APPLICATION OF THE RANGE SAFETY TEMPLATE TOOLKIT TO UAS RISK HAZARD ANALYSES SUPPORTING AIRWORTHINESS REGULATION

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Abstract

Australia's Defence Science and Technology Organisation (DSTO), in partnership with Aerospace Concepts Pty Ltd, has developed and fielded a new capability for quantitative risk assessments for a wide range of aerospace vehicles, including Unmanned Aerial Systems (UAS). This capability, called the Range Safety Template Toolkit (RSTT), offers rapid generation of mission-specific safety templates which comply with international standards for range risk criteria, including casualty and damage estimates for mission operational planning and ground safety case analyses.

This paper discusses the application of the RSTT to UAS flight safety analysis where risks to the public and ground infrastructure can be estimated as well as risks to other air traffic.

1 Introduction

1.1 RSTT History

Over the past eight years, the Australian Defence Science and Technology Organisation (DSTO) and industry partners, including Aerospace Concepts Pty Ltd and the University of Adelaide, have developed a capability for the quantitative flight safety analysis of aerospace vehicles. This capability, called the Range Safety Template Toolkit (RSTT), offers rapid generation of mission-specific trajectories and templates. These can be combined with geospatial information, such as asset locations and population densities, to provide casualty and damage estimates for aerospace vehicle mission operational and safety planning.

RSTT was originally developed for air-launched guided weapon flight safety analysis (the ASRAAM air-to-air missile and the JASSM cruise missile) but has now been applied far more broadly:

- Risk Hazard Analyses (RHA) for space launch and re-entry vehicles including those for the US/Australia HIFiRE hypersonics flight research program being conducted from Woomera, South Australia and for an upcoming series of rockets launches in Western Australia.
- Provision of independent verification services to the Australian Government in authorising the return of the Japanese Aerospace Exploration Agency (JAXA) Hayabusa Sample Return Capsule to Woomera in June 2010 from the asteroid *Itokawa*.
- Independent verification of the Javelin anti-armour missile safety template in support of acceptance into Australian Defence Force (ADF) service.

Aerospace Concepts has previously presented work ([1],[2],[3],[4],[5],[6],[7]) describing the broad RSTT capability, theoretical underpinnings, operational user and regulatory needs, our consequent development approach and the successful application of the RSTT capability to guided air weapons and space vehicles.

1.2 Application of RSTT to UAS

This paper discusses the application of RSTT to UAS flight safety analysis by outlining the commonality with previously-developed methodology used in support of cruise missiles and other guided weapons. This paper argues that UAS operations can be managed under the same or similar risk management arrangements as those used to manage guided weapons. The risk management criteria used to develop ground safety templates for guided weapons can be adopted to provide an assessment of casualty expectation and property damage associated with UAS operations.

To exploit the full potential of UAS it is necessary for operations to be performed in mixed (controlled) airspace. Therefore, it is necessary to develop management criteria and risk analysis methods to allow UAS operations in controlled airspace. This paper explores the adaptation of RSTT to these environments.

Furthermore the RSTT-based Risk Hazard Analysis can be used as a mission planning tool to assist in route selection (particularly in mixed airspace), design of control measures and in making operational risk decisions.

1.3 Safety Templates

Safety templates, variously known in other disciplines as ‘weapon danger areas’ (WDAs), ‘safety traces’ and ‘safety footprint areas’, are tools for the assessment and management of the ground impact risk associated with the operation of aerospace vehicles including space launch vehicles, returning spacecraft, various forms of guided and unguided munitions and UASs.

A safety template is calculated for a particular set of mission conditions and can take a number of forms, including:

- A curve representing an enclosed area where the aerospace vehicle might land with a specific probability, or
- A contour plot representing different regions of ground impact probabilities.

These plots are overlaid on maps or aeronautical charts of the intended area of operation and used to assess the risk of the flight affecting the safety of people and / or ground infrastructure. The results of the risk assessment can lead to the conditions of the flight being changed. For example, if the curve representing the vehicle debris impact area with a probability of 1×10^{-6} lies outside the template boundary the flight plan might be adjusted for a lower altitude or a different route.

2 How RSTT Works

2.1 Overview

A generic process for generating safety templates, adapted to the RSTT method, is shown in Fig. 1.

The templates are generated from a mission-specific pre-calculated ground impact distribution database. The process for creating the impact database, such as for a UAS or cruise missile, is a per-mission, computationally-intensive activity that simulates the mission with suitably selected tolerances on the independent variables.

This process requires a fit-for-purpose model of the weapon system, usually Six-Degree-of-Freedom (6-DOF), which includes modelling of Failure Response Modes (FRMs). Calculating the impact databases typically takes days to weeks on a large ‘computer farm’ of several hundred high-end computers. The database, along with client software, is then used by operational planning or flight safety specialists who then generate templates in minutes to hours on a single computer.

The remainder of this section discusses how a safety template is generated, beginning with failure analysis which is common to all weapon and aerospace vehicle variants covered. However a waypoint-following vehicle such as a UAS or a cruise missile has variability in the route for each mission and may be capable of dynamically rerouting during flight.

Fig. 1. Common safety template process

2.2 Failure Analysis

As noted in one of our previous AIAA papers [2], the safety generation begins with failure analysis of the aerospace vehicle or weapon of interest. The failure analysis provides information about potential failures, their likelihood and effects, and a measure of how critical the failure is to system operation. Certain individual sub-system failures often result in the same system behaviour. The behaviour of such a group of failures is referred to as a Failure Response Mode (FRM). For example, failures in the servo components, the autopilot, or icing/damage to the control surface can all cause loss of control surface performance. This is a case of three failure types giving rise to one FRM. Fig. 2 shows some sample potential FRMs for a typical UAS.

Systematic failures such as software errors and guidance failures are included either by accurately describing and assigning them probabilities of occurrence or by conservatively assuming a wide range of possible effects of such failures, and assigning a high probability of occurrence.

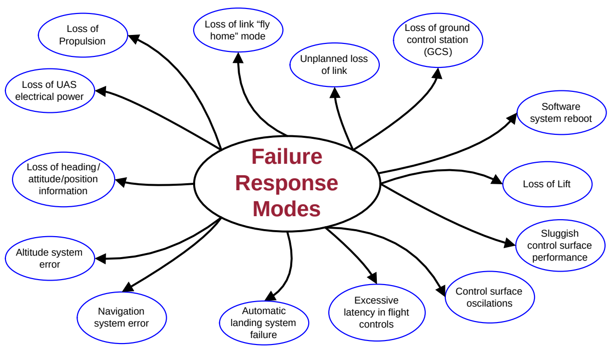

Fig. 2. Potential Failure Response Modes

2.3 Safety Template Generation

The safety template generation process for waypoint-following vehicles such as UAS begins by constructing a 6-DOF model of the vehicle including its FRMs. This model is then simulated for nominal and failure conditions to produce mission specific ground impact distributions. For each simulation the ground impact points and a history of the trajectory are recorded.

First, waypoints corresponding to the intended mission are overlaid on a range map, as illustrated in Fig. 3; this can be done via some form of mission planning software or manually.

Fig. 3. Mission waypoint overlaid on range map

We then perform many Monte Carlo simulations of the planned mission using the 6-DOF model, as shown in Fig. 4, where the flight paths are shown in black. The variations in flight paths are due to vehicle and mission parameter tolerances. In practice, thousands of simulations will be needed to characterise the dynamic state of the system at points along the nominal mission. Using these nominal dynamic flight paths the FRMs can be simulated at all points along the trajectory. All ground impact points, for both nominal and failure cases, are recorded in a Weapon Data Store (WDS).

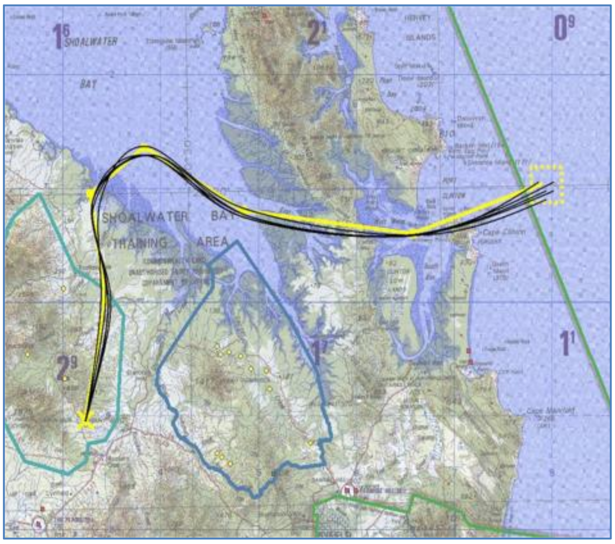

Fig. 4. Possible flight paths simulated by RSTT

The ground impacts are then statistically processed to generate a combined, whole-of-mission ground impact Probability Density Function (PDF). From this PDF, a number of risk contours and other products can be calculated defining specific levels of individual and collective risk. An example of an individual risk contour is shown in Fig. 5 (PDF shown in red, template boundary in blue).

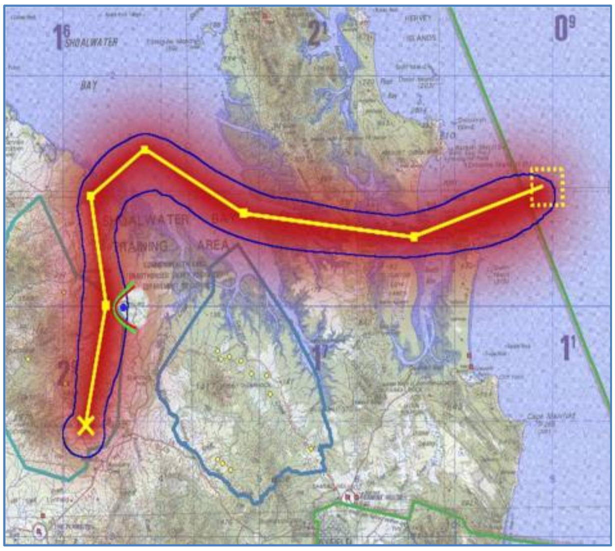

Fig. 5. PDF with range safety boundary showing reduced risk to ACC through use of safeguards

In some situations, an Area of Critical Concern (ACC), such as a valuable piece of ground-based infrastructure, could lie within the safety template boundary and may therefore be subjected to an unacceptably high level of risk. This risk could be mitigated by using a return to base, flight termination system or other area avoidance safeguards to 'protect' the ACC. Specifying return to base or area of avoidance safeguards around the ACC, with consideration given to the reliability of the UAS software and associated systems, can reduce the risk to which the ACC is exposed. This situation is illustrated in Fig. 5 where the ACC is represented by a blue dot, the avoidance lines are indicated in green, and the debris impact area in red.

3 RSTT Architecture

3.1 Architectural Basis

The RSTT has been developed within DSTO's mature, flexible and standards-based Mars and SimFramework [8] modelling and simulation environment from standard component models that comply with an internationally-accepted standard.

Consequently, new weapons or vehicles can be quickly added to the system (assuming sufficient aerospace vehicle technical data is available) and the resulting model can be used for many other purposes besides generation of range safety templates. For example, an RSTT model could also be used to characterise the performance of a preliminary or detailed design of a UAS.

3.2 High-level System Architecture

The RSTT architecture, shown in Fig. 6, consists of two segments and a data store.

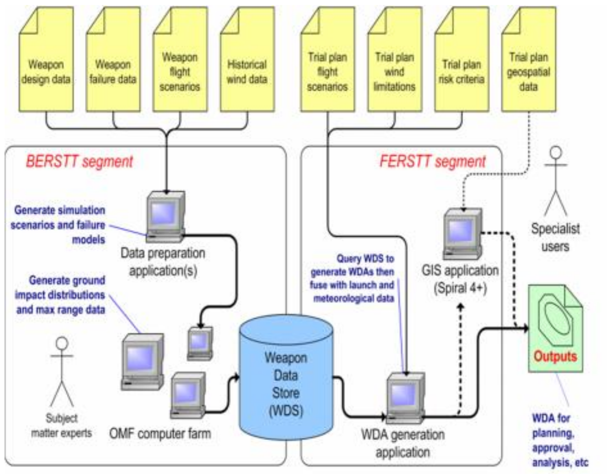

Fig. 6. RSTT high-level architecture

The 'Back End RSTT' (BERSTT) is a set of libraries and applications ('tools') used to model and simulate the aerospace vehicle to produce ground impact sets, where each ground impact set corresponds to a particular vehicle, mission and FRM combination. Within each ground impact set there may be sets of ground impacts for each class of debris that is generated by a given FRM. Impact data is stored in a weapon-specific Weapon Data Store (WDS).

The 'Front End RSTT' (FERSTT) includes an application that enables generation of PDFs from the ground impact data set in the WDS, the subsequent creation of templates and then analysis of mission safety issues.

3.3 Model Architecture

Development of weapon (and other aerospace vehicle) models is accomplished through an interface specification known as 'MIST' [8]. This provides a functional decomposition of a guided weapon system, as shown in Fig. 7, a specification of the signals passed between model components and a modelling architecture blueprint.

Each of the vehicles addressed to date (ASRAAM, JASSM, HIFiRE, *Hayabusa*, Javelin and Shark) have been modelled using a combination of standard MIST components that have been used as-is and others that have been modified. For example, an existing MIST compliant 'Motor' component was modified to support the multi-stage launch vehicles being used in the HIFiRE Program. Furthermore, component models have been created or modified to represent failure behaviours such as motor case burn-through or jammed control surface servos.

3.4 Simulation Architecture

An integral part of DSTO's philosophy of reuse and multinational interoperability is the evolving simulation architecture known as SimFramework. This architecture is consistent with MIST and allows development of component-based models of aerospace vehicles that interact with other models such as terrain in a portable hierarchy. Fig. 8 illustrates such a hierarchy of models, each of which can be developed independently.

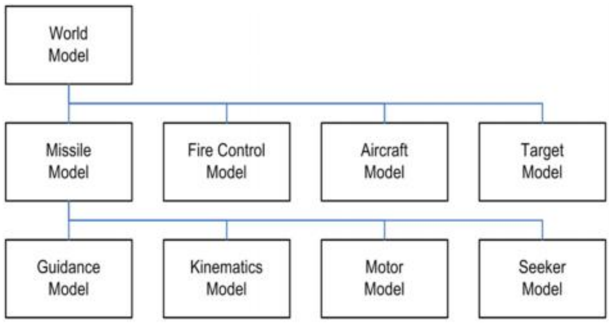

Fig. 8. SimFramework

4 RSTT Development

4.1 Challenges

Because the RSTT capability represents a new approach to template creation, both in Australia and internationally, we faced a number of distinct development challenges:

- **End-user needs.** End-user needs were not clear and were necessarily elicited over a considerable timespan, initially via prototyping and spiral development.
- **Policy issues.** The policy framework that governs the ability of the Australian Department of Defence to conduct potentially-hazardous flight test

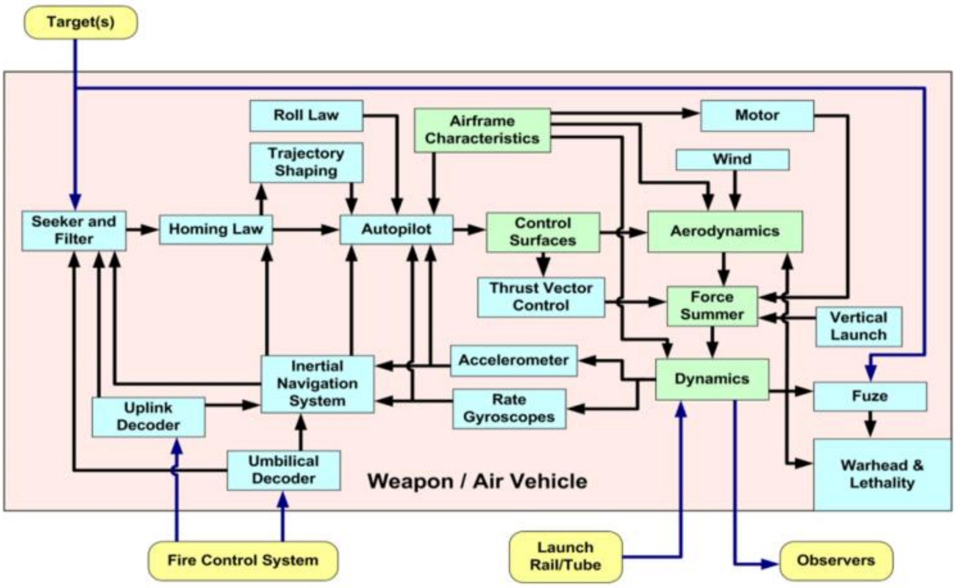

Fig. 7. MIST model architecture

activities was found to be somewhat dated and a significant effort was expended in supporting changes such as a broad acceptance of probabilistic approaches to range safety management.

- **Data availability.** The engineering practicality of the conceptual solution could not be guaranteed because sufficient data was usually not available to adequately model the subject vehicle. This required the creation of a Data Item Description (DID) to capture relevant design information, and the development of a risk-based approach to addressing deficiencies in the eventual input data.
- **Multi-object simulation.** Most flight simulation is concerned with nominal flight profiles and usually does not consider aerospace vehicle break-up and where the resulting debris might fall. As described below, it was necessary to adapt the modelling and simulation environment to simultaneously simulate the ‘main vehicle’ and any debris generated from failures or collisions.
- **Vehicle behaviours.** The different nature of the first three aerospace vehicles to be modelled meant that the design has had to incorporate a diverse range of vehicle behaviours which include from air-to-air engagement of moving targets, waypoint-following and exoatmospheric flight.
- **Vehicle design variability.** The experimental nature of the HIFiRE vehicles required that RSTT be able to accommodate significant vehicle design changes and uncertainty between flights. Coping with this diversity of behaviours necessitated advances in modelling techniques, including development of a unified method of modelling vehicle break-up and fragmentation [9]. How this design variability was addressed is discussed in more detail below.
- **Mathematical practicality.** The mathematical practicality of the statistical analysis techniques used by RSTT was also not guaranteed. Considerable work in adapting statistical techniques, such as Kernel Density Estimation (KDE), to treat the large simulation data sets was needed.
- **Computational tractability.** The high-fidelity modelling and Monte Carlo design concept for RSTT required significantly more computing power than past safety template generation methodologies. Solving this has required the development of a ‘farm’ of computers and the development of specialised distributed simulation job management software.
- **Assurance.** Finally, assuring that RSTT outputs represent the actual risks to people and infrastructure as closely as practicable is fundamental to the usability of the system. RSTT must be reliable and produce repeatable results. Assurance efforts, including validation approaches, are described below.

4.2 Multi-object Simulation

As noted previously, most flight simulation undertaken by DSTO is concerned with nominal flight and usually does not consider vehicle break-up and the resulting debris. Consequently, it was necessary to upgrade the modelling and simulation environment to simulate both the ‘main vehicle’, using the central 6-DOF vehicle simulation model, and any debris generated using a 3-DOF debris propagator model.

The application of this debris modelling capability to UAS becomes important in the case of collisions with other air traffic.

4.3 Vehicle Design Variability

RSTT had its beginnings with ASRAAM, an ‘off the shelf’ weapon with a fixed and known configuration and performance. Our work to support the experimental programs such as HIFiRE presents a different challenge to supporting weapons because experimental vehicles usually do not have a fixed configuration unlike an ‘off the shelf’ weapon.

Furthermore, there is a very real risk that model data with a sufficient level of provenance will not be available. Therefore, the RSTT ground-impact generation process has been developed to handle uncertainty in model data by incorporating a level of tolerance.

The method for allowing tolerance in the model design and mission parameters without invalidating the template is threefold:

- The data management system was developed to manage uncertain or unavailable data. The response to and uncertainty in, data with low provenance is managed and recorded.
- The existing parameter manager tool, used for assigning Monte Carlo figures to mission and vehicle parameters, was upgraded to support specification of a percentage tolerance on any value including physical parameters such as aerodynamic coefficients, moments of inertia and thrust profiles.
- We included techniques to demonstrably not underestimate the risk anywhere within the ground impact zone. This has been achieved by first running a scenario at full tolerance, then arbitrarily picking a battery of additional scenarios with a tighter tolerance range. The wide tolerance PDF is 'scaled up' so as to not underestimate risk compared to the results of the tight tolerance range. That is, the risk floor is raised to the highest 'tight tolerance' PDF.

5 RSTT Assurance

5.1 Overview

Assuring that RSTT outputs represent the actual risks to people, infrastructure and air traffic as closely as practicable is fundamental to the usability of the system given the trust that decision-makers will be placing in RSTT. Ideally, this assurance would be in the form of statistically-meaningful comparisons with actual flight data for the aerospace vehicles concerned. However, given that guided air weapons are not usually tested in statistically meaningful quantities and that experimental vehicles are, by their nature, unique or near-unique, assurance has been addressed in other, more subtle, ways.

5.2 Engineering Management

RSTT has been developed under an engineering management system that meets the requirements of the Australian Department of Defence airworthiness regulatory framework. This engineering framework closely resembles that of an Approved Design Organisation under civil aviation regulations. Furthermore, given that RSTT is a safety-related software-intensive system, it has been developed as 'Level C' software under RCTA/DO-178.

5.3 Validation

Originally, validation of RSTT outputs posed a problem particularly due to the lack of statistically-meaningful flight data as discussed above. Validation is an ongoing activity as opportunities arise. Efforts thus far have focused on validating RSTT via comparison against radar track data from similar flights, ground impact point sets generated by other means, and independent trajectory simulations.

In the first two cases RSTT was validated against HyShot 2, hypersonic flight experiment conducted in 2002 at Woomera [10]. RSTT outputs closely matched both the radar track data (when corrections for certain known differences were applied) and the safety template generated for the mission.

5.4 Operational Assurance

RSTT must be properly employed to assure the output. As per how airworthiness encompasses both the technical and operational aspects, RSTT employment encompasses not only the software but the context in which it is 'operated' including organisational competence, personnel, processes, data and assumptions.

6 RSTT Application to UAS

6.1 Introduction

In order to realise the full potential of UAS capabilities it is highly desirable to operate in mixed airspace. The current the approach to the management of risks to other air traffic is codified in the US Range Commanders Council criteria for UAS safety, RCC 323-99 [11].

6.2 Exclusive Airspace Use

RCC 323-99 contains a number of Mid-air Collision Avoidance Criteria, the most common being, and the simplest to comply with, being *Exclusive Use within Restricted Airspace or Warning Areas*. UAS operations are required to be contained within restricted airspace or warning areas from which other air traffic is excluded.

6.3 Shared use within Restricted Airspace

The second most commonly used RCC 323-99 Mid-air Collision Avoidance Criterion is *Shared Use within Restricted Airspace or Warning Areas*. In this scenario the UAS could be flown in restricted or warning areas along with other aircraft which may not be participating in the UAS mission. This scenario is not usually adopted in civil airspace without National Airworthiness Authority approval. However, in military combat operations this has been approved with careful management of operational risks. Nevertheless, the risks associated with such shared operations in restricted airspace can provide benefits that can be realised with careful management of risks and the development of mitigating actions.

6.4 Operations in the National Airspace

The third RCC 323-99 Mid-air Collision Avoidance Criteria covers *UAV Operations in other than Restricted and Warning Areas*. Operating a UAS in compliance with this criterion involves approval from the National Airworthiness Authority (NAA) or regulator, and relates to entry and operation in National Airspace (other than restricted or warning areas). The NAA is responsible for aircraft separation during Instrument Flight Rules (IFR) conditions, and is responsible for regulations regarding aircraft separation in Visual Flight Rules (VFR) conditions. The NAA must also authorise and approve the flight. In this case the risks to the travelling public are considerably higher, and therefore these approvals are conditional on numerous operational constraints and hazard mitigation actions.

6.5 Mid-air Collision Risk Assessment

The existing functionality of the RSTT capability can be adapted to support risk assessments for RCC 323-99 Mid-air Collision Avoidance Criteria in two ways.

The first is by providing a statistical characterisation of the probability of a UAS

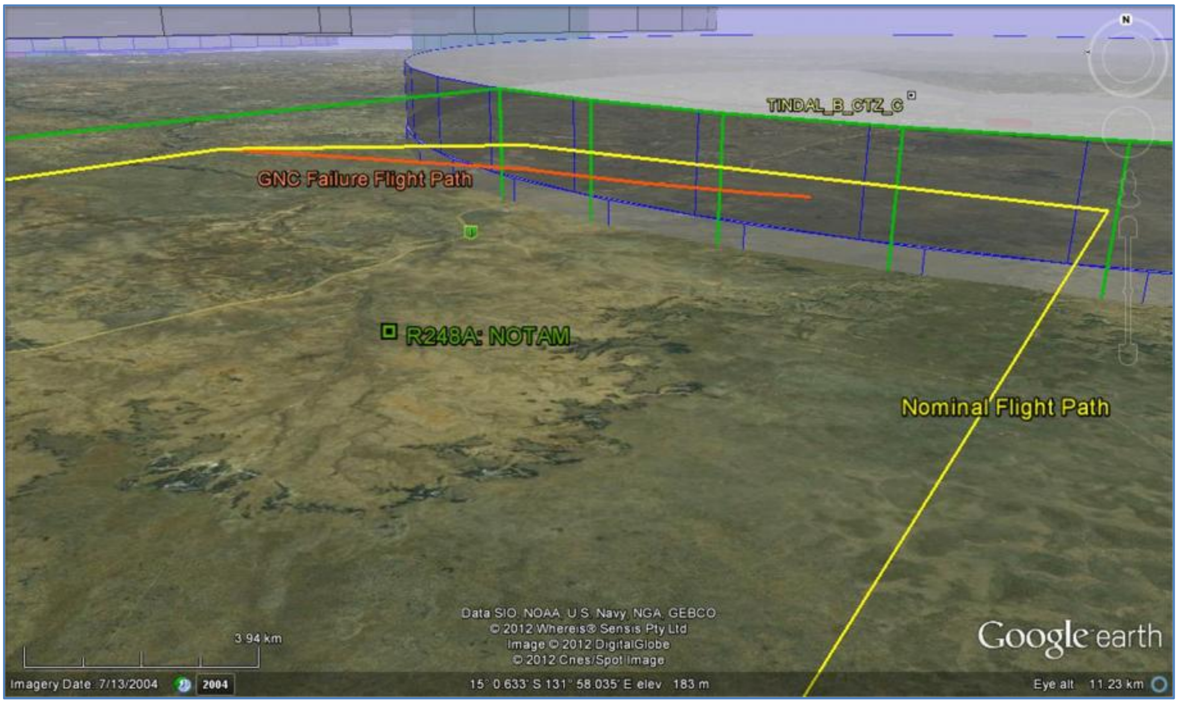

Fig. 9. UAS restricted airspace boundary violation scenario (illustration only)

violating Restricted or controlled airspace boundaries under both nominal and failure flight conditions. The sophistication of this analysis could be increased by indicating the most probable locations for such airspace boundary violations, as shown in Fig. 9. RSTT could provide risk estimates compatible with the Probability per flight hour categories used in RCC 323-99, by estimating the number of *airspace boundary violation incidents per 100,000 flight hours*.

The alternative is to regard air traffic as 'targets' to be avoided rather than intercepted. It is therefore the inverse of the approach adopted for air-to-air missile modelling (such as undertaken with ASRAAM), with the UAS being the primary aerospace vehicle and other air traffic comprising the 'targets' to be avoided. In this case, RSTT can provide a statistical analysis of minimum separation distances between the UAS and other air traffic. These separation distances are defined by lateral and vertical separation minima by airspace management authorities. Therefore RSTT could be configured to provide two measures of air traffic collision risk relating to *near misses* and *collision*, which are again compatible with the RCC 323-99 probability per flight hour categories.

Near miss incidents could be estimated per 100,000 flight hours as defined by Air Traffic Control lateral and vertical separation minima. These are the 'near collisions' that are reported as incidents, using the pre-determined vertical and lateral separation minima.

Collisions could be estimated per 100,000 flight hours. Obviously not all collisions result in fatalities. So we could potentially extend the analysis to look at closure velocities and energy at collision. Data from actual mid-air collisions could be used to make an assessment of collision energy and outcome.

Note that both *Near miss* and *collision* risk as estimated by RSTT could be compared with historical data of actual occurrences to make and assessment of equivalent flight safety. Furthermore, RSTT could be configured to ensure that the simulated conditions equate to categories of operation and airspace classes to ensure valid comparisons.

6.6 Collision Avoidance Manoeuvring

Modelling of UAS and air traffic *near miss* and *collision* risk is relatively easily implemented within RSTT. However, the main challenges relate to 'end-game' manoeuvring where a potential collision is subject to UAS pilot intervention, Air Traffic Control air traffic intervention, manned aircraft intervention, and use of automated systems such as Traffic Collision Avoidance Systems (TCAS). Given this complexity, this modelling may adopt a staged approach applying conservative assumptions relating to latencies and the use of automated systems to avoid collisions. In this way further fidelity can be added as required to incorporate the latencies and functionality as required.

6.7 Post-collision Debris Modelling

The RSTT capability can model debris associated with collisions between UAS and other air traffic. The resulting debris would be generated using a 3-DOF debris propagator model based on the debris catalogues of the UAS and the air traffic. The generation of debris catalogues covering the envelope of both relevant FRMs and flight conditions can also cope with a likely lack of suitable data. The RSTT methodology [9] for generating debris catalogues applies equally to UAS and manned aircraft. This catalogue can be populated with statistically representative data relating to manned aircraft debris characteristics resulting from mid-air collisions and/or breakup.

7 Conclusions

RSTT has proved to be a functional and highly adaptable capability for the creation of safety templates and associated analysis for a broad range of aerospace vehicles from anti-armour weapons to space launch and re-entry vehicles. RSTT produces outputs which conform to relevant assurance standards and the capability itself has been developed under formal engineering management arrangements.

Applying RSTT to the airworthiness regulation of UAS is shown to be relatively straightforward. By applying a common standard to the management of UAS-related risks to other air traffic, RSTT is shown to be useful in dealing with a range of common airspace management situations including exclusive use of Restricted airspace, shared use within Restricted airspace, operations in the National Airspace, mid-air collision risk assessment and avoidance, and post-collision debris field modelling.

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