

The Challenges of Flight-Testing Unmanned Air Vehicles

Warren Williams

Aerospace Sciences Corporation Pty. Ltd.

Michael Harris

Systems Engineering and Evaluation Centre
University of South Australia

ABSTRACT

Unmanned Air Vehicles (UAVs) remain a developing technology of keen interest to the military as well as certain commercial enterprises (such as mining exploration companies), with over 200 UAV types in use throughout the world. UAVs present a difficult challenge for the T&E community as well, with present military UAV interest focussed on total autonomy to reduce operator skill requirements and increase the reliability of tactical systems. This paper postulates that there is an optimum level of 'man-in-the-loop' air vehicle control, as opposed to totally autonomous operation to conduct particular missions. Although it may be desirable to operate autonomously, practical constraints may enforce a requirement to adopt a level of manual control to ensure navigation and altitude control functions, initiate in-flight emergency procedures and maintain traffic separation (particularly in civil airspace), all of which need to be tested as part of the system package. The authors argue the UAV mission and payload should determine the requirements for autonomy and these will directly affect the conduct of the T&E. The thrust of this paper is that a systems approach is necessary when developing the UAV system and planning its T&E programme. Discussion points in this paper draw on the authors' experiences in a current project developing a UAV for an Australian mining exploration firm.

INTRODUCTION

An unmanned air vehicle (UAV) may be defined as 'an aerial vehicle without an on-board human operator that uses aerodynamic forces to support its flight in a desired, non-ballistic path under autonomous or remote control to carry lethal or non-lethal payloads' (Lax and Sutherland, 1996, p. 2). The main use of

UAVs has been in military reconnaissance and surveillance until recently, but a rejuvenated interest in UAVs has resulted from the modern technological advancements in airframe materials, guidance systems, propulsion and payloads which promise more complexity to be achievable and yet remain cost-effective.

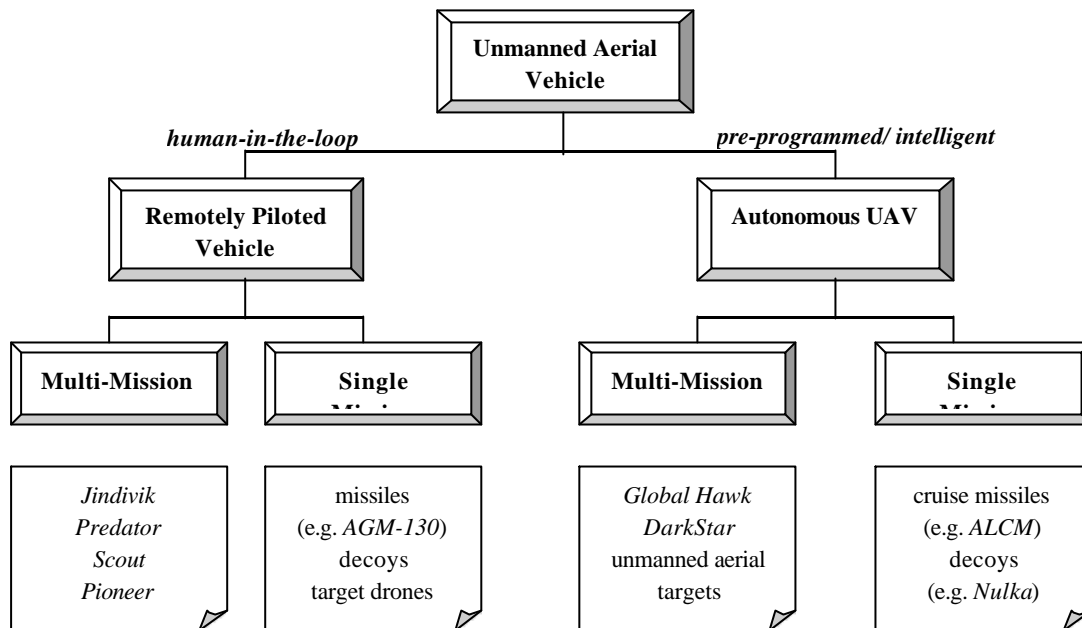


Figure 1 UAV Classifications (after Lax and Sutherland, 1996)

Modern UAVs are highly capable aircraft, with the trend definitely towards fully autonomous flight control (Wong, 1997). With over 200 UAV types currently in use throughout the world (Williams, 2002a, p. 6), UAVs now have a variety of uses including:

- * Military Applications:
 - * reconnaissance
 - * surveillance
 - * weapon platform
 - * target drone
 - * decoy
 - * radio retransmission
- * Commercial Applications:
 - * mining exploration
 - * communications
 - * power line surveillance
 - * fisheries patrol
 - * environmental monitoring
- * Research Applications:
 - * weather research
 - * artificial intelligence
 - * aerospace systems research & development

Drive Towards Autonomy. Although there is no generally accepted UAV classification system, they can be classified

by control system and reusability, as shown in Figure 1. Generally, as technology advances have been made, the trend in UAVs has been from developing Remote Piloted Vehicles (RPVs) to developing autonomous UAVs. However, certain specialist missions (such as mining exploration), combined with developing regulatory environments for UAVs (driven by concerns over autonomous UAVs sharing the airspace with air passenger vehicles), have created further needs for developing RPVs.

Testing RPVs. The test and evaluation (T&E) of RPVs has usually been platform-centric, in the mould of autonomous UAV T&E experiences. The emphasis of the T&E programme is normally developmental in nature, with the single-minded approach of developing the air vehicle and proving its airworthiness as a platform. RPVs, by their very inclusion of a human-in-the-loop, have an added dimension that demands an operational T&E (OT&E) approach to validate the effectiveness and suitability of the UAV system to the typical end-users (including operators and maintainers).

SPECIALIST MISSIONS

UAVs have traditionally been designed and developed for specific missions. In order to balance platform characteristics with payload requirements, the resultant UAV systems are mission-specific and tend to be difficult, if not impossible, to adapt for other mission types.

Example - Mining Exploration. The application of UAVs to airborne mining exploration activities is a good example of a specialist mission for UAVs of such complexity that an RPV solution is needed. The use of RPVs for this specialist mission is a logical progression from the traditional survey methods employing fixed-wing aircraft and helicopter-based systems. The missions typically flown by fixed-wing aircraft and helicopters are inherently dangerous due to the requirements of conducting such flights at low altitudes and low airspeeds. There are many examples (Mathews, Mitchell et al., 2002) of serious accidents, some fatal, which have occurred in Australia and overseas as a direct result of mining exploration flights.

A UAV for mining exploration purposes presents special challenges not addressed by other systems developed for other missions. This particular vehicle is designed for a low-level mission (altitudes below 400 ft) where turbulence, ground obstacle clearance and radio frequency communications are a challenge. Furthermore, the necessary requirements to provide an airframe layout that has minimal adverse effect on the sensor, is robust and simple in design to cope with harsh operating environments, and has the necessary stall-proof flying qualities, demand a unique design configuration.

CONSTRAINTS

Navigation. UAV-based mining exploration missions impose navigational requirements in terms of track accuracy, flight termination and flight planning. These constraints are primarily concerned with safety of flight and the necessary requirement to provide accurate survey

data. From a flight safety and operability standpoint it is necessary to know air vehicle position, altitude, heading and speed at all times. The design of the ground-based primary flight display should provide a GPS-generated map view function, which presents this information in addition to the takeoff point location.

The major difference between manned and unmanned exploration is a necessary requirement to have a fail-safe ability to terminate the flight. Flight termination boundaries are determined in much the same way missile cutdown boundaries are employed in defence T&E. In most cases these boundaries will correspond to the area of operations described in the Notice to Airmen (NOTAM). In addition to real-time navigational requirements, it is necessary that flight planning capabilities exist to translate terrain topology and survey grid requirements to provide optimal radio frequency (RF) coverage for the control telemetry. Testing this capability will require a mix of simulation and cautious flight-testing. In this phase of flight-testing 'man-in-the-loop'-based control provides the best flexibility through ensuring that adequate RF margins are maintained.

Altitude. Typical mining exploration missions are flown at low altitude (generally below 400 feet above ground level (AGL)) where the payload sensor provides optimal data resolution. However several difficulties arise when an air vehicle is operated in close proximity to the ground, with obstacle avoidance being the most obvious. However, lesser-known problems arising out of flight at low altitudes include mini-tornadoes (colloquially known as willy-willies) and severe turbulence, which can cause loss of control of the air vehicle, particularly those vehicles operated at low wing loadings. These are very real operational constraints which have been experienced on numerous occasions by helicopter-based and fixed-wing platforms. In these platforms, near loss of control has been experienced by the operators of such platforms. The

implications to UAV control system design are important. The development of such a control system to cope with the many combinations of aircraft attitude and flight vector would be very complex. The simpler solution involves 'man-in-loop' control with the flight displays providing the appropriate information to recover from unusual flight attitudes. However it is still expected that loss of the air vehicle will occur in the most severe cases.

The other aspect of low-level flight involves that of terrain height keeping capability. In order to provide a near constant height above ground level it is necessary to employ techniques that can cope with the diverse ground profile found in most survey regions. The system needs to cope with rising and falling terrain, trees and bushes, boulders, rocky outcrops and cliffs. This is not a trivial task for an autonomous control system. Again operational experience has shown that fully automated systems do not work well in such environments. However a system of pilot command guidance, outside visual cues and autopilot assistance has been applied successfully for many years in helicopter-based towed array operations. This technology may be transferred into UAVs with the same principles of control applied.

Note that a clear understanding and experience of the flight operational environment and mission is necessary to make these design decisions. For instance, in a current project for mining exploration, the UAV mission definition was based on the design team's experience of over 1 000 geosurvey flight hours flown in various fixed-wing and helicopter platforms operated at low altitudes (Williams, 2002a).

Systems Failures. An RPV system is subject to many failure modes, which may involve the communications signal uplink and downlink, engine, avionics, flight control system, servos, and onboard generator. By far the most serious failure is that of the communications uplink and downlink, which will result in flight termination after a predetermined time

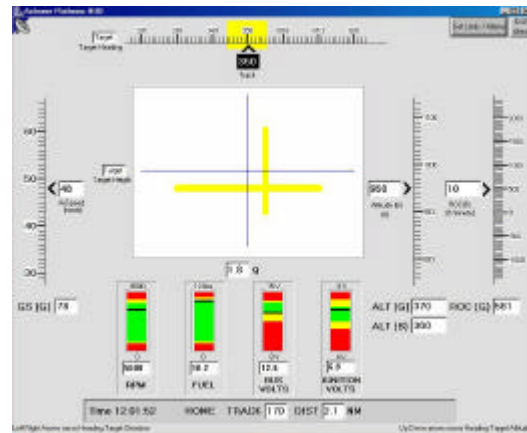


Figure 2 - Primary Flight Display.

period. However in accordance with standard airworthiness practice, most other failures can be accommodated through redundancy or airframe secondary control effects. For example the failure of the air data system can be accommodated through provision of differential GPS altitude and ground speed data, which is sufficiently accurate to 'get the air vehicle home'. Furthermore if any flight surface control axis fails then the RPV can be flown by secondary effect - an important air vehicle design consideration. Recent experience has shown that this can be satisfactorily demonstrated using a flight simulator (Williams, 2002a).

The design of the flight display, shown in Figure 2, reflects the requirement to apply an appropriate level of flight data redundancy in addition to systems warnings and cautions in the event of a failure or exceeding a threshold. In some cases three levels of data redundancy are provided for pilot flight cues. It is important to note that no attempt has been made to fully automate the system. Rather the approach has been to provide the appropriate level of data to the pilot and provision of the appropriate level of autopilot assistance.

Airspace Management. Mining exploration missions usually take place outside controlled airspace, typically in remote areas. As stated earlier, operations are usually undertaken at low altitudes to satisfy the onboard sensor data resolution

requirements. Nevertheless there is a requirement that a UAV be operated in accordance with established civil airspace procedures. In Australia, the Civil Aviation Safety Authority (CASA) has drafted legislation specific to UAV operations (2001). Although this legislation is aimed at commercial UAV operations, flight test activities will also need to comply, which may mean the operator will require a CASA operator's certificate. This requires that the operator have a pilot's licence with the appropriate ratings, and supported by an appropriate maintenance organisation with established operational procedures. This legislation is logical in implementation, but it infers that the UAV operator be appropriately skilled in aspects of airspace operations, airworthiness and systems. It is therefore not a simple matter to develop a totally autonomous UAV system without the ability to take active control to either manage traffic conflicts, or terminate the flight. Furthermore, it is the responsibility of the certificate holder to make those judgements on UAV air vehicle airworthiness when necessary. Therefore, regardless of the degree of autonomous UAV control, the operator will still require a reasonable level of skill and training, and the ability to take active control of the flight when necessary.

T&E OF UAVs

Real Needs of Flight-testing. The flight-testing of UAVs emphasises an additional measure to the usual range of system performance measures. It is well known in the aeronautical industry that an air vehicle is evaluated on the basis of flying qualities, flight performance and avionics functionality (National Test Pilot School, 1995). Although an air vehicle forms an important component part of the UAV system, it is the performance of the system as a whole that determines whether it can provide an efficient and cost effective operational solution. This total solution is therefore driven through cost economics and safety. As a result, system

reliability is an important performance measure along with the flying qualities, flight performance, and avionics functionality.

System reliability will determine the loss rate of air vehicles, the production quantity, maintenance requirements and consequently the operating costs and viability of the solution system. Furthermore, the level of air vehicle autonomy will also determine the system reliability to a varying degree depending on the maturity of the technology. Whether autonomous control can significantly increase system reliability depends on many factors, and cannot be determined without detailed knowledge of the particular system. However, it can be said that the reliability of a complex system cannot be verified without structured testing. This is a classic engineering conundrum, for without reliability data one cannot make an assessment of the system's economics. Furthermore gathering this reliability data involves considerable flight test risk. This issue comprises one of the major difficulties faced in the flight-testing of UAVs.

Challenges Faced. In addition to system reliability, the other flight test challenges relate to the degree to which manned aircraft flight test techniques can be applied to unmanned aircraft. Flight-testing of UAVs can be broken into the classical categories of flying qualities, performance and avionics evaluations, as alluded to earlier. In the area of flying qualities evaluation, the challenges relate to the absence of control stick force feedback, an absence of vibration and buffet response, and higher longitudinal, directional and lateral control sensitivities due to the small size of the air vehicle. These control sensitivities are similar to the problems in small homebuilt aircraft detailed by Stinton (1996). In addition, the absence of 'seat-of-the-pants' acceleration flight cues can provide a piloting challenge for an air vehicle possessing relatively low wing loading, high power loading and low inertia.

In the area of performance, the high susceptibility of the air vehicle to gusts and turbulence makes stabilisation of test points difficult. Airspace vertical and lateral limits make it necessary to adapt existing flight test techniques to achieve test points, although options exist to increase vertical limits through NOTAMs. Given the considerable piloting challenges associated with the conduct of UAV testing, a priority problem is to determine the degree of autonomy (the level of autopilot control) implementation within mission and cost constraints. Furthermore the provision of flight display formats may not completely follow conventional aeronautical practice due to the nature of the instrumentation and the display technology constraints. In the absence of these flight cues and the inherent control sensitivities due to small physical size, it is necessary to determine whether the air vehicle possesses satisfactory flying qualities and performance. In addition, the sensor payload may be sensitive to particular rate disturbances, which also factor into the autopilot implementation. Therefore air vehicle longitudinal and lateral-directional flying qualities and how the autopilot is implemented will have a significant effect on data quality and hence mission effectiveness.

Test Facilities. Another area not given significant attention is the ground-based infrastructure required to conduct flight and ground based testing of UAV systems. Instrumented test ranges are not required to conduct flight-testing of traditional UAV systems since the air vehicle position, altitude, heading and speed are provided by the necessary downlink data system to control the flight. However what is required is a region of airspace possessing the appropriate vertical and lateral limits as alluded to earlier. Like an instrumented test range, this area should be located outside civil controlled airspace, should not be in a 'built-up' environment, and possess few obstructions such as power-lines, tall structures and trees. Commuting time to and from the test area is an important issue



Figure 3 – 'Trainer' UAV Concept Demonstrator #1.

and this plays an important part in the selection of a potential test area for developmental T&E (DT&E). However OT&E will require transportation of the UAV system to a typical survey area that is usually located in remote area. This of course is accompanied with considerable costs associated with transportation and travel, accommodation, and supporting such an OT&E campaign in a region where very little engineering support can be provided.

Another area usually not considered in the T&E of UAVs is wind tunnel testing and associated aerodynamic analysis support. In the mining exploration example cited here, use of software-based aerodynamic modelling tools was sufficient to provide most data to develop the wing design. However, these software tools are not able to predict aerodynamic control surface (aileron, elevator & rudder) hinge moments. The aerodynamic hinge moment is an important parameter as it is this quantity that determines the magnitude of the load imposed on the servo. A large hinge moment will have high power servo demand and will also have an adverse effect on servo reliability due to the high current draws. Although wind tunnel methods can provide a first order approximation of this parameter, it is generally accepted that flight-testing is the most reliable method. Nevertheless, power budget estimates are required to size the UAV power system, particularly for long duration missions flown in high duty time (gusty and turbulent) conditions. As

alluded to earlier, the high power demands imposed on a servo also affects reliability. The project team developing the UAV for mining exploration has experienced one servo failure, occurring during a pre-flight control surface test. This failure initiated an extensive ground-based servo testing task to address this issue. Like other elements of this UAV development program, this servo testing task uses preliminary estimates of hinge moment derived from similar set-ups. The servo testing task is continuing, and has already resulted in several modifications which will potentially improve servo reliability.

PROPOSED METHODOLOGY

Flight Test. A well known 'rule-of-thumb' in the aircraft design field states that one should not test an untried engine in an untried airframe. The developmental T&E (DT&E) of a UAV system is further complicated by having to test an untried airframe with untried avionics and untried Ground Control Station. In addition, the engine used in a UAV is usually based on model aircraft technology where the usage profile and mission profile is significantly different. This introduces another unknown quantity in the testing equation. In summary there are four major system elements to be tested incrementally, each with varying risk level.

How one approaches the incremental integration of various subsystems within technical risk constraints is the key to a successful flight test program. The test program is designed to sequentially build-up from relatively low-risk to high-risk test points or systems using a number of airframes and avionics combinations.

A Test and Evaluation Master Plan (TEMP) is an integral document serving to formalise and coordinate this process. The TEMP should break the flight-testing into DT&E and initial operational T&E (IOT&E) phases. DT&E will address air vehicle flying qualities, flight performance and flight displays, while IOT&E will address mission task element evaluations.

The mission profile and constraints determine the structure of this test program through flight test matrix design and selection of the flight test techniques. (For an example, refer to Williams (2002b).)

The number of air vehicles required for a relatively high-risk flight test program is difficult to resolve given that real-world reliability data is unavailable. In the absence of this data, this issue is guided somewhat by historical trends. An example would be the X aircraft research undertaken by NASA where generally three airframes have been used for flight test purposes. The first in a series of three UAV concept demonstrators for a mining exploration firm is shown in Figure 3.

Associated with the flight test program is a comprehensive ground test program that addresses RF data link range, flight termination systems, avionics functionality, engine runs, electromagnetic compatibility, airframe weight and balance, and flight display software functionality. Although not the focus of this paper, this aspect of testing needs to be closely integrated with DT&E.

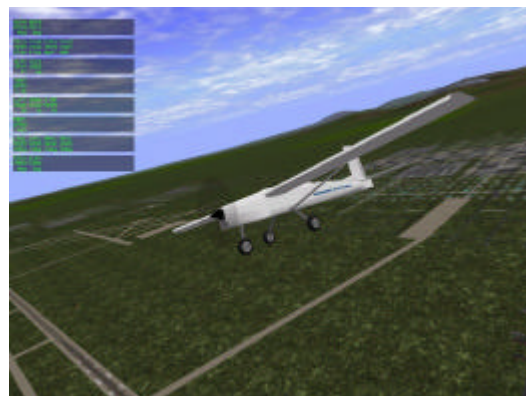


Figure 4 - 'Trainer' UAV Flight Simulator Model.

In all of these areas simulation plays a significant role where autopilot function is added incrementally depending on the level of skill required to conduct the mission task elements.

Flight Simulation. A mathematical model of the UAV has been used extensively in the development program. A model of this type can be used for flight test planning,

systems failure mode investigations, mission task element autopilot evaluation, emergency and failure mode procedures development and operational flying qualities evaluation. A screen shot of a model in a flight simulation environment is shown in Figure 4.

The flight simulation has the capability to model the terrain profile, take-off and landing site topography, the atmospheric conditions (wind, turbulence and air temperature), engine and avionics equipment failures based on statistical probability, and autopilot functionality.

Simulation of the air vehicle and the associated flight display provides an important method to determine whether the air vehicle can be accurately flown in a manual mode under realistic atmospheric conditions at low altitudes. For mining exploration missions, the simulator allows investigation of the piloting skill level requirements under gusty and turbulent conditions whilst flying a low-level survey-tracking task.

Flight simulation also provides additional information not available from flight-testing. Air vehicle control surface deflections, body rates and 3 axes accelerations can be monitored and recorded, and various parameters such as CG position, total weight, and atmospheric properties can be varied within a single flight. Furthermore it is possible to undertake the riskier elements of the flight test program in greater detail as it is possible to “fly” more test points with fewer flight safety restrictions. In both cases the actual GCS “flight” hardware setup is identical to the hardware employed in the simulated Ground Control Station (GCS). Therefore it possible to conduct these ‘simulated’ test flights as if there were actual flight ‘hardware-in-the-loop’.

The other major benefit arising from the simulator-based approach is that an extensive study into the flying qualities, performance and flight displays can be completed prior to actual flight tests. Therefore it will be possible to compare simulator and flight test hardware derived

data, thus providing a useful design and analysis tool for follow-on development.

SUMMARY

The T&E of UAVs, particularly RPVs for specialist mission, has been discussed from a systems viewpoint. A systems approach to the design and development of UAVs requires acceptance that the air vehicle is really only a means to an end. Designers and testers need a clear understanding of the mission and the sensor payload sensitivities, as these determine the size, configuration and performance needs of the air vehicle along with the configuration of the ground control stations and the launch/retrieval methods. RPVs (UAVs with a human-in-the-loop) are attractive for specialist missions such as mining exploration to allow the required navigational and altitude control, handling of in-flight emergencies, and meet regulatory requirements for maintaining airspace separation.

The risk matrix of testing an untried engine in an untried airframe using untried avionics and an untried ground control station complicates the T&E of most UAVs. In this test environment, UAVs provide further challenge, as flight test point stabilisation is very difficult to achieve given the characteristics of UAVs including low wing loading, high power loading and low inertia. Also, by their very nature UAVs cannot provide flight test cues to the tester such as acceleration sensation, vibration and buffeting.

Further T&E challenges presented by specialist missions were highlighted by consideration of UAVs in mining exploration missions. The need to operate (and thus test) at low altitude, low airspeed while following the terrain requires good use to be made of modelling and simulation to evaluate control link RF coverage, failure modes, flight control by secondary effect and other critical issues.

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ABOUT THE AUTHORS

Author name: Warren Williams
Business affiliation: Aerospace Sciences Corporation Pty. Ltd.
Address: PO Box 667 Elizabeth, S.A., 5125, Australia
Phone number and fax:
Phone: +61 8 8289 9555
fax: +61 8 8289 9555
E-mail: warren@aerosciences.com.au

Warren Williams is a consulting engineer with fourteen year's experience in the aeronautical engineering field. Mr Williams' career has been in the areas of store separation, aircraft aerodynamics and weapon aerodynamics wind tunnel testing, missile flight dynamic modelling, aircraft structural design and analysis, and aircraft flight-testing. His flight test experience has included weapons separation testing, towed target flight dynamics evaluations, helicopter towed array testing, aircraft drag performance tests, stall speed tests, vibration testing and flight loads measurement. Mr Williams is a recent graduate of the National Test Pilot School (USA), completing courses in fixed-wing flying qualities and performance flight-testing, and avionics flight-testing. His employment history includes experience with the Defence Science and Technology Organisation, the RAAF Aircraft Research and Development Unit, Aerostructures Australia and Vipac Engineers and Scientists.

Mr Williams is currently a consultant to the mining exploration industry in the area of airborne systems. He holds a current fixed-wing pilots licence, and B class glider pilots certificate.

Author name: Michael Harris
Business affiliation: Systems Engineering and
Evaluation Centre,
Address: Room F2-36, Mawson Lakes Campus,
University of S.A., Mawson Lakes, S.A., 5095,
Australia
Phone number and fax:
Phone: +61 8 83025274
Fax: +61 8 8302 5344
E-mail: michael.harris@unisa.edu.au

Michael Harris BSc (Hons), MSc (mvt) served in the Australian Army with several postings in Australia and overseas managing the test and evaluation (T&E) of armoured fighting vehicle systems and training simulators. His practitioner experience also includes development and evaluation of electronic warfare systems with CEA Technologies Pty Ltd (Canberra, Australia). In his current position with the Systems Engineering and Evaluation Centre, Michael has consulted in T&E to Australia's Defence Department. He manages the University's T&E post-graduate programmes and the Australian involvement in the U.K. Ministry of Defence's Graduate Engineer Trainee Programme. He is a part-time PhD student, researching a systems approach to evaluating complex, real-time information systems. Michael's other interests include coaching cricket and umpiring Australian football.