Simulation of automatic helicopter deck landings using nature inspired flight control

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ABSTRACT

Research studies have indicated that the optical flow parameter, time to close tau, is the basis of purposeful control in the animal world, and used by both fixed wing and helicopter pilots during manoeuvring. This parameter is defined as the instantaneous time to close a gap (spatial or force) at the current closing rate. A novel automatic flight control strategy has been developed that makes use of optical flow theory and in particular, the parameter tau. This strategy has been applied to two distinct problems; (1) the landing of a helicopter on a ship and (2) the lateral repositioning of a helicopter. The first is a challenging case because the landing of a helicopter on a ship is one of the most dangerous of all helicopter flight operations. Furthermore, helicopters are often subject to torque oscillations during rapid collective control, which increases pilot workload significantly when operating with low power margins and/or whilst performing tasks that require accurate heave control. The second case demonstrates the generality of the technique. Both automatic manoeuvres were simulated successfully within desired limits, with the novel control strategy creating a 'natural', smooth, tau motion.

NOMENCLATURE

k	variable describing profile of motion [-]
p, q, r	angular roll, pitch and yaw rates in aircraft body axes [deg/s]
Q_e	engine torque [Nm]
t	time [s]
T	total duration time of motion [s]
x, y, z	position [m]

Greek notation

ϕ, θ, Ψ	Euler angles, describing aircraft attitude [deg]
θ_0, $\theta_{0,tr}$	main rotor and tail rotor collective pitch [deg]
θ_{1s}, θ_{1s}	lateral and longitudinal cyclic pitch [deg]
χ	gap [m, deg, N, etc.]
τ	time to close a gap [s]
Ω	main rotor rotational speed [%]
X	state [m, deg, etc.]

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Subscripts

ref	reference
m	measured value

Abbreviations

ACAH	Attitude command attitude hold
ASRA	Advanced systems research aircraft
DVE	Degraded visual environment
FTM	Flight test manoeuvre
GVE	Good visual environment
HQ	Handling qualities
HELI-ACT	Helicopter active control technology
MTE	Mission task element
RC	Rate command
RCDH	Rate command direction hold
TRC	Translational rate command
WOD	Wind over deck



Figure 1. Bell 412 Advanced Systems Research Aircraft.

1.0 INTRODUCTION

Various studies have indicated that a fundamental optical flow parameter, the time to close on a goal, tau (τ), is used in nature, both by humans and animals, for the guidance of purposeful motion. If such a parameter can be used by a flight control system for the guidance of motion, the hypothesis is that this will generate a natural movement, similar to a pilot's normal control strategy. Research carried out at The University of Liverpool on optical flow theory in low-level helicopter flight and fixed wing approach and landing[1-3] has already shown that pilots use so-called 'τ-couplings' in flight control. The general aim of the research presented here is to apply this theory to the development of an active flight control law for a challenging real-life guidance problem.

The test configuration for the research was the FLIGHTLAB simulation model of the Bell 412HP Advanced Systems Research Aircraft (Fig. 1) — and in-flight simulator operated by the National Research Council (NRC) of Canada. FLIGHTLAB is an advanced simulation environment for rotorcraft analysis with a modular structure, enabling rotorcraft models of varying levels of complexity to be created[4]. This particular aircraft exhibits an under-damped second-order like dynamic response in engine torque following collective control inputs; a characteristic determined from flight-testing by the Flight Research Laboratory, of the Institute for Aerospace Research (IAR) of the NRC[5]. The mast torque, closely related to the engine torque, should not exceed certain limits. The pilot therefore has to monitor torque closely, particularly when performing vertical manoeuvres. The need for close monitoring can cause an increase in workload and, unless this issue is addressed, may compromise the handling qualities; this is especially the case when operating with low power margins and/or whilst performing tasks that require accurate heave control. One such task is the landing of a helicopter on a ship. A pilot will then have to deal with (1) an invisible and disturbing ship air wake, (2) poor visible cueing and (3) a landing spot which is moving up and down, rolling, pitching and yawing. The landing of a helicopter on a ship is acknowledged to be one of the most difficult and dangerous of all helicopter flight operations[6-9]. In short, landing a helicopter on a ship deck is a hard task with a high workload. It is therefore hypothesised that a flight control system, that can perform this task automatically for the pilot, would be very useful.

The first aim of this research is the development of a control system that is capable of performing automatic deck landings whilst providing torque envelope protection. A novel control strategy based on optical flow theory has been used to achieve this. The aim is to make the landing system behave in a natural way, similar to that achieved by an actual pilot, closing the vertical gap using natural visual cues. Besides performing automatic deck landings, the flight control system should be able to provide torque envelope protection throughout the manoeuvre.

The second aim of the research presented is to apply the same control technique on a different helicopter with a different task, in order to demonstrate the generality of the control technique. The FLIGHTLAB Generic Rotorcraft, a nonlinear helicopter model similar to the UH-60 Black Hawk was chosen for this demonstration. An automatic control system has been designed that performs the lateral repositioning manoeuvre with this helicopter. The choice for this particular helicopter model and manoeuvre is quite arbitrary.

The structure of this paper is as follows. Some basic theory on optical flow and the concept of nature inspired flight control is treated in Section 2. The two helicopter models used as test vehicles to perform the research are described in Section 3. Subsequently the design of a control law for the FLIGHTLAB Bell 412 ASRA is discussed and the results of the simulation of an automatic deck landing are presented in Section 4. In Section 5, a control law for the FGR is presented and an automatic lateral repositioning manoeuvre is simulated. Finally, conclusions and recommendations are presented.

2.0 NATURE INSPIRED AUTOMATIC FLIGHT CONTROL

2.1 Optical flow parameter tau

Much work has been performed in the field of ecological psychology on the theory of guidance of movement. Initially, Gibson suggested that pilots make use of information from the optical flow field when controlling an aircraft[10]. Based on this work, Lee[11] introduced the variable 'tau of a gap', which is defined as: 'The instantaneous time it would take the gap to close at the current closing rate'.

The gap can be either spatial gap (such as distance, angle) or a force gap. The tau of a gap can also be written as an equation.

$$\tau_\chi = \frac{\chi}{\dot{\chi}} \qquad \ldots (1)$$

where χ is the gap and $\dot{\chi}$ the gap closure rate. Tau is essentially the time it will take until the gap is reduced to zero at the current closure rate. In the context of this paper, only spatial gaps are under investigation. Lee hypothesised that the tau of a motion gap can be coupled to an intrinsic tau guide.

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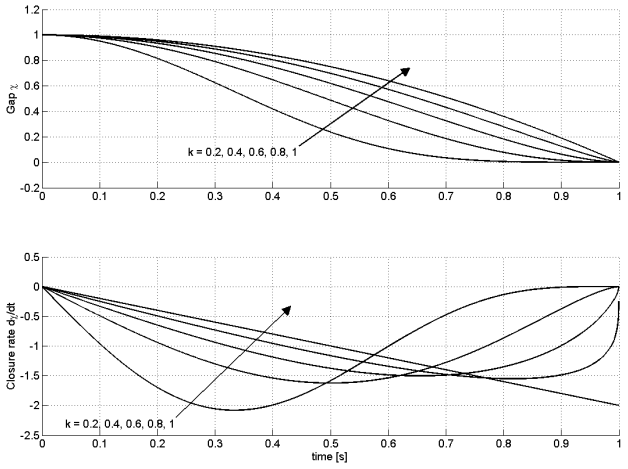


Figure 2. Closure of a gap χ described by tau theory for various values of *k*.

$$\tau_\chi = k\tau_g \quad \ldots (2)$$

in which the intrinsic tau guide is a function of time[3,11,].

$$\tau_g = \tfrac{1}{2}\left(t - \frac{T^2}{t}\right) \quad \ldots (3)$$

T is the duration of the motion and *k* defines the profile of the motion (constant acceleration, deceleration, etc.). Several studies have supported this hypothesis. Examples are: suction by newborn bottle-feeding, movement of the hand to mouth by adults when eating, control of movement of the foot from one footfall to the next when sprinting, hand movements by a drummer[11] and the flight path of birds coming to rest. Research performed at The University of Liverpool using optical flow theory in flight control[1-3] has indicated that pilots' motion control correlates strongly with tau coupling. The motion described by Equations 1, 2 and 3 is visualised in Fig. 2. It can be observed that the factor *k* influences the profile of the motion. For *k* equal to 1, the motion has a constant acceleration form and there is a velocity present at the time that the gap is closed. For $k < 1$, then motion takes the form of an acceleration followed by a deceleration, finally stopping at the goal; with $k = 0{\cdot}4$, the maximum velocity occurs exactly at ½*T*.

Later, a more general intrinsic tau guide was proposed[12].

$$\tau_G = \frac{t(T+t)}{T+2t} \quad \ldots (4)$$

Tau coupling on such a guide is valid when the object starts with an initial velocity whilst the original Equation 3 is only valid for an object starting at rest. It can be derived that Equation 3 reduces to Equation 4 when only the second half of the motion is considered[1]. In this paper, only cases are considered where the object starts at rest. Therefore, Equation 4 is not used. For more general applications in future work, Equation 4 should be applied.

In summary, it is postulated that the variable tau, fundamental in nature, is also applicable to flight control. In the context of helicopter flight, and based on this theory, it would make sense to use this variable in automatic control solutions. A tau-based flight control strategy is therefore proposed in the next sub-section. Published work on the ecological theory of tau suggests that in nature it is the variable tau that is picked up directly by the perceptual system. In the present work the normal position and rate sensors are assumed to pick up the spatial motion, from which tau is computed. It is recognised that this is far less efficient that using direct measurements of tau, but in the absence of a tau sensor, it is considered adequate to demonstrate the principles of tau control.

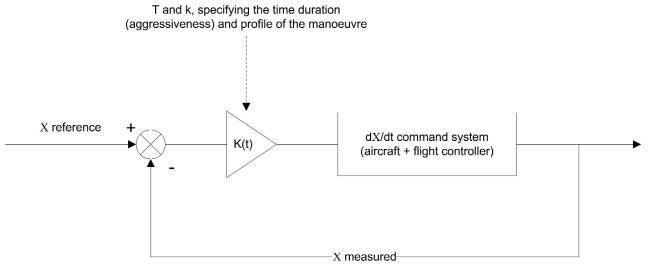


Figure 3. Use of tau in feedback control system.

2.2 Tau-based flight control

Equations 1, 2 and 3 can be combined to derive an expression for the closure rate.

$$\dot{\chi} = \frac{2\chi}{k\left(t - \frac{T^2}{t}\right)} \quad \ldots (5)$$

The variable χ in this equation can be interpreted as the error, or gap, between a desired (reference) state χ_{ref} and the current (measured) state χ_m, whilst the time derivative of χ can be seen as a reference signal for the time derivative of the state. Rewriting the equation then yields:

$$\dot{X}_{ref} = \frac{2\left(X_{ref} - X_m\right)}{k\left(t - \frac{T^2}{t}\right)} \quad \ldots (6)$$

A schematic of this system is presented in Fig. 3.

Such a system is very generic and can be used in many different applications. For example, it can be used to control a position (*x*, *y* or *z*) by generating a velocity reference signal. Of course, a translational rate command system must be present in such a case. It can also be used to control an attitude (ϕ, θ, ψ) by generating an angular rate reference signal ($\dot{\phi}$, $\dot{\theta}$, $\dot{\psi}$). The parameter *T* can be used to specify the time duration of the manoeuvre, and is a measure of the aggressiveness. The variable *k* can be used to specify the profile of the manoeuvre, as already discussed. In the context of this paper, tau-control is only used for position control in the two situations:

(a) Vertical position control during deck landing with a FLIGHTLAB Bell 412

(b) Lateral position control for the reposition mission task element (MTE) with the FLIGHTLAB generic rotorcraft

The reader must bear in mind that tau-control can be applied to many more situations. The philosophy behind using optical flow theory as the basis of a flight control law is that it represents how a human pilot would actually perform the manoeuvre, as demonstrated in Refs 1-3.

3.0 HELICOPTER SIMULATION MODELS

3.1 Bell 412 Advanced Systems Research Aircraft

A high fidelity nonlinear simulation model of the Bell 412 ASRA has been developed within the HELI-ACT project at Liverpool[13], using the comprehensive real-time flight simulation software FLIGHTLAB4. The data required for the development of this model were partly acquired from literature in the public domain and partly by measurements performed on the ASRA at the NRC Canada.

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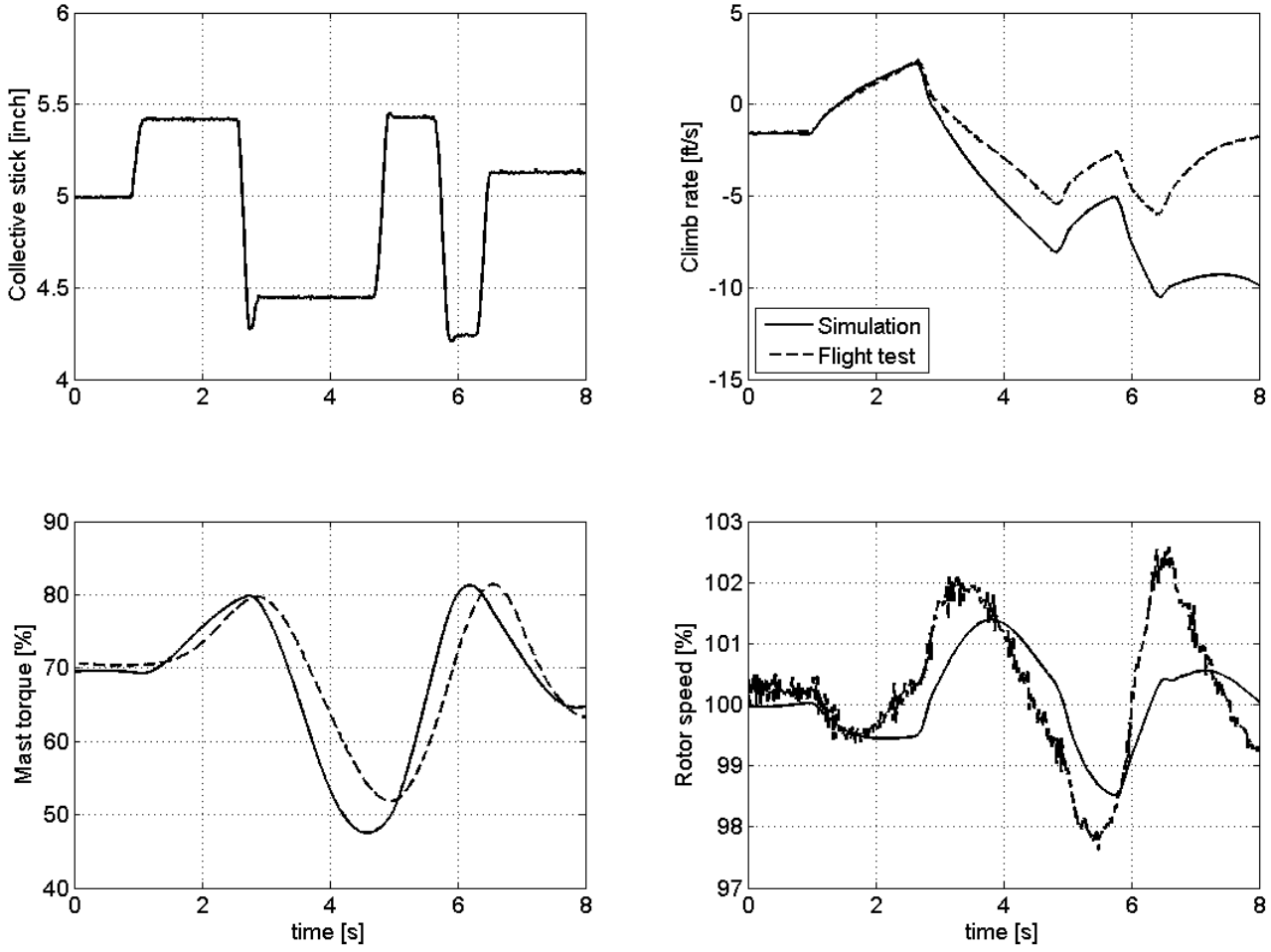


Figure 4. Comparison of the heave axis response of the nonlinear Bell 412 model with flight test data

The Bell 412 has a hingeless rotor. A fully-coupled elastic model representing the flap, lag and torsional degrees of freedom is, in principle, the most accurate way of modelling this configuration. However, to create such a model it is necessary to know the flap, lag and torsional stiffness and mass distributions, and the location of the flexural and centre of mass axes of the blade along its span. As information on the blade structural properties was not readily available, a rigid-blade model with equivalent offset hinge and spring stiffness was deemed to be an appropriate model for the elastic deformation of such a moderately stiff hingeless rotor blade. With a first flap mode frequency ratio of 1·03, the Bell 412 rotor system is also relatively 'soft' out-of-plane (i.e. in flap), hence an offset hinge and spring model is a reasonable approximation[14]. For the FLIGHTLAB modelling of the Bell 412, the hub attachments are modelled by using separate flap and lag hinges and springs with parameters chosen in such a way that the first flap and lag frequencies matched those found in the literature (1·03 and 0·6-0.7). The rotor aerodynamics are modelled with a Peters-He finite state inflow model[15] and with quasi-steady aerofoil aerodynamics. The number of inflow harmonics used here is 4. Aerodynamic data for the aerofoil sections are stored in look-up tables. The inner section of the blade is modelled with a VR7 aerofoil[16] and the outer section with an OA309 airfoil — sections with published aero data that show reasonably close shape fits to the Bell sections on the aircraft. The tail rotor is modelled relatively simply as a Bailey disc rotor[17]. The calculation of fuselage aerodynamic forces/moments for helicopters is a complex subject. In the present cases they are stored in look-up tables, constructed from wind tunnel data of the Bell UH-1 airframe[18-20], which is similar to that of the Bell 412. The aerodynamic surfaces (vertical fin and horizontal stabiliser) are also modelled with look-up tables. The horizontal surfaces have two special features. First, the left hand section of the elevator has a different geometric incidence (5·6°) than the right hand section (–2·4°) because they are in a different flow conditions due to the main rotor downwash. These settings were measured on the ASRA. Second, both sections are connected to a spring-loaded tube, attached to the structure of the tail boom. The pitch angle of the left-hand and right-hand elevator is a function of the moment caused by the torsional spring and the aerodynamic moment. It can therefore change dynamically during flight and is designed to increase the stability of the aircraft. The stiffness of the spring-loaded tube assembly (0·030 deg/Nm) was measured at the NRC.

The propulsion system of the Bell 412 is modelled as a simple engine model[14]. The NRC has developed a state space model of the Bell 412 engine dynamics, based on system identification of flight test data[21]. The time constants and gains of this simple engine model were tuned to match the response of the NRC state space engine model in hover. It is comparable to a second order system with an undamped natural frequency of 0·53 rad/s and a damping ratio of 0·11, together with a pure time delay of 0·105s.

The flight control system (FCS) of the bare airframe aircraft is a simple sequence of mechanical linkages and actuators, connecting the stick to the swashplates. The actuators are modelled as simple first order lags with a time constant of 1/60s, in combination with

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Table 1
Propulsion system parameters

Parameter	Value
Gas turbine moment of inertia	0·061 [kg - m^2]
Power turbine moment of inertia	0·084 [kg - m^2]
Gas turbine design speed	44,700 [rpm]
Power turbine design speed	20,900 [rpm]
Fuel flow transport delay	0·02 [s]
Drive train effective rotational moment of inertia	2,983 [kg - m^2]
Drive train effective rotational spring constant	33,895 [Nm/rad]
Drive train effective rotational damping constant	136 [Nm-s/rad]

Table 2
FGR actuator limits

	Saturation limits [deg]	Rate limit [deg/s]
Longitudinal	–12·5 /16·3	28·8
Lateral	–8/+8	16
Heave	5·9 / 29·9	16
Directional	4·5 / 36·5	32

rate limiters. The rate limits, of which no measurements are readily available, are assumed to be 100%/s of the total available actuator travel. The stick limits were measured on the ASRA, as well as the mechanical gearing ratios. From this, it was possible to calculate the operational blade angle range.

A comparison of the model with flight test data following a collective stick '2-3-1-1' input is presented in Fig. 4 to give an impression of the model fidelity in the heave axis. In this multi-step input, the pilot first raises the collective lever for two seconds, lowers for three seconds, raises again for one second, lowers it for one second and finally brings the lever back to the original position. A main rotor rotational speed of 100% equates to 324 revolutions per minute. The model matches the flight test data in the heave axis reasonably well, especially the initial response. After eight seconds, errors in all axes (pitch, roll and yaw) have accumulated which makes the overall error fairly large. This is also the case when the time lag between simulation and flight test is analysed. Nevertheless, the dynamic behaviour still matches reasonably well. A more detailed analysis and comparison in the other axes can be found in Ref. 13. In general, the on-axis responses (pitch due to longitudinal inputs, roll due to lateral inputs, etc.) of the helicopter model match well with flight test data in all four axes. The off-axis response of the model (roll due to pitch, pitch due to roll and yaw due to collective) matches less well[13].

3.2 FLIGHTLAB Generic Rotorcraft

The FLIGHTLAB Generic Rotorcraft (FGR) simulation model is similar to the UH-60A Black Hawk helicopter. This model is available with selective levels of fidelity. The main modelling features of the FGR selected for the purpose of this paper are very similar to the Bell 412. The main rotor system is modelled as a rigid blade element model with a three-state inflow model and quasi-steady air loads. The blade is modelled with a SC1095 aerofoil[22]. Aerodynamic data of the blades are stored in look-up tables as a function of the local angle of attack, Mach number and Reynolds number. The aerodynamics of the fuselage, vertical tail and horizontal tail are also stored in look-up tables. The fuselage structure is modelled as rigid. Power is provided by two general electric T-700-GE-700 turboshaft engines. The engine model includes engine dynamics as well as the fuel flow control unit which consists of a hydro-mechanical unit and an electronic control unit. Engine gas and power turbine dynamics are modelled using second-order ordinary differential equations with inertia and damping effects. Thermodynamics are modelled in a quasi steady fashion. The pressures and temperatures at each station of the engine are computed via table look-up. A model of the drive train is also included in the propulsion system. Some key parameters of the propulsion system model are provided in Table 1.

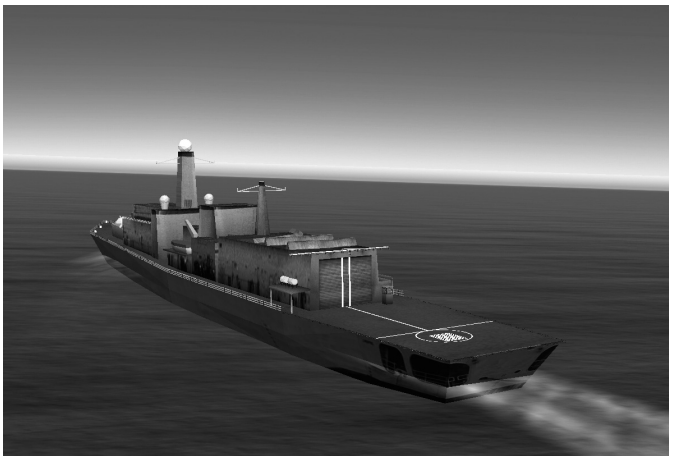


Figure 5. Simulator view of Type 23 frigate on the approach.

The tail rotor is modelled as a Bailey rotor[17]. The flight control system consists of a mechanical flight control system (MFCS) in combination with a stability and control augmentation system (SCAS). The SCAS was removed from the model to allow the implementation of novel control laws and the evaluation of the bare airframe dynamic behaviour. The MFCS is modelled with (1) gains representing the gearing from the pilot inputs to the blade angles, (2) actuator dynamics, (3) actuator saturation limits and (4) actuator rate limits. The data required to model the MFCS are obtained from Howlett[22]. The actuator limits are summarised in Table 2.

The actuator dynamics are modelled as second order systems with an undamped natural frequency of 29·6 [rad/s] and a damping ratio of 0·7.

4.0 AUTOMATIC DECK LANDING USING TAU CONTROL

4.1 Introduction

The aim is to perform a deck landing automatically with the nonlinear simulation model of the Bell 412 by using tau-control and flight envelope protection. The deck landing was undertaken in Liverpool's HELIFLIGHT[23] simulator, to a Type 23 Frigate (Fig. 5).

The requirements for this manoeuvre are defined in the deck landing MTE7. Two additional requirements are also specified. First, the mast torque should be protected (i.e. not exceed limits) by the flight envelope protection system. Second, the vertical positioning during the manoeuvre should be performed 'automatically' in a 'natural' way by using tau-control. The flight profile can be compared to the tau gap closure profiles and the test-pilot was asked to comment on the profile.

4.2 Control law

First a basic flight control law was developed providing an attitude command attitude hold (ACAH) response type in pitch and roll combined with a rate command response type in yaw. This controller was designed using classical techniques in combination with a nonlinear element in the pitch axis, used to specify the pitch attitude

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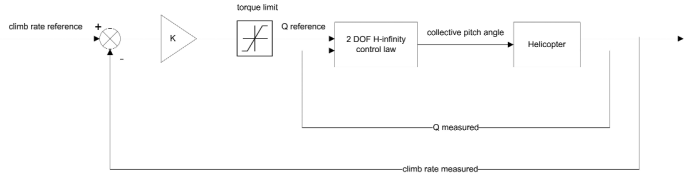


Figure 6. Height rate control.

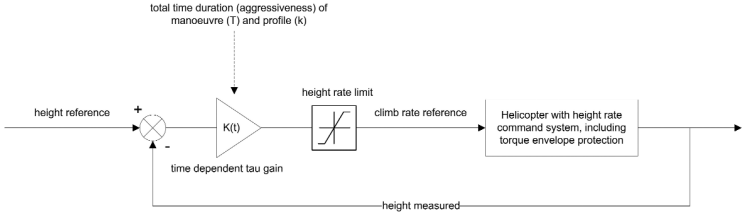


Figure 7. Height control using tau theory.

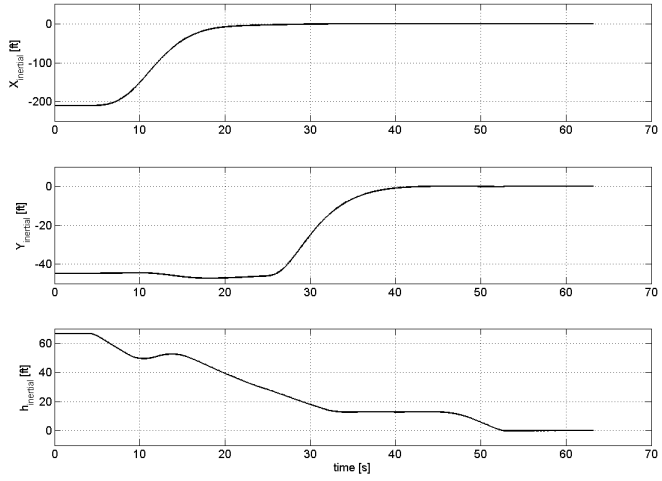


Figure 8. Aircraft inertial position during the automatic shipboard landing.

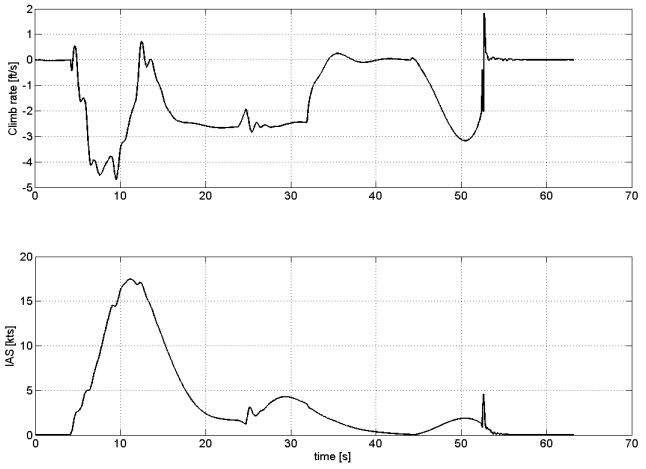


Figure 9. Aircraft speed and climb rate during the automatic shipboard landing.

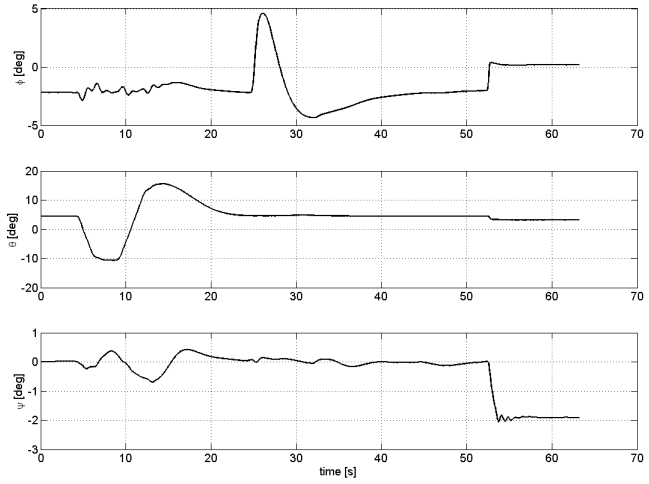


Figure 10. Aircraft attitude during the automatic shipboard landing.

quickness, and implemented on the Bell 412 ASRA and flight tested successfully[24]. Outer loops were developed in conjunction with the basic flight control law to achieve a longitudinal and lateral position command system and a heading command system.

The nature inspired flight control system and the flight envelope protection system were both implemented in the vertical axis. The control system, featuring a height rate command response type, and simultaneous torque envelope protection, is presented in Fig. 6. This system consists of two loops. The inner loop is a torque control system, which uses the measured torque as a feedback signal to demand a collective pitch angle. The torque controller was designed with the *H*-infinity, loop shaping design method[25]. The torque reference signal is created by the outer loop, which is simply a proportional controller, and is limited to the maximum transient torque. A detailed analysis of the height rate control law, including nonlinear stability analysis, predicted handling qualities analysis and piloted simulation can be found in Ref. 26. Next, the tau-control system was applied to this control law to confer control over the altitude (Fig. 7). A saturation limit was introduced in the tau-control vertical positioning system to prevent large height rate commands.

4.3 Results

The automatic landing system was tested in HELIFLIGHT, where the test pilot was required to observe and comment on the behaviour of the system. The results of the test in terms of aircraft performance — position, attitudes and velocities — are displayed in Figs 8-10. The position is expressed in the inertial reference frame, where *X* is directed north, *Y* points to the east and *Z* points down. The ship is oriented to the north and the origin of the axis system is placed at the landing spot. The altitude hinertial points upwards with zero at the ship deck.

The three phases (approach, sidestep, landing) of the automatic deck landing can be seen. The approach phase was initiated a few seconds after the start of the simulation. The aircraft pitched nose down to accelerate and nose up to decelerate. The desired *X* position in the inertial frame was successfully acquired and held. The 'sidestep' over the deck was then initiated at approximately 25 seconds which can be observed by an increase in the roll angle to the right. The desired position above the landing spot was achieved within approximately ten seconds. Finally the landing with the

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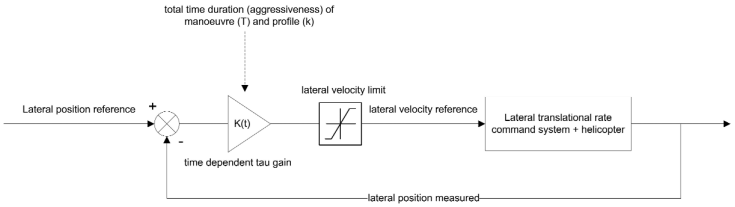


Figure 11. Lateral position control using tau theory.

nature inspired tau flight control law was initiated. The desired duration time T specified was seven seconds and the factor k set to 0·7. It had been determined from several manual deck landings that these values were appropriate. The total duration time influences the maximum descent rate and the factor k, set at 0·7, determines the profile of the manoeuvre.

The landing was successfully achieved within the desired limits of the deck landing MTE[7]. The 'observing' pilot commented that the final phase of the landing for which the tau flight control law was used appeared natural to him.

As soon as the landing gear contacts the deck, the collective pitch was lowered to its minimum value and all automatic flight control functions were disengaged. This is important because a ship deck can move and thereby determining the attitude, and vertical velocity, of the helicopter. An active flight control law will try to counteract this. One can see that there is a slight nose up attitude due to the fact that the landing gear has an inclination. Furthermore, as a consequence of lowering the collective pitch, the helicopter yawed slightly to the left (–2deg). This steady state error remains because the helicopter is on the deck and the autopilot is switched off.

In bad weather conditions, it is quite possible that the helicopter needs to be put on the deck rapidly. The aggressiveness and profile of the landing can then be adjusted by varying the time T and the factor k. It is a recommendation for future research to determine how the appropriate value of T might vary as a function of the sea-state, and possibly the type of ship on which the landing is performed.

The automatic deck landing presented in this paper was performed in good weather conditions without ship motion. It is another recommendation for further research to perform these automatic deck landings on a moving ship deck with an unsteady ship air wake present. Furthermore, in bad weather conditions, timing of the start of the vertical manoeuvre is essential. It will be beneficial to have an algorithm that predicts when a quiescent period will occur in which the landing can be performed safely. Such a landing period designator[27] (LPD) was developed recently and applied to ship board operations with uninhabited aerial vehicles (UAV). This device is capable of predicting a quiescent period. Finally, when control systems are developed, it is most important to prove their stability. This has not been undertaken for the tau-control system, which is essentially a nonlinear, time varying system. Stability analysis of the tau-control system is therefore also a topic of future work.

5.0 AUTOMATIC LATERAL REPOSITION WITH THE FGR

5.1 Introduction

The aim in this design was to achieve an automatic lateral repositioning with the FLIGHTLAB generic rotorcraft by using tau-control. The method is similar to the vertical position control during a deck landing; however, the controlled motions are now in the horizontal plane, and we have a different helicopter type.

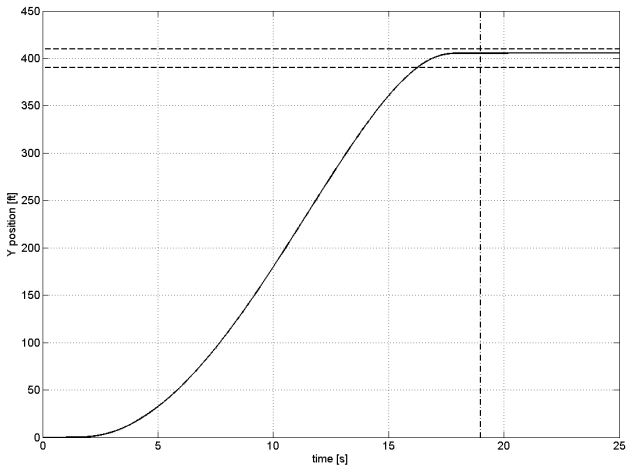


Figure 12. Lateral position during automatic lateral repositioning manoeuvre.

5.2 Control law

First the basic flight control law was developed, providing an ACAH response type in pitch and roll, an RC response type in yaw and a height rate command response type in the heave axis. Classical control theory was again used and gains were manually tuned to provide good handling qualities. The helicopter model used for the design was a high order linear model (41 states) derived from the nonlinear model in the hover condition by numerical perturbation. Predicted handling qualities, in terms of inter-axis coupling, small amplitude response bandwidth and moderate amplitude manoeuvring (attitude quickness) were analysed. All predicted Level 1 handling qualities for non-combat manoeuvres[28], except for the yaw attitude quickness (Level 2).

The basic control system was used as the core of an automatic positioning system. Outer loops were developed that provided lateral and longitudinal translational rate control (TRC), a height hold and heading control. The tau control system was implemented in the lateral axis (Fig. 11).

5.3 Results

The lateral repositioning MTE, taken from ADS-33E-PRF28, prescribes that the rotorcraft has to reposition laterally over a distance of 400ft within 18 seconds. The total duration time of the manoeuvre (variable T in the tau control law) was therefore set to 17 seconds to leave a small margin for error. The factor k, describing the profile of the manoeuvre was set to ½. This means that the maximum velocity occurs near halfway during the manoeuvre and the final velocity was equal to zero. This is not necessarily the optimal strategy since the pilot can decelerate with larger roll angles than the acceleration. Nevertheless, this manoeuvre was flown to demonstrate the generality of the technique and not to find the best strategy. The proposed strategy was deemed sufficient to fulfil the requirements of this MTE. The lateral position of the aircraft is shown in Fig. 12, showing that the MTE was performed within the desired limits. Furthermore, the profile of the manoeuvre seems, again, natural. There is a smooth acceleration and deceleration and the final velocity is equal to zero. The longitudinal position and the altitude are shown in Fig. 13.

The longitudinal controller featured a translational rate response type and without pilot command, attempts to keep the velocity equal to zero. This is seen to be adequate to keep the longitudinal position within the desired (Level 1) limits. The vertical controller was a height hold system. Clearly the altitude is kept within the

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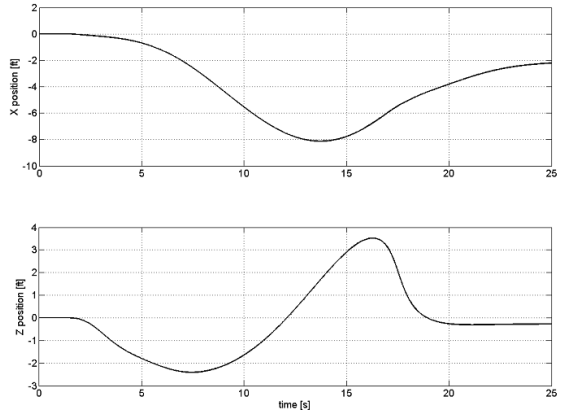


Figure 13. Longitudinal position and altitude during automatic lateral repositioning manoeuvre.

desired limits with the final altitude approximately the same as the initial altitude at the start of the manoeuvre. Of course, this was all achieved by rolling, pitching and yawing the helicopter. The aircraft attitudes are shown in Fig. 14, which indicates that the aircraft has to be banked approximately 10 degrees to the right to accelerate the aircraft and a roll angle of 25 degrees to the left is used to decelerate the aircraft. The pitch attitude deviation from trim remains quite small and the heading angle stays within the desired limits. Finally, the height rate remains within approximately ±5ft/s. The corresponding blade angles required to achieve the manoeuvre are shown in Fig. 15. These angles are all sufficiently far from the actuator limits.

Overall, it can be concluded that the lateral repositioning MTE was performed successfully and the flight control law functioned as desired. This verifies that tau flight control can be used not only for vertical control as shown in Section 4 but also for lateral control. In principle, the method is applicable to any rotorcraft type and to any 'gap' that needs to be closed. An important design feature of the system is that it does not need to be tuned. Only the total duration time and profile of the manoeuvre need to be provided and then it will work.

One important question arises however. If such a system is implemented on a helicopter, then how should the pilot indicate to the flight controller what his or her intentions are? It might be useful to use a three dimensional situation display in which the pilot can point (1) where to go, (2) the level of aggressiveness, and (3) the final velocity. It is even questionable if a pilot would really want such a controller to support fully automatic flight control, certainly in good environmental conditions. However, this kind of control would be ideally suited to control the motion of UAV's from a remote control station. It could also be useful to drive an autopilot mode with the tau control technique such as a 'transition

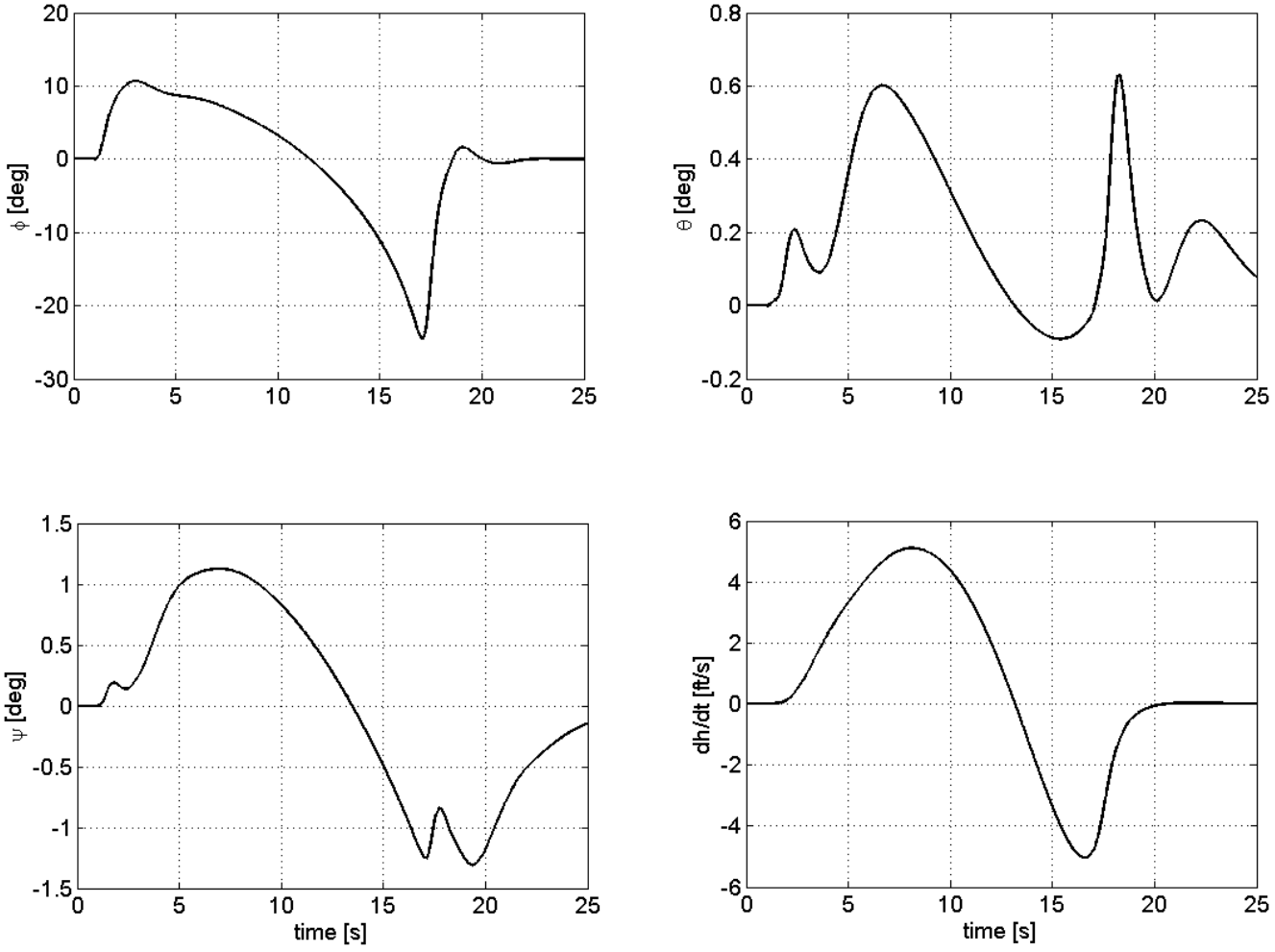


Figure 14. Aircraft attitudes and height rate during manoeuvre (deviation from trim).

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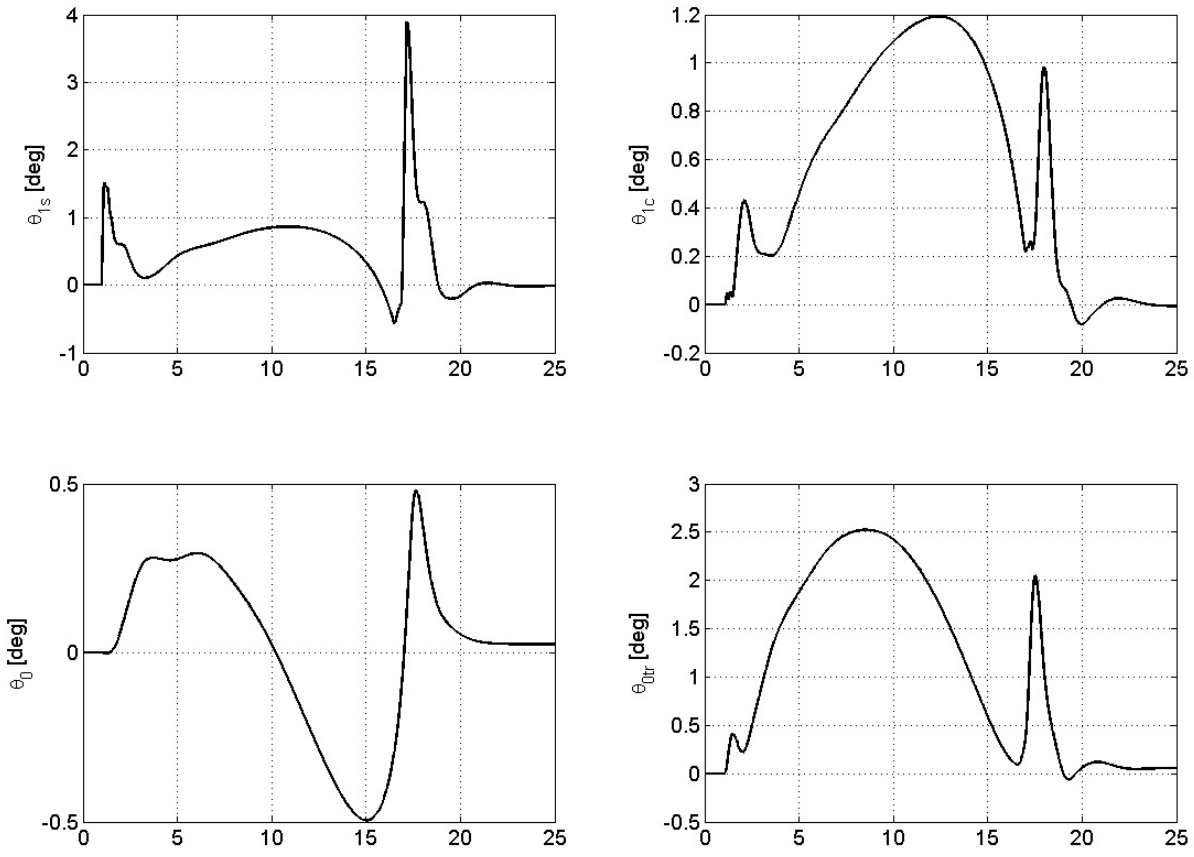


Figure 15. Blade angles during manoeuvre (deviation from trim).

down/up mode', which is available on the AW101 maritime helicopter, for example. A transition down is an automatic descent and deceleration from an entry point (e.g. 80kt, 200ft) to hover at a prescribed height (e.g. 40ft). The research reported in Ref. 1 postulated an automatic flare system for fixed wing aircraft landings, based on tau control. These are all suggestions and remain topics for further investigation.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The first aim of this paper was the development of a control system capable of performing automatic deck landings with a nonlinear simulation model of the Bell 412 ASRA, while at the same time providing torque envelope protection. The control system made use of optical flow theory to fly the helicopter in a natural way, similar to an actual pilot. A control strategy was therefore developed based on optical flow theory. This strategy, designated as tau-control, is applicable to many different situations. In principle, it can be used to close any gap of interest, such as a position gap, an angular gap or a force gap. Tau-control requires only two parameters; (1) the aggressiveness of the manoeuvre and (2) the profile of the manoeuvre. There are no explicit gains present that need to be tuned. However, it does require the system to be controlled to have a specific response type. In the context of this paper, tau-control is applied to the vertical position control of a Bell 412 helicopter. This implies that this helicopter should have a height rate command system present for the tau-control system to work. A translational rate command system was therefore developed, including a torque envelope protection system. An automatic deck landing was then simulated with the complete control system. Longitudinal and lateral position control were achieved with classical control techniques. Vertical position control was successfully achieved with tau-control and the observing pilot commented that the motion seemed natural to him. The second aim of this paper was to apply this technique to the lateral position control of a UH-60 like helicopter model to demonstrate the general applicability of the technique. The lateral repositioning MTE was successfully performed within desired limits by using tau-control.

There are five recommendations for future research. First, a stability analysis of the tau-control system needs to be undertaken. This is not a straightforward task because tau control is a nonlinear time-varying strategy. Second, since the automatic landing system will give most benefits in bad weather conditions, ship motion and an unsteady ship air wake need to be introduced. More generally, atmospheric disturbances can introduce changes to task demand during an MTE that the pilot normally attends to with stabilisation control inputs. Development of the tau control technique to

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provide this additional function is an obvious next stage. Third, a LPD-type system needs to be incorporated to predict quiescent periods in which the landing can be performed safely. Fourth, an interface needs to be designed for the pilot to indicate his or her intentions to the tau-control system. For example, it might be appropriate to use a three dimensional situation display where the pilot can point (1) where to go, (2) the level of aggressiveness, and (3) the final velocity. Finally, a tau-control system should be tested in-flight on the Bell 412 ASRA to validate the concept in the 'real world', an activity planned in the near term.

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