MODELLING, SIMULATION AND FLIGHT TEST EXPERIENCE IN THE DEVELOPMENT OF UNSTABLE ROBOTIC AIRCRAFT

P.G.Thomasson
Senior Lecturer
Flight Test & Dynamics
Cranfield College of Aeronautics
Cranfield University
Cranfield, Bedford, MK43 0AL, UK
Fax: 1234 751550
Email: p.g.thomasson@cranfield.ac.uk

ABSTRACT

The experiences and lessons learnt over the past twenty years developing a range of unstable unmanned aircraft are described along with the extensive use made of modelling and simulation to this development process. The scope for future developments is addressed and indicates even more on board intelligence is possible and desirable.

INTRODUCTION

The design and development of remotely controlled aircraft dates back some 80 years or so to the First World War, at which time they were perceived to have a place as aerial torpedoes or as aerial targets. Over the years that followed, the role of aerial torpedo was developed into the guided missile, whilst the Second World War provided the impetus for the development of the target drone, with many thousands being produced during the war years. In the early cold war period, peacetime aerial reconnaissance came to have great importance and the infamous U2 incident spurred on the development of unmanned reconnaissance aircraft. During the Vietnam War, unmanned air vehicles were used extensively on various intelligence-gathering activities. However most of this generation of vehicles were either drones that flew a pre-programmed course, or were remotely piloted vehicles (RPV's), in that ground based pilots (usually more than one) flew the aircraft using readings transmitted to ground based instrument displays. In the simplest cases they closed the loop with the human eyeball and flew the vehicle like a radio controlled model.

With modern developments in electronics and the massive reduction in size and power consumption of TV systems it became possible to devise real time image relaying unmanned aircraft. In the Gulf War extensive use was made of such systems to such an extent, that at least one was in the air at all times for the whole duration of the war. At the present time we are at a significant stage in the development of pilotless aircraft in that the miniaturization of radios, computers, TV cameras and navigation systems now offer an opportunity to produce quite small vehicles that have significant advantages in terms of cost and risk compared to manned vehicles. They are in fact autonomous aerial robots that can be simply "commanded" remotely and left to get on with a task, as opposed to having remote pilots in the loop. This deskilling of the tasks associated with using such a system, plus their small size, opens up the way for many civilian uses of this military technology and gives us the opportunity to turn swords into ploughshares.

EARLY EXPERIENCES

In the late 1970's, Cranfield was awarded two independent but significant unmanned aircraft contracts. The first was to design and build a ground station simulator to be used to evaluate the human factors problems anticipated to be associated with RPV helicopter operation by non-aeronautical personnel. The second was a contract from MoD and GEC to develop a fixed wing research air vehicle for flying imaging payloads; the vehicle was subsequently named MACHAN.

A major outcome of the early use of the simulation facility in conjunction with the Army Personnel Research Establishment was the demonstration that the direct control of the air vehicle by the ground crew was very undesirable since it required the operator to be a trained RPV 'pilot' who was also familiar with the specific airframe type. It was possible to demonstrate that if the air vehicle had its own control computer then very simple control laws were required to give the operator a 'command' mode of operation in which the operator simply demanded an action such as 'acquire a heading', instead of having the operator fly the manoeuvre. The simulator demonstrated this to many senior visitors from Industry, Government and the Armed Forces and had a profound effect not only on Cranfield's thinking but also on that of the MoD and of the team that subsequently developed the PHOENIX fixed wing system now in service with the British Army.

The first flight of MACHAN took place on the 27th November 1980 and it was the first remotely piloted vehicle in the world to have a full authority, all digital flight control system, Figure (1). The aircraft was flown as a visual range RPV with a three-axis rate demand system as the normal control system for the ground based pilot. The Flight Test program provided both Cranfield and GEC staff with valuable trials experience regarding unmanned aircraft. In particular, it reinforced the view that the vehicle should not be remotely piloted.

This requirement to give the vehicle more autonomy meant that much more detailed mathematical models of the dynamical behaviour of the vehicle were required for design and evaluation purposes. The design work on MACHAN had only used simple models but subsequently a full six-degree of freedom model of the vehicle dynamics was developed. This was programmed in the Advanced Continuous Simulation Language (ACSL) and run on the departments VAX computer system. Slow as the program was, it proved to be a very valuable tool for the investigation of the flying qualities of the vehicle and the effectiveness of various flight control systems.

GUST INSENSITIVE AIRCRAFT (GIA) DEVELOPMENT

XRAE1

Following the successful development of the MACHAN system, DRA (Farnborough) contracted Cranfield to develop a new Digital Flight Control System (DFCS) using the latest available integrated circuit technology so as to provide a unit that was much smaller and lighter than the previous system and as a result could be used as a replacement for the analogue auto stabilisation system used by Farnborough in their XRAE research RPV's. This system was subsequently flown for its first flight in March 1986.

With the development of the DFCS, DRA (Farnborough) requested ways of minimising the response of unmanned aircraft to gusts. The motivation of this request was that as the vehicle gets smaller the weight penalties of carrying a complex gimbal stabilisation system get greater, and hence it was pertinent to ask, "can we stabilise the aircraft as opposed too the sensor?" A theoretical study of the possibilities concluded that if the natural aerodynamic stability was removed from all axes by suitable aerodynamic design, then the angular response to gusts could be eliminated but the aircraft would become unflyable. The major contributors to gust sensitivity are the following aerodynamic derivatives,

- Rolling moment due to side slip L_v
- Pitching moment due to forward speed M_u
- Pitching moment due to heave velocity M_w

- Yawing moment due to sideslip N_v

If these derivatives are made nominally zero, most of the angular sensitivity to gusts is removed; this however results in an aircraft that will not fly in the conventional way since it is invariably dynamically unstable about all axes. For example if such an aircraft is banked it does not start to turn as does a conventional aircraft it simply sideslips, loses altitude and keeps pointing in the same direction. As a result, a flight control system must be designed to compensate for this, but without reintroducing sensitivity to gusts. The College of Aeronautics has designed, built and flown two such aircraft systems [1],[5] quite successfully. Existing airframe designs were modified for this work; namely, Defence Research Agency (DRA) designs called XRAE1 and XRAE2. The aerodynamics modifications made to the aircraft to zero the derivatives were,

- The M_w derivative was zeroed by moving the centre of gravity aft
- The L_v derivative was neutralised by adding anhedral to the wings.
- The N_v derivative was cancelled out by the addition of a nose fin
- The M_u derivative was reduced but not zeroed, as it is primarily a result of vertical centre of gravity position and there was limited scope for change.

The inner loops of the control system feed back rate gyro outputs to improve vehicle damping, whilst the outer loops provide an attitude and heading demand system via a vertical gyro and a three axis magnetometer, finally an autothrottle and height and heading acquire/hold loops are provided.

The XRAE1 gust insensitive configuration system first flew in December 1988 and following a series of test flights work was started on the larger XRAE2 gust insensitive aircraft and flight-testing of this aircraft took place during July 1991 with very satisfactory results [5].

For the first stage of this work, a full six degrees of freedom simulation of the aircraft dynamics was developed against which the small amplitude theoretical designs were evaluated. This produced a preliminary design for a gust insensitive aircraft that was derived from simple aerodynamic modifications to the existing XRAE1 airframe and DFCS. The lessons learnt in the earlier simulator studies were also taken to heart in that the flight control system design allowed for both RPV and UMA operation, the piloted operation being required for the landing phase alone.

The next steps for the production of a flying demonstrator were planned very carefully. First the simulation models was further developed and into it were put the best estimates of the vehicle characteristics and those of its systems, for the full flight envelope of the vehicle. Secondly, the control system design was refined using the Jacobian matrices obtained from the new simulation model for small perturbations about a range of flight conditions. These designs were then checked by incorporating them back into the large amplitude simulation model. This was a considerable amount of work, since not only normal operation over the whole flight envelope, but also all the various failure options needed to be studied as well, for example, engine failure on take off could result in a stall if the control gains and authorities were not designed with the potential of engine failure in mind. In addition, the airframe was unstable about all axes and it needed to be under controlled flight as soon as it left the catapult. Many other cases had to be covered and the control system was redesigned via the simulation many times before a satisfactory combination was established that in current parlance provided "care free handling".

As part of this phase, all mathematical details of the airframe and its systems were modelled in the simulation. Non-linear and discontinuous effects such as quantisation in the DFCS were modelled, along with amplitude and velocity limiting in the actuator dynamics. To handle the later new analysis techniques had to be developed [4]. All simulation work was carried out using ACSL on the VAX computer [3] and most importantly, the simulation program was treated as the control document for the definition of the air vehicle mathematical model. This had the advantage over conventional paper alone definitions that the compiler checks the completeness and consistency of the vehicle definition in a way that is just not possible with a paper record. In addition, new test cases are easily documented and program modifications to the model can be tested for correctness and consistency with earlier test cases. This approach of using a computer-based definition for the air vehicle and its systems has been used very successfully in all subsequent projects.

The airborne computer implementation of the final control laws was also carried out in a rigorous manner in that not only were standard fault avoidance techniques used in the development of the software but also extensive ground based simulation with in-situ end to end testing of the final installed flight software was carried out. This was in turn carried over to extensive built in test facilities that were (and still are!) an important aspect of the pre flight tests that have been established as part of standard operational procedure.

The first flight to test the full gust insensitive configuration was in December 1988, Figure (2). The aircraft was fully fly by wire in that the pilot did not have direct control of the control surfaces even when in RPV mode. In that mode the pilot could have either a rate demand system or an attitude demand system, the former only being provided for pilot operation prior to adequate familiarisation with the attitude mode (this being an unconventional form of manual control). After the initial few flights, the pilot's assessment of the care free attitude demand system was that it was extremely straightforward but somewhat unusual for an experienced model pilot such as himself.

All flights since the first flight have been with the aircraft launched under full auto pilot control and with no pilot input, the flight plan being executed via commands to hold or to acquire, speed, heading or altitude. The simulation program developed during the design process has been used prior to each test flight to predict the air vehicle's behaviour, so that the trials team knew what to expect. Via this technique, several potentially hazardous situations were identified and corrected prior to flying. Post flight analysis also used the simulation program as a way of identifying various aerodynamic parameters and the causes of any unexpected behaviour.

For landing, the pilot is put into the loop during the crosswind leg of the approach and uses the attitude demand mode to achieve the touch down. In terms of gust response the pitch data from the flight trials was sufficiently smooth for the outstanding feature to be a $\pm 0.1°$ pitch oscillation at about 2 Hz. that was traced to resolution effects in the actuators. Replacing the actuators with alternative ones having 9 bits as opposed to 6 bits equivalent resolution rectified this.

XRAE2

Following the successful development of the DFCS and the XRAE1 GI aircraft, a development contract was obtained from DRA to bring the larger XRAE2 research air vehicle up to the same standard. A similar development plan was followed to that for XRAE1 with CoA and DRA staff working together. The first stage of this work was to develop a simulation model of the XRAE2 airframe. This was done using ACSL as previously, but by this time it was available on PC and so PC based development was used and has been used ever since.

Prior to the first flight concerns were raised about the longitudinal trim of the aircraft as data from various sources conflicted not only in magnitude but also in sign! Both extremes were run through the simulation. In one extreme, when the aircraft came off the launcher it dived into the ground, for the other case it came off the launcher, stalled and then dived into the ground! In the light of this, some of the system gains were modified to reduce the sensitivity to trim errors at the expense of the response characteristics, and the simulation predicted that the launch should be safe so long as the errors were within the assumed range.

The first flight took place in July 1991 with completely satisfactory results. Particularly rewarding was the observation in flight of a low frequency Dutch Roll type oscillation that had been predicted using the simulation. The origin of the oscillation was the non-linear behaviour of the Nv derivative interacting with the heading hold control at minimum aircraft speeds [5]. Final proof of the GIA work was demonstrated later in the same year when the XRAE2 system was flown with a miniature infrared linescan sensor and the XRAE1 system was flown with a strap down TV camera.

AUTOMATIC LANDING

The removal of the only phase of flight involving manual control began in 1990 with the award to CoA of two contracts in conjunction with STC Technology Ltd and Barr & Stroud Ltd. The contracts were placed by DRA (Farnborough) for a study into the feasibility of automatic landing systems for unmanned air vehicles. Cranfield were responsible for the control system design and simulation, whilst STL and Barr & Stroud were responsible for the design of the tracker, using microwave and laser technology respectively. Detailed simulations involving the air vehicle and the tracker characteristics in poor weather established the viability of the systems [2].

An important aspect of the work was the adoption of a landing technique based upon the flight experience of using the GIA attitude demand system. The approach was performed with the auto throttle engaged and an attitude demand that gave a 6° glide slope. As the air vehicle approached the ground a flare manoeuvre was carried out by changing the attitude demand, and this resulted in the aircraft flying horizontal and a few metres off the ground. Once the aircraft was a suitable distance from the touch down point the engine was cut and the aircraft then entered a constant attitude glide until it made contact with the ground. The attitude demand control system maintained the wings and fuselage level during this manoeuvre and also prevented the aircraft ballooning back up into the air following ground contact. The constant attitude glide provided a touch down accuracy and vertical impact velocity that was relatively insensitive to errors in the round out altitude.

GLOBAL POSITIONING SYSTEM

In 1992, DRA in conjunction with the CoA began evaluating GPS as an UMA aid. A 6 channel receiver was interfaced to the DFCS and the first flight of a GPS equipped GIA XRAE1 aircraft took place on the 24th March 1993. In the mean time GPS navigation and track keeping algorithms were developed using the simulation, that provided an autonomous navigation capability and flight trials were under taken successfully. In differential mode, GPS can replace the microwave or laser trackers used in the auto land studies and provide sufficient accuracy to land UMA's as well as providing a simple tracker. The advent of GPS has created a digital air space in which the vehicle at all times knows its earth-referenced position and velocity

PARAFOIL RECOVERY.

In 1996, as an alternative to conventional landing Cranfield worked with Target Technology Limited on a DRA funded development of a GPS guided parafoil system for automatic air vehicle recovery. Cranfield’s responsibility was the development of a complex simulation model of the coupled dynamics of the aircraft and the parafoil system [7]. This was set up as two six-degree of freedom models, one of the aircraft, the other the parafoil, coupled via the rigging system. This ACSL model was used to develop the guidance and control laws prior to the flight trials, Figure (3).

XRAE1 AIRFRAME MODIFICATIONS

On behalf of the DRA we have undertaken a redesign of the XRAE1 airframe and systems. This has resulted in more equipment space within the fuselage but at the same time hopefully leaving the basic aerodynamic characteristics little changed. The DFCS has been steadily evolved and at the last count contained seven processors dedicated to different tasks. The avionic systems have also been reorganised onto a new instrumentation pallet further increasing the space available. In addition a new engine system has been commissioned that provides a significant increase in power and hence AUW. The improvements were justified by using the simulation model to predict the performance with the new engine and the increased all up weight. In the subsequent flight testing the simulation was used in a matching exercise to identify the aerodynamics changes that had taken place following the modifications. In this way it was possible to show that the new engine and propeller system had changed the downwash at the tailplane thereby changing the longitudinal trim, and more importantly, the fuselage shape changes had resulted in a significant drag reduction.

SENSOR GUIDANCE STRATEGIES

In 1994 we began a series of studies aimed at providing some further technological solutions that would help make a sub 30 Kg vehicle possible. One of these was to develop the concept of a gust insensitive vehicle with a strap down sensor even further. The use of imaging sensors on board small Un-Manned Aircraft usually requires them to be articulated so that various regions in the vicinity of the flight path can be examined. Mounting such sensors in a ‘dome’ below the aircraft provides good coverage but it imposes a significant drag penalty if it is fixed or if the dome is retractable it imposes a weight and complexity penalty. A nose mounted sensor on the other hand, has reduced drag but a smaller angular coverage. In both cases full articulation of the sensor (e.g. pan, tilt and possibly roll) involves complex and delicate mechanics often made even more complex by stabilisation requirements.

A major difficulty with any remotely controlled airborne sensor is the effect of wind on the vehicles track in that the vehicle heading and the track heading are not the same. For low speed UMA’s the airspeed can be close to the wind speed and so the angular difference between heading and track can be very large. In addition turning flight in wind using ground-based references is potentially hazardous for low speed vehicles in that the vehicle is easily stalled, as many light aircraft pilots have found to their cost. However as mentioned earlier ground GPS provides both earth referenced position and velocity information and proves to be most valuable in these conditions.

A remotely based observer has some considerable problems in deciding what to do in any particular guidance case. Should the operator manoeuvre the aircraft, rotate the sensor or zoom the image? Which ever is decided upon has to be done bearing in mind not only the flight restrictions of the aircraft but also the effects of wind and the gimbal constraints of the sensor. This is a complex task well beyond the capabilities of most observers

A simple alternative to the mechanical complexity of two or three axis precision gimbals is a roll only sensor installed on a Gust Insensitive Aircraft. This is much simpler and lighter; it takes out the bank angle of the vehicle and enables points either side of the flight path to be examined. We have been able to show that with such a roll only sensor the flight control and navigation computers can use the air vehicle tracking system (GPS) to fly the vehicle in such a way that points on the ground can be continuously observed even in the presence of wind and gusts with large track angle differences and with stall protection included [6,8]. All this can be done by software without the need for further instrumentation. An example of such a trajectory along with the aircraft heading and the sensor footprints is given in Figure (4).

Such a combination of sensor articulation and of navigation and guidance systems has human factors ramifications and in order to address these we have developed a real time UMA simulator system complete with a complex airvehicle and sensor model along with a digital terrain model and computer generated imagery system to provide the operator with a realistic environment [Walster 1996].

MEASUREMENT OF ATMOSPHERIC TURBULENCE

The original application of the gust insensitive aircraft is of course as an observation platform for imaging sensors (hence the requirement for angular stability), but a new application of this military technology is that the vehicles may be ideal as measurement platforms in the planetary boundary layer and especially for turbulence measurement, due to their very small angular response to gusts and their unmanned autonomy. Contacts with interested scientists outside Cranfield (UK and Europe) indicate strong interest in a platform based on our current UMA technology. The awarded of the Handley Page Award of the Royal Aeronautical Society. in conjunction with valuable and essential MoD co-operation, has provide funding for sensor equipment to be installed on a MoD airvehicle so that we can 'piggy back' meteorological measurements on the back of the planned MoD flight trials. A departmentally funded PhD student is carrying out this project. Analysis of this flight data should establish the viability or otherwise of such UMA based measurements techniques and in conjunction with further theoretical work we plan to demonstrate the practical levels of accuracy that can be achieved. It is hoped that the results of this investigation will be the demonstration of techniques that will enable the measurement of important meteorological flows that are at present too expensive or too hazardous for the aeronautical community to obtain. The resulting knowledge of meteorological flows will in turn lead to greater safety in manned flight.

THE OBSERVER AIR VEHICLE

The first flight of a new unstable air vehicle design took place on the 11th March 1999, at DERA Shoeburyness. It was a propeller driven gust insensitive configuration called OBSERVER, with a nominal AUW of 30kg and a span of 2.42m. It flew under pilotless automatic control from launch until just prior to touch down when a ground pilot was used, via the attitude demand control system, to complete the skid landing. Subsequent flights have used the automatic parachute recovery system developed as the standard recovery for this aircraft. Details are shown in Figure (5).

THE ECLIPSE AIR VEHICLE

The ECLIPSE, is a turbo jet powered vehicle with an AUW of 35kg and a span of 2.1m. Like the OBSERVER it use the avionics and flight control systems developed from the XRAE vehicles and is fully autonomous. Unlike the XRAE and OBSERVER vehicles it has a retractable tricycle undercarriage. It is due to fly during the second half of 2000. Details are shown in Figure (6).

THE FUTURE

The preceding paragraphs have described the lessons that have been learnt over the past twenty years of Robot aircraft development. In order to look at UMA’s in the next millennium it is useful to look at the potential developments in the basic technological drivers of UMA technology.

We may see modest weight reductions due to new materials but these will be limited by minimum gauge requirements and the primary design loads for small aircraft are related to launch and recovery. With regard to aerodynamics, boundary layer control may reduce drag somewhat and may provide stealthy alternatives to conventional control surfaces.

With regard to engines and propulsion, heavy fuel engines may become available and Full Authority Digital Engine Control and Monitoring may improve the performance and reliability of small engines as it has done for the private motorcar. Sensors will reduce in size and cost and most importantly greatly increased computing power will be available.

Of the above, by far the greatest change will be in computers and computing. In order to assess this it is useful to look back at the past so as to be able to extrapolate forward. For the past twenty years Cranfield has been a major developer of UMA technology and this provides valuable experience to extrapolate to the next millennium. For example if we look at the development of digital flight control computers for UMA's, details of two Cranfield designs are given in Table 1 along with a simple extrapolation.

	MACHAN	XRAE 1	?
	1979	1997	2015
Volume	27 l	2 l	0.1 l
Mass	5 kg	1 kg	0.2 kg
Power	20 W	5 W	0.25 W

Table 1

This indicates that we can expect substantial reductions in size, mass and power consumption by the early part of the next century. In addition we can also expect an increase in functionality at the same time.

If we look at the development of computing power for both main frame and microcomputers, the speed increases (Grosh's Law) by a factor of ten every five years. By the early part of the millennium we can anticipate having the computing power of a Cray 1 on board a small unmanned aircraft with a take of weight of less than thirty or even twenty kilograms.

This raises the important question, what can we do with such on board computing power? The answer is Real Time Computing of things that need to be done in the aircraft rather than in the ground station plus things that would require excessive datalink bandwidth if they were done on the ground. Some possible areas are considered below.

Sensors

Some guided missiles currently use Kalman filters to estimate the errors in their low cost, imperfect flight control sensors. Such systems are real time and computationally intensive but with the increase in on board computing power that ceases to be a problem, and as a result we can anticipate significant reductions in size weight and cost of the flight control sensors used in UMA's. This will also have an impact upon flight safety in that reversionary modes will be available following the failure of sensors, actuators etcetera.

Engines

The engines available for small UMA's are unsophisticated when it comes to control and monitoring. Starting in particular requires technician support, especially in non-standard climatic conditions. Direct engine monitoring and control by computer would improve starting, performance and reliability as it has done for the motorcar.

Data processing

The widespread interest in Multimedia has resulted in the latest microprocessor chips having extensive graphics and video processing capabilities. As a result we can anticipate that many forms of automatic feature identification can be carried out by the on board computing system and the ground station then cued as to the locations of interest. In addition the same graphics capability can be used for guidance and control via the real time extraction of attitude, flight path etc. from imagery changes.

Datalinks

Lack of data link bandwidth will be one of the most important limitations of future UMA's. The items listed above will all help to reduce the bandwidth requirements substantially. Control band width will be very small since the vehicle will be autonomous and merely requires intermittent, brief commands as to what it has to do, the on board systems then get on and do it. The return data link bandwidth will be reduced due to the pre-processing done on board, such as the location of areas of interest. The intelligent, autonomous nature of the vehicle will remove the need for the high bandwidth video required by ‘ Virtual Reality ‘ ground based pilots

Guidance and Control

Novel airframe configurations can be considered and advanced flight control used to compensate for the lack of stability in such systems. In an unstable manned aircraft, loss of the flight control computing functions is critical since the aircraft is then unflyable, unlike its stable counterpart. For an unmanned aircraft, failure of the flight control computer results in the loss of the aircraft whether it is stable or not! As a result unstable configurations pose no greater risk than stable.

Terrain Data Bases

Currently terrain databases are memory and computationally demanding and hence slow. Future UMA’s will have the capability to carry such databases and access them in real time. When combined with satellite navigation this will further enhance the autonomy of the vehicle and will not only provide terrain avoidance but will also enable it to compute inter visibility contours, to carry out terrain reference navigation and many other tasks.

In conclusion, in the next millennium we can look forward small low cost UMA’s that autonomously carry out dull, dirty and dangerous tasks and whose operators manage the systems as opposed to flying them.

CONCLUSIONS

Whilst the genesis of unmanned aircraft can be traced back more than eighty years it has been the developments in electronics in the past twenty years that have presented the opportunity to do so much more with an unmanned air vehicle. As a result the remotely piloted vehicle has evolved into a command driven, autonomous, gust insensitive, unmanned aerial robot that can be used by unskilled operators for a wide range of aerial tasks ranging from surveillance to pollution monitoring or even crop spraying. None of this could have been achieved without the extensive use of modelling and simulation facilities, they have prevented disasters and enabled much more sophisticated navigation and control systems to be developed. In the immediate future even more intelligence can be carried on board such vehicles, enhancing their capabilities even further.

REFERENCES

[1] Dyer DJ. The Design and Development of a Digital Flight Control System For UMA. 9th International RPV Conference, Bristol UK 1991

[2] Dyer DJ, Lewis DJ, Thomasson PG. The Automatic Landing of Unmanned Aircraft. 9th International RPV Conference, Bristol UK 1991

[3] Thomasson, PG. The Use of Simulation in the Development of a Gust-Insensitive Aircraft. Proc. UKSC Conf. on Computer Simulation, Brighton UK 1990.

[4] Thomasson P.G. ‘A Method for the Analysis and Simulation of Discontinuous Systems’. European Simulation Symposium, Delft ,1993.

[5] Thomasson P.G, “The Flight Dynamics of an Unstable Unmanned Aircraft”. “Aerospace Vehicle Dynamics and Control”, Clarendon Press, Oxford 1994.

[6] Thomasson, P G, “Integration of Sensor and Airframe Guidance”.12th International RPV Conference, Bristol UK, Nov. 1996

[7] Thomasson, P.G. , “Modelling the Dynamics of Ram Air Parachutes.” 15th IMACA World Congress on Scientific Computation, Modelling and Applied Mathematics, Berlin, August 1997.

[8] Thomasson P G, “Guidance of a Roll only Sensor in the Presence of Wind.”, AIAA Journal of Guidance, Control & Dynamics. Vol 21. No. 1, Jan 1998, pp 39-44.

[9] Walster, R.A.. “Try it before you Fly it”. Proceedings of the 12th Bristol International RPV Conference, Bristol, Sept 1996.

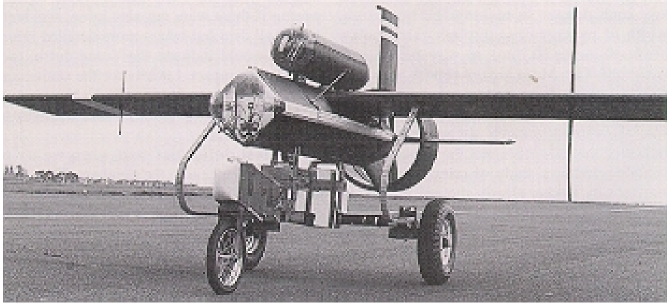

Figure 1 The MACHAN with initial tricycle launch trolley

Figure 2 The modified XRAE1 airvehicle

Figure 3 Parafoil recovery of the TTL BANSHEE

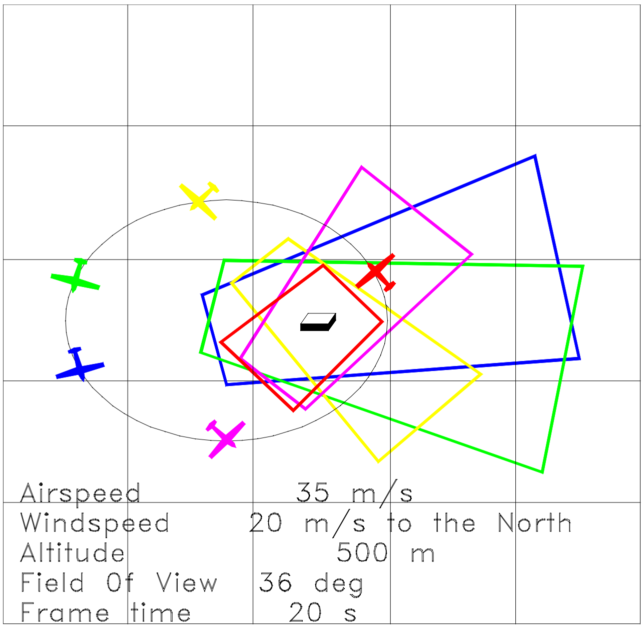

Figure 4 Example of the orbit observation mode in wind.

Figure 5 The Cranfield A3 OBSERVER airvehicle

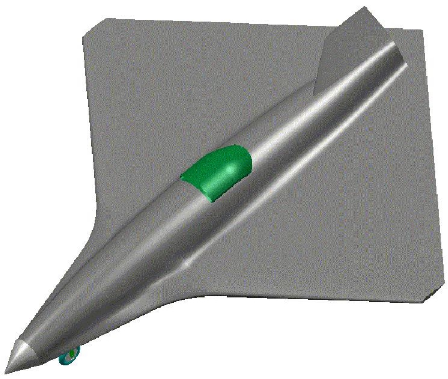

Figure 6 The Turbojet powered ECLIPSE airvehicle.