flight trajectories, especially during strategic/pre-tactical planning. TPAS functionalities have been used to preliminary quantify how the introduction of extra safety buffers may affect the airspace capacity, traffic planning robustness, and trajectory efficiency. Preliminary essays have been conducted with a real European peak day traffic scenario of more than 4000 trajectories, simulating direct routes flights. Conflict detection was performed with 3, 5, 7 and 10NM. Early results indicate that the introduction (or elimination) of 1 extra NM in the standard safety distances adds up (or reduces) around 70 conflicts in the global scenario. Thus, the introduction of safety buffers seems to have a considerable impact in the European network capacity, as well as in the amount of trajectories requiring modifications with respect their nominal direct route (efficiency is reduced).

![Image](315x411 to 567x565)

![Image](315x574 to 567x726)

Figure 14: 4010-trajectories scenario with conflicts (a) and solution found (b)

V. CONCLUSIONS

In this paper, the architecture, functionalities and key contributions of the Test-bed Platform for ATM Studies have been described. The TPAS is an innovative approach to allow ATM researchers a rapid prototyping, thus easing and improving the evaluation of new ATM concepts and tools, allowing the introduction of the complexities that a real ATM scenario could impose.

The framework developed can support a high diversity of traffic scenario patterns, although it has been mainly used in European traffic context. Some applied case-studies have confirmed the utility of TPAS for the test-bed and benchmarking of new ATM concepts and tools.

Future work includes the development of extended functionalities and capabilities such as the introduction of weather simulators and complexity maps information. Simulation of flight dynamics could be also provided using BADA models as an alternative to the FACET provided aircraft dynamic models. Lastly, a cloud-computing version of TPAS is under consideration in order to ease the installation and configuration of TPAS as well as to centralize and generate a benchmarking database for public interest.
ACKNOWLEDGMENT

This work is funded by the Ministry of Economy and Competitiveness in the project “Fire Guided Unmanned Aircrafts and Resources Distribution (FireGUARD), CICYT Spanish program TIN2011-29494-C03-01.

REFERENCES