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AUTOMATED SEPARATION ASSURANCE AND COLLISION AVOIDANCE FUNCTIONS IN THE CNS+A CONTEXT

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Abstract

The introduction of automated separation assurance and collision avoidance functions in Next Generation Flight Management Systems (NG-FMS) has the potential to provide a pathway for manned/unmanned aircraft coexistence in all classes of airspace. The NG-FMS is designed to be fully interoperable with a ground based 4DT Planning, Negotiation and Validation (4-PNV) system, enabling automated Trajectory/Intent-Based as well as Performance-Based Operations (TBO/IBO and PBO). In the Communication, Navigation and Surveillance/Air Traffic Management and Avionics (CNS+A) context, 4-Dimensional Trajectory (4DT) optimisation algorithms are employed in the NG-FMS and 4-PNV system allowing planning and optimisation of 4DT intents for strategic, tactical and emergency tasks After describing the NG-FMS architecture, novel algorithms developed for a unified approach to separation assurance and collision avoidance are presented. In this method, navigation and tracking errors affecting the host aircraft platform and intruder sensor measurements are translated to unified range and bearing uncertainty descriptors. Key aspects of the Human Machine Interface and Interaction (HMI^2) design for self-separation and collision avoidance are also presented. Simulation case studies are carried out to evaluate the performance of the proposed approach in both cooperative and non-cooperative scenarios. Results corroborate the validity of the unified approach and demonstrate its impact towards providing a cohesive logical framework for the development of an airworthy separation assurance and collision avoidance capability.

1 Introduction

In recent years, avionics system developers are faced with a number of challenges in introducing innovative Communication, Navigation and Surveillance (CNS) technologies, which are required to meet the ambitious goals set by global and regional Air Traffic Management (ATM) modernisation programmes including Single European Sky ATM Research (SESAR) and Next Generation Air Transportation System (NextGen) [1, 2]. State-of-the-art Flight Management System (FMS) software functions are not sufficient to provide increased safety, efficiency and an optimal demand-capacity balancing in the CNS/ATM and avionics (CNS+A) context. Technological challenges also exist in the Unmanned Aircraft System (UAS) domain, as effective integration of these aerial robots in non-segregated airspace relies upon realization of certifiable collision avoidance systems [3, 4]. Higher levels of on board autonomy are also required to mitigate the risks arising in connection to possible failures to the Command and Control (C2) loop involving the ground pilot. In this perspective, the objectives can be summarised as follows:

- Improved safety – Through the introduction of innovative surveillance technologies and automated functions on board the aircraft. Hence the overall surveillance awareness for pilots, Air Traffic Controllers (ATCs) and UAS operators increases.
- Increased airspace efficiency – Through the use of innovative CNS+A technologies allowing a more effective and efficient use of the available resources.

- Optimal demand-capacity balancing – Through dynamic reconfiguration of airspace resources, taking into account traffic, airport and weather updates/forecasts.
- Reduced environmental impacts – Through optimised aircraft trajectories that minimise fuel consumption as well as noise/pollutant emissions.
- Trusted autonomous operations – Through reliable human-machine interactions supporting multi-platform (manned and unmanned) cooperation and coordination, and also enabling a safe and reliable integration of UAS into civil-military dual use ATM as well as into UAS Traffic Management (UTM) systems.

2 Onboard CNS Automation Systems

State-of-the-art FMS are primarily responsible for providing automated navigation and guidance services from take-off to landing [5]. Currently, only some decentralized, short-term collision detection and avoidance functions are carried out by the FMS. Additionally, some automated communications/ message management and Separation Assurance (SA) functions are performed by the FMS. The hardware components of modern FMS include a dedicated processor for the Flight Management Computer (FMC), a Multi Control Display Unit (MCDU) with keypad and a database storage and access unit. Key functions provided by FMS are:

- Positioning and navigation of the aircraft in all flight phases. Measurements from a number of navigation sensors are obtained and suitable multi-sensor data fusion techniques are employed.
- Guidance computations performed by lateral and vertical steering laws.
- Trajectory generation and optimisation.
- Short-term and long-term performance computation.
- Dual and single flight management modes.
- Data base management.
- Interface management.
- Monitoring and management of system faults including support for Built-In-Test (BIT) functions.

FMS provides Lateral Navigation (LNAV) and Vertical Navigation (VNAV) information that are used as guidance when flying manually or are used to control the aircraft automatically via an autopilot and autothrust system. The main navigation functions provided by FMS include:

- Selection of navigation modes.
- Radio navigation functions including manual and auto selection.
- Inertial Reference System (IRS) initialisation and alignment.
- Global Navigation Satellite System (GNSS) constellation and signal initialisation and processing. Various constellations or a combination can be selected including Global Positioning System (GPS), Galileo, GLObalnaya NAvigatsionnaya Sputnikovaya Sistema (GLONASS), BeiDou (or Compass), Navigation with Indian Constellation (NAVIC), Quasi-Zenith Satellite System (QZSS).

A conceptual representation of a typical FMS architecture is shown in Fig. 1.

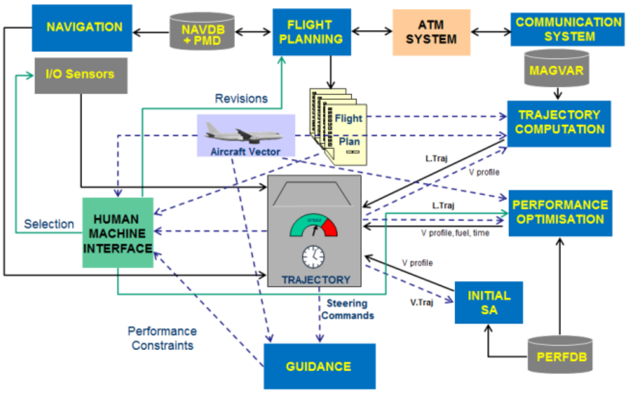

Fig. 1. State-of-the-art FMS architecture.

Databases employed for performing flight management computations include magnetic variation (MAGVAR), performance database (PERBDB), navigation database (NAGDB) and Pilot Modifiable Database (PMD). In addition to these databanks, weather, demographic distribution, digital terrain elevation, environmental and pilot modifiable databases can be introduced for time based operations.

3 CNS+A Systems

The novel automated CNS+A systems (on airborne and ground systems) allow suitably equipped aircraft (manned and unmanned) to fly user-preferred optimal flight paths, limiting the intervention of human operators to high-level and emergency decisions [6]. The CNS+A systems equipped manned and unmanned aircraft generate 4DT intents that consist of a number of flyable optimal trajectories in order of priority that are subsequently transmitted to the ground-based Next Generation Air Traffic Management (NG-ATM) system via reliable data links [7]. In this paper, the architecture and mathematical algorithms of the key on board avionics system named the Next Generation Flight Management System (NG-FMS) is presented. 4-Dimensional Trajectory (4DT) planning and optimisation models are employed in the NG-FMS. The NG-FMS supports real-time and automated negotiation and validation of 4DT intents with the NG-ATM systems. 4DT intent data are generated by the NG-FMS as 4D waypoints (latitude, longitude, altitude and time), leg and turn information. Real-time air-ground transactions ensure the validated 4DT intents are updated frequently when any change in operational conditions occurs. The provision of multiple trajectory options decreases the transaction duration and reduces the dependence on remotely calculated optimal trajectories from the NG-ATM system. When feasible trajectories cannot be identified based on the transmitted NG-FMS intents, the NG-ATM 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. Information from the trajectory prediction component of NG-FMS enables the flight crew to perform on board decision making tasks such as analysing if the next manoeuvre performed by the aircraft is within the operational envelope of the aircraft and/or if the altitude, airspeed and time constraints are compatible with the current phase of flight, etc. Additionally, the same information is transmitted to the ground-based decision support system for enhanced situational awareness assisting in 4DT planning, negotiation and validation processes. In the CNS+A context, the general case is that of multiple manned/unmanned traffics performing cooperative and/or non-cooperative surveillance. In terms of granting the required levels of operational safety when considering manned and unmanned aircraft coexistence in an airspace characterised by dense air traffic, the emphasis is on CNS+A equipment that can meet strict performance requirements while also supporting enhanced ATM functionalities. In particular, in order to provide the Required Surveillance Performance (RSP) in autonomous separation maintenance and collision avoidance tasks, a combination of non-cooperative sensors, including active/passive Forward-Looking Sensors (FLS) and acoustic sensors, as well as cooperative systems, including Automatic Dependent Surveillance Broadcast (ADS-B) and Traffic Collision Avoidance System (TCAS) are employed.

4 Next Generation FMS

The design and implementation of Next Generation Flight Management Systems (NG-FMS) algorithms is aimed at satisfying the CNS performances namely Required Communication Performance (RCP, Required Navigation Performance (RNP) and Required Surveillance Performance (RSP). Additionally, higher levels of automation are required to support the dynamic adaptation of decision logics required to enable single pilot and UAS operations. The NG-FMS software is based on multi-objective and multi-model 4DT optimisation algorithms for strategic, tactical and emergency scenarios. The NG-FMS architecture is shown in Fig. 2.

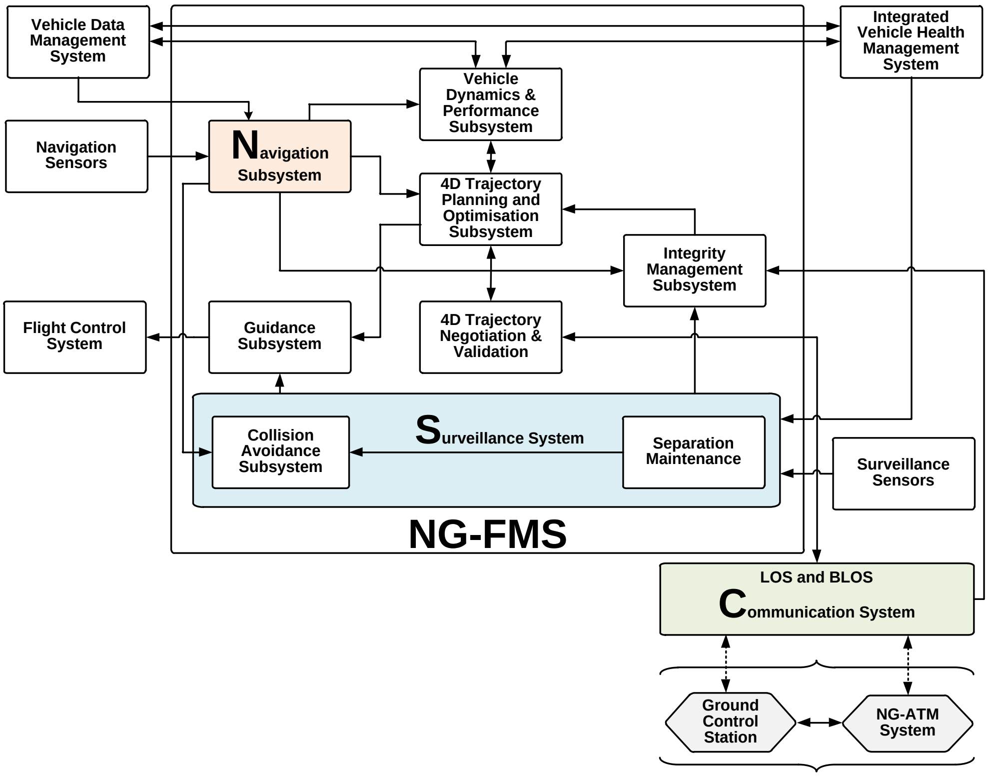

Fig. 2. NG-FMS architecture.

The following software modules are introduced in the NG-FMS:

- 4D trajectory planning and optimisation – to perform 4D trajectory planning and optimisation functions for strategic (offline and online), tactical (offline and online) and emergency tasks. A number of performance criteria and cost functions are used for optimisation including minimisation of fuel consumption, flight time, operative cost, noise impact, emissions and contrails.
- 4D trajectory monitoring and correction – to perform state estimation, to calculate of deviations between the 4D trajectory intents and the estimated/predicted aircraft states and to provide steering commands to the automatic flight control system.
- Automated Separation Assurance and Collision Avoidance (SA/CA) – to support cooperative and non-cooperative separation maintenance as well as collision avoidance tasks.
- 4D 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 air traffic controller via the 4-PNV system.
- Performance manager – to monitor active 4D trajectory intents for errors and to address RCP, RNP and RSP requirements in all flight phases.
- Integrity manager – to generate integrity C/N/S caution (predictive) and warning (reactive) flags. Inputs from a number of sensors/systems and predefined decision logics are used to provide annunciations, which are then used to perform preventive/corrective actions. A typical example is in which the main causes of GNSS signal outage and degradation in flight including antenna obscuration, multipath, fading due to adverse geometry and Doppler shift are modelled in an Avionics-Based Integrity Augmentation (ABIA) system. This increases the levels of integrity and accuracy (as well as continuity in multi-sensor data fusion architectures) of GNSS in a variety of mission- and safety-critical applications. [8].

4 Automated Separation Assurance and Collision Avoidance Functions

A unified approach to cooperative and non-cooperative separation assurance and collision avoidance is described in this section, enabling the translation of navigation and tracking errors to unified range and bearing descriptors. Navigation sensors including Global Navigation Satellite Systems (GNSS), Inertial Measurement Unit (IMU) and vision based sensing are considered in this approach. Errors in the obstacle/intruder measurements are estimated considering a combination of non-cooperative sensors, including active/passive Forward-Looking Sensors (FLS) and acoustic sensors, as well as cooperative systems, including Automatic Dependent Surveillance Broadcast (ADS-B) and Traffic Collision Avoidance System (TCAS). Non-cooperative sensors are employed to detect intruders or other obstacles in the aircraft Field of Regard (FOR) when cooperative systems are unavailable to the intruders. Boolean decision logics are employed for optimal selection of state-of-the-art technologies for non-cooperative sensors and cooperative systems. Additionally, ATM radar tracks/air traffic controller instructions in digital format transmitted by data links are also used in the data fusion process [9]. The trajectory information of the intruders is determined after performing multi-sensor data fusion. Criticality analysis is carried out to prioritise (i.e., to determine if the specified collision risk threshold is exceeded by the tracked intruders) and to determine the action commands.

Let R, α and ϵ be the range, azimuth and elevation obtained from the non-cooperative sensor or cooperative system. Let R_0, α_0 and ϵ_0 be the nominal values of range, azimuth and elevation. Let σ_R, σ_α and σ_ϵ be the standard deviations of the errors in range, azimuth and elevation respectively. Navigation and tracking error ellipsoids are expressed as:

$$\frac{(R-R_0)^2}{{\sigma_R}^2}+\frac{(\alpha-\alpha_0)^2}{{\sigma_\alpha}^2}+\frac{(\epsilon-\epsilon_0)^2}{{\sigma_\epsilon}^2}=1 \qquad (1)$$

In case of a static non-cooperative obstacle, the errors in range, azimuth and elevation are given by:

$$\delta R = R_0 + \sigma_R \cdot \sin\psi \qquad (2)$$

$$\delta\alpha = \alpha_0 + \sigma_\alpha \cdot \cos\varphi \cdot \cos\psi \qquad (3)$$

$$\delta\epsilon = \epsilon_0 + \sigma_\epsilon \cdot \sin\varphi \cdot \cos\psi \qquad (4)$$

where R_0, α_0, ϵ_0 are the nominal range, azimuth and elevation measurements and $\{\varphi, \psi\}$ are parameterisation factors. The transformation of $\{R, \alpha, \epsilon\}$ to $\{x, y, z\}$ is given by the following relationships:

$$x = R \cdot \cos\alpha \cdot \cos\epsilon \qquad (5)$$

$$y = R \cdot \sin\alpha \cdot \cos\epsilon \qquad (6)$$

$$z = R \cdot \sin\epsilon \qquad (7)$$

The navigation and tracking error ellipsoids are combined statistically to obtain the uncertainty volume. There are two possibilities: uncorrelated and correlated errors. Correlated errors can be further categorised into covariant and contravariant cases. The uncertainty volumes obtained, in the uncorrelated case, for range only error is shown in Fig. 3 (27 combinations in total).

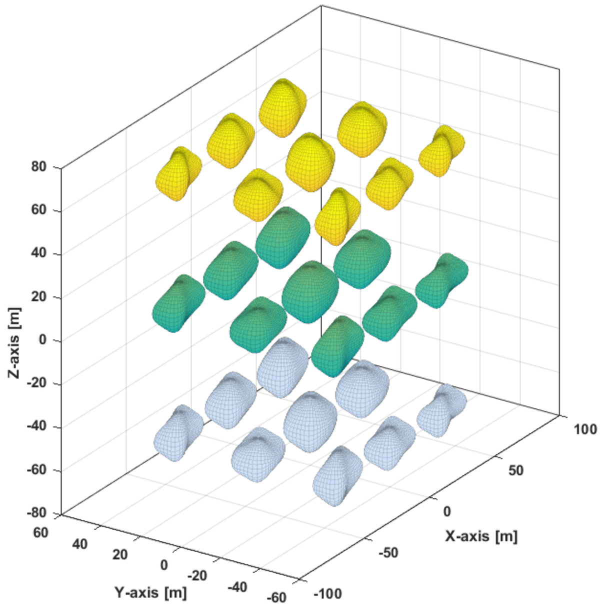

Fig. 3. Range only error uncertainty volumes.

In the case of intruders/obstacles that are in motion, the uncertainty volume is obtained based on a confidence region given by:

$$\delta v_0 = v_0 + \sigma_{v_0} \cdot \sin\psi \qquad (8)$$

$$\delta \nu_0 = \nu_0 + \sigma_{\nu_0} \cdot \cos\varphi \cdot \cos\psi \qquad (9)$$

$$\delta \upsilon_0 = \upsilon_0 + \sigma_\upsilon \cdot \sin\varphi \cdot \cos\psi \qquad (10)$$

where v_0, ν_0, υ_0 are the nominal velocity measurements. When there are errors in bearing measurement, a conical inflation is obtained at the estimated range. The uncertainty volume varies at different time epochs and is dependent on the relative dynamics between host aircraft and of the intruder (Fig. 4).

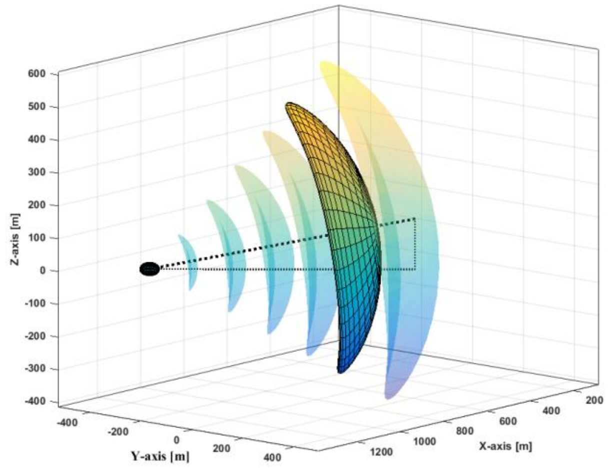

Fig. 4. Uncertainty volumes at different epochs.

Automatic separation assurance defined as separation assurance being implemented by airborne equipment is a key enabler of the free flight concept. The Airborne Separation Assurance Function (ASAF) couples with navigation component of the NG-FMS and gradually transfers the current Air Traffic Controller (ATCo) controlled modes to distributed modes. The ASAF system architecture is illustrated in Fig. 5. The subsequent step involves the selection of the optimal trajectory from the generated set of safe trajectories, which is then provided in the form of steering commands to the automatic flight control subsystem. The implemented decision logics are based on minimisation of the following cost function:

$$J = w_t \cdot t_{SAFE} - w_d \cdot d_m(t) + \int [w_f \cdot SFC \cdot T(t)]\, dt \qquad (11)$$

where, given T_T as the time-to-threat and T_M as the avoidance manoeuvre time, t_{SAFE} is the time at which the safe avoidance condition is successfully attained, defined as:

$$t_{SAFE} = T_T + 2\,T_A \qquad (12)$$

and SFC $\left[\frac{kg}{N} \cdot s\right]$ is specific fuel consumption, $T(t)$ is thrust profile and the coefficients w_t, w_f, w_d are the weights attributed to time, fuel and distance respectively. The term $d_m(t)$ is given by:

$$d_m(t) = \min\left[\sqrt{\begin{array}{l}\left(x(t) - x_{UV}(t)\right)^2 \\ +\left(y(t) - y_{UV}(t)\right)^2 \\ +\left(z(t) - z_{UV}(t)\right)^2\end{array}}\right] \qquad (13)$$

and is corresponds to the minimum distance from the uncertainty volume, where x_{UV}, y_{UV} and z_{UV} are the coordinates of the bounding surfaces of the volume.

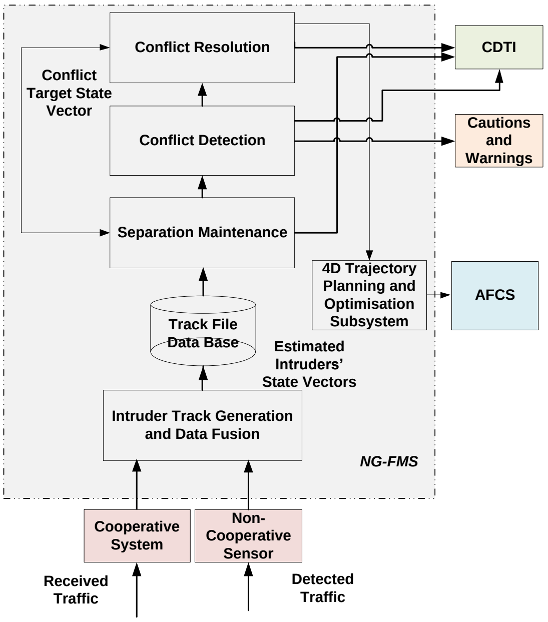

Fig. 5. ASAF system architecture.

Based on the identified state-of-the-art technologies, Boolean-logic based decision trees are used in the SAA system reference architecture. Boolean logics are generally hard wired and cannot be reconfigured and this limits the scope of cooperative and non-cooperative SAA unified framework in terms of automatic decision making capability. Therefore adaptive Boolean decision logics, which are based on real-time monitoring of the surveillance sensors/systems performance are implemented to support trusted autonomous operations. Covariance matrices are used for determining RSP and its compliance based on the current flight phase. Field Programmable Gate Arrays (FPGA) are adopted for data fusion through an array of dedicated programmable logic blocks. Fault Tree Analysis (FTA) and Failure Modes Effects and Criticality Analysis (FMECA) are performed with respect to the identified state-of-the-art SAA technologies to determine reliability of cooperative systems and non-cooperative sensors [10]. The sensor/system, which provides the best estimate, is selected automatically. The trajectory information of the intruders/obstacles is determined after performing multi-sensor data fusion techniques [11]. The presented approach thus provides autonomy and robustness in all flight phases, and supports all-weather and all-time operations. The method lays foundations for the development of an airworthy SAA capability and a pathway for manned/unmanned aircraft coexistence in all classes of airspace.

5 Simulation Case Studies

Simulation case studies were performed in a realistic scenario to assess the SA/CA functions implemented in the NG-FMS. Fig. 6 shows the uncertainty volume and avoidance trajectories generated in a non-cooperative scenario. In this case, a ground obstacle is detected by a non-cooperative sensors and an appropriate geo-fence is constructed around the detected obstacle. The obstacles are typically categorized into point, lateral (e.g., wires) and extended structures and the geo-fence is constructed based on the classification. The re-join trajectory is computed using pseudospectral optimisation techniques described in [12-14]. These simulations were executed on a Windows 7 Professional workstation (64-bit OS), supported by an Intel Core i7-4510 central processing unit with clock speed 2.6 GHz and 8.0 GB RAM. The total execution time for uncertainty volume determination as well as avoidance trajectory optimisation algorithms was in the order of 1.4 sec, supporting real-time implementation of these algorithms. The algorithms thus support the generation of appropriate dynamic geo-fences, whose characteristics are dictated by the obstacle classification and intruder dynamics, to allow computation of the optimal avoidance flight trajectories.

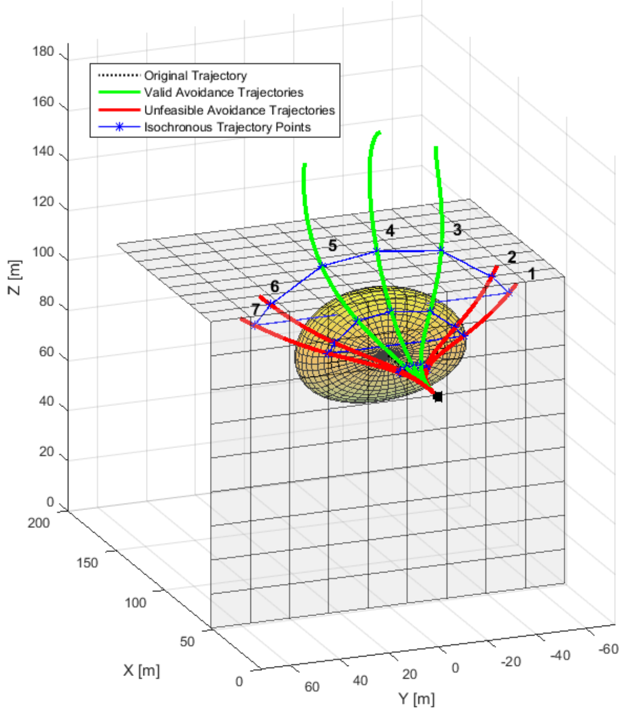

Fig. 6. Avoidance of a ground obstacle
(non-cooperative case).

In case of moving targets, a suite of non-cooperative sensors and cooperative systems can be employed to detect and predict the intruders' trajectories respectively. The Risk of Collision (RoC) is evaluated and based on this assessment, if there is a possibility of a collision, an uncertainty volume is computed according to the models described earlier. Trajectory re-optimisation routines are performed to obtain a safe avoidance of all the detected collisions (Fig. 7).

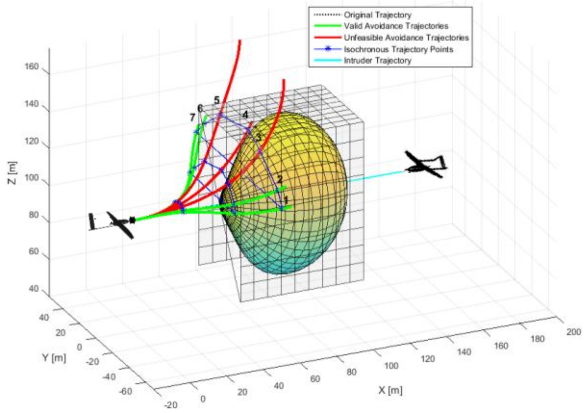

Fig. 7. Avoidance of an aerial target (cooperative case).

6 Human Machine Interface and Interaction

In a PBO/UTM context, separation assurance and collision avoidance is handled in a distributed system, where the pilot/remote pilot is designated with some of the conventional Air Traffic Controller's (ATCo) responsibilities in order to achieve increased capacity-demand balancing. Eurocontrol has identified three levels of delegation for achieving SA/CA. They are: *limited*, where the ATCo performs conflict detection and resolution tasks while the pilot executes the ATCo's decision; *extended*, where the ATCo performs conflict detection, and delegates the conflict resolution to be executed by the pilot; *full*, where the ATCo delegates full responsibility to the pilot for detection and resolution of any conflicts as well as execution of avoidance trajectory manoeuvre [15]. The concept of distributed control is to provide higher levels of delegation for SA/CA tasks, since highly centralised ATM systems limit the air traffic density within a specified sector. In addition to delegation of tasks between ATCo and pilots, the responsibility for SA/CA can also be delegated between the human operator and the automation system [16]. A highly distributed system relies on the pilot/controller as well as human-automation integration, and hence requires high levels of integrity for each component of the system. To address human-machine teaming in the CNS+A context, three human factor concepts are discussed. These are: situational awareness, trusted autonomy and ergonomics. Situational awareness has featured prominently in aviation-related human factors research over the past few decades [17, 18]. A loss of situational awareness has been a major cause of aircraft accidents and incidents. Increased levels of automation in the flight deck have provided opportunities for increased situational awareness, by reducing the need for constant vigilance over low level flight tasks. The pilot can therefore expand his cognitive resources on higher level tasks. A typical example is the automated navigation and guidance services provided by state-of-the-art FMS. However, higher levels of automation can also lead to a loss of situational awareness due to automation complacency, which is detrimental to the overall system performance. Additionally, the lack of low-level vigilance might impede the pilot's response to emergencies such as loss of self-separation. Trusted autonomy plays an increasingly important role in systems with high levels of delegations including ATCo-pilot/pilot-copilot/system-pilot interactions. As an example, radio phraseology and crew resource management provides a framework for building trust through proper communication and decision making protocols. With higher levels of automation, human-machine teaming becomes a key issue, and automation trust is required for optimal performance. Over- or under- trust results in non-optimal human-machine teaming scenarios [19]. In under-trust situations, the pilot allocates excessive vigilance for automation-monitoring or out rightly rejects the automation commands. When conflicting instructions are provided, the pilot executes the commands from the agent (person or system) in whom or which a greater level of trust is allocated to. Over- or under-trust might result in incorrect decision-making.

Ergonomics describes the functional design of systems to complement the human operator's work or cognitive processes. SA/CA systems shall factor in these considerations when designing the feedback mechanisms such as advisories, warnings and resolutions. Appropriate feedback shall be prioritized in terms of overall urgency, and be sufficient to draw the pilot's attention without distracting him from his current task. The identification and resolution of the conflict shall be timely – with sufficient time for the pilot to react – and easily comprehensible – not requiring a high cognitive effort to process. Feedback can be visual, audial or haptic. Visual feedback is the primary information channel for the pilot, and is constantly being refined based on the functions of the flight crew. Fig. 8 shows the conceptual design for the interface of a NG-FMS. Synthetic vision can enhance the pilot's situational awareness, as shown in the Primary Flight Display (PFD) on the left. Terrain data stored in the system is fused with navigational data, surveillance data and flight data. The location of the next waypoint, "LIN" in the Navigation

Display (ND), shows up in the PFD as series of indicator rings. The optimal route, represented as a magenta line in the ND, shows up as a 'tunnel-in-the-sky' in the PFD, along with the optimal pitch, bank angle and airspeed. Nearby aircraft communicate their position and attitude to the NG-FMS via ADS-B system and are displayed in the ND as well as the pilot's field-of-view in the PFD. Auditory feedback takes the form of a standard message, or a warning siren. Ergonomic design of this feedback channel requires tailoring the frequency and volume of the sound to achieve its desired effect. Haptic interfaces provide feedback through the pilot's sense of touch. It can be integrated into control devices, like the yoke and rudder, with force displacement gradients during separation loss to provide warnings against incorrect maneuvers.

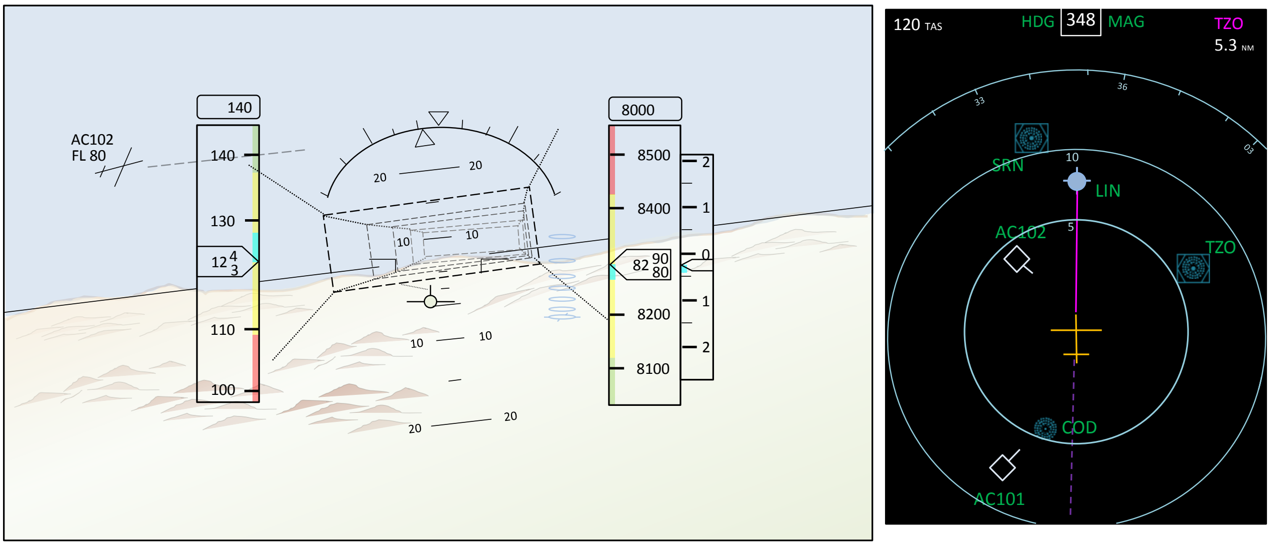

Fig. 8. NG-FMS display formats for increased situational awareness. PFD (left) and ND (right).

7 Conclusions and Future Work

The system architecture and algorithms of a novel Next Generation Flight Management System (NG-FMS) was presented. This system provides 4-Dimensional Trajectory Optimisation (4DT-O), air-to-ground trajectory negotiation/validation as well as automated separation assurance and collision avoidance functionalities supporting Trajectory/Intent based operations (TBO/IBO) and UAS Traffic Management (UTM). Mathematical models were described for a unified approach to non-cooperative and cooperative separation assurance and collision avoidance. Simulation case studies were performed and the results demonstrated the functional capability of the NG-FMS to generate safe and efficient avoidance trajectories when an obstacle or intruder is detected and categorized as a collision threat. Future research will include Communication, Navigation and Surveillance (CNS) integrity monitoring and augmentation algorithms as an integral part of NG-FMS producing caution and warning integrity flags based on an assessment of CNS performance. CNS data driven methodologies and networked system concepts are also being explored. Additionally, data link requirements in high density air traffic scenarios are being considered, including the associated trajectory data descriptors and negotiation/validation protocols.

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