Novel ATM and Avionic Systems for Environmentally Sustainable Aviation

Roberto Sabatini\(^1\), Alessandro Gardi\(^1\), Subramanian Ramasamy\(^2\), Trevor Kistan\(^1,2\), Matthew Marino\(^1\)

\(^1\)School of Aerospace, Mechanical and Manufacturing Engineering
RMIT University, Melbourne, Australia
\(^2\)THALES Australia, Melbourne, Australia

Abstract

Large-scale air transport modernisation initiatives including the Single European Sky Air Traffic Management Research (SESAR), Next Generation Air Transportation System (NextGen) and Clean Sky Joint Technology Initiative for Aeronautics and Air Transport aim to improve the operational efficiency, safety and environmental sustainability of aviation. Scientific advances in Air Transport Management (ATM) and avionic systems are required to achieve the ambitious goals set by national and international aviation organisations. This paper presents the recent advances in ATM and avionic system concepts, integrated architectures and trajectory generation algorithms, to be adopted in Next Generation Avionics Flight Management Systems (NG-FMS) and ground-based 4-Dimensional Trajectory Planning, Negotiation and Validation (4-PNV) systems. Current research efforts are focussed on the development of NG-FMS and 4-PNV systems for Four Dimensional (4D) Trajectory/Intent Based Operations (TBO/IBO), enabling automated negotiation and validation of aircraft intents and thus alleviating the workload of operators. After describing the NG-FMS/4PNV concept of operations, the overall system architecture and the key mathematical models describing the 4DT optimisation algorithms are introduced. Simulation case studies utilising realistic operational scenarios highlight the generation and optimisation of a family of 4DT intents by the NG-FMS corresponding to a set of performance weightings agreed between Air Navigation Service Providers (ANSP) and Airline Operation Centres (AOC). The savings on time, fuel burn and gaseous emissions (CO\(_2\) and NO\(_x\)) associated with the globally optimal 4DT intents are presented. The developed optimisation and negotiation/validation loops meet the timeframe requirements of typical online tactical routing/rerouting tasks.

Keywords

Aviation Sustainability, Air Traffic Management, Avionics, Trajectory Based Operations, 4D Trajectory Optimisation, Flight Management System.

1. Introduction

The demand for improved safety, efficiency and capacity due to the rapid expansion of global air transport and the growing concern for environmental sustainability issues pose significant challenges for the development of future Communication, Navigation and Surveillance/Air Traffic Management (CNS/ATM) and Avionics (CNS+A) systems. In this context, the key performance improvement areas identified in the Global Air Navigation Capacity and Efficiency Plan by the International Civil Aviation Organization (ICAO) are (ICAO, 2014a):

- Airport operations.
- Efficient flight path planning and execution.
- Optimum capacity and flexible flights.
- Globally interoperable systems and data.

The air transportation system is expected to expand significantly within the next two decades. Clearly there is a potential negative impact on the environment associated with this expansion if the sustainability aspects are not addressed (Graham et al., 2014). While many eco-friendly technological solutions are contemplated for addressing the long term challenges associated with the steady growth of the aviation sector, novel ATM and avionic systems can provide an immediate effect on alleviating the environmental impacts of aviation. A number of global and regional research initiatives are addressing ATM modernisation issues beforehand. The Advisory Council for Aviation Research and Innovation in Europe (ACARE) has set specific target goals to address environmental sustainability of aviation in its Strategic Research Agenda (SRA) and Strategic Research and Innovation Agenda

\(^1\) Lead Author/Presenter and Corresponding Author: roberto.sabatini@rmit.edu.au
(SRIA) (ACARE, 2008, ACARE, 2012). The initiatives led by the National Aeronautics and Space Administration (NASA) in the United States resulted in creation of the Environmentally Responsible Aviation (ERA) project to explore and document the feasibility, benefits and technical risks of advanced vehicle concepts and enabling technologies that will reduce the impacts of aviation on the environment. The benefits of such initiatives have already resulted in significant improvements in fuel efficiency, reduced gaseous emissions and lowered noise levels (Collier, 2010, Nickol, 2011). The key objectives of the project can be summarised as:

- To explore and mature alternative unconventional aircraft designs with the potential to simultaneously meet mid-term goals (in the order of 5-10 years) for community noise, fuel burn and nitrogen oxides (NOx) emissions.
- To determine the potential impact of alternative aircraft designs and technologies if successfully implemented into the air transportation system.
- To determine the potential impact of the implemented technologies on advanced aircraft designs.

Table 1 highlights the fuel-burn, gaseous emissions and noise reduction goals proposed by ACARE in its vision for 2020 and FlightPath 2050, and NASA for the N+1, N+2 and N=3 generations of aircraft.

<table>
<thead>
<tr>
<th>Agency</th>
<th>ACARE – SRA and SRIA</th>
<th>NASA - ERA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Programme</td>
<td>Vision 2020</td>
<td>FlightPath 2050</td>
</tr>
<tr>
<td>Fuel/CO₂</td>
<td>50%</td>
<td>75%</td>
</tr>
<tr>
<td>NOx</td>
<td>80%</td>
<td>90%</td>
</tr>
<tr>
<td>Noise</td>
<td>50%</td>
<td>65%</td>
</tr>
</tbody>
</table>

The Single European Sky ATM Research (SESAR) and the Clean Sky Joint Technological Initiative (JTI) for Aeronautics and Air Transport are the major regional programmes defining the future air transportation in Europe addressing both operational improvements and environmental issues (SESAR, 2011, Ky and Miaillier, 2006, EU, 2014). In Europe, air transportation causes approximately 3% of the total greenhouse gas emissions (EU, 2010). The Clean Sky JTI implements the ACARE SRIA FlightPath 2050 objectives in multiple phases. The Next Generation Air Transportation System (NextGen) programme in the USA, in collaboration with SESAR, leads the transformation towards global air transport modernisation (FAA, 2013). The NextGen programme is a major collaborative research initiative addressing the five pillars of environment and energy namely noise, air quality, climate, energy and water quality by adopting ATM modernisation, operational improvements, technology maturation, scientific knowledge and integrated modelling, alternative jet fuels and policy measures. Other regional ATM modernisation programs include Collaborative Action for Renovation of Air Traffic Systems (CARATS) in Japan, SIRIUS in Brazil, Future Indian Air Navigation System (FIANS) in India, and others in Australia, China, Canada, and Russia (ICAO, 2014a).

The CNS+A concept was introduced by the Future Air Navigation Systems (FANS) special committee of ICAO (Bradbury, 1991) and is addressed as part of the global and regional research programs including Clean Sky and SESAR/NextGen. The combined SESAR and Clean Sky environmental objectives can be summarised as follows:

- Achieving substantial fuel savings per flight based on the improvement of ATM procedures.
- Minimising noise impact through climb and descent path optimisation.
- Developing, implementing and enforcing rules for ATM related environmental protection.

The key CNS+A concepts include:

- Four Dimensional (4D) Trajectory-Based Operations (TBO).
- Augmentation Systems enabling Global Navigation Satellite System (GNSS) as the primary means of navigation.
• Enhanced ground-based and satellite-based Aeronautical Communication Systems (ACS), involving a substantial exploitation of data-links.
• Enhanced ground-based and satellite-based surveillance, including Automated Dependent Surveillance Broadcast (ADS-B) and self-separation.
• Collaborative Decision Making (CDM) to allow all stakeholders involved in flight planning and management to participate in the enhancement of system performance by exploiting more accurate information from airborne systems.
• Dynamic Airspace Management (DAM) for an optimised exploitation of airspace resources.
• System Wide Information Management (SWIM).
• Improved Human Machine Interface and Interaction (HMI) systems design, interoperability and higher levels of automation.
• Role shifting of ground ATM command and control oriented units to a highly automated decision-making system in an interoperable environment, based on the User Preferred Routes (UPR).

In the Asia-Pacific region, the Australian ATM system is evolving into a highly integrated network where civil, military and Remotely-Piloted Aircraft Systems (RPAS) will continuously and dynamically share the common airspace in a highly automated and collaborative decision-making environment. Optimised ATM procedures such as Tailored Arrivals (Bronsvoort et al., 2011) and the Brisbane Green Required Navigation Performance (RNP) project (Airservices, 2008) have been implemented. These national initiatives are now aligned with those of the Asia-Pacific region with Australia’s involvement in the Asia and South Pacific Initiative to Reduce Emissions (ASPIRE) programme. Optimised Flextracks have been implemented, which allow long-haul traffic to benefit from favourable winds and slot management is performed to optimise the allocation of airport and Air Traffic Control (ATC) slots. Improvements including reduced ground delays to tackle critical congestion situations, thereby reducing fuel consumption, noise and gaseous emissions at the same time have been implemented. In recent times, implementation of UPRs, extension of national CDM processes and Air Traffic Flow Management (ATFM) operations to support long-range ATFM strategies for the Asia-Pacific region are considered.

2. The CNS+A Systems for TBO/IBO

In order to enable enhanced concepts and capabilities, new ground-based and airborne CNS+A systems are required. The novel automated systems allow the better equipped aircraft to fly user-preferred optimal flight paths, limiting the intervention of the Air Traffic Control Operators (ATCO) to high-level and emergency decisions and thus decreasing the overall workload and increasing the situational awareness. Increased airspace flexibility enables more efficient and greener flight profiles. The CNS+A systems will provide better and precise airborne automated navigation services aided by optimal aircraft separation assistance to fully exploit the available airspace resources and ground facilities. The key enabling CNS+A systems include:

• Modern avionics and ground-based ATM systems for planning and real-time execution of 4DT functionalities, including multi-objective 4DT optimisation, negotiation and validation in the TBO/IBO context.
• Network-centric ATM technologies for strategic, tactical and emergency operations.
• High-integrity, high-throughput and secure Next Generation ACS networking all the CDM stakeholders and SWIM.
• Satellite-based CNS systems including multi-constellation GNSS, space-based data-link and ADS-B system, as well as Ground/Aircraft/Satellite Based Augmentation Systems (GBAS/ABAS/SBAS).
• Integrated health management systems for both airborne and ground-based systems.
• CNS+A technologies for RPAS.

In order to fulfill the SESAR / Clean Sky and NextGen objectives, the online air traffic flow is optimised by the novel automated systems considering high-density airspace, re-routing and re-scheduling in real-time (Gardi et al., 2013, Ramasamy et al., 2013, Gardi et al., 2014, Ramasamy et al., 2014b). The overall 4DT decision making is enhanced by exploiting automated negotiation and validation schemes. The methodology adopted involves the sharing of airspace constraints, aircraft performance parameters, flight path restrictions, and global optimisation criteria with the Next Generation Flight Management System (NG-FMS) equipped aircraft, which generates 4DT intents consisting of a number of flyable optimal trajectories (in the order of priority). The trajectory intents are subsequently
transmitted to the ground-based 4DT Planning, Negotiation and Validation (4-PNV) system via the NG-ADL. The 4DT intent negotiation and validation by the CNS + A systems is illustrated in Figure 1. The innovative 4-PNV system receives multiple preferences of 4DT intents from each manned and unmanned aircraft equipped with NG-FMS (Flow of information I in Figure 1). The provision of multiple trajectory options decreases the length of negotiation time and reduces the need for the ATM system to calculate optimal trajectories in a remote location. Once the optimal conflict free trajectories have been identified, the 4-PNV system instructs each aircraft to fly the validated trajectories (Flow of information II in Figure 1) and the aircraft sends a confirmation to the ground (Flow of information III in Figure 1). When feasible trajectories cannot be identified in the NG-FMS intents, the 4-PNV system, calculates a new set of optimal trajectories based on performance weightings agreed between Airline Operating Centres (AOC) and Air Navigation Service Providers (ANSP) and uplinks them to the respective aircraft. The on-board NG-FMS then identifies the preferred trajectory and sends a confirmation to the 4-PNV system. A sub-case of this is when a new negotiation loop is initiated by the 4-PNV system (e.g., due to conflicting air traffic and/or direct inputs from the ANSP/AOC).

Figure 1: 4DT intent negotiation and validation by the CNS + A systems.

3. Trajectory Optimisation

Significant research activities on multi-objective and multi-model 4DT optimisation algorithms are being carried out as part of the major ATM research programmes worldwide. The trajectory flown by each aircraft dictates a number of operational aspects and environmental impacts associated with the mission. In an ATM perspective, trajectory optimisation is the identification of the most suitable 4DT from origin to destination, based on constraints, user preferences, and meteorological and traffic information. A number of limitations are associated with the conventional flight planning approach, which consists of a preliminary lateral airway choice based on the shortest path encompassing favourable winds aloft and a vertical planning, subsequently performed to obtain the ideal cruise level based on the aircraft category and route length. From an operational perspective, the main disadvantages of the classical approach are due to the result of its offline nature (i.e., information are formulated before flight operations, with very limited real-time online inputs). Since the offline flight plans are submitted well ahead of the scheduled flight time, unforeseen weather and air traffic scenarios can progressively compromise its validity and optimality. A number of extensive rerouting occurrences in the past have revealed that reinsertion into the originally planned route resulted in a suboptimal solution if not unfeasible. Another major limitation of conventional flight planning is due to the very narrow set of optimality criteria and their limited modelling capability. As shown in Table 2, a number of different environmental and economic aspects are associated with the aircraft flight trajectory in different phases of the flight, and therefore they have to be integrated as part of the
optimality set. In conventional flight planning, the environmental impacts associated with pollutant gases such as carbon oxides (CO₂), nitrogen oxides (NOₓ), sulphur oxides (SO₂), unburned Hydrocarbons (HC), as well as condensation trails (contrails) and noise are neither included in the mathematical modelling nor are quantitatively assessed.

Table 2: Common multi-objective trajectory optimisation criteria.

<table>
<thead>
<tr>
<th></th>
<th>Departure</th>
<th>Climb</th>
<th>Cruise</th>
<th>Descent</th>
<th>Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel / CO₂</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>HC / SOₓ</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Noise</td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>NOₓ / CO</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Weather</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Flow / Capacity</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contrails</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

The present day generation systems adopt methods wherein the reduction of the amount of perceived noise and emissions, which are subject to uncertainties associated with severe weather or traffic perturbations are performed in a static manner. Research efforts are therefore gathered in addressing more effective and versatile mission and trajectory planning, optimisation and management algorithms to be implemented in next generation airborne and ground-based CNS+A systems. As part of this endeavour, a multi-model approach is exploited to obtain globally optimal 4DT solutions addressing multiple objectives at the same time. Figure 2 conceptually represents the multi-objective 4DT optimisation problem. The model suite comprising of noise, engine and emissions, operational business, airframe systems, airspace, weather, aircraft dynamics and contrails models, support the core multi-objective trajectory optimisation framework. The demographic distribution and digital terrain elevation databases are used in conjunction with the noise model.

Figure 2: Illustration of the multi-objective trajectory optimisation problem.

3.1 Mathematical Formulation
From a mathematical perspective, optimisation of an aircraft trajectory is defined as the process of determining the best possible trajectory that can be flown between any two given points in an n-dimensional space-time domain. The optimisation process must include the specific objectives, path constraints and boundary conditions. The optimisation of flight trajectories is typically a finite-dimensional nonlinear optimisation problem that is based on both deterministic and stochastic formulations on either continuous or discrete search spaces. Let $x(t)$ be the state variable vector, $u(t)$ be the control variable vector, $p$ be the vector of problem parameters and $t \in [t_0; t_f]$ be the time. The system of ordinary differential equations introducing the complete behaviour of the system dynamics is expressed as:

$$\dot{x}(t) = f[x(t), u(t), t, p]$$  \hspace{1cm} (1)

The system of equations are differential constraints to the optimisation process. Nonlinear and discrete dynamics can be also encompassed by adopting adequately relaxed mathematical formulations. A set of scalar indices $J_i$ quantify the achievement of the corresponding optimality objective $i \in [1; n_i]$. The optimisation process can then be formulated as the mathematical minimisation (or maximisation) of the performance index $J_i$. Adopting the generalised Bolza form, the cost function $Q_i(\cdot)$ used to determine $J_i = Q_i(\cdot)$ comprises of two contributes: the Lagrange term, which is the integral function of the states, controls and parameters along time, that is $\int_{t_0}^{t_f} L_i[x(t), u(t), p] dt$, and the Mayer term, which is a function of the initial and final values of the states and parameters, $\Phi_i[x(t_0), x(t_f), p]$. Thus the performance index is expressed as:

$$J_i = \Phi_i[x(t_0), x(t_f), p] + \int_{t_0}^{t_f} L_i[x(t), u(t), p] dt$$  \hspace{1cm} (2)

Equality constraints and inequality constraints are considered in the optimisation problem. And thus allows to effectively represent any given path constraint in the formulation. For the sake of generality, both equality and inequality path constraints are expressed in a convenient and univocal form as:

$$C_{\text{min}} \leq C[x(t), u(t), t; p] \leq C_{\text{max}}$$  \hspace{1cm} (3)

where an equality constraint is encompassed by imposing $(C_{\text{min}})_i = (C_{\text{max}})_i$.

Similar to the path constraints already introduced, we express the boundary conditions as:

$$\Phi_{\text{min}} \leq \Phi[x(t_0), x(t_f), u(t_0), u(t_f); p] \leq \Phi_{\text{max}}$$  \hspace{1cm} (4)

where equality conditions are encompassed by imposing $(\Phi_{\text{min}})_i = (\Phi_{\text{max}})_i$.

In summary, having introduced the dynamics, the performance indices, the path constraints and the boundary conditions, the nonlinear optimisation problem can be formulated as (Betts, 1998, Rao, 2009): determining the states $x(t)$, the controls $u(t)$, the parameters $p$, the initial time $t_0$ and the final time $t_f$ $t_f > t_0$, that optimise the performance indices given by:

$$J = \Phi[x(t_0), x(t_f), p] + \int_{t_0}^{t_f} L [x(t), u(t), p] dt ,$$  \hspace{1cm} (5)

subject to the dynamic constraints

$$\dot{x}(t) = f[x(t), u(t), t, p] ,$$  \hspace{1cm} (6)

to the path constraints

$$C_{\text{min}} \leq C[x(t), u(t), t; p] \leq C_{\text{max}} ,$$  \hspace{1cm} (7)

and to the boundary conditions

$$\Phi_{\text{min}} \leq \Phi[x(t_0), x(t_f), u(t_0), u(t_f); p] \leq \Phi_{\text{max}}$$  \hspace{1cm} (8)

Each performance index provides a quantitative measure of the attainment of a specific objective and different objectives are typically conflicting, and thus the optimisation in terms of two or more objectives typically leads to a number of possible solutions. Therefore, a trade-off is required in the context of multi-objective trajectory optimisation. In the aviation domain, single and bi-objective optimisation techniques have been exploited for decades but they considered only minimum flight time and/or minimum fuel consumption criteria. These techniques have also been implemented in a number of
current generation FMS in terms of a Cost Index (CI) allowing the flight crew to manually select the desired trade-off between fuel and time costs. In order to achieve the ambitious environmental goals set by the aviation policy makers in the national and international context, it is essential to include a higher number of objectives and to adopt a more dynamic and flexible approach. The weightings are varied dynamically during the different flight phases. While noise criteria can be included in the 4DT optimisation during the departure and arrival phases, optimisation based on gaseous emissions and contrails are considered predominantly in the cruise phase.

3.1 Emission Model

The general expression to calculate the emission of the gaseous pollutant \((GP)\) based on its Emission Index \((E_{I_{CO}})\) is:

\[
GP = \int_{t_0}^{t_f} E_{I_{GP}} \cdot FF \, dt \quad [\text{Kg}]
\]  

where \(FF\) is the Fuel Flow \([\text{Kg s}^{-1}]\), for which the Eurocontrol Base of Aircraft Data (BADA) provides an accurate calculation method as a function of the engine thrust, of the ambient pressure and of the true airspeed conditions (Eurocontrol, 2013). The ICAO has established an extensive and constantly updated databank for engine emissions based on data collected independently by a number of entities, which provides the ideal reference for engine emission models (ICAO, 2014b). The fuel-specific Emission Indices \((E_I)\) are measured at the standard throttle settings defined in ICAO Annex 16 volume 2 (ICAO, 2008). In particular, for an exclusively subsonic engine, the reference throttle settings are take-off (100% of rated engine thrust), climb (85%), approach (30%), and idle (7%). The various aviation-related pollutants taken into consideration have different dependencies, which are discussed separately. An empirical model for CO and HC emissions \((E_{I_{CO/HC}})\) at mean sea level based on nonlinear fit of turbofan engines experimental data available in the ICAO emissions databank is:

\[
E_{I_{CO/HC}} = c_1 + \exp(-c_2t + c_3) \quad [\text{Kg}] \quad (10)
\]

where, as a first estimate, the fitting parameters \(c_{1,2,3}\) comprehensively valuable for the CO emissions of 165 currently operated civil turbofan engines from the ICAO emissions database are \(c = \{0.556, 10.208, 4.068\}\) for CO and \(c = \{0.083, 13.202, 1.967\}\) for HC. All the carbon contents of the fuel that are not transformed into CO, HC are transformed in CO\(_2\), which is a major contributor to the greenhouse effect. The reference value is 3.1 \(t_{\text{CO2/UnitAl}}\). Based on the ICAO emission databank, an empirical curve fit model can also be introduced for the NO\(_X\) emission index at mean sea level based on the throttle setting. The following expression is a nonlinear fit comprehensively accounting for 177 currently operated civil aircraft engines:

\[
E_{I_{NOX}} = 7.32 \tau^2 + 17.07 \tau + 3.53 \quad [\text{Kg}] \quad (11)
\]

The empirical models for \(E_I\) are valid at mean sea level and do not take into consideration the installation aspects. In order to obtain an accurate estimate of pollutant emission at height, a methodology was developed by Boeing in 1995 and is commonly referred to as “Boeing Method 2” (Martin and al, 1996). The method proposes an empirical correction to account for installation effects, and subsequently introduces EI corrections based on ambient temperature, pressure and relative humidity.

4. Next-Generation Flight Management Systems

FMS is the primary airborne system responsible for providing automated navigation and guidance services. In particular, the Guidance, Navigation and Control (GNC) functionalities implemented in state-of-the-art FMS include:

- Lateral and vertical navigation.
- Trajectory computation, estimation and optimisation.
- Performance predictions.
- Lateral and vertical guidance.
- Continuous monitoring and correction of the flight path.
- Comprehensive radio management functions.

The key components of a typical FMS architecture are the Flight Management Computer (FMC), Multi Control Display Unit (MCDU), Flight Control Unit (FCU), Electronic Flight Instrument System (EFIS), Multi-Function Display (MFD) and Navigation Display (ND). Present day FMS provide area navigation (RNAV) services adhering to the Required Navigation Performance (RNP) levels in all flight profiles ensuring that accuracy, availability, continuity and integrity requirements are met (Cramer et al., 2010).
A number of integrated navigation and guidance system architectures can be adopted in the FMS architecture to achieve the required performance levels (Sabatini et al., 2013a, Sabatini et al., 2013d). FMS incorporating autopilot loops have the capability of ensuring the Required Time of Arrival (RTA) and do not have any database size or processing issues (Brooker, 2014).

Next Generation Flight Management Systems (NG-FMS) are key enablers for generating globally optimal trajectories fulfilling the safety, operational, and environmental requirements in the 4D TBO context. In recent years, a number of concepts have been proposed including an ATM model for generating safe, fuel-efficient, very accurate, and air-ground synchronized 4D-trajectories by using flight segment groundspeed profiles and linking GNSS data to the aircraft FMS with feedback control (Brooker, 2014). The key functionalities of the NG-FMS for TBO are multi-objective 4DT optimisation for both flight planning and real-time operations. 4DT monitoring, 4DT negotiation/validation with the ground ATM/ATFM systems and real-time rerouting and information updating. Each aircraft equipped with NG-FMS generates 4DT intents, which are defined according to the Flight Management Computer (FMC) ARINC 702A-3 characteristic (ARINC, 2006) as a string of 4D points that describe the predicted trajectory of the aircraft along with the point type and turn radius associated with the flight path transition. The trajectory computation and optimisation component of the NG-FMS is reconfigurable with that of the ground-based counterpart (4-PNV system) to enable negotiation and validation updates in real-time. Additionally, the intents are recomputed based on flight plan revisions, weather updates, guidance mode modification, performance weightings and corrections for position uncertainties in real-time based on the 4DT optimisation algorithms. The primary NG-FMS functions are:

- **Trajectory planning and optimisation**: to provide optimal trajectory solutions based on an appropriate set of performance weightings agreed between the ANSP and AOC based on operational and environmental criteria. The 4DT planning and optimisation is performed for strategic, tactical and emergency situations and a number of different optimisers are adopted accordingly. Specific functions including Sense-and-Avoid (SAA) are incorporated as part of the trajectory predictions module (Ramasamy et al., 2014a, Sabatini et al., 2014b, Sabatini et al., 2014a).
- **Trajectory monitoring**: to perform state estimation and calculation of the deviations between the active 4DT intents and the estimated/predicted aircraft states.
- **Path correction**: to correct the path deviations in terms of lateral, vertical and time profiles when the maximum tolerance associated with the RNP level of the current flight phase is not satisfied. The generated steering commands are provided to the guidance module of the NG-FMS.
- **Trajectory negotiation and validation**: to carry out the process of negotiation that can be initiated by the pilot via the NG-FMS, making use of the information available on board, or by the NG-ATM system, supervised by the ATCO.
- **Performance management**: to monitor the active 4DT intents for errors to address integrity requirements. The monitoring is based on the threshold levels for the required RNP, Required Communication Performance (RCP) and Required Surveillance Performance (RSP) parameters. To ensure integrity, if the aggregated errors exceed the alarm limit with respect to threshold levels, inputs are provided to an integrity management subsystem.
- **Integrity management**: to generate integrity caution (predictive) and warning (reactive) flags based on inputs from different sensors/systems and predefined decision logics. A loss of data leads to re-initialising the trajectory planning and subsequently the 4DT optimisation process. For instance, the main causes of GNSS signal outage and degradation in flight, namely: antenna obscuration, multipath, fading due to adverse geometry and Doppler shift are identified and modelled to implement suitable integrity thresholds and guidance algorithms (Sabatini et al., 2013b, Sabatini et al., 2013c).

Conventional The NG-FMS architecture is illustrated in Figure 3. In addition to the databases typically found in FMS, demographic distribution, digital terrain elevation, weather and environmental data are accessed for executing algorithms specific to the models used.
Since individual, per-aircraft operational and environmental benefits are marginal, to achieve significant and sustained benefits, a large proportion of the fleet will have to adopt optimised 4D TBO/IBO techniques. Scaling up 4DT operations in dense airspace introduces further considerations including:

- **Bandwidth and datalink**: Increased bandwidth will be required to support the increased amounts of datalink traffic between NG-FMS and 4-PNV systems. New infrastructure (such as Air-Ground ACS) has to play a key role, but improved protocols with compression and reduced alphabets can also be adopted.
- **Maintenance of separation**: As each NG-FMS negotiates a 4DT with the 4-PNV system, the 4-PNV system considers whether the requested trajectory would cause a loss of separation with other aircraft in the vicinity. As long as the look-ahead times are moderate, computational performance issues on the 4-PNV side can be addressed by distributed parallel processing.
- **Resource loading**: Several NG-FMS may request a similar 4DT, for example, to utilise favourable tailwinds or to avoid adverse weather. As successive requests are processed by the 4-PNV system, cumulative load on resources including routes and sectors increases to a point where capacity may be exceeded and Dynamic Airspace Management (DAM) / Dynamic Capacity Load Balancing (DCB) are required.
- **Self-separation**: If a wide-scale roll-out of NG-FMS equipage can be achieved in less-dense airspace, then self-separation concepts may experience a revival when coupled with surveillance technologies such as ADS-B In.

- **Stability of metering and sequencing**: The downstream impact of NG-FMS-initiated 4DT changes may have to be considered if it impacts the sequence over metering points. For example, an arrival sequence may be frozen a certain time before landing or the flow of aircraft through a co-ordination point to an adjacent Flight Information Region (FIR) may be subject to exit separation criteria. Until the 4-PNV system evolves to perform metering and sequencing, it may be prudent to create non-automation zones around problematic areas of airspace.

5. **Simulation Results**

Results of representative case studies of 4DT intent optimization, negotiation and validation between the NG-FMS and the 4-PNV system were presented in (Gardi et al., 2013, Gardi et al., 2014, Ramasamy et al., 2014b, Ramasamy et al., 2013). In order to be adopted for strategic online and tactical online tasks, it is imposed that the total duration of the optimisation and negotiation/validation loops remain under 300 seconds. 4DT intents are generated from the NG-FMS and the optimisation of the generated intents is accomplished for minimum flight time and fuel costs. An Airbus A320 aircraft with take-off weight of 68,000 kg is assumed to be flying the mission. The aircraft takes off from Melbourne Tullamarine airport in Australia (ICAO code: YMML) and proceeds towards Darwin airport (ICAO code: YPDN) with a planned cruise flight level 340 (34,000 feet). Depending on the cost functions and gains selected (i.e., minimum time, minimum fuel and other environmental costs such as gaseous emissions of CO$_2$, NO$_X$, etc.), there are different trajectory possibilities for all flight segments. Figure 4 illustrates the Google Earth image of the different trajectories generated, each resulting from different weightings of time and fuel optimisation criteria. For the climb phase, the CO$_2$ and NO$_X$ reductions are approximately 251.7 kg and 1.5 kg respectively. The trajectory corresponding to minimum fuel burn provides 90 kg fuel savings when compared to the minimum time optimisation case.

![Figure 4: Simulated set of 4DT intents.](image)

In order to validate the trajectory negotiation and validation process, the arrival sequencing problem in the Terminal Manoeuvring Area (TMA) is considered wherein a single landing runway is available and hence not all traffic can be cleared to overfly the Final Approach Fix (FAF) at their originally intended time. The FAF, in particular, marks the beginning of the common approach leg, where strict longitudinal separation is enforced. The final approach leg has been modelled as a typical Instrument Landing System (ILS) approach profile, starting at 9.5 Nautical Miles (NM) from the runway at 3000 feet. After the initial intents have been stored in the 4-PNV system, the point-merge sequencing algorithm allocates the available time slots accordingly. Considering a minimum horizontal separation of 4 NM on the ILS approach and approach speeds around 140 knots, the generated time slots on the merge-point are characterized by a 100 s separation. The resulting scenario is represented in Figure
5. The average processing time was 84 seconds for 10 simulation runs. The lowest computational time was 69 seconds and the highest was 166 seconds.

Figure 5: Validated intents – Melbourne ILS FAF (Gardi et al., 2014).

6. Conclusion
This paper reviewed the systems concepts and functional architectures proposed for the next generation of avionics and ATM systems required for Trajectory/Intent Based Operations (TBO/IBO) and to enhance the environmental sustainability of aviation. The advancements in ATM and Avionic systems described will provide substantial benefits by mitigating the environmental impacts in a multifaceted approach and thus addressing climate change issues. The NG-FMS provides 4-Dimensional Trajectory (4DT) optimisation and negotiation/validation functionalities interoperable with future ATM systems. Realistic simulation case studies were performed and the results demonstrated the functional capability of the NG-FMS to generate cost-effective trajectory profiles satisfying both the operational constraints and the environmental objectives. The 4-PNV simulation cases also showed that the processing time required to elaborate a conflict-free solution was consistently below 180 seconds for up to 10 aircraft in a Terminal Manoeuvring Area (TMA) environment, accounting for both arriving and departing traffic over a ten minute timespan. Therefore, in high air traffic density conditions, the complete process of NG-FMS intent generation, downlink to the 4-PNV and negotiation/validation can be performed in less than 300 seconds. These results meet the timeframe of typical online tactical routing rerouting tasks and make the approach feasible for the intended applications. Current research is addressing Dynamic Airspace Management (both in the time and space domain), advanced Air Traffic Flow Management (ATFM) techniques, Human Factors Engineering, and the development of a Next Generation ACS fulfilling the throughput, integrity and security requirements of future avionics and ATM/ATFM systems.

7. References
ACARE 2012. Strategic Research & Innovation Agenda (SRIA).


ICAO 2014b. ICAO AIRCRAFT ENGINE EMISSIONS DATABANK. March 2014 ed.: The International Civil Aviation Organization (ICAO) - European Aviation Safety Agency (EASA).


