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Test Architecture for Prototyping Automated Dynamic Airspace Control

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1. Introduction

The automation of various aspects of air traffic management has many wide-reaching benefits including: reducing the workload for Air Traffic Controllers; increasing the flexibility of operations (both civil and military) within the airspace system through facilitating automated dynamic changes to en-route flight plans; ensuring safe aircraft separation for a complex mix of airspace users within a highly complex and dynamic airspace management system architecture. These benefits accumulate to increase the efficiency and flexibility of airspace use(1). Such functions are critical for the anticipated increase in volume of manned and unmanned aircraft traffic. One significant challenge facing the advancement of airspace automation lies in convincing air traffic regulatory authorities that the level of safety achievable through the use of automation concepts is comparable to, or exceeds, the accepted safety performance of the current system.

Boeing Research and Technology (BR&T), together with collaborators at the University of Sheffield and the Boeing/Australian Research Center for Aerospace Automation (ARCAA) Smart Skies project have developed and are continuously testing a prototype automated airspace system architecture(2). This paper describes the research, development and practical flight-testing activities undertaken to characterize the performance of the prototype automated airspace system. The objective of this activity is to increase understanding of the capabilities and issues (such as safety performance), which are associated with an increased level of autonomy in an airspace traffic management system.

Development and testing of the prototype architecture is currently focused on the automation of an Air Traffic Control (ATC) system for unrestricted Class G airspace encompassing both cooperative and uncooperative airspace users. Real world flight tests aimed at characterizing the performance of the system are being conducted in Australian airspace using a mix of manned, unmanned and simulated aircraft(2). This paper summarizes some of the results obtained from the recently completed second phase of flight tests, with a further six flight test phases scheduled throughout 2009 and 2010. Although the development effort is focused towards automation of uncontrolled airspace, many of the concepts and algorithms could potentially be applied (with additional rules and constraints) to controlled airspace to help address the challenge of introducing further airspace automation within the National Airspace System (NAS).

Fundamental to the prototype architecture is a dynamically networked system of aircraft-based Flight Management Systems (FMS) with automated airspace control segments. Central to this concept are communication networks and data link technologies(3)(4).This test automated airspace system architecture is composed of three main components:

1. The data communications or *Common Information Network* (CIN).
2. The *Airspace* component consisting of aerial platforms (real and simulated)
3. The *Automated Dynamic Airspace Controller* (ADAC).

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Figure 1 illustrates the high level relationships between the major components of this architecture. The ADAC provides an automated ATC role and is discussed in more detail in Section 4. The CIN provides the infrastructure for the communication of information relating to aircraft state and intent, the conditions of the airspace environment (e.g., weather) and trajectory management information to flow between the ADAC, airspace users and other nodes of the automated airspace management system. The network facilitates the application of automated aircraft conflict detection and resolution to maintain safe aircraft separation. The CIN functionally enables communication channels between cooperative aircraft (suitably equipped) and the ADAC. The CIN also enables additional data channels (e.g., track data obtained from a primary radar or from the Automatic Dependent Surveillance(5) – Broadcast (ADS-B) surveillance system), to provide more information on other airspace users lacking compatible equipment.

The *Airspace* component currently consists of a mixture of simulated and real aircraft. Cooperative aircraft must be suitably equipped to communicate within the CIN. Practically, this means the installation of transceivers, modems and antennas to enable the establishment of communication channels with the ADAC. All cooperative aircraft require integration with an aircraft's FMS. In this paper we use the term *predictive Flight Management System* (pFMS) to signify an enhanced FMS containing the CIN interface software to enable communication with the ground-based ADAC. Further, the pFMS contains additional functionality including: Estimation of current and future aircraft states (position, attitude, time and uncertainties); Management of multiple communications links; Receiving, loading and execution of ADAC generated commands; Intelligent algorithms for the management of on-board sensors and related information (e.g., such as passive *sense-and-act* systems). Other research groups are also evaluating the integration of an aircrafts FMS, data link technology and automated trajectory-based operations(6). The tests presented in this paper employ a pFMS that does not provide a decentralized separation function.

The project adopts a phased research, development and testing program with the aim of progressively exploring increasingly decentralized separation architectures. The general architecture accommodates aircraft with several different equipage levels. Uncooperative platforms do not share their state information or communicate with the CIN due to the lack of suitable equipment. To expose such aircraft to the ADAC, tracking can be provided using additional sensors such as ground based radars or sensors on-board other cooperative or semi-cooperative airspace users. Semi-cooperative aircraft have sufficient equipage to enable the transmission of aircraft state and intent data. Such aircraft would not be expected to execute trajectory modification commands transmitted by the ADAC. To summarize, the airspace component is populated by cooperative and uncooperative platforms. Cooperative platforms are fully networked to the ADAC via the CIN. Data describing uncooperative aircraft are networked to the CIN using radars and other external information sources.

Central to the prototype architecture is an ADAC which: a) Continually maintains situational awareness of the state of the airspace system by receiving aircraft tracking information and changes within the airspace environment (e.g., weather, dynamic/temporary airspace activations etc); b) Monitors the airspace system state, and if necessary, transmits recommended control information to cooperative airspace users where there is the potential for a Loss of Separation (LOS). The ADAC hosts an aircraft Separation Management (SM) software component which monitors current and future aircraft separation distances, determines and issues recommended modifications to aircraft trajectories which ensure adequate separation between aircraft. The term *Dynamic* in ADAC implies that the aerial platforms are not necessarily constrained to fly pre-approved flight plans, or to fly in designated airspace corridors, or that the airspace system/environment itself is static (e.g., activation of special use airspace, weather or the loss of a particular communications network). The SM determines safe separation distances based on its information on the airspace environment, the performance of the air traffic management system (e.g., communications latencies), the type and performance of the aircraft and on the quality of the information received describing the aircraft trajectory.

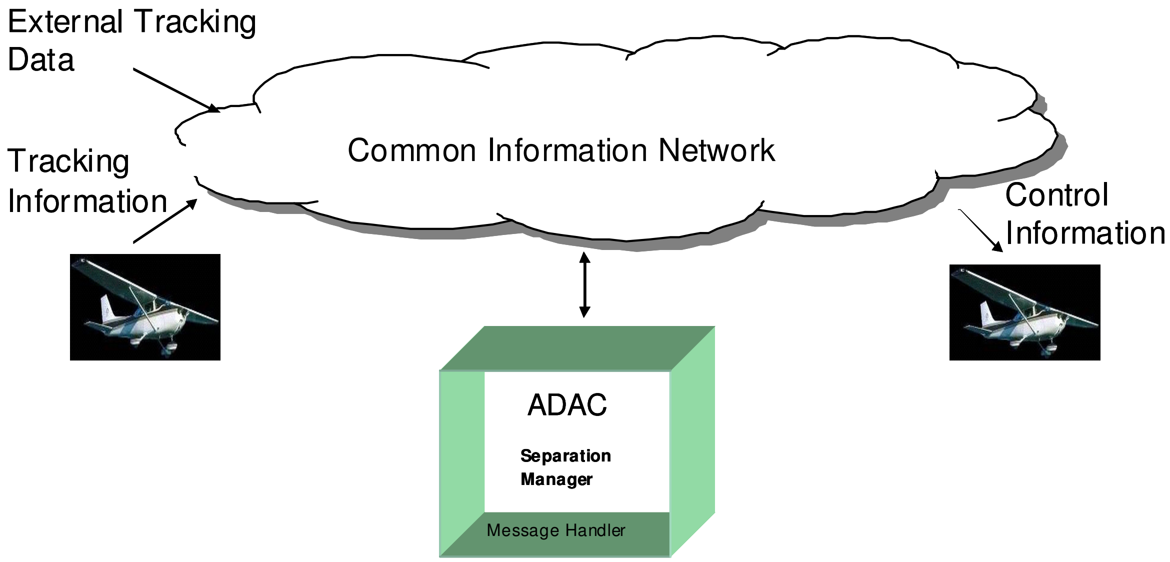

Figure 1. High level architecture

The information flow in Figure 1 represents a real-time closed-loop control process. Each component of this process has an associated latency and reliability. The desired end-to-end latency of this system is approximately three seconds for Class G airspace. Achieving this desired latency implies that a relatively fast airspace user (e.g., with an indicated airspeed of 250 knots – the current restriction permitted for aircraft operations under 10,000ft AMSL in ICAO Class G airspace(7)) could travel approximately 400 meters in the amount of time it would take the ADAC to detect and resolve loss of separation conditions and transmit the appropriate trajectory control to cooperative aircraft. The relative displacement for two such example aircraft in a head on closure scenario would be ~800 meters. The purpose of our investigations is to explore how successfully we can achieve this target latency for the prototype architecture being developed under the Smart Skies[*] program using real test data. Such testing and subsequent analysis should highlight where future improvements may be required to increase the level of autonomy in airspace management systems.

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2. Common Information Network

The Common Information Network (CIN) allows for communications between cooperative aircraft and the ADAC. In addition it can accommodate communications with external data sources to facilitate the characterization of uncooperative aircraft trajectories. ***Figure 2*** represents a prototype CIN developed for the Smart Skies program. This CIN has been used for two sets of airborne trials (referred to as the Phase 1 and Phase 2 Flight Trials, P1FT and P2FT) in Australia and will continue to evolve and be tested through 2010.

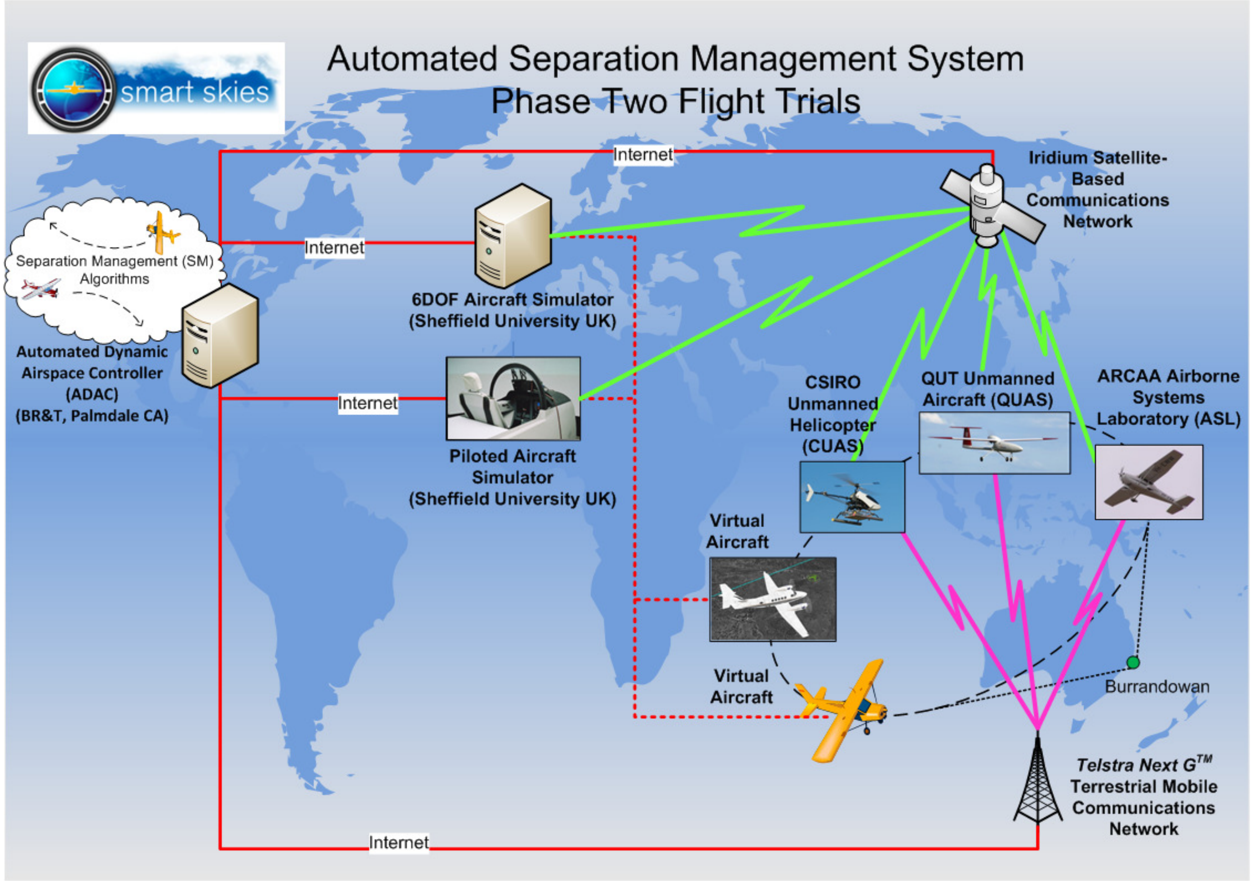

Figure 2. Smart Skies Phase 2 Test Architecture

Two existing communications systems are currently being explored as part of the CIN: the Iridium Satellite System(8)(9) and the Telstra Next Generation (3G) cellular system, referred to as *Next G*™. ***Figure 2*** shows how the ADAC and CIN were implemented for Phase 2 Flight Trials (P2FT).

The Iridium System has the advantage of near global coverage. Aircraft flying in Australian airspace, installed with an Iridium transceiver and antenna, communicate with Iridium satellites and establish a full-duplex 2.4 Kbits/s data link with the ADAC. Even with aircraft states data transmitted at 1 Hz, this narrowband channel is more than adequate for the exchange of the information required by the ADAC. The number of Iridium available data call channels exceeds any Smart Skies test requirements.

The *Next G* cellular system was designed for ground-based cellular communications. However, during testing the system has worked well for airborne applications where coverage is available. Extensive mapping of the cellular coverage over the test site (Burrandowan, Queensland) indicated that *Next G* coverage was sufficient for the flight trials. The *Next G* data rate can be up to several Mbits/s tower dependent on the number of users. The typical data rate observed during testing is approximately 200 Kbits/s.

On paper the two communications systems are markedly different in performance in terms of their coverage, latency, drop outs, and bandwidth. One of the broader objectives is to better understand the overall performance of the prototype automated airspace management system with variations in the performance of the underlying communications networks comprising the CIN. The disparity in performance between the two chosen case-study networks provides coverage over a broad range of communications performance.

TCP/IP connections are established over the Internet to provide the ground communications links between the ADAC and the various wireless communication systems. Employing the *best-effort* Internet is not considered a major constraint for this project. Additionally, most commercial digital communications systems such as Iridium and *Next G* provide Internet connection services. Data link technology without TCP/IP connectivity could be added to the ADAC as and when required, or alternatively, TCP/IP connectivity bridges could be created. An Iridium service called the Router-based Unrestricted Digital Internetworking Connectivity Service (RUDICS) allows any aircraft with an Iridium transceiver and antenna to send data through the Iridium satellite system, to a ground-based gateway, which in-turn establishes a bi-directional ADAC connection over the Internet. For communications utilizing the 3G cellular network, a Network Address Translation (NAT) router is used to manage the dynamic IP addresses assigned by the service provider to each 3G modem hosted on an aircraft.

This communications architecture implies that the ADAC need not be geographically co-located with the aircraft and can be located anywhere on the globe provided there is Internet connectivity. Further, the architecture can support redundant and geographically distributed ADAC systems. For the purposes of P2FT only one ADAC was deployed and only one communications network was used by the ADAC at any single point of time (however both links were active during experiments). Future phases will employ multiple ADACs that will utilise data received over multiple networks simultaneously acknowledging that future requirements on an automated airspace management system will likely necessitate redundancy to meet system reliability, coverage and availability requirements.

In the prototype system the ADAC provides the role of a messaging server and the cooperative aircraft act as clients. Aircraft enter the network by establishing TCP/IP connections and periodically transmitting state vector information and flight plan information. All messages are constructed with binary characters enabling more efficient usage of data link bandwidth when compared with ASCII messages. In practice, some legacy communication systems require additional encoding of binary data to avoid erroneous insertion of control characters into data streams. This approach has been adopted in this project and all differing data channels use a consistent encoding scheme to support such legacy systems. In typical use, the airborne pFMS transmits a binary state data message, here termed *Trajectory Array Data Set* (TADS), to the ADAC at a nominal rate of 1 Hz (the actual rate is also a parameter varied for particular tests). There are approximately 80 bytes per state vector, including message overheads. In this project, we term recommended flight plan modifications issued by the ADAC as *Commanded TADS* (CTADS).

To provide a human ADAC operator and flight test personnel with decision support and situational awareness, the entire aircraft tracking and CTADS generation process is displayed on a visualization tool. An example screen capture (***Figure 3***) of the visualization tool depicting two aircraft, their conflicting flight plan trajectories (indicated in pink) and the CTADS issued by the ADAC (indicated in blue). Note that in ***Figure 3***, the aircraft ID (AID) six is an actual flight test aircraft flown in Australia.

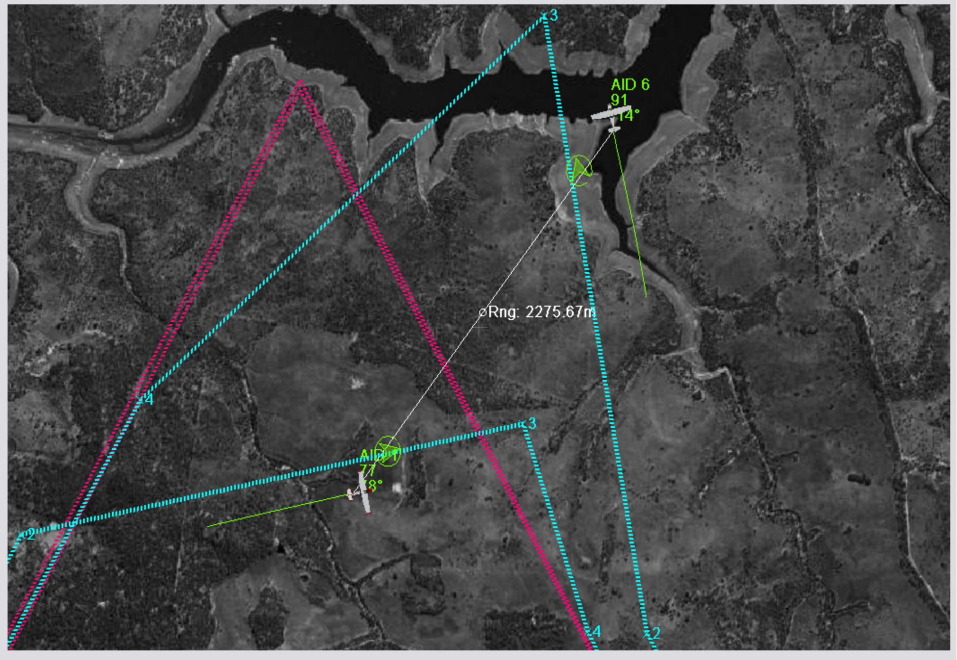

Figure 3. Sample Screen Capture of Situational Awareness Display

In addition to nominal flight plans, TADS and CTADS messages, the ADAC and cooperating aircraft exchange additional application protocol overhead messages including *pings*, local situational awareness (uploading local traffic information to aircraft) and acknowledgement messages. As mentioned, CTADS are commanded flight plan modifications. This is usually represented as a near-term flight plan in the form of a set of waypoints (e.g., the blue trajectories illustrated in ***Figure 3***). These waypoints are intended to provide guidance cues to the pFMS, a pilot or a UAS operator in the event of a predicted LOS scenario. A typical CTADS message payload containing five commanded waypoints contains approximately 128 bytes. *Table 1* lists the main message types communicated over the CIN, including the associated message frequencies.

Message communication latencies on the prototype CIN have been tested on numerous occasions(1)(10)(11). ***Figure 4*** shows the typical latencies for a single trip *ping* message transmitted from the ADAC to a receiving aircraft using Iridium (left) and Next G (right). For Iridium, the mean recorded round trip latency was 0.98 seconds with a standard deviation of 0.29 seconds. Likewise, the round trip message latency recorded over a *Next G* data link was 0.91 seconds with a standard deviation of 0.28 seconds. This round trip latency includes the airspace segment processing latency on board the airborne platforms.

Message Type	Length[%] (Bytes)	TX Frequency (Hz)	Comments
TADS (aircraft state data)	**80**	**≥ 1**	
Proposed aircraft flight plan	**Variable, 160 for 10 waypoints**	**Once**	**Retransmitted if modified**
CTADS (commanded flight plan modifications)	**Variable, 128 for 5 waypoints**	**As needed**	**Transmitted by the ADAC to any cooperative aircraft requiring separation**
Ping	**30**	**0.1**	**Includes response message**
Acknowledgement	**28**	**As needed**	**Transmitted by ADAC or pFMS in response to receipt of a flight plan or CTADS respectively**
Situational Awareness	**Variable, 178 for 4 local aircraft**	**0.1**	**Transmitted by the ADAC to provide surveillance data to neighboring aircraft**

[%] All message lengths reported include 26 bytes of overhead inclusive of timestamps and aircraft identification.

Table 1. Message Traffic on the CIN

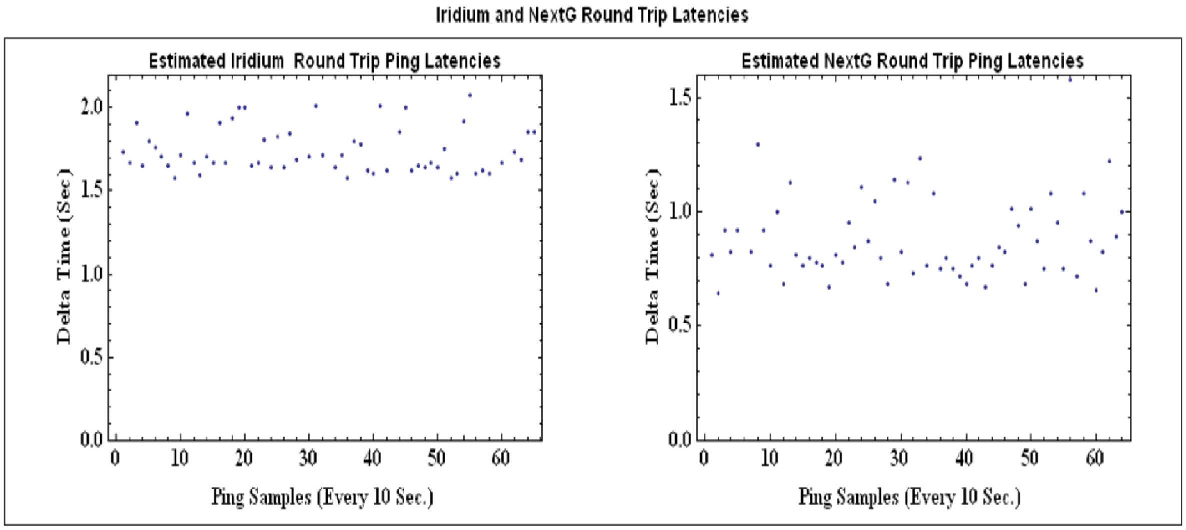

Figure 4. Characteristic message latencies using Iridium (left) and Next G (right) connections

3. Airspace Segment

The Airspace Segment consists of simulated and real aircraft which have been custom modified to communicate with the ADAC using the CIN. For the Smart Skies project prototype CIN, several real aircraft and flight simulation tools have been developed and tested during the P1FT and P2FT. The primary flight test aircraft used in Smart Skies testing include:

1) A Cessna 172R aircraft referred to as the Airborne Systems Laboratory (ASL). Developed by ARCAA, the custom-modified aircraft is fitted with a GPS-INS truth data system, pFMS, custom flight display (for visualizing flight plans, CTADS, situation awareness and other information received from the ADAC) and a communications management system. The ASL is capable of conventional human piloted control or an optionally auto-piloted mode (en-route lateral auto-pilot) where CTADS received from the ADAC are fed directly into the Cessna autopilot. For P1FT the ASL was flown under a conventionally piloted mode of operation, and for P2FT the ASL was flown in an optionally piloted or auto-piloted mode of operation. ***Figure 5*** (top left) illustrates the antenna placement on the ASL. Note that Iridium antennas face upward where as *Next G* antennas face downward ensuring a measure of independence between the two communication channels.
2) A small autonomous fixed-wing UAS, referred to as the QUAS Flamingo (***Figure 5***, bottom left). The Flamingo has a maximum takeoff weight of 20kg, a payload capacity of 4kg and an endurance of approximately one hour (full fuel and payload). Onboard systems include a pFMS, a commercial off-the-shelf autopilot, UHF, Iridium and 3G communications, and a vision-based sense and avoid payload.
3) A small autonomous helicopter, referred to as the CUAS (***Figure 5***, top right). The CUAS has a maximum takeoff weight of 13kg and endurance of approximately 45 minutes (full fuel and payload). Onboard systems include: a pFMS, custom-designed flight computer and autopilot, UHF communications, and an integrated LIght Detection And Ranging (LIDAR) and stereo vision-based sense and avoid payload. Iridium and 3G communications systems are located at the CUAS ground control station.

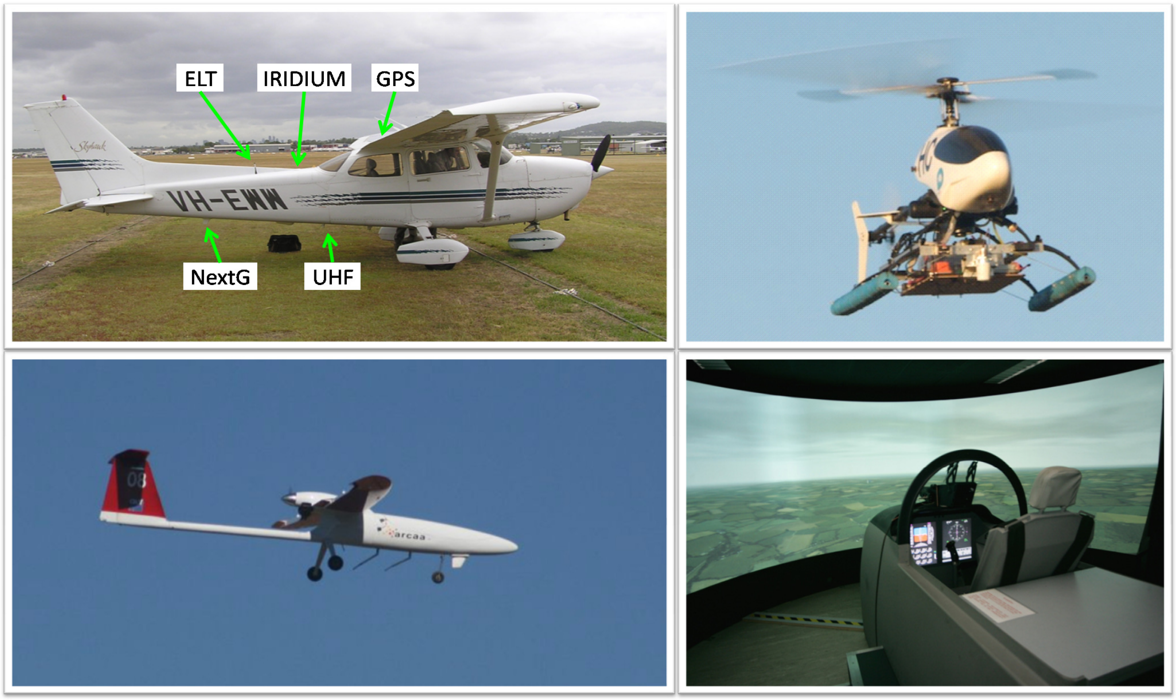

Figure 5. Flight Test Aircraft: ASL, CUAS Heli, Sheffield Piloted 6DOF Simulator, and QUAS Flamingo (clockwise from top left)

In addition to the real flight test aircraft described, multiple virtual aircraft are also used to increase the number of aircraft involved in a conflict scenario. These virtual aircraft are provided by the piloted engineering flight simulator(12) or the standalone/autonomous 6 Degree-Of-Freedom (6DOF) flight simulation models developed by researchers at the University of Sheffield. The 6 DOF simulations can be run on low specification personal computers and are networked to the ADAC via the internet or run locally on a local network (as illustrated in ***Figure 2***). Each 6 DOF model uses a very simple script language to initialize and program desired flight plans. The engineering flight simulator (***Figure 5***, bottom right) can be piloted and connected to the CIN using the Internet or an Iridium transceiver. From the perspective of the ADAC and the separation algorithms under test, no distinction is made between the different test aircraft (manned or unmanned, real or simulated). Using simulated aircraft in combination with real aircraft and real communications links provides a safe and efficient testing environment for the evaluation of complex potential loss of separation scenarios. **Table 2** summarizes the Airspace Segment assets which have been used or plan to be used in Smart Skies testing.

Real Aircraft	Simulated Aircraft	Sheffield Flight Simulator
ASL - Cessna 172	**Cessna 172**	**Cessna 172**
Vario CUAS Heli	**Flamingo UAS**	**Jetstream**
QUAS Flamingo	**Jetstream**	
Shadow UAS %	**Shadow UAS**	

% Expected to be deployed for phase three flight trials (November, 2009)

Table 2. Real and simulated aircraft used in flight testing

4. Automated Dynamic Airspace Controller

The final segment of the prototype architecture is the ADAC which hosts the message handling server(10) and the aircraft tracking and separation software. ***Figure 6*** illustrates a specific centralized ADAC concept used to support the Smart Skies project. This section describes the messaging component and the aircraft separation management component.

a) *Messaging System*

The ADAC communication function is provided by a software layer termed the Message Handler (MH), developed for BR&T by the University of Sheffield. The messaging layer allows the ADAC to communicate with external entities such as real or simulated aircraft and radar data feeds via the CIN. The MH communicates with the ADAC Separation Manger (SM) via a prescribed interface and in effect, isolates the SM from the task of managing the external communication links. The MHL essentially acts as a server, listening for new connections from client aircraft and providing the interface to the SM to post and receive messages. The MH has been implemented in a classic client-server architecture, where each client is handled by a single processing thread. Upon initialization, a single thread is created which is dedicated to listening and accepting new connections from client aircraft. Upon acceptance of a new connection, a thread is created to exclusively handle the network I/O for that connection alone. For data sources that stream multiple aircraft targets (such as a Radar feed), one thread is created to handle the multiplexed data. However, such connection threads may have extra computational resources (memory, CPU) dedicated to processing the I/O for multiplexed data. The MH layer buffers incoming and outgoing messages from the SM and it is the responsibility of the SM to check for, or initiate the transmission, of new messages.

Performance of the messaging system is crucial and it is clear that as the number of aircraft connections increases, the computational resources required by the messaging system increases. For actively handling the message I/O of 50 connections, the MH requires approximately 35% of the CPU resource. This result is based on the MH executing on a 3 GHz Intel Xeon (single core) chip with 2 GB of RAM. Although the requirement for RAM also increases, the CPU utilization is the limiting factor curtailing the acceptance of significantly more connections. Due to the low bandwidth requirements of each message (see **Table 1**), the network interface utilization for 50 simultaneous connections never increased beyond 0.5%. This result is expected; any networking bottlenecks would likely be found external to the MH server itself, for example in the regional network infrastructure. Several techniques could be used to allow an increased number of connections to the ADAC:

- Reduce the amount of CPU resource dedicated to each connection thread.
- Use a multi-core processor.
- Move the MH component to a dedicated network node within the ADAC. This is the preferred solution because it will increase the robustness of the ADAC and provide a dedicated CPU for the SM algorithms.

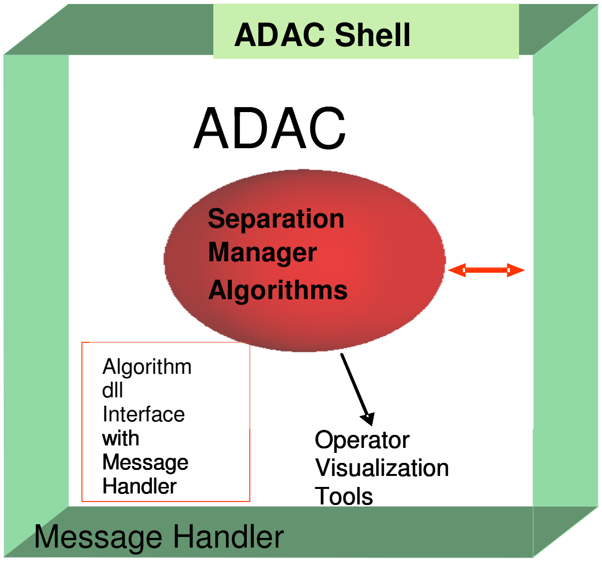

Figure 6. Components of the ADAC

b) Aircraft Separation Management

The conflict detection and resolution algorithm discussed in this paper is named the Virtual Predictive Radar (VPR). This proprietary algorithm developed by a contributing author, Dr. Estkowski, uses input data from cooperative aircraft and other sources to build a synthetic radar-like display, to estimate the times and positions of future LOS events. The primary objective of the VPR algorithm is to provide trajectories which ensure safe separation but secondarily, to do so at minimum *cost* to the airspace users. Upon determination of a suitable conflict resolution, the SM aligns the final waypoint of any CTADS so that it is coincident with a waypoint on the nominal aircraft flight plan. This ensures that commanded avoidance maneuvers always return cooperative conflicting aircraft back to their desired flight plan once separation has been assured.

The VPR algorithm is continuously being developed and is currently not optimized for execution time. ***Figure 7*** shows a typical execution cycle time for the SM for several "random" pair-wise separations. The mean SM cycle latency for this example is 0.29 seconds with several instances exceeding the desired one second threshold. One improvement under investigation for future tests is to move the SM to a parallel processing environment in an attempt to lower the processing spikes in ***Figure 7***.

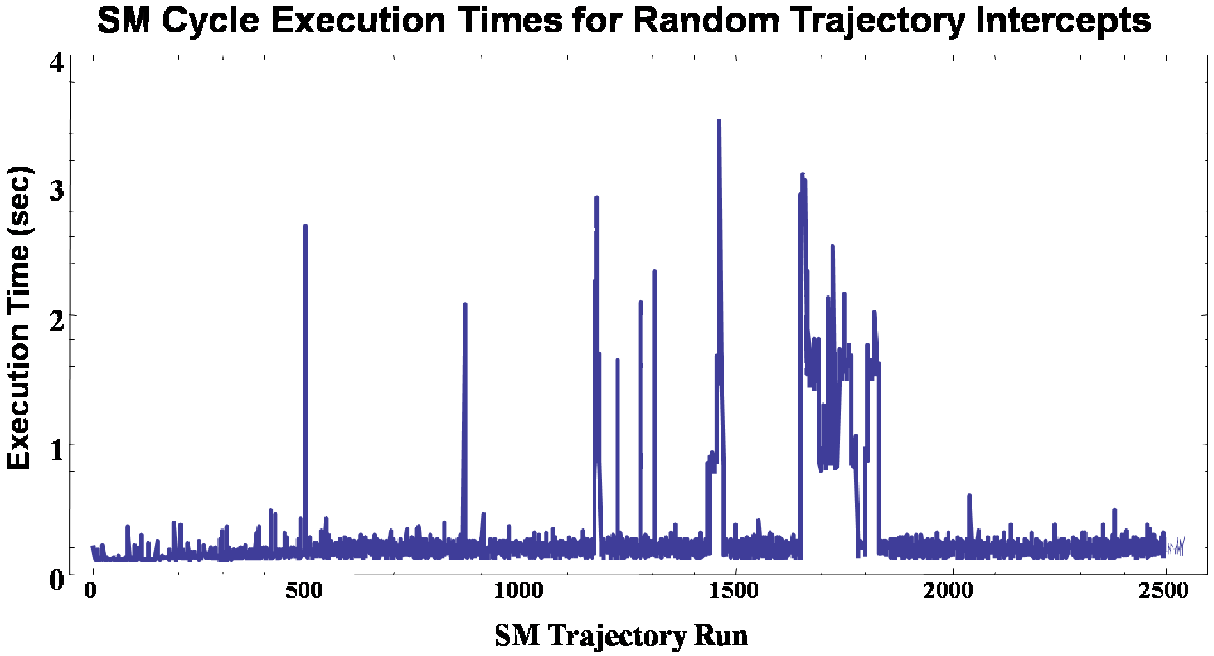

Figure 7. Example SM Execution Times

5. Example Phase 2 Test Results

Phase 2 Flight Trials (P2FT) consists of a set of controlled flight tests conducted from July 8 – July 16, 2009. The aircraft were flown at the Australian test site near Burrandowan Homestead, approximately 100 miles northwest of Brisbane. The ADAC was located in Palmdale, CA (See ***Figure 2***). One of the more challenging tests in P2FT involved the CUAS helicopter and the QUAS Flamingo. The test setup is illustrated in ***Figure 8***. Each UAS was constrained to be within visual range of their respective ground stations. The trajectories were oriented such that the QUAS would fly an elliptical type path over the CUAS helicopter which was flying a "U" shaped path. There was approximately 50 m vertical planned separation between the aircraft. The SM in Palmdale, CA tracked and exercised automated control necessary to maintain a separation distance of greater than 100m. In contrast with the ASL, the UAS modems and antennas for communicating with the CIN were located at their respective ground stations. For future testing these will be integrated onboard the aircraft. Both UAS were under the autonomous control of the ADAC except for the takeoff and recovery phases of flight.

Figure 9 shows the results from over 300 seconds of testing. The left hand side of the figure shows the QUAS and CUAS trajectories vs time. The right hand side of the figure shows the mutual aircraft distances vs time. ***Figure 10*** shows a picture of the two flight test aircraft (left) and the situational awareness display (right) illustrating the real-time position of both UAS, with the conflicting flight paths (red) and the CTADS generated by the ADAC (blue).

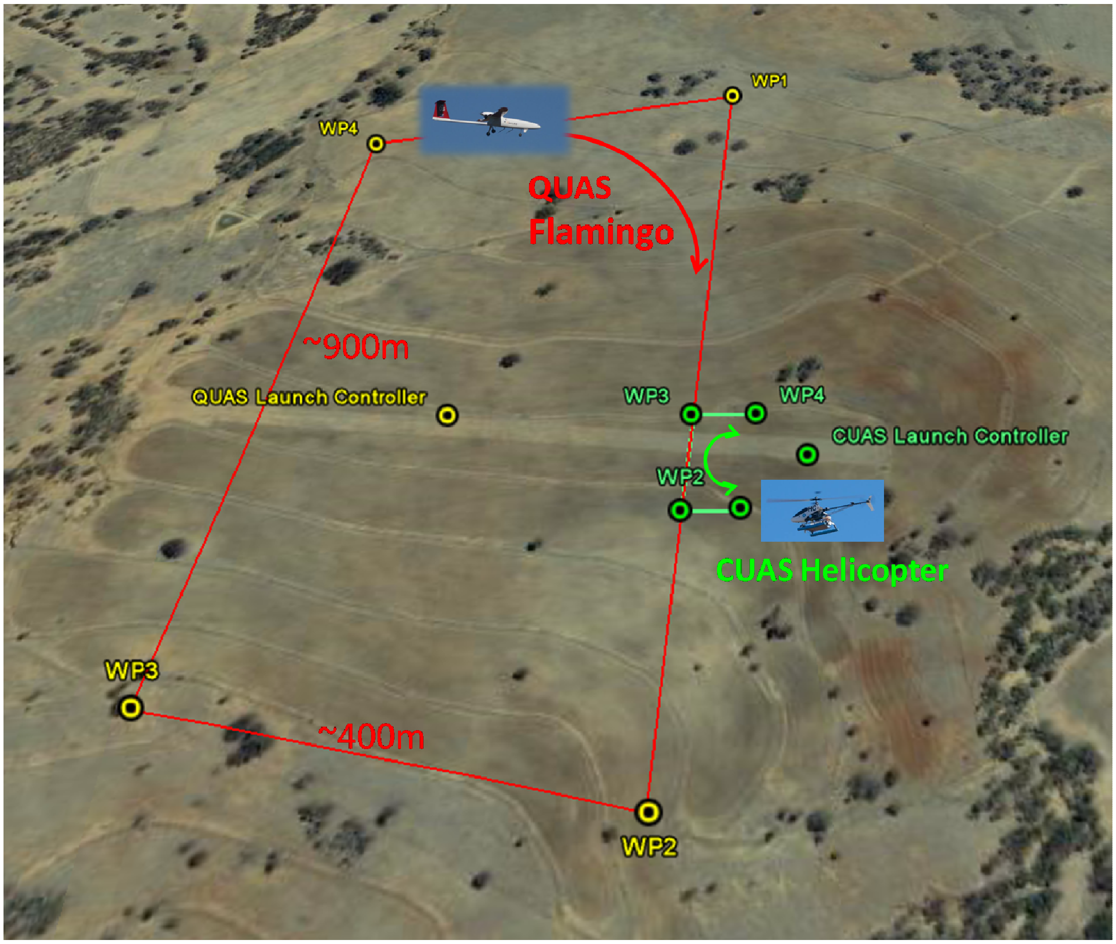

Figure 8. Illustration of flight test setup between the QUAS and CUAS

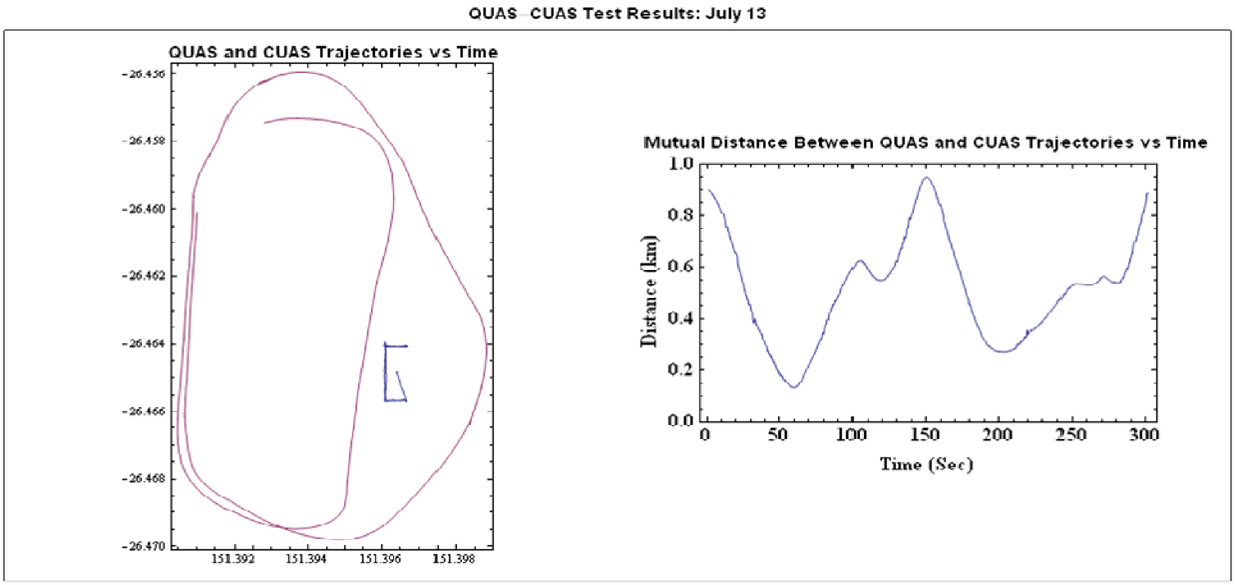

Figure 9. Example Flight test results for conflict scenario between the QUAS and CUAS

Figure 10. Photo of the two flight test UAS and the situational awareness display showing the CTADS issued by the ADAC (indicated in blue)

6. Summary

This paper describes a prototype communications architecture and capability that can be used for exercising automated airspace control in Class G airspace. The main components are:

- The *Common Information Network* which uses commercial data links to network real and simulated aircraft with a centralized automated aircraft separation management system.
- The *Air Segment* which consists of real and simulated aircraft. Cooperating aircraft must add a pFMS layer to communicate with the Flight Systems of the particular aircraft.
- The *ADAC*, which tracks and exercises separation control via information transmitted over the CIN.

This approach has the advantage of enabling safe testing of algorithms and concepts with real manned and unmanned aircraft from an ADAC located anywhere globally with Internet access. A series of flight trials have successfully used the prototype architecture to demonstrate remote aircraft separation control in Class G airspace. Details of the latencies of key components of the test architecture have been presented. Typically, the end-to-end latency has met the desired threshold of three seconds. Future test phases will: a) address the infrequent violations of the desired threshold through parallel processing within the ADAC; b) *tune* the test architecture to increase the reliability of the CIN and reduce SM latencies; c) continue to stress the VPR algorithm under demanding conditions.

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