MODELLING OF AN AUTONOMOUS MUAV AT THE SHIP DYNAMIC INTERFACE WITHIN A MULTINATIONAL SIMULATION FRAMEWORK

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Abstract

The NATO/PfP Interoperability and Re-use Study, NIREUS, was a twelve-nation project to apply the High Level Architecture (HLA) to investigate multinational distributed simulation for system design and acquisition. The NIREUS test case was focused on the distributed simulation of Vertical Take-Off and Landing (VTOL) air vehicles landing on ships, initially focusing on the automated recovery of Maritime Unmanned Air Vehicles (MUAVs). The test case aimed to demonstrate the interoperability of different nations' simulations and domain experts and assesses the interoperability of the platforms and systems they represent.

Amongst the many simulation elements required to achieve the objectives of the NIREUS programme, were models of the air vehicle, the air wake environment above the ship's deck and their interaction. Additionally, as the simulation was not intended to involve any "pilot-in-the-loop" activity, the simulated air vehicle had to exhibit a high level of autonomy.

This paper discusses the development of the MUAV model and the design and implementation of its flight and approach control systems, including the subsystems required to detect, and react to, landing abort situations. Also discussed is the structure of the airwake model and the manner in which this provided disturbances to the air vehicle simulation. Details of the multinational simulation framework in which the air vehicle and air wake models were expected to operate are given along with a summary of the development process and integration tools employed. The outcome of the work was successfully demonstrated to the NATO/PfP in October 2001.

Introduction

Overview of the NIREUS programme

The NATO/PfP Interoperability and Re-use Study, NIREUS, was a thirteen-nation project to apply the High Level Architecture (HLA) to investigate multinational distributed simulation for system design and acquisition. The NIREUS test case concerned distributed simulation of Vertical Take-Off and Landing (VTOL) air vehicles landing on ships, initially focusing on the automated recovery of Maritime Unmanned Air Vehicles (MUAVs) [1] but also addressing conventional manned aircraft. The test case demonstrated the interoperability of different nations' simulations (and domain experts) and assessed the interoperability of the platforms and systems they represent [2].

With the forthcoming procurement of MUAV systems and trends towards NATO systems' interoperability, NIREUS addressed a problem space that was both challenging as a technology demonstrator and increasingly pertinent to NATO navies.

NIREUS was born out of the technology studies performed by the NATO Study Team on Simulation Based Design and Virtual Prototyping (ST-SBDVP). The requirements definition and federation design phase was completed in 2000 and federates were then developed and integrated within concept demonstrations conducted in France in autumn 2001.

The NIREUS concept demonstrator project was technically progressed by four international teams (Figure 1). Each "colour" team considered different domain areas within the NIREUS problem space

a) The Blue Team considered ship issues - ship motion modelling, prediction and measurement systems [3]

b) the Yellow Team addressed air vehicle systems issues and the aerodynamic effects caused by

the interaction of the air vehicle and ship air wake,

c) the Green Team addressed ship-air vehicle interface issues and, finally,

d) the Red Team led HLA technology and system integration activities [4].

Figure 1: NIREUS Team Structure

This paper focuses upon the activities performed by the NIREUS Yellow Team and in particular upon the modelling of the MUAV and the ship airwake federates. In the next section an overview of the Yellow Team's activities is presented, including the general requirements defined for the air vehicle and airwake federates. Subsequent sections provide detailed summaries of the MUAV and its control system, and the air wake and its operation. Test cases are then presented to illustrate the functionality of the combined MUAV and airwake simulation. The paper concludes with a short discussion of the lessons learned from the Yellow Team activities and recommendations for future work are presented.

NIREUS Yellow Team

General requirements

The NIREUS concept study Yellow Team was led by the UK but also received valuable inputs from air vehicle, simulation and ship air wake domain experts from Australia, France, Germany, Sweden and the United States. This wide international mix helped the team define an architecture that aimed to be inclusive of NATO wide approaches to MUAV and air wake modelling and simulation.

During the early stages of the project, Yellow team members provided domain expertise to support the key early FEDEP/Systems Engineering requirements definition, conceptual design and

federate allocation stages [4]. Unlike most federations, NIREUS was configured to be a generic architecture to support a wide range of candidate simulations; the Yellow Team therefore did not constrain their requirements and initial design activities to relate to particular candidate simulations but considered the breadth of NATO MUAV and Ship Air Wake M&S approaches. The actual candidate simulations chosen for incorporation within the initial demonstration were not selected until after the federation and federate requirements engineering and initial federate design phases were completed.

Following federation requirement definition and scenario definition phases, the combination of NIREUS domain teams produced the conceptual design for the recovery problem space. This formed a basis for the clarification of team boundaries, data flows and functional requirements.

Data flows with the simulated air vehicle included command and measurement signals from a landing deck prediction system, relative position measurement system and the communication of ship air wake air flow data relating to air vehicle position points.

Although the ship air wake is largely influenced by the ship design and motion (by rights the domain of the Blue Team), within the NIREUS scenario the air wake only affected the air vehicle dynamics. In addition, air wake modelling and simulation expertise within NATO is more closely aligned to the aerodynamics and air vehicle simulation domains, and the Yellow Team therefore took on the responsibility for considering ship air wake modelling issues as well as air vehicle dynamics and control.

A more detailed account of the Yellow Team federate can be found in [5].

Requirements of the air vehicle

In addition to the general simulation requirements, the Air Vehicle simulation module was responsible for the following functions:

1) Air vehicle flight dynamics
2) Landing path planning
3) Flight control (stabilisation and path tracking)
4) Landing abort definition and response
5) Definition of pre touchdown aircraft status

The air vehicle flight dynamics were to be representative of a nominal rotary-wing MUAV but were not required to represent any extant platform. The model was required to accept and react to local atmospheric conditions, provided to the air vehicle, via the simulation federate, from the air wake

simulation. The simulation was also required to be able to be initialised in any point in space in either a north-facing hover or forward flight at any heading.

The air vehicle simulation had to contain representations of the control systems necessary to plan, guide and manoeuvre the flight dynamics model towards designated locations in a ship trajectory referenced inertial axes set. The control system suite comprised the flight control system and the landing path planning, or approach guidance, system.

The Flight Control System (FCS) was to embody representative air vehicle stabilisation and control laws, whilst the approach guidance system was to generate commands to the FCS in order to satisfy the NIREUS-specific functionality requirements. These functionality requirements described the structure of the approach pattern (shown in Figure 2), the various approach phases, and the conditions and logical events that were required in order to proceed through the approach, or to generate an abort to an earlier phase.
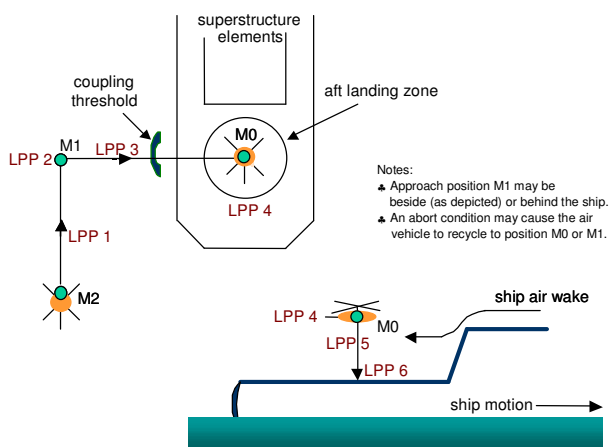

Figure 2: NIREUS Approach Pattern, waypoints and primary Landing Path Planner (LPP) modes/phases

The "coupling threshold" in Landing Path Planner (LPP) phase 3 marks the point where the air vehicle began receiving and using ship-relative position information derived from an external simulation of a shipboard optical tracker.

For the primary test case, which was an approach to a steady ship travelling at 15 knots in still air, the notable performance requirements were:

- Hold Position at M1 within +/-1m
- Hold Position at M0 within +/-1m
- Touchdown within +/-1m of designated point
- Touchdown within +/-0.2s of designated time
- Touchdown within 80% of U/C limits

Abort functionality was required in order to represent those functions which serve to protect the safety of the ship and air vehicle in the event of difficulties.

The required abort functionality comprised:

1) External (manual) abort from the ship
2) External data unavailable (datalink dropout or sensor failure aboard the ship)
3) Automatic internal aborts
   i) Control Margin Exceedance
   ii) Out of Position
   iii) Too Far Forward (danger of collision)
   iv) Descent Rate Too High for U/C

The response to these aborts differed according to the approach phase and the immediacy of the danger from the condition encountered, but invariably it served to manoeuvre the air vehicle into a position of safety.

Finally, the air vehicle simulation was required to detect imminent touchdown and to generate a status message describing its dynamic state and the time required to reduce the collective to zero. This message was to serve as the initial condition for a post-touchdown simulation elsewhere in the federate.

Table 1 defines the required mode functionality and sequencing.

Requirements of the air wake

The NIREUS air wake simulation was required to provide a representation of the airflow features in the vicinity of an aft-located flight deck. In so doing, the model had to

a) represent the main features of the ship air wake, comprising the flow features due to the interaction of the ambient airflows with the ship structure,

b) provide time varying values of air flow, speed and direction at one or many Earth-referenced points in the region of the air vehicle,

c) use externally generated ship motion data in order to convert between the Earth-referenced air flow point position values and ship referenced air flow data.

The Earth-referenced positions of the points in the region of the air vehicle were to be provided by the air vehicle simulation.

Although no specific implementation requirements were imposed on the air wake simulation, the option was available for pre-calculated look-up table data to be used for particular combinations of ship-type and free-stream wind direction. Likewise, the spatial

and/or temporal interpolation of pre-calculated air wakes was permitted.

The air vehicle simulation

Defining the basic air vehicle basic configuration

The air vehicle simulation component developed for the NIREUS programme was based upon the Helistab model developed at QinetiQ for use in flight control, handling qualities and piloted simulation studies [11]. This model was recently reengineered and extended to form a Simulink-based helicopter library, Helilink, from which modular, moderate complexity rotorcraft simulations can be created.

The MUAV being simulated in NIREUS was assumed to be a conventional helicopter configuration, and was constructed from Helilink rotor, aerodynamics, engine and undercarriage components, combined with standard flight dynamics elements such as the rigid body equations of motion, Euler angle attitude equations and ISA standard atmospheric model. Having been used extensively in previous QinetiQ helicopter-ship studies (for example [8]) the model was already configured to accommodate aerodynamic disturbances and other environmental effects. In particular, additional terms had been added to the main rotor equations to represent the effect of air flow distribution across the rotor disk, an important factor in the flight regimes being simulated in NIREUS, along with terms to apply aerodynamic velocities to the fuselage, fin and tailplane.

The specific air vehicle simulated for NIREUS did not exist in reality. However, the configuration chosen for NIREUS was based upon a design drafted on behalf of the UK MOD as part of a broad-ranging study of rotary-wing UAV operations. As

such, sufficient engineering data were available to allow a reasonable estimate of the vehicle's flight dynamics to be defined.

The significant parameters of the MUAV were:
- 4-bladed, 6.8m diameter main rotor
- 1600 kg operating weight
- Single turboshaft engine
- Tricycle undercarriage

The NIREUS requirement mandated only that the air vehicle simulation should contain a geometric representation of the undercarriage in order to detect imminent touchdown of any wheel. However, as the Helilink model already contained a full, moderate-fidelity generic undercarriage model, this was included without modification. This provided both the pre-touchdown detection and continued operation of the flight-mechanics model and visualisation after touchdown.

Operating the MUAV within the federate required the development of guidance and control algorithms representative of those that would be found on an autonomous vehicle. More specifically, a flight control system model provided rejection of atmospheric disturbances, stabilisation of the vehicle and manoeuvre response to velocity commands from the approach guidance controller.

The approach guidance controller was required to dynamically select appropriate way-points, route-plan between these and generate 4-axis steering commands for the air vehicle. In addition, the guidance system was also required to respond to commands from the external deck landing control algorithms, to abort the approach procedure in the event of unsafe conditions and to identify which abort condition was encountered.
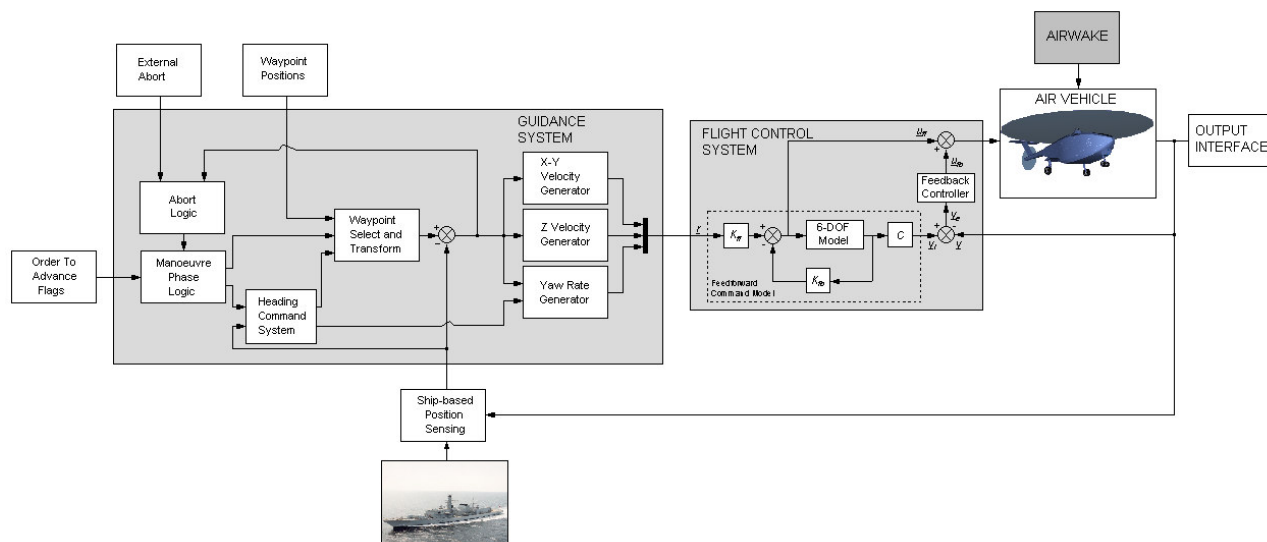

Figure 3: Architecture of NIREUS air vehicle guidance and control systems

Flight control system design

The flight control system was a full-authority implementation of the partial authority architecture used in a previous QinetiQ research programme [6-9]. Whilst this programme had focused on piloted applications, two recent outputs were of direct benefit to the NIREUS requirement, these being a coupled flight control and relative GPS guidance system for helicopter-ship recovery [8] and a 4-axis augmentation system for improved handling qualities in adverse environmental conditions [9].

The selected system architecture, shown in Figure 4, used two degree-of-freedom, explicit model-following in order to provide high-bandwidth, decoupled responses in all 4 control axes.
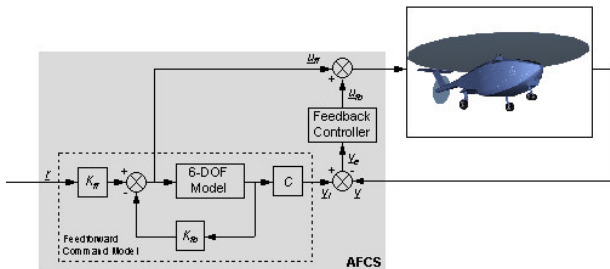

Figure 4: MUAV FCS Architecture

Dynamic feed-forward command augmentation is provided by an idealised command reference model, using a full state feedback law synthesised around a 6 degree-of-freedom reduced order linear model of the unstabilised aircraft dynamics. This feed-forward control aims to confer the desired response type, command tracking, and dynamic decoupling upon the vehicle, whilst proportional, integral and derivative (PID) attitude and velocity feedback control is also provided in order to attenuate errors resulting from external disturbances, non-linearities and model inaccuracies.

The FCS was configured to provide longitudinal and lateral Translational Rate Command (TRC – i.e. velocity command) whilst the vertical and yaw axes used velocity command, displacement hold schemes.

As a result, the FCS controlled the air vehicle heading and height, with the approach controller required only for setting the appropriate height and heading datums. However, the longitudinal and lateral positions were effectively controlled by the guidance system.

This configuration was selected in order to accommodate easily the transition from internal to external sensor models as the vehicle approached the ship, with minimal modification to existing control schemes.

Approach Control System

The MUAV simulation was required to fly through the approach sequence and possess the functionality summarised in Table 1, in order to represent the type of system that would be found on an operable autonomous vehicle. Whilst these requirements were specific to the NIREUS programme, the need for increased automation of shipborne helicopter recovery had been appreciated for some time and QinetiQ had conducted research in this area.

A previous QinetiQ study [8] had simulated combining a highly augmented control response with relative GPS guidance in order to relieve the pilot of the longitudinal and lateral station-keeping task during approach, when in close proximity to the ship. The developed system included the functionality to acquire an over-the-deck hover from a substantial distance from the ship using longitudinal and lateral velocity demands.

In parallel with this study, QinetiQ was conducting research into the assessment of vertical take-off MUAV handling during recovery, as part of a broad-ranging study of rotary-wing UAV operations for UK MOD. As part of this study, there was a desire to conduct a desktop evaluation of manoeuvrabilty and controllability. The approach adopted was to establish, through simulation, the vehicle behaviour associated with the conduct of a set of manoeuvres related to the shipborne recovery task. This required the development of a command generation tool, referred to as SLAVE (Ship Landing and Approach Velocity generator) that, through interaction with a pilot model or control system, would guide an air vehicle simulation through prescribed manoeuvres.

When these manoeuvres were selected in the appropriate sequence they essentially formed most of the short-range approach and recovery phase. SLAVE was configured such that it was possible to fly this sequence by navigating through a set of ship-referenced waypoints, each with a short hold period upon arrival.

As a result, this tool was well suited to satisfy the NIREUS requirement for a Landing Path Planning system. The primary area for improvement was the development of NIREUS-compliant phase logic. Table 1 summarises the functional requirements of each mode.

Figure 5 illustrates that SLAVE was capable of guiding the air vehicle to the ship from substantially further away than was required in NIREUS and this functionality was retained, under entirely automatic control. The additional SLAVE modes were all reported under an additional LPP mode 0: "Approach to M2", comprised of an initial turn

towards a nominal initial point, acceleration to cruising speed and flight towards the glidepath entry point (effectively point M2 on Figure 2).
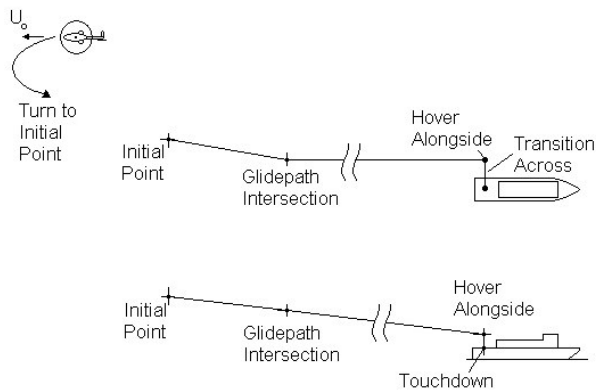

Figure 5: SLAVE Approach

It is worth noting here that the NIREUS requirement effectively specified the functionality the system must possess, whilst the LPP modes acted only as reports to the federate that a certain function was being performed.

It can been from Table 1, and indeed Figure 2, that there were essentially 3 waypoints of interest – M1, M0 and the designated touchdown point. LPP modes 2, 4 and 6 all occurred upon arrival at their respective waypoints, with modes 2 and 4 requiring the air vehicle to stabilise before their engagement. LPP mode 6 occurred immediately upon touchdown and required only that the approach and flight control systems rapidly reduce the collective pitch to its minimum setting and hold the other controls.

The abort modes (LPP 7 and 8) were effectively equivalent to modes 1 and 3, except for the change of sensor and applicable abort conditions.

Grouping the LPP modes by their target waypoint leads to the concept of fundamental modes each with a certain control task (i.e. fly to and maintain position, or arrive at position at time X) and a set of advance, abort and override conditions. These conditions represent those that allow the system to advance to the next fundamental mode, retreat to the previous one or override the approach controller and impart a set response regardless of the specific condition of the air vehicle.

Table 2 summarises the behaviour of the fundamental SLAVE modes and how these were mapped to the required LPP mode reports.

The two "Waiting" modes became active when the air vehicle was within 1 m of the target waypoint for a continuous period of 5 seconds.

Whilst there were a significant number of aborts, and their behaviour varied, it was possible to combine them into 3 functional groups:

1. **Possible unsafe condition**

    MUAV reaction: Return to previous waypoint

    Circumstances:

    i)   External abort order

    ii)   Out-of-position

    iii) Descent rate excessive

2. **Probable unsafe condition**

    MUAV reaction: Return directly to waypoint M1

    Circumstances:

    i)   Too far forward (too close to hangar)

    ii)   Control limits exceeded (controllability in question)

3. **Definite unsafe condition**

    MUAV reaction: Immediately escape to safety and wait until safe to re-start approach

    Circumstances:

    i)   Data Unavailable (ship position information lost – guidance impossible)

Group 1 aborts, which corresponded to possible unsafe conditions, were triggered when there was an indication that continuing with the current action was unsafe. These aborts were active in LPP modes 3-5, and caused a switch to the previous SLAVE mode.

- External abort orders indicated that an operator, or some system aboard the ship, believed that there might have been an imminent safety risk

- Out-of-position aborts were triggered automatically when the air vehicle position deviated from the predicted path by more than some margin

- The "Descent Rate too High" abort was triggered, in the final landing phase, when the descent rate required to touchdown at the target time was greater than the undercarriage limits

Group 2 aborts, which responded to probable unsafe conditions, were triggered when there was an indication that the current action was unsafe. These aborts overrode those in group 1. The group 2 aborts were active in LPP modes 3-5, and switched SLAVE into mode E.

- The "Too Far Forward" abort was triggered when the air vehicle drifted forward of some point, indicating that there was a danger of collision with the hangar. Due to the "Out-of-Position" abort, which triggered upon deviation from the planned approach path, the primary trigger for the "Too Far Forward" abort was incorrectly set waypoints.

- The "Control Margin exceedance" abort was triggered when any of the air vehicle actuators was within 10% of full travel in any direction. This indicated a danger of loss of control, likely induced by airwake turbulence and wind effects.

Finally, group 3 aborts, composed entirely of the Data Unavailable abort, was triggered when safe approach became impossible.

The "Data Unavailable" abort was triggered on receipt of an external logical flag, indicating that the ship position information, including the estimated relative position of the air vehicle, had become unreliable or had been lost entirely. This abort overrode all others, and was active in all modes except after touchdown.

The response to this abort was to execute a simple, but aggressive, "flyaway" manoeuvre. This commanded the aircraft to climb to greater than 100 ft above sea level (the nominal mast height of the ship) as rapidly as possible, and to simultaneously attain 10 knots of rearward flight before settling into a hover. This manoeuvre attempted to ensure that the air vehicle was clear of any obstacles, by providing longitudinal and vertical separation from the ship even if it was stationary, and hence prevent collision between the ship and air vehicle.

The "flyaway" manoeuvre was commanded by a logical subsystem that was part of the air vehicle FCS, which was separated from the approach guidance system and used only sensor inputs internal to the air vehicle. As this abort was available throughout the approach sequence, once the "Data unavailable" flag was cancelled, SLAVE was either returned to its original mode (if the air vehicle had not yet passed M1) or was switched to mode E (reported as LPP mode 7, "Aborting to M1"). Once SLAVE was reset, the control of the air vehicle was returned to the approach guidance system.

The guidance laws themselves were based around simple PD or PID controllers, using the appropriate position error as their input.

Prior to the final landing phase, the simplest of the guidance laws was the vertical axis. If there was an error between the desired height and the datum of the height hold, then an airspeed-scheduled constant rate was applied until the error was negligible. The schedule attempted to ensure that vertical rates would not generate excessive torque on the air vehicle (although no torque protection was implemented).

However, once landing was ordered, then the vertical axis control systems were required to place the air vehicle down onto the deck within +/- 0.2s of a desired time. During this stage of the approach, the guidance law constantly adjusted the demanded height datum rate in order to achieve touchdown within the time window.

This was achieved by first calculating the constant descent rate that would be required to get the air vehicle down in time, then applying knowledge of the first-order height rate response imposed on the air vehicle by the FCS. This generated a vertical rate demand that compensated for the lag between demand and response, and allowed the air vehicle to achieve a precise time-at-height.

Sensors

The NIREUS requirement mandated that the air vehicle simulation be able to approach and land on the ship, whilst receiving ship position information solely from a shipboard optical tracking system simulation elsewhere in the NIREUS federation. This tracking system was used in LPP modes 3-5.

The tracking system information was expected to contain random errors with a "mean + 2σ" measurement error of up to 10m, with the air vehicle nevertheless required to land successfully and accurately. For this reason, some degree of sensor error compensation was required.

The selected solution was to use simple complimentary filtering (with $T = 2s$) of the tracking system input (low-passed) with perfect air vehicle velocities (high-passed). This was based on the reasonable assumption that a coupled INS/GPS would be used to drive the velocity-command FCS, and as such would have to be sufficiently robust to reject spurious transient changes in air vehicle velocity. Hence it was possible to use its signal to reject such changes from the external tracking system simulation. Compensation for steady-state position errors in the information from that system was not required of, or provided by, the air vehicle.

The air wake simulation

Air wake structure and architecture

Like the MUAV model, the air wake simulation had been developed at QinetiQ for use in helicopter-ship dynamic interface studies. The primary function of the airwake model was to represent the aerodynamic disturbance induced by a ship's

superstructure and consisted primarily of predefined look-up tables of 3-D flow across a grid of points specified relative to the ship's deck.

These tables were generated using the WAMAS model [10] which constructs the flow field around bluff bodies through the assembly of characteristic flow features (Figure 6) using a mixture of physical and heuristic rules to impose flow boundary conditions. The combined action of these flow field elements calculated by WAMAS is expressed in terms of the perturbation to free stream flow induced by the ship at a given point. Once calculated, these perturbations are normalised by the wind speed, and re-scaled when used for a different wind strength at the same wind over deck angle.
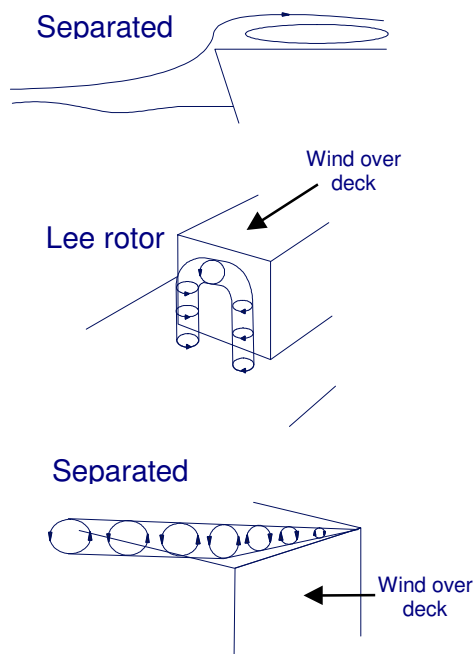

Figure 6: WAMAS flow elements

Airflow unsteadiness, required in the Yellow Team specification, was introduced by estimating the local wind strength (absolute velocity) at the helicopter' s hub centre and multiplying this by a time varying signal generated using the Statistical Discrete Gust (SDG) model [12]. Finally, the total 3-D flow speed components were obtained by adding the airwake perturbation, unsteady flow and undisturbed ambient airflow.

Although stated as an optional requirement, the airwake federate developed for NIREUS used azimuthal interpolation between airwake tables to allow simulation of arbitrary wind speeds and directions. During the course of the programme an open file format was defined to allow data from alternative ship configurations to be incorporated.

Implementation approach

As discussed earlier, one of the objectives of NIREUS was to demonstrate the reuse of legacy models and in this respect neither the MUAV nor air wake models was an exception. Nor was it exceptional that the engineers best equipped to develop the required NIREUS functionality were also the least familiar with HLA and the federate-level simulation technology. The solution to this problem was the definition of a Software Interface Function (SIF) specifying the actions required of the model, in essence *initialise*, *update* and *shutdown*, and defining all required data transactions. This SIF provided an interface through which the model could be accessed by a test stub program for use at the unit testing stage or an HLA wrapper for integration within the federate.

In this case, both the air vehicle and air wake models were implemented in Simulink™ as this provided a convenient, and familiar, environment in which the modelling engineers could prototype, test and develop the required functionality. From the SIF specification it was straightforward to define a very simple top level Simulink diagram on which input and output ports were provided for each of the SIF data items. All other model information was contained within subsystem blocks communicating with the top-level diagram indirectly. Although this produced rather anodyne diagrams it introduced a degree of information hiding, allowing the SIF/Simulink interface to be defined and tested in advance of either of the models being fully operational.

Once each model was completed, it was passed through the Simulink Real-Time Workshop to create standard ANSI C code suitable for integration with the SIF. Again this process was relatively straightforward as the generated code provided functions that mapped closely to the *initialise*, *update* and *shutdown* functions specified in the SIF.

Finally, it was a requirement of the NIREUS Yellow Team federates that local visualisations of each model should be provided. In the case of the MUAV and air wake models, this was achieved through the development of a Simulink function, using OpenGL, which displayed the status of the combined ship, MUAV and air wake models (see Figure 7). Air vehicle abort states were reported using colour coding of the vehicle's image, wind vector arrows were used to indicate airwake conditions and a text bar was used to quote the status of the landing algorithm. The visualisation was written to be compatible with both models and following code generation using RTW was available for use when operating with the test stub or HLA wrapper.

This local visualisation proved especially useful during federation integration and testing, as it gave quick feedback on the relevant federation data (e.g. air vehicle position, ship position) as viewed by the air vehicle or air wake federates.
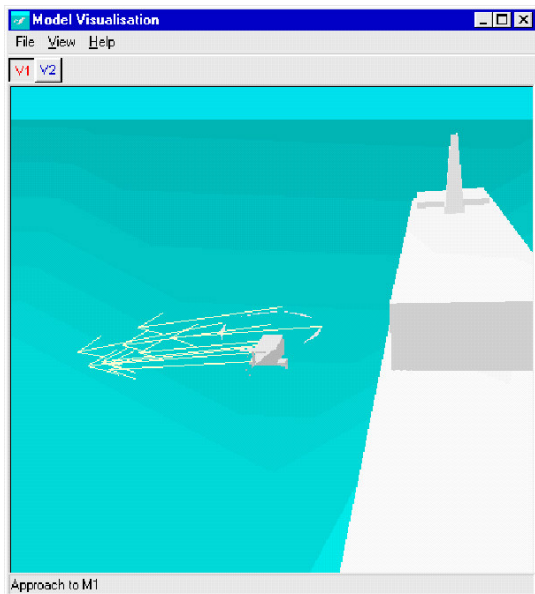

Figure 7: Example visualisation window showing wind vectors and aircraft approach phase

Example results

The influence of the ship air wake on the ambient aerodynamic flow field is illustrated in Figure 8. In this case, data are presented for the case of the MUAV transitioning from port to starboard across the centre of the ship' s landing deck. It is clear that the ship' s hangar introduces a substantial reduction in longitudinal airflow, which would require the MUAV control system to retrim to a different effective airspeed.
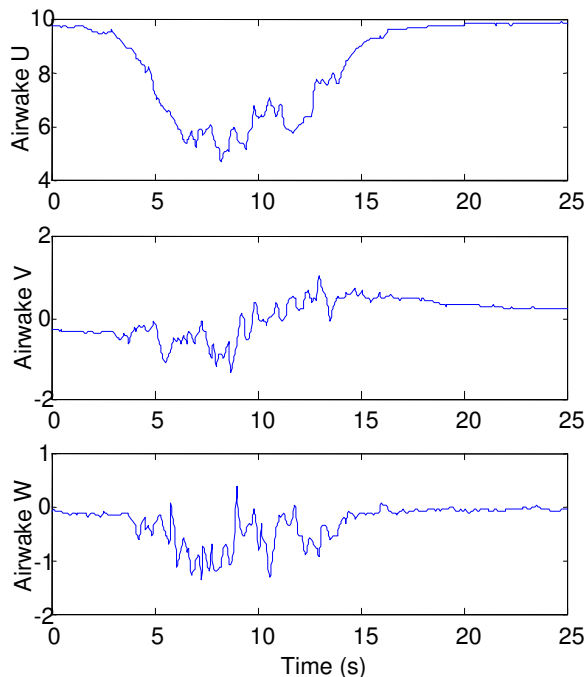

Figure 8: Airflow at hub centre during transition across deck

Figure 9 shows the LPP mode and the various user-issued orders during a sequence of aborted approaches, the last of which is introduced soon after the MUAV is ordered to land.
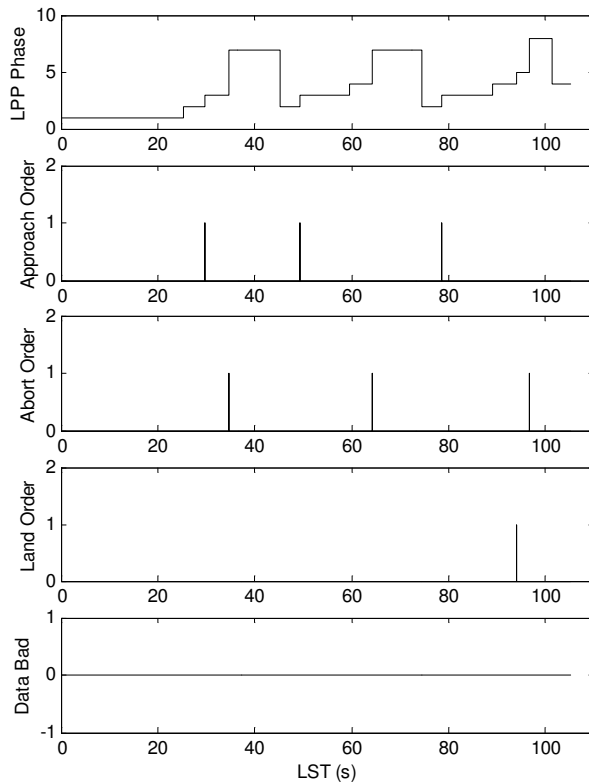

Figure 9: LPP modes and order during repeatedly aborted approach

In the first two cases the MUAV aborts to M1 while in the last it aborts to M0.

A related case is shown in Figure 10, where the MUAV receives two landing orders. The first of these is given while the MUAV is transitioning to M0 (LPP mode 3) and is thus ignored by the MUAV ' s landing system. In contrast the same order received while the MUAV is waiting at M0 (LPP mode 4) initiates a landing manoeuvre.
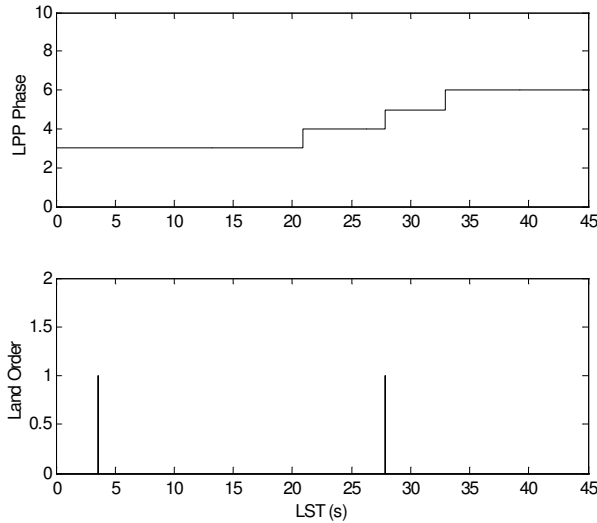

Figure 10: LPP phases and landing orders during final approach

Finally, Figure 11 shows the deck-centre-referenced undercarriage positions during a completed landing. (Note the expanded timescale on the final axes). An indication of the MUAV' s flight path can be obtained from the positional information, shown relative to the deck landing point. Between 0 and approx. 22 seconds, the MUAV is approaching the ship (LPP Mode 3) and attempting to reach point M0. This point is reached and held for approx. 5 seconds at which point an order to land is issued. The MUAV declares itself "landed" at approx. 34 seconds.

The final plot shows the predicted/commanded landing time and the logical flags for weight-on-wheels (WOW) and pre-touchdown detection (to Transfer to the Touchdown simulation). It is clear that the MUAV lands within less than a quarter of a second of the predicted touchdown time.
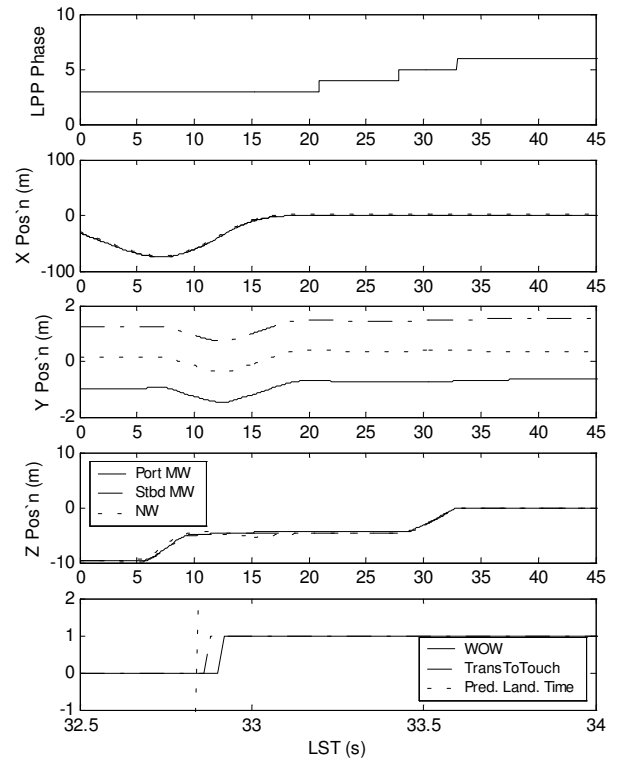

Figure 11: Deck-referenced U/C positions and touchdown flags

Conclusions

The NIREUS concept federation is a successful example of a multinational interoperable simulation framework addressing a relevant multidisciplinary problem space. The resulting simulation infrastructure and integration tools allow for the assessment of recovery issues for a wide range of NATO MUAVs and ships with potential for expansion to include the piloted air vehicle recovery case.

The separation of the MUAV approach into discrete phases, each with their own set of abort conditions for safety preservation, led to a successful automatic approach and landing system, with no requirement for a skilled operator.

A suitably robust flight control system has been developed, capable of reaching and maintaining a designated position, even during significant ship-airwake encounters. Accurate time-at-position has also been achieved.

The integration of multiple systems, simulated or otherwise, benefitted inordinately from a well crafted requirement specification and interface definition.

Satisfying the requirements of a new specification with legacy systems has shown that it can be easier to retain surplus functionality than to remove it.

The use of suitably configured software tools, such as Simulink, allows for multi-disciplinary teams to implement complex systems using tools and techniques appropriate to their own domain specialisms.

Within the NIREUS federation, air vehicle and air wake wrappers and associated test tools provide a mechanism to support the interoperability of NATO simulations using a generic HLA interface layer. This approach has been practically demonstrated using largely legacy air vehicle and air wake simulations.

NIREUS has adopted the novel step of separating air vehicle flight dynamics and ship air wake playback functionality into different federates. This approach fosters interoperability between different air vehicle and ship air wake modules, provides a placeholder for future air wake M&S technology improvements and has led to reuse of conceptual model, federate and FOM components within other international simulation programmes.

Acknowledgements

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LPP Mode	Description	Specified Sensor Options	Specified Proceed Conditions	Specified Abort Conditions	Exceptional Requirements
1	Approach to M1	Internal sensors (INS/GPS)	Stablisation at M1	Data Unavailable	None
2	Wait at M1	Internal sensors (INS/GPS)	Approach Order	Data Unavailable Out of Position#	Hold position within +/-1m
3	Approach to M0	Off-board sensor	Stablisation at M0	Manual Abort Order Data Unavailable Out of Position Out of Control Limits Too Far Forward	None
4	Wait at M0	Off-board sensor	Land Order	Manual Abort Order Data Unavailable Out of Position Out of Control Limits Too Far Forward	Hold position within +/-1m
5	Final Descent	Off-board sensor	Touchdown detection	Manual Abort Order Data Unavailable Out of Position Out of Control Limits Too Far Forward Descent Rate too High*	Achieve touchdown within: +/- 0.2s of specified time, +/-1m of designated point, 80% of U/C limit load
6	Touchdown	Off-board sensor	N/A	N/A	Send touchdown status message. Shutdown Approach and flight control systems
7	Abort to M1	Internal sensors (INS/GPS)	Stablisation at M1	Data Unavailable	None
8	Abort to M0	Internal sensors (INS/GPS)	Stablisation at M0	Data Unavailable Out of Control Limits Too Far Forward	None

\# - Mode cancels but does not generate abort code

* - Not explicitly stated in specification, but inferred from requirements and agreed with customer

Table 1: NIREUS approach controller functional requirements

SLAVE Mode(s)	Description	Basic LPP Mode	Waiting LPP Mode	Aborted LPP Mode	Basic Mode aborts	Wait Mode aborts	Abort Mode aborts	Advance to next SLAVE mode when:
A-D	Begin approach	0	-	-	Data Unavailable	-	-	Point M2 passed
E	Fly to M1	1	2	7	Data Unavailable	Data Unavailable	Data Unavailable	M1 Wait established AND Order to Approach received
F	Fly to M0	3	4	8	Data Unavailable Manual Abort Order Out of Position Out of Control Limits Too Far Forward	Data Unavailable Manual Abort Order Out of Position Out of Control Limits Too Far Forward	Data Unavailable Out of Control Limits Too Far Forward	M0 Wait established AND Order to Land received
G	Land	5	-	-	Data Unavailable Manual Abort Order Out of Position Out of Control Limits Too Far Forward Descent Rate too High*	-	-	Touchdown detected
Touchdown Override	Shutdown	6	-	-	None	-	-	Never - Approach concluded
Data Unavailable Override	Emergency Flyaway	-	-	7	-	-	None	Data made available AND M1 Wait established

Table 2: Approach controller modes