"This paper was presented at the "Warship 2009 – Airpower At Sea" Conference, Organised by the Royal Institution of Naval Architects".

FEASIBILITY STUDIES FOR VTOL UAV AUTONOMOUS OPERATIONS WITH THE POSSIBILITY OF SHIP BOARD AUTO RECOVERY USING QUIESCENT PERIOD PREDICTION

BY

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ABSTRACT

The objective of the work described here is to demonstrate the ability to recover a UAV on-board a moving vessel within reasonable safety margins regardless of the seaway. The Energy Index, the operative component of the Landing Period Designator, identifies quiescent periods to initiate aircraft descent based on aircraft deck limit definitions. Dynamic Interface simulation provides the physical information from which initial deck limits might be derived. Energy Index quiescent indications for UAV recovery opportunities are presented outside of current operating limits. A brief synopsis of the theory and calculation of the ship motion simulation and Energy Index programs, are discussed. The use of flight simulators to forecast physical deck motion and deck motion limits, is discussed. UAV flight test programs using simulation, are described. Using a real-time ship motion-based helicopter recovery monitoring system, operators perform flight-testing evolutions (DLQ) just as they would at sea. Undercarriage deflection to encountered deck forces and aircraft stability, were calculated. Impacts on the proposed deck limits, are discussed. Percent improvement of operational availability is demonstrated.

Nomenclature

ASIST	Aircraft/Ship Integrated Secure and Traverse System also RSD
CD	Clear Deck Recovery
DI	Dynamic Interface Study
DIPES	Deck Interface Pilot Effort Scale

DLQ	Deck Landing Qualification
DOF	Degree-of-freedom
EI	Energy Index (Value calculated by LPD)
FD	Free Deck Recovery (RAST trap used only)
FDO	Flight Deck Officer
HARPOON	helicopter handling Sys (UK,USCG)
HCO	Helicopter Control Officer
HLA	High Level Architecture
HSL	Helicopter (Attack) Squadron Light
LCAC	Landing Craft Air Cushion
LPD	Landing Period Designator
LPDLOOP	Landing Period Designator software
LSE	Landing Signal Enlisted
LSO	Landing Signal Officer
MFS	Manned Flight Simulator
MRU	Motion Reference Unit
NVG	Night Vision Goggles
ONR	Office of Naval Research
PfP	Partnership for Peace
RA	Recovery Assisted
RAO	Response Amplitude Operator
RAST	Recovery, Assist, Securing and Traversing
RNAS	Royal Navy Air Station (UK)
RSD	Rapid Securing Device (also ASIST)
SAMAHE	Helicopter Handling Sys (France)
SHOL	Ship-Helicopter Operational Limit
SMP	Ship Motion Program
SMS	Ship Motion Simulation composed of routines identified as NAV
TCS	Tactical Control Station
TD	Test Director
TP	Test Pilot
UAV	Unmanned Air Vehicle
VLA	Visual Landing Aid
VMC	Visual Meteorological Conditions
VTUAV	Vertical take-off and landing Unmanned Air Vehicle
WOD	Wind-over-deck

INTRODUCTION

The simulation of helicopter operations from naval vessels provides a unique set of challenges, requiring realistic modelling of the interactions between the aircraft, the ship platform, and the environment. The aim of the NIREUS (NATO Interoperability and RE-Use Study) and SAIF (Ship/Air Interface Framework) programmes was to use a simulation standard called High Level Architecture (HLA) to integrate air vehicle simulations, ship simulations and environment models to aid the assessment of the dynamic interface for a range of helicopter/ship and UAV/ship combinations.

The main aim of NIREUS was to undertake a practical application of distributed simulations using the HLA methodology. With a view to demonstrate multi-national cooperation, simulation re-use and interoperability and to support the guidelines supplied by an Allied Naval Engineering Publication (ANEP 61) on the application of simulation based design and virtual prototyping in ship design. A VTOL-UAV application was chosen as the example due to the NATO/PfP interest in Maritime UAV operations [1]. The milestone for NIREUS was to create a working demonstration of a UAV landing on a ship. Using terminology from HLA the simulation of Federation consists of component called Federates.

The NIREUS concept Federation pioneered a number of different approaches to the problem, including the successful de-coupling of the aircraft flight dynamics and ship air wake models into separate federate models.

Elements from NIREUS were leveraged within the SAIF project, with model re-use being a key principle behind the use of HLA and distributed simulation. The system architecture designed in NIREUS allowed the replacement of a PC-based simulation of the UAV, by a "Man-in-the-loop" full cockpit motion-based helicopter simulator. This demonstrates the scalability of the HLA architecture.

The key objective of SAIF was to provide a system capable of conducting SHOL assessments during ship design, prior to full-scale sea trials. Real-life flight trials are expensive operations and are also limited by the prevailing weather conditions available for the duration of the test period. It is envisaged that a cost-effective combination of simulation and first-of-class flight trials at sea will maximise the operating envelope for the various new ship platforms from which a manned helicopter or UAV is intended to operate. In the SAIF project, the existing flight simulator, traditionally used for fleet training, at RNAS Culdrose was modified with external physics based federates introduced to provide ship and environment functionality such as the real time representation of ship motion and the air wake flow field. Each external federate was then introduced into the simulation and run on a remote computer, separate from the core flight simulator.

FEDERATION DEVELOPMENT

The HLA process, developed for distributed simulations, is outlined by the U.S. Defence modelling and Simulation Office (DMSO) as the Federation Development and Execution Process (FEDEP) [2]. The six basic steps of the FEDEP can be summarised as:

- Define the Federation objectives;
- Develop a conceptual model that sufficiently describes the real-world problem space;
- Allocate functionality to federates;
- Negotiate the Federation Object Model (FOM) and agree to other common standards;

[1] S. White, R. Reading (2001). NATO/PfP HLA Federation of VTOL Operations Supporting Simulation Based Acquisition. 01E-SIW-032. Brussels.
[2] High Level Architecture (HLA) Federation Development and Execution Process (FEDEP) Model, version 1.4, April 1999, United States DoD Defence Modelling and Simulation Office.

- Integrate, test and verify the Federation;
- Execute the federation.

The focus of both NIREUS and SAIF was the simulation of the final approach, landing and recovery of an air vehicle (unmanned in NIREUS and manned in SAIF) on the deck of a ship.

Thus, to meet this focus, once the decision was made to produce a distributed federation, the system architecture (or federates) was developed.

As part of the control structure of NIREUS, the realisation of the project was by four teams, each being responsible for the development of a particular aspect of the simulation. The Blue Team was responsible for modelling the behaviours of the ship itself; the Yellow Team for modelling and simulation associated with the air vehicle and air wakes; the Green Team for the for ship-air vehicle system dynamic interface issues; the Red Team for overall federation development. The boundaries associated with these teams were arbitrary to a certain extent but reflected a combination of the then current capabilities. Thus, the conceptual model, separated by discipline, is shown in Figure 2.

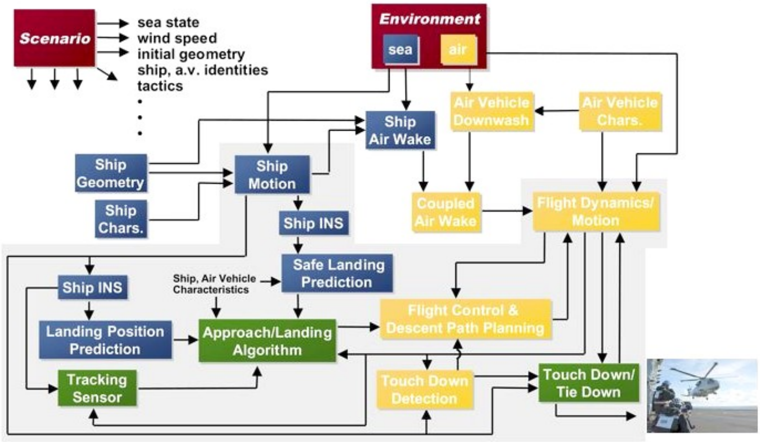

FIG.1 – NIREUS CONCEPTUAL MODEL

This conceptual model identified each of the individual federate elements within the simulation, and also defined the Federation Object Model (FOM) or the list of data items to be transmitted over the network. The design of the conceptual model resulted a number of separate federates being identified in NIREUS [1] and shown in Figure.2, connected via the HLA Run-time Infrastructure (RTI) software. The contributing nations indicated by the national flag.

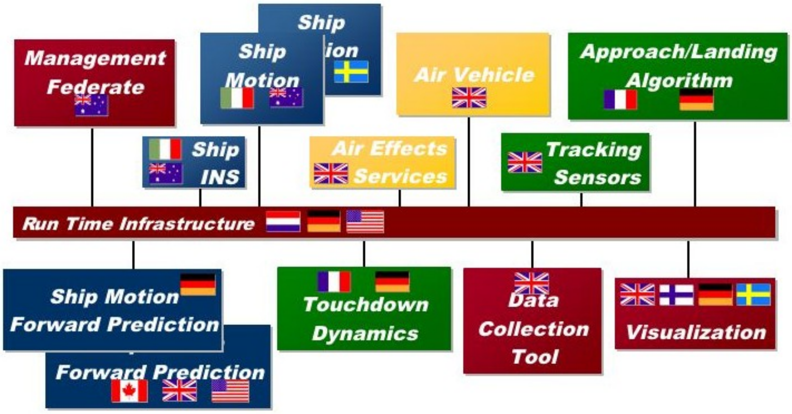

FIG.2 – NIREUS FEDERATION ARCHITECTURE

Air Vehicle

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. It resembled essentially a traditional helicopter with tri-cycle landing gear. 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 helicopter-ship studies 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.

Operating the UAV within the federate required the development of guidance and control algorithms representative of those that would be found on an autonomous vehicle. More specifically, an inner loop control law provided stabilisation of the vehicle and rejection of atmospheric disturbances, an outer loop guidance controller was required to steer the vehicle between flight path way points and a route-planning and way-point selection algorithm was defined to accommodate dynamic changes to the required flight path. Finally, control system abort logic and algorithms were defined to allow the vehicle to take instruction from the deck landing algorithm and to notify it of problems arising from within the air vehicle itself. Other aircraft configurations including, but not limited to, coaxial rotor air vehicles were developed [3].

Management Federate

The purpose of this federate was to supply all of the required initialisation data to the rest of the federation. This consists of the following environmental items:

- Sea State (in the range 0 to 6) and wave spectrum information (comprising amplitude, frequency, wavelength, phase and direction for each individual wave sinusoid). The sea surface is therefore described by the cumulative effect of each individual wave sinusoid;

- Freestream wind speed and direction;

- Fog Level (i.e. a visibility range) and time of day;

- Scenario origin point (a reference datum for the geographical location of the simulation);

- Environment timestamp (a reference 'start time' of the simulation, used in wave height calculations).

Ship Motion

The methodology involves stochastic spectral probabilities in order to produce deterministic synthetic time histories.

The ship motion program is divided into two basic themes, spectral analysis and the calculation of motion histories in the time domain. The SMS fundamental relationship is:

$$Sr = S_w(w) \bullet RAO \bullet \boldsymbol{f}(V, m)$$

where:	Sr:	Ship response spectrum
	$S_w(w)$:	Seaway spectrum
	RAO:	Ship transfer functions
	f(V,m):	Frequency mapping
	V:	Velocity
	m:	Relative wave angle

The energy contents of a sea state can be modelled by the 3-parameters of the JONSWAP spectrum [4], characterized by a Significant Wave Height (Hs), a Modal Period (T_0) and an Enhancement Factor (γ).

[3] I. Cox, G. Turner, J. Duncan (2005). Applying a Networked Architecture to the Merlin Helicopter Simulator. Royal Aeronautical Society Conference. London.
[4] Hasselmann D E, Dunckel M and Ewing J A. 1980, Directional spectra observed during JONSWAP 1973, Journal of Physical Oceanography, Vol. 10, pp.1264-1284.

By choosing an appropriate Enhancement Factor the user could choose waves that are typical of a sea area with limited fetch, North Sea for example, by setting γ =3.3 or alternatively waves typical of open ocean , North Atlantic by setting γ =1.0.

The analytical expression of the JONSWAP spectrum is:

$$S_\eta(\omega_i) = \frac{1}{2\pi} \cdot \alpha^* \cdot \frac{H_s^2}{f_i^5 \cdot T_0^4} \cdot \gamma^{e^{-\frac{(T_0 \cdot f_i - 1)}{2 \cdot \sigma^2}}} \cdot e^{-\frac{5}{4 \cdot (T_0 \cdot f_i)^4}}$$

where

H_s : Significant Wave Height

T_0 : Modal Period

γ : Enhancement Factor

$$f_i = \frac{\omega_i}{2\pi}$$

$$\alpha^* = \frac{0.0624}{0.0336 \cdot \gamma + 0.23 - \frac{0.185}{1.9 + \gamma}}$$

$$\sigma = \begin{cases} 0.07 & \omega_i \le \omega_0 \\ 0.09 & \omega_i > \omega_0 \end{cases}$$

So, the JONSWAP spectral energy density function assumes a distribution of wave heights at different frequencies.

The spectral characteristic of a vessel can be defined experimentally or computationally developed as transfer functions termed Response Amplitude Operators (RAO). The response amplitude operators define the dynamic ship responses for a specified load/operating condition.

The ship response spectrum is created as the product of the RAO and the driving sea spectrum over the entire range of frequencies. The response spectrum is reduced to sets of harmonic components for each degree-of freedom. Synthetic time histories are created stochastically by summing the harmonic components over a given time period. A typical time history equation is given by:

$$A_Z = \sum_{n=1}^{k} \left(A_{Z_n} \cos\left(w_n - e_{Z_n} \right) \right)$$

where

Az:	DOF amplitude
w:	a circular frequency
e:	phase angle

Time histories are produced by the sum of 48 synthetic functions (k=48). In summary, the Ship Motion Federate creates deterministic measures of ship motion from a probabilistic spectrum.

Ship Inertial Navigation System

In the NIREUS federation some components rely on information concerning the motion of the ship. Only in cases when the federation needs to represent the physical interaction between the ship and the air vehicle is it appropriate to use the true ship motion. For example, in visualisation, the screen needs to show what the ship is actually doing; so true ship motion data (as generated by the ship motion federate) is required by visualization tool. However, in cases where a federate requires measured ship motion information, it is not appropriate to use true ship motion because it would not be available in the real physical world. Thus, the ship INS federate is part of the federation to represent as closely as possible what happens in the real world. Any true ship motion information must be measured before it can be used by parts of the federation (e.g., other sensors) and there are inherent errors with any measuring device. For example, simple accelerometers that measure vertical motion will superimposed integration errors, signal drift errors and measurement noise onto the true ship displacement.

In the initial NIREUS federation development it was not intended to model the exact behaviour of a ship INS system and all of its measurement errors. Instead, the true ship motion was be artificially 'degraded' by adding noise at high frequencies to represent noise and at low frequencies to represent signal drift.

Ship Air Wake

A ship moving in waves, in a variable incident wind, generates an extremely complex unsteady wake about the superstructure and aft of the transom. Operation of helicopters through such air wakes can cause handling and performance difficulties that will ultimately limit the safe envelope for various combinations of relative wind speed and directions over the flight deck.

There is, currently, no practicable method of undertaking direct computations of the fully couple air wake, that is computing the unsteady pressure distribution due to the presence of the helicopter and the corresponding instantaneous forces and moments on the fuselage and its rotor during a landing operation in the unsteady air wake, including hot stack gas constituents, behind the superstructure of a ship moving at a constant velocity in an ambient wind field in calm seas. The problem is made considerably more difficult when the ship is moving in response to waves in an unsteady incident wind. The federate is however, capable of computing air wake about the ship, at many different locations for each frame of the simulation, corresponding to the environment specified by the management federate [5]. One of the software codes currently in use to compute the unsteady air wake around ships in calm seas is FEFLO, a multi-purpose, parallel, scalable, finite element code.

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[5] I. Woodrow, D. Spilling, A. McCallum (2002). The Interoperable Simulation of Air Vehicles and Ship Air Wakes within a Multinational Simulation Framework. 02E-SIW-047. Brussels.

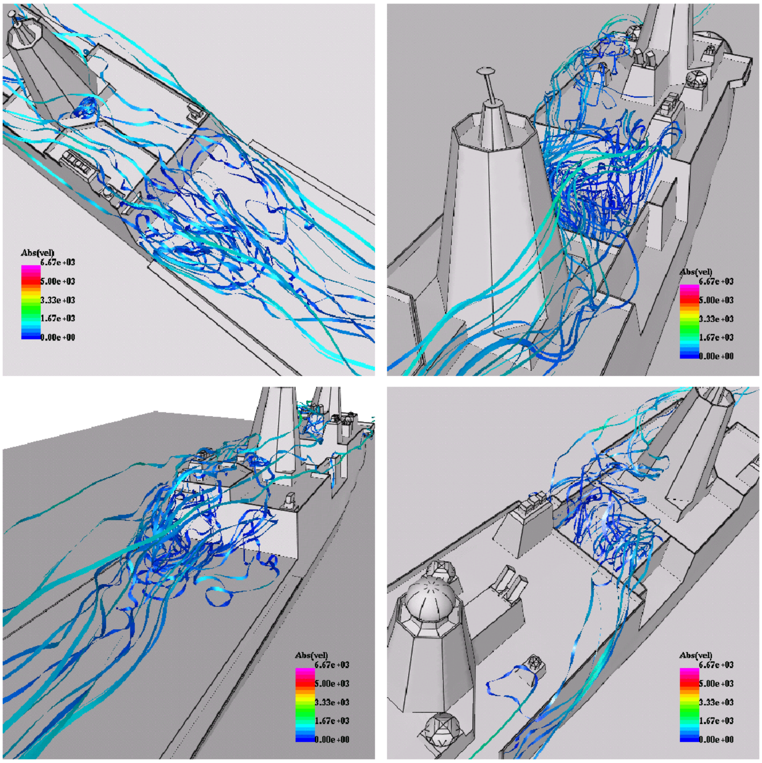

FIG.3 – VELOCITY RIBBONS IN THE LPD17 LANDING ZONE AND BETWEEN MASTS

The code is based on the following general principles: use of unstructured grids, automatic grid generation and mesh refinement, finite element discretization of space; and edge-based data structures for computational speed. The two most common types of grids used in the code for CFD simulations are body-conforming and embedded grids. FEFLO can operate in two levels of approximation: Reynolds Averaged Navier-Stokes (RANS) and Very Large Eddy Simulation (VLES). The Navier-Stokes equations are time filtered in RANS and space filtered in VLES. Our calm water airwake computations (extensively validated against several wind-tunnel experiments ([6,7,8,9,10,11]) used FEFLO in VLES mode. An example from an LPD 17 stack gas study is shown in Figure 3.

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[6] W.C. Sandberg, R. Ramamurti, J. Kellogg, and F.E. Camelli, Computational Challenges for Launch and Recovery Analyses for Novel Unmanned Air and Underwater Vehicles, ASNE Launch and Recovery Meeting, Annapolis MD 2005.

[7] W.C. Sandberg, F.E. Camelli, R. Ramamurti, and R. Lohner, Ship Topside Air Contamination Analysis: Unsteady Computations and Experimental Validation, ASNE Annual Meeting, Washington, DC 2004.

[8] R. Lohner, F.E. Camelli, W.C. Sandberg, and R. Ramamurti, A Very Large Eddy Simulation (VLES) Study of Ship Stack Gas Dynamics, AIAA-2004-0072, Proc. AIAA Meeting, Reno, NV January 2004.

The space-filtered equations are closed with the Smagorinsky model. This model gave good results for velocity time-histories and toxic gas concentration computations when compared with wind tunnel velocity data and gas concentration measurements.

Tracking

For UAV operations the air vehicle would use the on-board GPS to navigate back to the receiving ship. However, during the close proximity landing phase it is envisaged that a more accurate, independent, system of determining the position of the UAV relative to the ship is required. In the NIREUS federation, the tracking federate, developed by NNC Ltd., represented a simple model of non-perfect sensors that located the UAV position relative to the ship during final the approach and landing phases. In the first instance these sensors were represented in a very simplistic manner however its implementation into the federation enabled more sophisticated representation to be easily incorporated at a later date.

The tracker federate generated the position of the Air Vehicle relative to the landing grid which was then used by the Landing Algorithm to land the Air Vehicle on the landing grid itself. There were two types of tracking sensors represented in this federate, an optical tracking sensor and, a radar tracking sensor. The optical tracking sensor used as input a point of intersection of two imaginary lasers. Each laser had two angles associated with each of the horizontal and vertical planes. The radar tracking sensor used an imaginary radar to determine the air vehicle position as a function of the distance along an angle from both the horizontal and vertical planes.

The inputs to the federate included the air vehicle position and its orientation which were transformed to a suitable co-ordinate system. These inputs were then converted to the output expected from the tracking sensor itself (four angles for the optical device and two angles and two distances for the radar device). Then in a similar approach adopted for the ship INS federate the tracker output data were then degraded by applying noise (with Gaussian distribution) to each component of the reading.

The tracker sensor outputs were then re-converted to position information for sending to the landing algorithm. Possible unit failure was included as part of the functionality which can effectively stop the output from the tracker federate for a period of time during the simulation.

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[9] F.E. Camelli, R. Lohner, W.C. Sandberg, and R. Ramamurti, T-AKE 1: An Extensive Comparison and Validation of Massively Parallel VLES Simulations of Ship Stack Gas Temperatures and Toxic Gas Constituent Concentration Fields, Proc. DOD High Performance Computing Annual Users Group Meeting, Seattle, WA 2004.

[10] F.E. Camelli, O. Soto, R. Lohner, W.C. Sandberg, and R. Ramamurti, Topside LPD-17 Flow and Temperature Study with an Implicit Monolithic Scheme, AIAA-2003-0969, Proc. AIAA Meeting, Reno, NV 2003.

[11] R. Ramamurti and W.C. Sandberg, Unsteady Ship Airwake Computations for the LPD-17; A Successful Validation, Naval Engineers Journal, February 2002.

Ship Motion Forward Prediction

One of the key factors relating to the operation of Maritime Unmanned Air Vehicles is the ability to land it safely on the deck of a ship moving in response to the waves. Currently, the procedure for landing manned aircraft on the deck of a ship varies from navy to navy. In most cases the aircraft is piloted to a position of hovering over the moving deck, then when the Landing Safety Officer (LSO), who is standing on the ship's flight deck, perceives that the ship is suitably quiescent, he will instruct the aircraft to begin its final decent. The operational benefits of a UAV are increased if it can be landed autonomously, i.e. without the aid of an experienced LSO.

In order for the UAV to operate in this fashion it needs to know what the ship is doing now and what it will be doing during the final descent to touchdown. The Ship Motion Forward Prediction Federate is designed to predict or designate quiescent periods of ship motion suitable for the recovery of the UAV.

Ship motion forward prediction (SMFP) uses information on what the ship is doing right now and/or what it has been doing in the recent past to forecast what it may be doing in the very near future. In essence this is akin to the experience LSO standing on the ship's flight deck and 'guessing' the ship motion.

In the context of the NIREUS federation, the SMFP federate outputs a safe/unsafe to land logical variable with the UAV in a hover position. Once the deck has been called safe, the UAV will then land on the flight deck. It is important to note an assumption in the NIREUS federation was that once the safe-to-land call has been received by the landing algorithm and the landing phase had started, it could not be aborted by a subsequent 'deck out-of-limits' call from the SMFP federate. Only the UAV could abort landing due mainly to formulation of unachievable flight paths.

As the UAV begins it final phase of the landing, it is continually updated with the translational and angular position of the moving flight deck. This final phase of the landing operation is a key part of the landing algorithm in the NIREUS Federation and is described later. The SMFP federate deals entirely with the safe/unsafe to land logical variable.

This federate contained more than one solution in an attempt to highlight the interoperability objective of the NIREUS mission. The Landing Period Designator (LPD) attributes as a helicopter recovery aid is well documented and was chosen as one option for SMPF[12].

The standard LPD unit was implemented into the NIREUS Federation by utilising a HLA wrapper. This wrapper enabled the LPD unit to exchange data with the other federates in the simulation. In LPD's implementation in the NIREUS federation, its capability was based on using the ship motion data output from the ship INS federate and the use of data representing the mechanical and dynamic limits of the UAV. These limits, which formed part of the initialization data used during federation start up, were expressed as the ship's energy index, which is a scalar empirical formulation [12].

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[12] Ferrier, B (1997). "Étude Analytique d'Interface dynamique aéronef-navire." Projet de l'Indicateur d'appontage. Thèse de doctorat. École Polytechnique de Montréal. Montréal. Montréal.

The energy index value is correlated to the level of kinetic and potential energy contained in the ship. The ship can only displace from a very low energy state to an aircraft out-of-limit condition by the introduction of a certain quantity of energy from the sea. When the index is low the ship is stable and the ship motion is small. When the index value is below the high-risk threshold, the landing deck motion is acceptable for aircraft recovery.

The thresholds of the various energy levels are directly based on the combination of ship characteristics (measured), UAV limitations (defined). A limit is defined by the impact that a certain ship motion condition may impose on the structural integrity or dynamic response of a given helicopter. The sum of these limits produces a red line that is drawn on the EI scale for a given ship (see Figure 4).

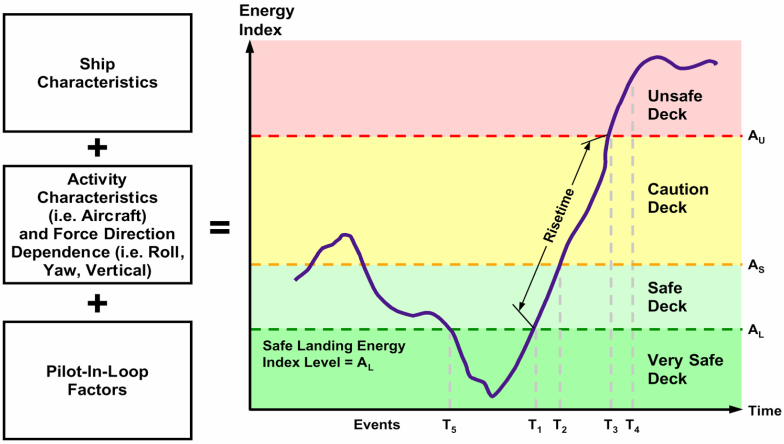

FIG.4 – DECK AVAILABILITY AND RISETIME

The time required to raise the deck from minimal motion (or very safe deck) to unacceptable motion is called the risetime. In terms of the EI scale, the risetime is defined as the period of time that is measured from the end of a green signal to the positive side of the red line. This is given as ($T_3 - T_1$) as shown on Figure 4. The risetime is a thumb print characteristic of the ship's response and rarely changes.

The very safe deck is a special condition in which there is insufficient energy in the aircraft-ship system to raise the deck out of limit for some defined time period or risetime and it is this concept that was used in NIREUS to indicate that the deck was safe to initiate landing.

A schematic representation of how the LPD is used to signal the onset of the descent (and of deck quiescence) is displayed in Figure 5. The approaching air vehicle comes to a hover at M_0 (here noted as PA). Throughout the approach and initial hover (M_1), LPD is monitoring the deck. It is only at the M_0 position that the Autoland System would accept a Green Deck signal from the LPD. The recovery can occur at any point within the green zone as indicated by the "signal to the top" arrow on the Energy Index trace. In a fully functional autoland program, should the vehicle be in descent at an unsafe deck point, a signal would be sent to the Landing Algorithm Federate to stop or abort the recovery [13].

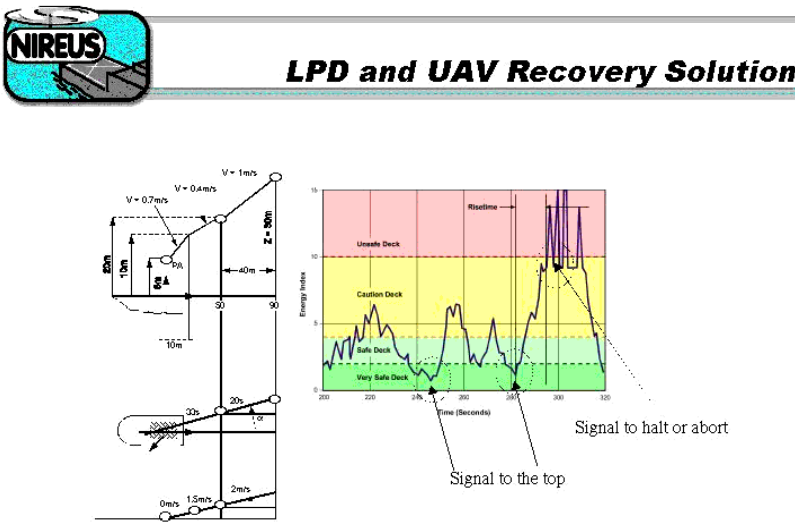

FIG.5 – LPD APPLICATION IN NIREUS

The position of M_0 is not fixed but input as the part of the initialization data for the federation.

Landing Algorithm

The Landing Algorithm federate identified the position of the UAV using the output from the tracker federate and predicted the position and orientation of the platform during the final phase of the recovery (specifically, the last five seconds). The federate supplied by France was created by ONÉRA CERT (Toulouse) and has successfully operated earlier as part of an autoland system in an alternative simulation. The Tracking Algorithms located the UAV in space as a function of the landing grid. The vehicle position and velocity were calculated using a Kalman filter. The 25 Hz module produced a state vector defining the vehicle position and velocity.

The landing grid prediction required five minutes to initialize before it could be used to land the air vehicle. The 2 Hz data exchange produced the coordinates of the landing grid to which the UAV was guided. The position of the grid was updated twice/second through a five second descent.

[13] Lumsden, R Bruce (2001). Helicopter/Ship Deck Landing Guidance Systems. Royal Aeronautical Society. London.

Touch Down Dynamics

The Touch-down Dynamics federate was contributed by the French Navy's CTSN Laboratory in Toulon. The federate calculated the interface forces and moments encountered by the air vehicle landing gear at the instant of recovery. The federate is based on a simulation program called IDYNA which may be used to assess encountered forces secured or unsecured on the deck. The module contained a rotor, landing gear and wind effect model producing non-linear solutions in time-history form. The program determined whether a UAV recovery was incident free.

Simulation Method and Sample Results

As displayed in Figure 6, a Tactical Control Station federate could be integrated with the Federation though gateways to the Inertial Navigation, Tracking Sensors and an operator control station.

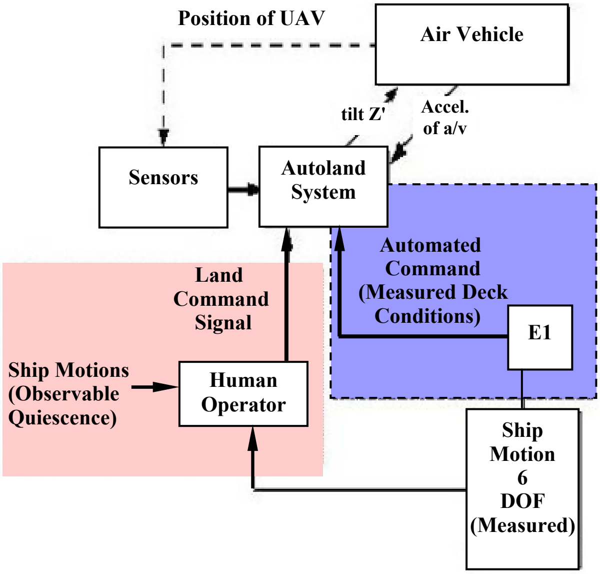

FIG.6 – CONCEPTUAL AUTOLAND INTEGRATION

Figure 7 displays a basic TCS Monitor graphical users interface (GUI) that displays the Energy Index (EI) and coloured land command.

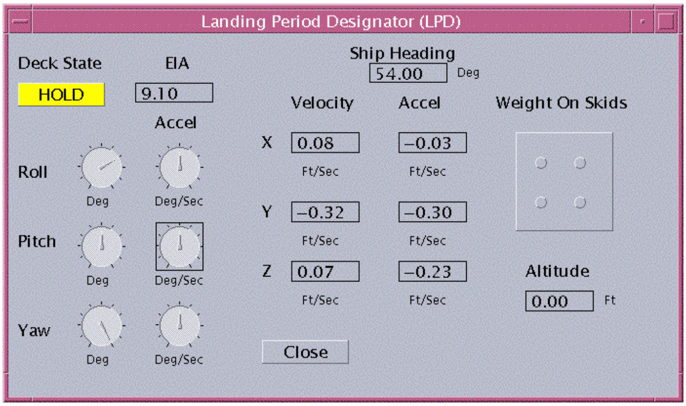

FIG.7 – SAMPLE UAV DECK MONITOR GUI

This LAND command button would be driven by the energy index green signal. From the 5 metres hover position; the green LAND would indicate the onset of quiescence and the beginning of the final descent (system being used to benefit from the rise time phenomena). Used as a Deck Monitor, energy index colours reflect deck status at that moment in time. Quiescent is reflected as green, safe deck is shown as green-amber, caution is amber and out-of-limit is red.

The ship motion element designed to insure recovery to an acceptable deck was evaluated at sea with an Unmanned Air Vehicle system. The objective was to verify the validity of the ship motion simulation data and the LPD signal to the top of recovery. The LPD was selected to document ship motion, identify appropriate periods to recover the Firescout UAV and to demonstrate reliability. This section describes the VTUAV/LPD testing program that was undertaken on the USS DENVER LPD-9 between 21- 25 July 2003.

The test was conducted on USS Denver LPD-9 Amphibious Transports, Dock Austin Class ship (Figure 8). The ship, weighing more than 9000 tons, has hull dimensions 173 x 25.6 x 7 metres was laid down in 1965. It has a helicopter coordination centre with two spots on its flight deck

FIG.8 - USS DENVER LPD-9

Fire Scout (a Hughes/Schweitzer light derivative helicopter) is designed with the ability to autonomously take off and land on any aviation capable ship. It was defined by its landing gear footprint; aircraft weight and inertias; its centres of gravity and pressures and lateral drag areas along with its deck location and orientation (Figure 9). The aircraft is modelled using its high centre of gravity definition and corresponding minimum mission weight (worst case scenario). While the actual time the air vehicle is unsecured on the deck is brief, the model is represented as being unattached. The HARPOON probe (handling system) is located off-centre with the skids modelled close enough to the grid to permit probe penetration.

Whilst still on-board USS Denver, several hours of data were downloaded from the LPD and analysed. Figure 10 displays a typical energy index trace.

Two instances of red deck were detected in this recording of deck availability measurement. Figure 11 and Figure 12 displays the corresponding roll and pitch and vertical, and lateral deck rates.

FIG.9 – NORTHROP-GRUMMAN FIRESCOUT UAV ON USS DENVER

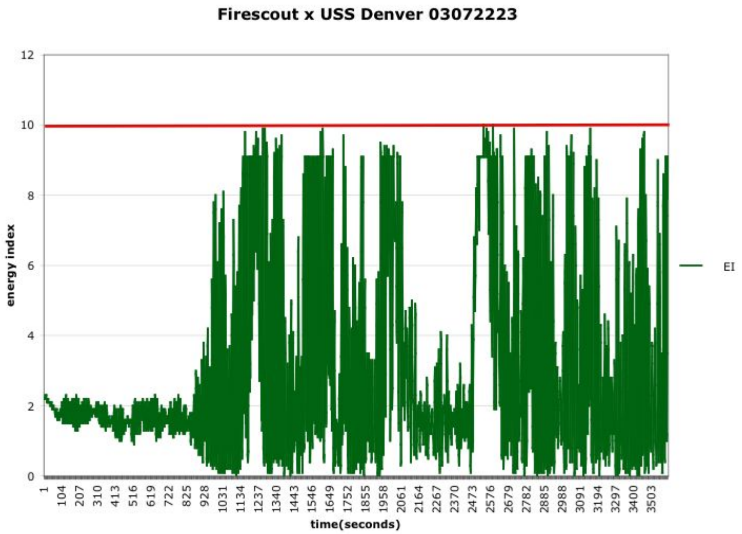

FIG.10 – ENERGY INDEX TRACE

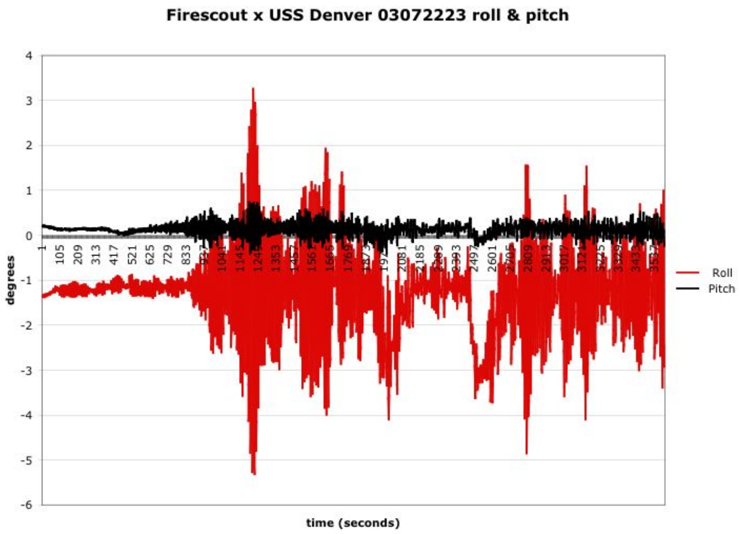

FIG.11 – CORRESPONDING ROLL, PITCH TRACE

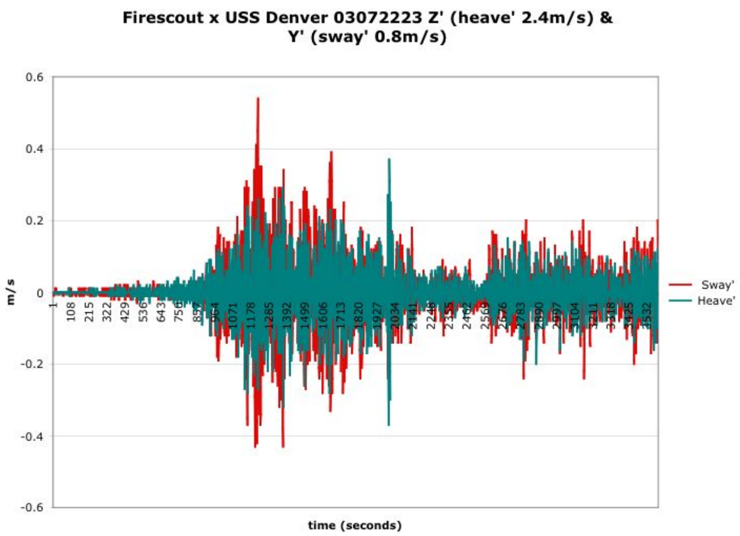

FIG.12 – VERTICAL AND SWAY RATE TRACES

An evaluation of the energy index gave a percent distribution of: Green- 59%, Green-Amber- 23%, Amber- 18%, Red- 0.0%. Total deck availability being 100% with no risetimes.

These results were compared with simulations run earlier. As in the NATO financed NIREUS program (Figure 13), the top of recovery was correctly and repeatedly identified by the LPD component in the autorecovery system.

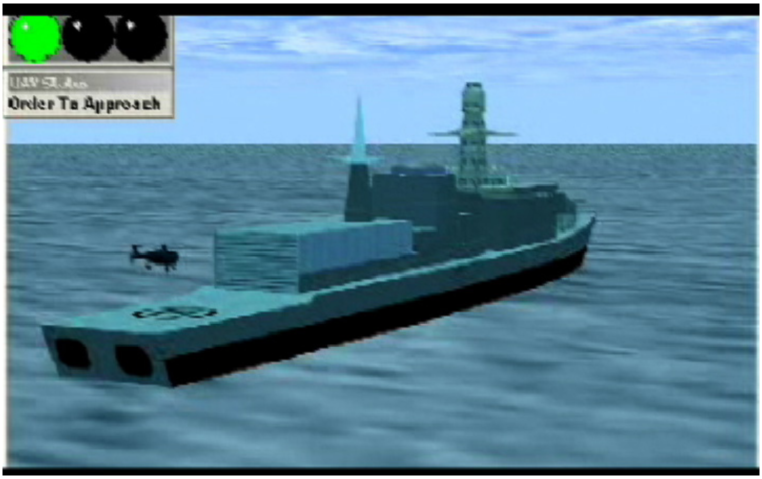

FIG.13 – SIMULATED UAV AUTO RECOVERY

Figure 14 displays several of the many platforms programmed to receive the VTOL UAV created by simulation.

FIG.14 – NATO FLEET PROGRAMMED FOR UAV AUTO RECOVERY PROJECT

PRELIMINARY TEST

An example of a similar air vehicle flight profile during recovery, undertaken at Naval Air Warfare Center (Paxtuent River), was as follows:

- Top of recovery called from 30 feet above the flight deck with a suspend at 15 feet.

- Await green to permit direct descent to flight deck with a descent rate of about 3 feet/sec.

- Top of recovery called from 15 feet then follows the same descent strategy as before.

Trials data have shown that the Austin Class rise time is around 8 seconds; inferring a 5 second descent strategy, allowing 3 seconds for grid secure.

The justification for programming the landing flight strategy is attributed to the benefits of the risetime phenomena calculated by the Energy index. LPDLOOP subject program uses the calculated ship motion time histories to calculate the energy index (EI) in real-time indicating the appropriate moment to begin the recovery descent. Analysis of the output of the energy index produces UAV deck availability.

Time histories representing a sea state 5 for the Austin class ship was used in the simulation. Figure 15 shows overall simulation recovery using ship's X, Y, Z and EI values.

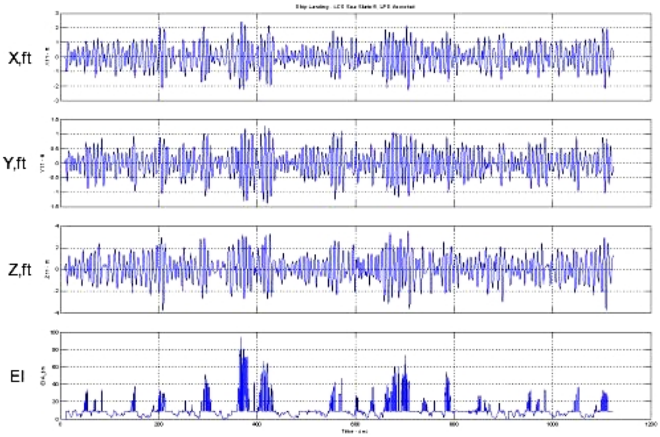

FIG.15 – UAV X SHIP WITH LPD FLAG SEA STATE 5

Focusing on a recovery period, Figure 16 displays the recovery zone in terms of Z, Y, X and EI whilst Figure 17, the corresponding roll, pitch, yaw ship's traces and EI.

Figure 19 displays the actual landing event compared to the energy index calculation at the moment of touch-down. Figure 20 combines all the recordings into a summary chart cross-correlating ship's motion with the UAV landing profile.

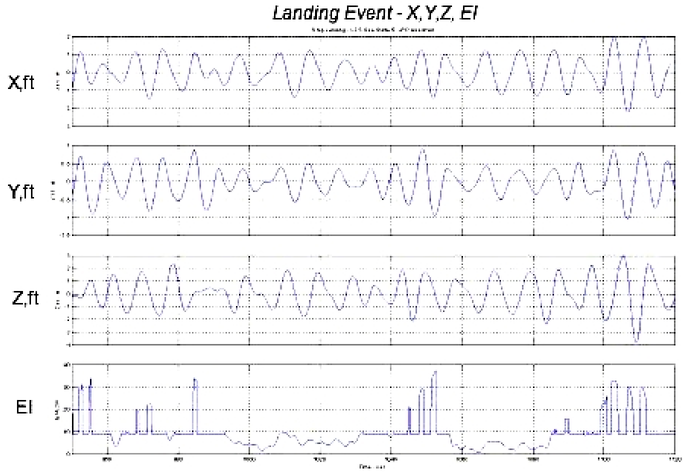

FIG.16 – UAV X SHIP WITH LPD FLAG SEA STATE 5 [X, Y, Z, EI]

FIG.17 - UAV X SHIP WITH LPD FLAG SEA STATE 5 [ROLL, PITCH, YAW, EI]

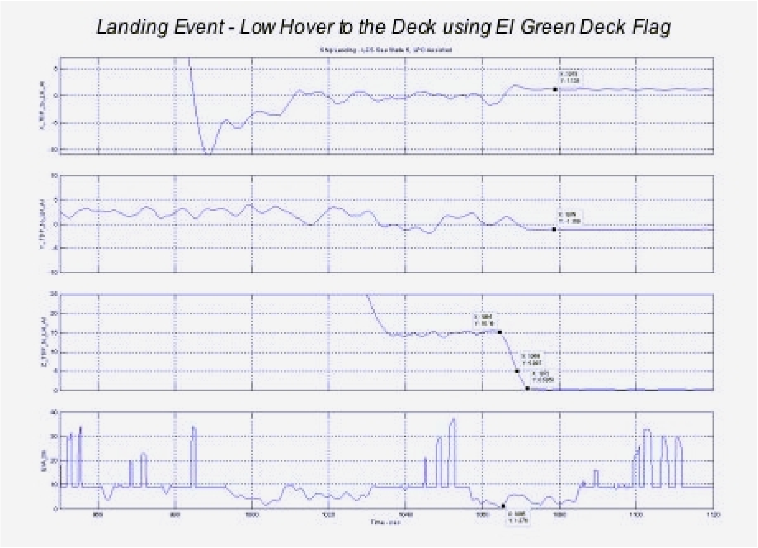

FIGURE.18 - UAV X SHIP WITH LPD FLAG SEA STATE 5 [UAV RECOVERY X EI]

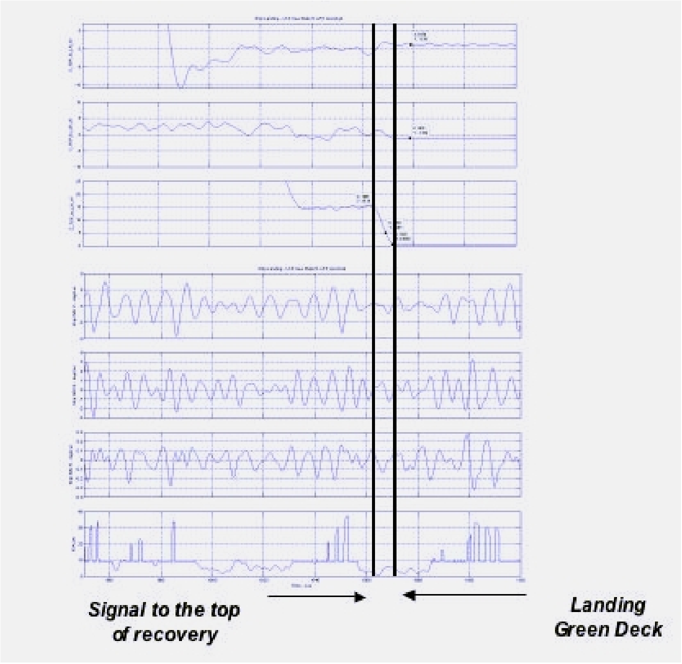

FIG.19 – UAV X SHIP WITH LPD FLAG SEA STATE 5

Normally, ship motion variations occur as a function of ship speed, wave heading and sea state. The LPD test points vary according to ship conditions and wind-over-deck speed and direction combinations that result in different levels of ship motion. The choices offered to the UAV are set by a truth matrix testing various conditions simultaneously. Given a descent time less than the risetime characteristic of the host vessel, deck motion conditions must physically be within air vehicle deck limits on recovery. Of the several test cases attempted, none had the air vehicle recovered on a deck other than within limits.

The preliminary analysis indicates favourable proof-of-concept solution. The impact for the Firescout program includes improved program safety and reduced risk in the launch and recovery operation. Other impacts for landing and launching within deck limits include: reduced ole - skid compression; lower engine torque; lighter gear deflection and improved aircraft stability. Finally, given the preliminary data results, the ONR LPD program appears to favourably support the fundamental ONR Future Naval Capabilities mission for UAV autonomous operations, in general, and towards UAV autorecovery in particular.

CONCLUSIONS

Trials data have only been analysed at a basic level to establish the conditions in which features of the real world SHOL for an auto recovery UAV have been produced. The paper described the development of a simulation that functions through a HLA Federation creating a reasonable representation of real world operations. This all within a controlled environment permitting greater opportunity to evaluate a candidate system well before the system is brought to sea. Initial at sea testing shows a tendency to favourably reflect very similar computations in the simulator. Whilst there remains some improvements to be made, the demonstration was successful.

In the laboratory, statistical analyses are being conducted on representative simulated scenarios. Very early preliminary results indicate that both the test methodology and the automatic landings may be anticipated, fairly accurately described and programmed into a federation. The implications for both the manned and unmanned aviation test and evaluation community may prove to be considerable.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the generous support of the Officers and Crew of HMS SUTHERLAND, USS DENVER and USS PREBLE. The authors would like to acknowledge the contributions made by the Scientists and Engineers at the NAVAIR Manned Flight Simulator and the MERLIN (SAIF) Simulator at RNAS Culdrose.

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