How long do pilots look forward?[i]

Prospective Visual Guidance in Terrain-Hugging Flight

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Abstract

The title of this paper reflects the notion that pilots need to predict their future flight trajectory, and hence exercise prospective control, to ensure safe passage through and over cluttered and undulating terrain. Of critical importance is how long, in time, a pilot needs to be able to see into the future to maintain an adequate safety margin for guidance. The emphasis here is on how long in time, rather than how far in space. Understanding the nature of the temporal mental 'models' required to support this prediction is considered key to understanding the workings of the human motion perception system, and how they might be exploited in the design of aids to flight guidance in degraded visual conditions. A related question is how the safety margin might connect to the handling qualities construct, the Usable Cue Environment, which was developed to help determine the optimum control augmentation requirements for flight in poor visibility. Answers to these questions can be used to inform the design of pilot vision aids on the one hand and to provide a more quantitative basis for the UCE construct on the other. The paper reports results from research underway in a collaborative project involving The University of Liverpool and the French Research Laboratory, ONERA, aimed at developing a more quantitative basis for the UCE, based on fundamental perception principles. In the present paper the visual requirements for vertical manoeuvring over undulating terrain are addressed, and how these lead to natural relationships between the selected speed and height. The theoretical framework is supported by results from piloted simulation trials, with a detailed examination of the temporal variables associated with vertical and horizontal flight path control in degraded visual conditions.

Symbols

a_g	constant acceleration of the τ guide
h	height above ground (ft(m))
k	coupling constant
t	time (s)
x, z	distance along x and z directions (ft(m))
x_e	distance in eye-heights (ft(m))
$\dot{x}_e$	velocity in eye-heights/s
x_g	distance to go in motion guide (ft(m))
x_m	distance to go in manoeuvre (ft(m))
T	manoeuvre duration (s)
$\bar{t}$	normalised time (*t/T*)
t_a	heave time constant $(-1/Z_w)$ (s)
V, V_x	aircraft forward velocity (ft(m)/s)
w	velocity along aircraft z axis (ft (m)/s)
w_{ss}	steady state velocity along aircraft z axis (ft (m)/s)
Z_w	heave damping derivative (1/s)
$Z_{\theta 0}$	heave control sensitivity derivative (ft(m)/s²·rad)
γ	flight path angle (rad)
γ_a	$\gamma - \gamma_f$ (rad)
γ_f	final value of flight path angle (rad)
δ	ratio of instantaneous normal velocity to steady state value $\delta = \frac{w}{w_{ss}}$
θ_0	collective pitch angle (rad)
$\bar{\theta}_0$	collective pitch normalised by θ_{0f}
θ_{0f}	final value of collective (rad)
θ	optical flow angle (rad)
τ	time to close on surface or object (s)
τ_g	τ guide (constant accel. or decel.) (s)
$\tau_{surface}$	τ to the surface (s)
τ_w, τ_γ	τ of normal velocity *w*, flight path γ (s)
τ_x	τ of the motion variable *x* (s)

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Introduction

The three functions of flight control – navigation, guidance and stabilisation – were discussed in Ref 1 in the context of the temporal nature of the control of motion. Timescales separated by orders of magnitude (100 seconds, 10 seconds, 1 second) were postulated to underlie this description, enabling the pilot to manage the functions separately, at least in normal operations. Because of the large temporal separation, the navigation function does not normally interfere with guidance, and only when the pilot operates with a relatively high level of agility do the guidance and stabilisation functions overlap. This interference can cause serious handling problems, as discussed in Ref 1 and also Ref 2, but this is not the primary concern of the current research. In the present work the focus is on flight in degraded visual conditions and particularly the guidance function for terrain and obstacle avoidance manoeuvres. The significance of the word 'long' (in time), as opposed to 'far' (through space), in the title of the paper is linked with the hypothesis that pilots use prospective control to ensure safe flight, based on a temporal mental model of future motion. Temporal mental models can be extrinsic where the pilot uses, or rather couples with, various sources of visual information to perform a task (e.g. pursuit manoeuvres), or intrinsic, where the control is stimulated by a simple motion guide, or dynamic pattern, in the pilot's mind. So prospective control is about controlling future motion and this familiar concept underpins the effectiveness of temporal-gradient type controllers, like attitude-command (AC) and translational-rate-command (TRC) systems in conferring good handling qualities. Such response types, essentially based on acceleration and velocity respectively, provide lead functions and lesson the demands on the pilot to anticipate the future motion and manage the stabilisation function.

TRC and AC response types are required by Aeronautical-Design-Standard-33 (ADS-33, Ref 3) as the basis of control (stability) augmentation for flight in degraded visual environments (DVE). The level of the DVE is characterised by the Usable Cue Environment (UCE), established through an aggregation of pilot 'visual cue ratings' awarded for the ability to manoeuvre with precision in a defined set of low speed tasks. Operations in a UCE 2, for example, require AC in pitch and roll; a UCE 3 requires TRC/position hold for horizontal motion and height-rate command/height hold in the vertical plane. In a good visual environment (GVE) or UCE 1, rate-command in pitch and roll are considered adequate to confer Level 1 handling qualities, the assumption being that the pilot has sufficient visual information to predict the future. The UCE links handling qualities, visual perception and active control (guidance and stabilisation) and provides a rational basis for its primary purpose – to define the control (stability) augmentation functions required for safe flight in the DVE. However, as the UCE degrades beyond 3, and this can occur inadvertently as a helicopter strays into low lying fog or disturbed obscuration (e.g. dust, snow), visual augmentation is required to aid the pilot with the guidance function. Extending the UCE construct into this domain, hence providing a metric for quantifying improvement, is one of the aims of the present collaborative research between Liverpool and ONERA. Within this project, piloted simulation trials are being conducted to examine the visual requirements for flight close to cluttered, undulating terrain. The present paper reports results from tests aimed to establish the requirements for look-ahead times and how these might be affected by visual obscuration - in this case fog.

The paper is structured as follows. The next section outlines the basic analysis for vertical motion of a helicopter and the associated optical flow-field. This is followed by a description of 'flight in the temporal world', developing key expressions for time to contact and presenting results from related studies; a presentation of results from simulations of terrain-following/hugging manoeuvres is then given. The manner in which τ of the flight-path angle is controlled during the initial climb (the terrain-avoid manoeuvre) is discussed, supported again by results from piloted simulations. The pilot control strategy under the influence of intrinsic guides is then examined and a short discussion on the relevance of the work to vision aids is followed by the concluding remarks.

Manoeuvring in the Vertical Plane and the Optical Flow Field

As a pilot approaches rising ground, the point at which the climb is initiated depends on the forward speed and also the dynamic characteristics of the aircraft, reflected in the vertical performance capability and the time constant in response to collective pitch inputs. A matched manoeuvre could be postulated as one where the pilot applies the required amount of collective at the last possible moment so that the climb rate reaches steady state, with the aircraft flying parallel to the surface of the hill. For low speed flight, vertical manoeuvres can be approximately described by a first order differential equation given with its solution to a step input in the pilot's collective lever by,

$$\dot{w} - Z_w w = Z_{\theta 0}\theta_0$$
$$w = w_{ss}\,(1 - e^{Z_w t}) \qquad (1)$$

where w is the aircraft normal velocity (positive down), w_{ss} the steady state value of w and θ_0 the collective pitch angle. Z_w is the aircraft heave damping or the negative inverse of the aircraft time constant in the heave axis, t_a. Writing $\delta = \dfrac{w}{w_{ss}}$, then the time to achieve δ can be written in the form,

$$\frac{t_\delta}{t_a} = -\log_e (1-\delta) \qquad (2)$$

When $\delta = 0.63$, $t_\delta = t_a$, the heave time constant. To reach 90% of the final steady state would take 2.3 time constants and to reach 99% would take nearly 5 time constants. In ADS-33, the Level 1 handling qualities are achieved if $t_a < 5$ seconds, although for many aircraft types, values of 3-4 seconds are not unusual. In reality, because of the exponential nature of the response, the aircraft never reaches the steady state climb following a step input. In fact, the aircraft approaches its steady state in a particular manner. The instantaneous time to reach steady state (τ_W) is defined as the ratio of the instantaneous differential (negative) velocity to the acceleration; hence,

$$\dot{w} = -w_{ss}\, Z_w\, e^{Z_w t}$$
$$\tau_w = \frac{w - w_{ss}}{\dot{w}} = \frac{1}{Z_w} = -t_a \qquad (3)$$

The instantaneous time to reach steady state is therefore a constant and equal to the negative of the time constant of the aircraft t_a. It has become the convention in τ analysis to define it as approaching zero from the negative side. The step input requires no compensatory workload but, of course, the aircraft never reaches its destination. To achieve the goal, the pilot needs to adopt a more complex control strategy and will use the available visual cues to ensure that τ_W reaches zero when the aircraft has reached the appropriate climb rate – the complexity of this strategy determines the pilot workload.

The use of the time to contact or time to close on a surface or object, τ, as a fundamental variable in the control of motion was introduced by Lee (Ref 4) as a development of Gibson's Optic Flow theory (Ref 5). A description of optic-flow within the context of helicopter flight over terrain will be given before returning to its temporal incarnation in the next section. The optic flowfield describes the way in which surfaces and objects stream past an observer from instant to instant during motion. For level flight over flat terrain, the centre of optical expansion is on the horizon, but no visual information is available here so a pilot would naturally direct his or her gaze to the ground closer to the aircraft. In nature, body scaled measures of height and speed can be defined as eye-heights and eye-heights/sec. Fig 1 illustrates the optic flow-field, projected onto a plane perpendicular to direction of flight, and the eye-height concept. The size of the flow vectors in the viewing window corresponds to an angular change during a 0.25 second snapshot, and inter-point distance is one eye-height. The flight speed is 3 eye-heights/sec, corresponding to about 50kts and a height of 30 feet; a similar optic flow would be seen by a person jogging. The length of the optic-flow vectors gives an indication of the motion information available to the pilot.

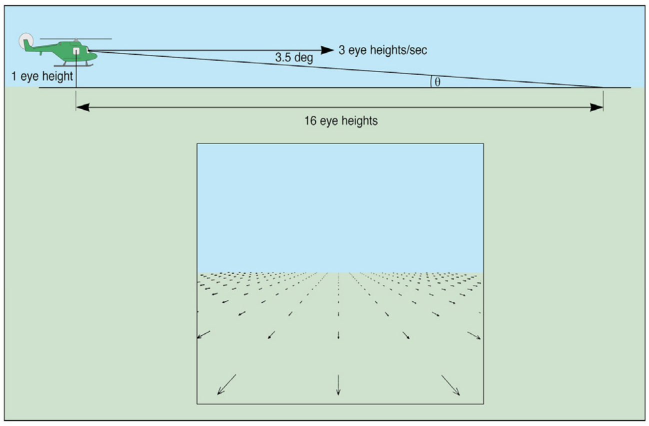


Fig 1 The optic flow-field and eye-height concept for motion over a flat surface

Considering the median plane, the optic-flow, or angular velocity, of a point on the ground a distance x in front of the pilot is given by the expression,

$$\frac{d\theta}{dt} = -\frac{dx}{dt}\left(\frac{z}{x^2 + z^2}\right) \qquad (4)$$

where θ is the elevation angle, $\dfrac{dx}{dt}$ is the horizontal velocity and z is the height of the observer. The optic-flow is seen to fall off as the square of the distance from the observer. In Ref 6, it is postulated that a realistic value for the threshold of velocity perception in practical, complex situations is about 40 min. arc/sec, corresponding to information being sub-threshold at about 15-16 eye-heights distant from the observer for the case shown in Fig 1. If a pilot elects to fly at, say, 3 eye-heights per second, motion would be perceptible on the surface about 5 seconds ahead; note that the angle of depression of the pilot's gaze is about 3.5 degrees in this case. The velocity in eye-heights per second is given by,

$$\dot{x}_e = \frac{dx}{dt}\frac{1}{z} \qquad (5)$$

The optic-flow can then be written in the form,

$$\frac{d\theta}{dt} = \frac{\dot{x}_e}{1 + {x_e}^2} \qquad (6)$$

x_e is the pilot's viewpoint ahead of the aircraft, scaled in eye-heights. The simple linear relationship between $\dot{x}_e$ and the ground velocity given by eqn. (5) is disrupted by changes in altitude. For example, if the pilot descends while keeping forward speed constant, $\dot{x}_e$ increases; if he climbs, $\dot{x}_e$ decreases. A similar effect is brought about by changes in surface layout, e.g. if the ground ahead of the aircraft rises or falls away. Also, if visual conditions degrade, a pilot might chose to reduce height to maintain a constant look-ahead distance in eye-heights. This suggestion will be revisited later in the paper when presenting the results from simulation trials.

Flight in the Temporal World

The previous section outlined the basis of optic-flow theory. Lee developed Gibson's visual perception theory, recasting in a temporal form, based on the time to contact or reach some future goal, τ, (Ref 4) and along with other researchers, has applied the theory to a wide range of natural behaviour (e.g. Refs 7-9). There is strong evidence to suggest that the control of motion is affected by the 'picking up' of visual information based solely on the times to close physical gaps. At a fundamental level, when approaching an object, or more generally changing state, τ-theory posits that explicit knowledge of the speed of approach or distance to contact is not required. The time to contact is perceived directly from the looming of objects and surface patterns on the retina; the cue to state change is provided by the time to close the gap, or to reduce the τ–error to zero. The ratio of instantaneous approach distance to velocity is the instantaneous time to approach, given by,

$$\tau(t) = \frac{x}{\dot{x}} \qquad (7)$$

The time rate of change of $\tau(t)$ is given by,

$$\dot{\tau} = 1 - \frac{x\ddot{x}}{\dot{x}^2} \qquad (8)$$

Research into τ has led to an improved understanding of how animals control their motion and also how humans control vehicles and perform purposeful actions (e.g. reaching for objects, playing musical instruments). In particular, there is evidence that animals maintain a constant $\dot{\tau}$ during approach to a stop manoeuvres. In Ref 10, the question "*how do pilots know when to stop?*" was addressed. Results were presented from piloted simulation tests which demonstrated how pilots use visual information to guide the time to close with the stopping point in a quick-stop manoeuvre. Maintaining $\dot{\tau}$ constant was the preferred guidance strategy, similar to results from experiments with pigeons landing on a perch (Ref 7). In the experiments reported in Ref 10, piloted simulation results for acceleration-deceleration manoeuvres were also presented, showing that pilots adopted a value of $\dot{\tau} \approx 0.6$ during stopping, holding this value constant for up to 10 seconds. A value of $\dot{\tau} = 0.5$ corresponds to a constant deceleration during the manoeuvre while values greater than 0.5 and less than 1.0 (constant velocity), imply maximum deceleration later in the manoeuvre. At low to moderate levels of aggressiveness (maximum pitch angles up to 20 deg in quick-stop) the pilots initiated the deceleration when $\tau \approx 6.0$ seconds. Figure 2 shows a typical result where τ is plotted against time revealing the tight linear correlation (*R^2 = 0.998*), with a slope ($\dot{\tau}$) of 0.582.

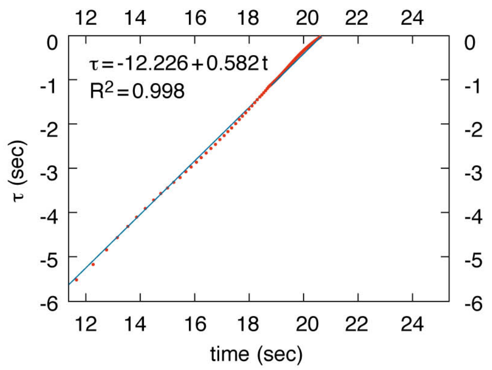


Fig 2 Regression fit of τ vs time for helicopter in quick-stop manoeuvre (Ref 10)

The initiation of the stopping manoeuvre with about 6 seconds to go reflects the pilot's confidence in the aircraft's stopping performance.

The maintenance of $\dot{\tau}$ constant during the stopping phase was also shown in Ref 10 to represent the final stages of the pilot following a more general 'intrinsic' motion guide with a constant acceleration form, with a τ variation of the form,

$$\tau_g = \frac{1}{2}\left(t - \frac{T^2}{t}\right) \quad (9)$$

$$\dot{\tau}_g = \frac{1}{2}\left(1 + \left(\frac{T}{t}\right)^2\right) \quad (10)$$

where T is the duration of the manoeuvre and t is the evolving time from the start of the movement. Provided sufficient visual cues are available, the pilot can fly the whole accel-decel by coupling the τ of the flight-path motion-gap, τ_x, onto an intrinsic τ-guide, τ_g; this coupling can be written,

$$\tau_x = k\,\tau_g \quad (11)$$

for some coupling constant k ($0 < k < 1$). This 'natural' intrinsic guide, τ_g, has a single adjustable parameter, T, the duration of the action. As discussed in Ref 10, increasing k results in the deceleration taking place later in the manoeuvre

When two variables (i.e. the motion x_m and the motion guide x_g) are related through their tau-coupling in the form of eqn (11), then it can be shown that they are also related through a power law,

$$x_m \propto x_g^{1/k} \quad (12)$$

This relationship is very intuitive and also ubiquitous in nature. The coupling parameter k determines exactly how the closed-loop control functions, e.g. proportional as k approaches 1 or according to a square law when k = 0.5. An example of the success of this more general strategy is shown in Fig 3 for the helicopter flying the accel-decel. manoeuvre. The coupling coefficient is 0.28, giving a power factor of 3.5., with a correlation coefficient of 0.98; the start and end of the manoeuvres were cropped at 10% of the peak velocity in the case shown.

An intrinsic τ-guide is effectively a mental model, created by the nervous system, which directs the motion. It clearly has to be well informed (by visual cues in the present case) to be safe. Constant accelerations are one of the few natural motions, created in the short term by the gravitational field, so it is not surprising that the perception system might well have developed to exploit such motions. They will now be examined in the terrain manoeuvre.

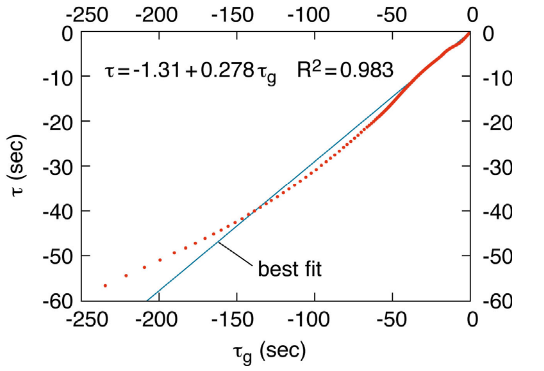


Fig 3 Regression fit of τ vs τ_g for helicopter in acceleration-deceleration manoeuvre (Ref 10)

The results presented for the accel-decel and terrain hugging manoeuvres in the throughout this paper were derived from flights on the Liverpool flight simulator using the FLIGHTLAB (UH-60 like) Generic Rotorcraft (FGR - Ref 11).

<u>τ Guidance on the Hill</u> The previous section presented compelling results for the use of τ guidance during a horizontal re-positioning manoeuvre, as an introduction to the terrain-following case. When considering the approach to rising ground, different issues arise; does the aircraft have the required climb performance and what is the climb response time constant? A series of simulation tests have been carried out to explore motion control for terrain-hugging flight. In the first series, pilots were launched from the hover and asked to accelerate and climb to various speeds and heights and to hug the terrain, maintaining speed and height. The visual conditions were changed by modifying the surface texture and including a corridor of trees to direct the pilot and provide additional height and speed 'cues', resulting in UCE's ranging from 1 to 3+. In handling qualities terms, the adequate performance boundary was set at 50% of nominal height and the desired boundary at 25%. Fig 4 shows results from a UCE 1 case (full surface texture and corridor of trees), where the pilot accelerated to about 35 kts and climbed to about 30 feet (speed ≈ 2 eyeheights/sec.), before negotiating a hill with a 9-degree slope. Shown on the upper part of Fig 4 is the flight path of the aircraft in the vertical plane (*height h(ft) vs range(ft)*). Also shown are the tangents to the flight path at two-second intervals, with the circles highlighting the crossings of the desired and adequate boundaries and, further ahead, the collision point. The lower diagram shows the instantaneous times to cross the HQ boundaries and contact the surface.

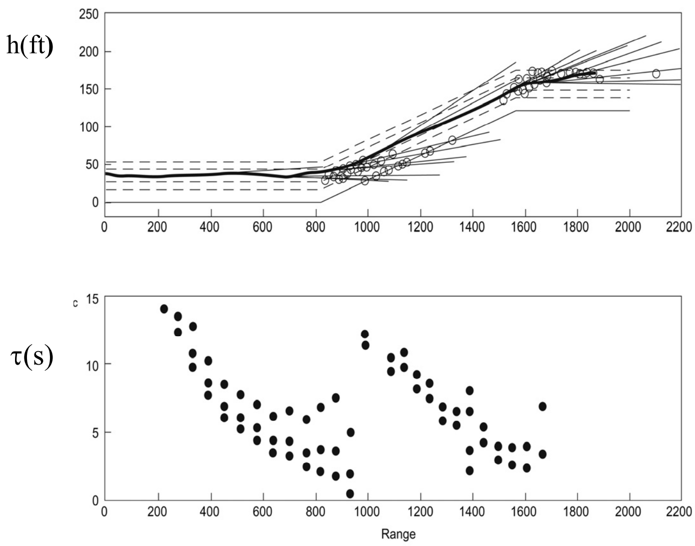


Fig 4 Variation of height and times to close during terrain hugging manoeuvre

For every point in the manoeuvre, the instantaneous velocity vector can be projected forward from which the times to cross the desired and adequate performance boundaries can be computed. The trajectory can be further projected to meet the terrain surface, so that at each point in the manoeuvre, 3 projected $\tau's$ can be derived, providing a measure of the safety margin. For the example shown in Fig 4, the visual scene was rich in micro and macro texture providing the UCE 1 to the pilot. As the aircraft approached the hill, the pilot allowed the time to contact the surface to reduce to about 6 seconds, corresponding to a distance of approximately 12 eye-heights; about half this distance being on the slope of the hill. The desired height performance boundary was within a fraction of a second of being breached as the climb was initiated. On some occasions there are fewer than three τ values on the chart, corresponding to situations where the aircraft is climbing away from the surface, and on other occasions more than three, when the aircraft is above the upper desired boundary and descending. A hypothesis that arises from this analysis is that for the UCE quality provided in the Liverpool simulator, the pilot elected to use the 12 eye-point distance ahead to 'pick-up' the visual information. When the looming information changed (i.e. when this point moved up the hill) the pilot continued in level flight for about three seconds (6 eye-heights distance) before initiating the climb. During this period it is surmised that the pilot rotated his viewing angle upwards to follow the 12 eye-height point. When this point was directly ahead on the aircraft's flight-path, the pilot knew that the base of the hill was half way between the aircraft and viewing point, and he initiated the climb. As previously stated, with the 9 degree slope, the distance between the aircraft and surface contact was about 12 eye-heights. A question that arises from this result is, with a shallower or steeper slope, does the pilot change his strategy, or is the result more general for terrain hugging? To explore these issues further a second series of trials were conducted, where fog levels were used to obscure the visual scene and degrade the UCE, and different hill slopes were investigated.

Another discovery made during the first test series was that, with the rich (unstructured) micro and macro textures, the pilot did not require his head-down instrument panel to return the visual cue ratings corresponding to a UCE 1. In the UCE 3 world, degraded by reduced micro-macro textures, the aircraft tended to stray to higher speeds and heights than the initial launch values without the pilot realising it, when instruments were turned off. This result spurred a new test where the pilots were launched at a range of different speeds and heights and asked to maintain condition for about 1 minute. Two pilots participated in these tests and their results were consistent. Figs 5 and 6 show an example of the remarkable effect that occurred. Fig 5 gives the aircraft velocity in eye-heights/sec as a function of time, for 3 consecutive runs by one of the pilots; the initial condition was 30kts at 70 feet above the surface, corresponding to a velocity of about 0.7 eye-heights/sec. The eye-height velocity remained fairly constant throughout the manoeuvre, but Fig 6 shows the actual ground speed and height increasing threefold over the course of the 50 second flight. The pilot was completely unaware of this evolution. A conclusion from this finding is that, while good surface micro texture provides excellent cues for maintaining optic flow, this unstructured surface texture is insufficient to provide cues for controlling actual speed and height.

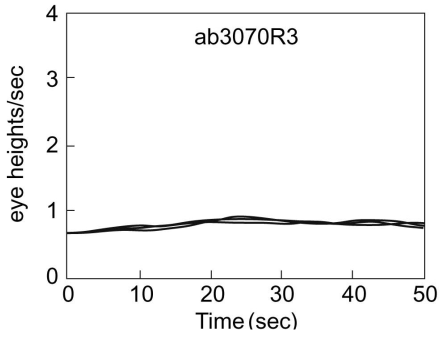


Fig 5 Aircraft velocity in eye-heights/sec over flat terrain (initial conditions, 30kts, 70 feet agl)

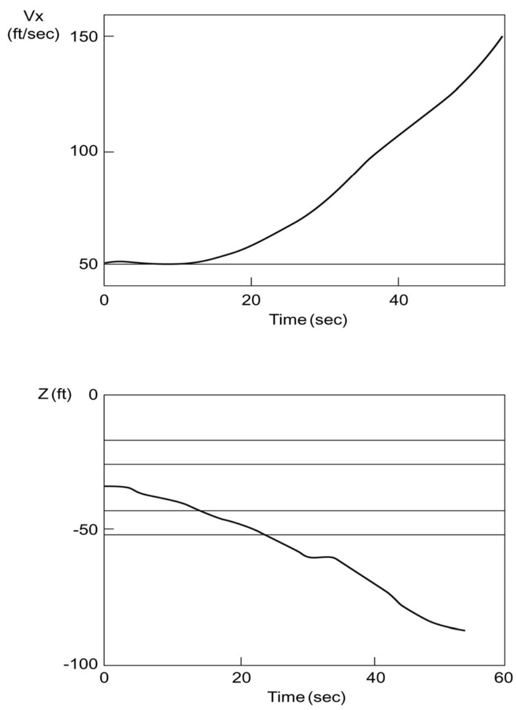


Fig 6 Aircraft velocity and height over flat terrain (initial conditions, 30kts, 70 feet agl)

Terrain Flight in the DVE – Effects of Fog

In the second series of tests, the pilot was once again launched in the hover and requested to accelerate forward and climb to a condition that he considered suited the environment; head-down instruments were turned off. The 5-degree slope hill was located 750m ahead of the hover point and rose 60m above the terrain. The terrain was textured to the same rich, unstructured level as in the first series of tests and the fog was located at distances of 80m, 240m, 480m and 720m ahead of the aircraft. The visual cue ratings (VCRs) and associated UCEs and handling qualities ratings (HQRs) for the different cases are given in Table 1. As expected, the increased workload arising from the DVE led the pilot to award poorer HQRs, as the UCE degraded from 1 to 3.

Table 1 HQR's and UCEs for the terrain hugging manoeuvres

Fog-line	80m	240m	480m	720m
HQR	6	5	4	4
UCE	3	2/3	2	1
		VCRs		
Pitch	4.0	3.5	2.5	2.0
Roll	3.5	3.0	2.0	2.0
Yaw	3.5	3.0	2.0	2.0
Longitudinal	4.0	3.5	2.5	2.0
Lateral	3.0	3.0	2.0	1.5
Vertical	4.0	4.0	3.0	2.5

Key questions to be answered by these tests were - would the pilot elect to fly at different heights and speeds in the different conditions, and how would these relate to the body-scaled measure, the eye-height? Also, would the pilot use intrinsic τ guides to successfully transition into the climb, and what form would these take? Additional questions then emerge as to the nature of the pilot control strategy during the climb manoeuvre. Data will now be presented that address these questions

Figure 7 shows the vertical flight path (height in m), distance to the fog layer (in eye-heights) and flight velocity (in eye-heights/sec) plotted against range (m) for the three cases, each having 3 runs. The average heights (m) and speeds (m/sec) at the base of the hill for the 3 fog cases were 24/55, 15/40, 14/31 and 6/10. The pilots were requested to fly along the top of the hill for a further 2000m to complete the run.

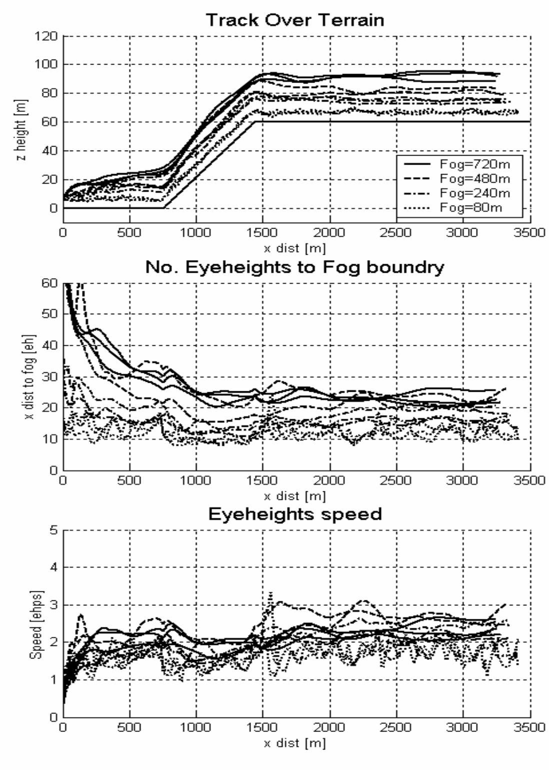


Fig 7 Flight trajectories and eye-height parameters for terrain hugging manoeuvres

The average distances (m) and times (secs) to the fog-lines, along with the velocity and time to the 12 eye-height point ahead of the aircraft are given in Table 2. A clear result is that as the distance to the fog-line reduces the pilot flies lower and slower, while maintaining eye-height speed relatively constant. Comparing the 720m fog-line case with the 240m case, the average eye-height velocity is almost identical, while the actual speed and height has almost doubled. For the UCE 3 case the aircraft has slowed to below 2 eye-heights/s, as the distance to the fog-line came within 20% of the 12 eye-height point.

Table 2 Average flight parameters for the terrain hugging manoeuvres

Distance(Time) to Fog (m(s))	Velocity (eh/s)	Time to 12 eh point (s)
720(13.0)	2.25	5.3
480(12.0)	2.70	4.4
240(7.7)	2.24	5.36
80(8.0)	1.78	6.74

The distances to the terrain surface along the flight path, as the sloping ground is approached, are shown in Fig 8. While the actual distances vary significantly, the eye-height distance to the surface vary between about 12 and 18 eye-heights, during the climb phase. The times to contact the terrain, shown as continuous curves (rather than the discrete data on Fig 4) are shown in Fig 9. Typically, in all UCE conditions the pilot allowed the $\tau_{surface}$ to reduce to about 6 seconds before initiating the climb. These results are consistent with those derived in the first test series without any visual obscuration. In the UCE 3 case (fog at 80m) the pilot is flying at 10m/sec, giving 8 seconds look-ahead time to the fog time and about 2-3 seconds margin from the look-ahead point. It is worth noting that the pilot, who has extensive military and civil piloting experience, declared that the UCE 3 case would not be acceptable unless urgent operational requirements prevailed; it simply would not be safe in an undulating, cluttered environment, and where the navigational demands would strongly interfere with guidance.

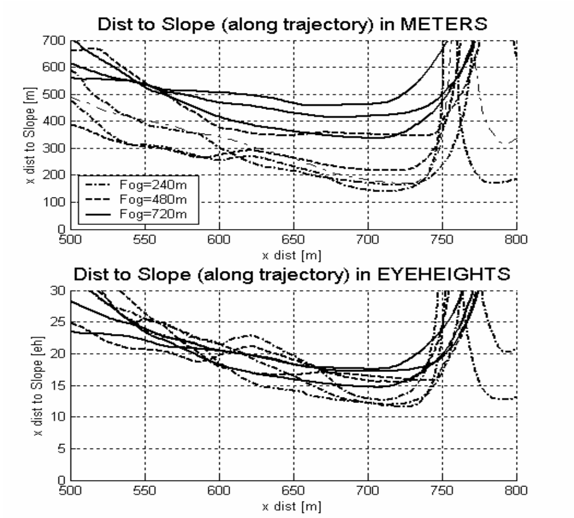


Fig 8 Distance to the slope surface (in meters and eye-heights)

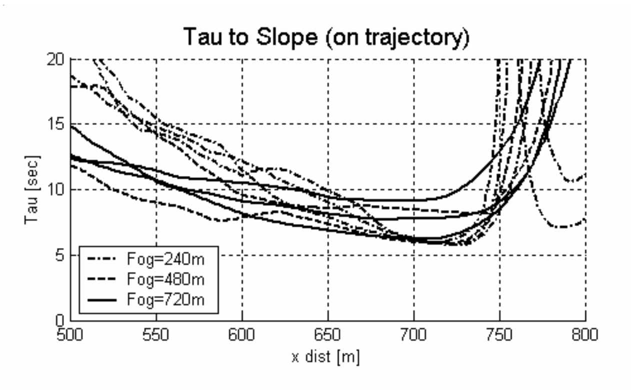


Fig 9 Times to the slope surface *(τ to surface)*

In the following section the variation of flight-path angle during the climb is analysed to investigate the degree of τ–guide following during this change of state.

<u>τ on the Rising Curve.</u>

For the τ analysis, the flight path angle γ is converted to γ_a, the negative perturbation in γ from the final state or goal, as illustrated in Fig 10 and the following equations.

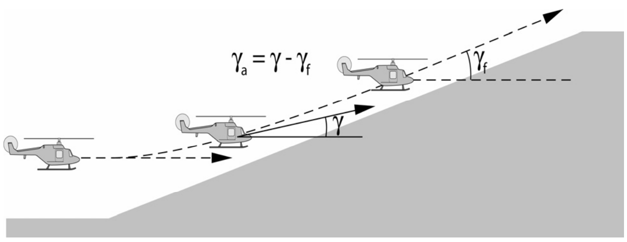


Fig 10 Flight path angle

If the aircraft's normal velocity w is small relative to the forward velocity, V, the flight path angle can be approximated as,

$$\gamma = -\frac{w}{V} \qquad (13)$$

If the final flight path angle is γ_f , then the γ- to-go, γ_a, can be written,

$$\gamma_a = \gamma - \gamma_f \qquad (14)$$

The γ's-to-go and associated time rates of change are plotted in Fig 11 for the UCE 1 and 2 fog cases. At the very low speeds for the UCE 3 cases, the data was too noisy to give sensible results, an issue that will be returned to in the continuing research. The final value of the flight path angle was chosen as the value when $\dot{\gamma}$ first became zero (defining T

and γ_f). From that time on, the pilot closes the loop on a new $\tau-$gap, from above. As can be seen from Fig 11, the pilot tends to overshoot the hill slope (5 degrees) with increasing margin as the UCE degrades; 10 degrees for the 240m fog-line (UCE 2/3), 7 degrees for the 480m fog-line case (UCE 2) and 6 degrees for the 720m case (UCE 1).

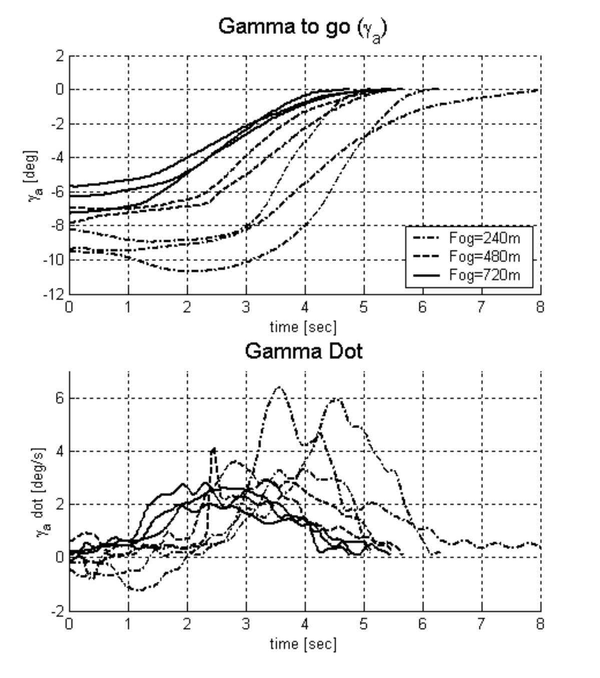


Fig 11 γ_a, $\dot{\gamma}_a$ during the climb

Fig 12 shows the τ functions for the UCE 1 and 2 fog cases as a function of time to go. The fluctuations reflect the higher frequency content in the $\dot{\gamma}$ function. As the goal is approached, with one or two notable exceptions, the curves straighten out and develop a slope between 0.6 and 0.7, corresponding to the pilot following the $\dot{\tau}$ constant guide with peak deceleration close to the goal.

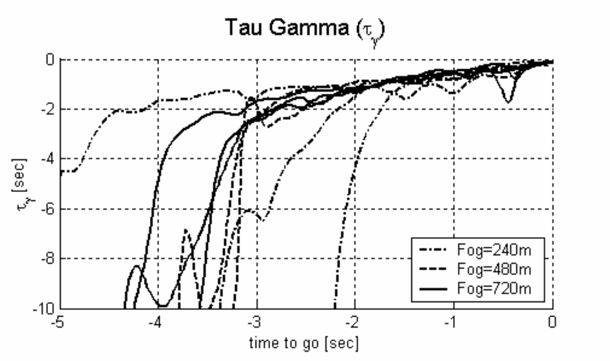


Fig 12 Variation of τ for manoeuvres as goal is approached

As with the accel-decel manoeuvre, the pilot is changing from one state to another (horizontal position for the accel-decel, flight-path angle for the climb). As discussed earlier, the natural guide for ensuring such changes of state are achieved successfully is the so-called constant acceleration guide, given previously in Eqns. 9 and 10, with the guide relationship, $\tau_\gamma = k\,\tau_g$.

A typical correlation between τ_γ and τ_g is shown in Fig 13, plotted against time. Both the constant acceleration and constant deceleration guides are shown for completeness, the latter corresponding to a constant $\dot{\tau}$ strategy. The slope of 0.5 indicates that the pilot has adopted a constant deceleration over the final 1.5 seconds. As expected the test data tracks the constant acceleration guide fairly closely over the whole manoeuvre.

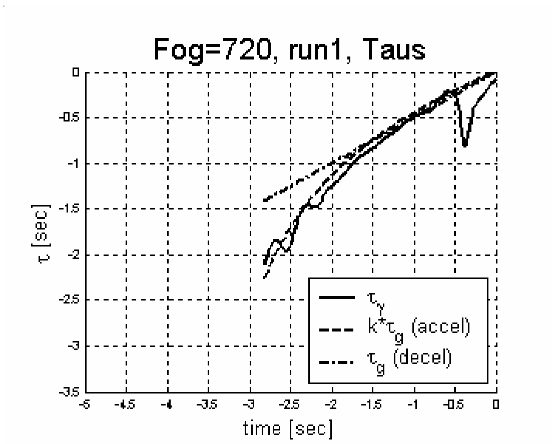
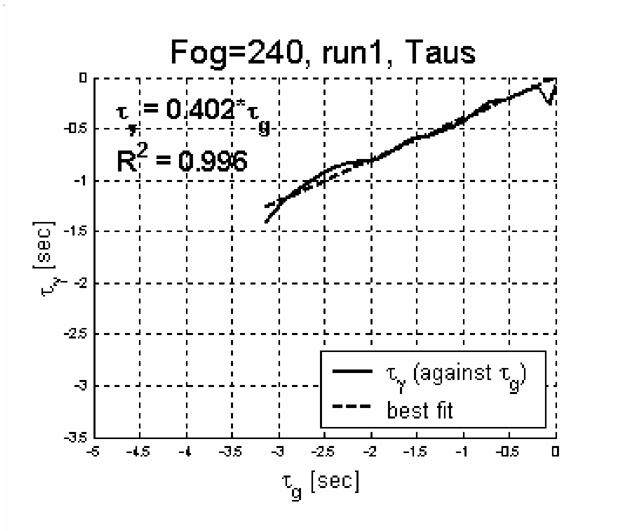
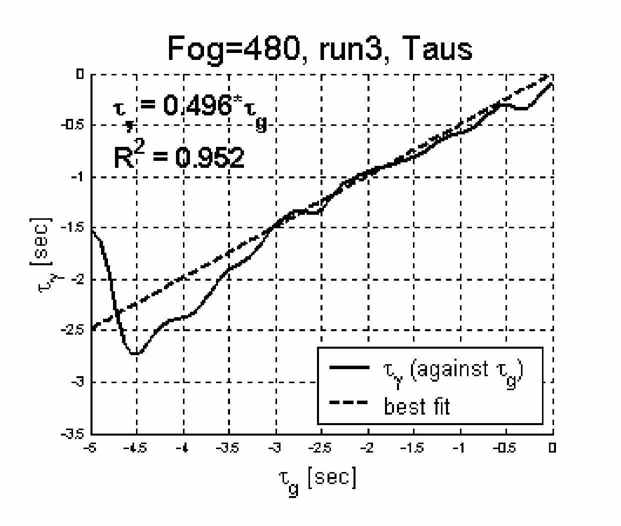


Fig 13 Correlation between times to close on the goal for the motion and guides

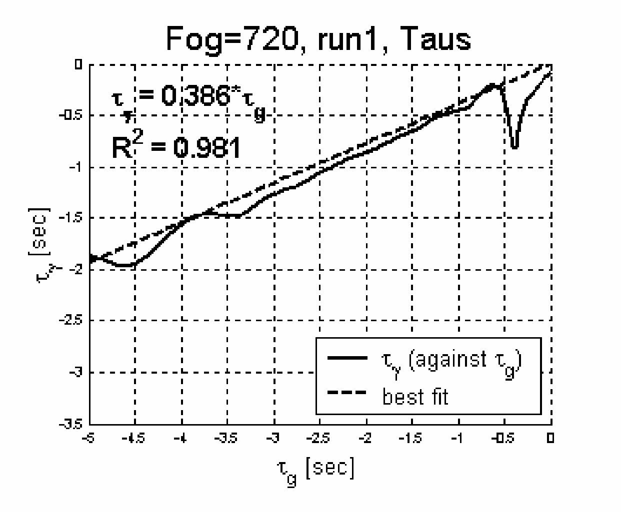
Fig 14 shows typical results for the τ_γ vs. τ_g correlation for the terrain climb in the three fog conditions. The guide following is very close, e.g. in the UCE 1 case (720m fog), apart from a slight departure close to the goal, the fit is tight for the full 5 seconds (R^2 = 0.98). The departures from the close fit at both the beginning and end of such state change manoeuvres are considered to be transient effects partly due to the need for the pilot to 'organise' the visual information so that the required gaps are clearly perceived, and partly due to the contaminating effects of the pitch changes that disrupt the visual cues for flight path changes picked up from the optic flow. There is no clear and obvious trend for the coupling coefficients in Table 3, which vary approximately between 0.3 and 0.5. The lower the *k* value, the earlier in the manoeuvre the maximum motion gap closure rate occurs (a value of 0.5 corresponds to a symmetric manoeuvre).



(a) fog = 240m



(b) fog = 480m



(c) fog = 720m

Fig 14 Typical τ_γ vs τ_g variations for 3 fog cases

Table 3 Correlation constants and fit coefficients - following the constant acceleration guide

case	*k*	R^2
F720_1	0.386	0.981
F720_2	0.331	0.923
F720_3	0.399	0.982
F480_1	0.304	0.967
F480_2	0.496	0.952
F240_1	0.402	0.996
F240_2	0.273	0.873
F240_3	0.441	0.992

The results reveal a strong level of coupling with the τ guide. This was not unexpected. In a complementary study, τ analysis has been conducted on data from approach and landing manoeuvres for fixed wing aircraft (Refs 12, 13). During the flare the pilot follows the τ-guide to the touch down. Instrument approaches where the visibility was reduced to the equivalent of Cat 111b (cloud base 50ft, runway visual range 150ft) were investigated and in some cases the coupling reached the limiting case of constant τ, the pilot effectively levelling off just above the runway. The results presented in the present paper are consistent with those presented in Ref 13, unsurprisingly as the flare and terrain climb tasks make very similar demands on the pilot in terms of visual information.

Pilot's Control Strategy

Earlier in the paper the point was made that application of a step collective input by the pilot results in a motion where the time to reach steady state is a constant and equal to the heave time constant of the aircraft. This constant-τ strategy requires zero workload but is unsuccessful because the pilot never achieves the goal of reaching a new steady state. The control strategy adopted by a pilot following the much more effective constant acceleration guide can be derived by recognising the key power relationship between the actual motion and the guide. The derivation of the expression for the τ_g - following strategy is given in Appendix A, based on the normalised equation of motion for the flight path angle (γ_a) written in the form,

$$\bar{\gamma}_a' + \frac{1}{\bar{t}_a}\bar{\gamma}_a = -\frac{1}{\bar{t}_a}(1-\bar{\theta}_0) \qquad (13)$$

The normalised collective pitch is then given by the expression (from eqn A13),

$$\theta_0 = \left(\frac{V Z_w \gamma_f}{Z_{\theta 0}} \right) \overline{\theta}_0$$

$$\overline{\theta}_0 = \left(1 - (1-\overline{t}^2)^{1/k} \left[1 - \frac{2 \overline{t}_a \overline{t}}{k(1-\overline{t}^2)} \right] \right) \qquad (14)$$

The functions $\overline{\theta}_0$ and $\overline{\gamma}_a$ (eqn. A11) are plotted in Fig 15, as a function of normalised time for different values of coupling constant *k*. The parameter $\overline{t}_a$ is set to unity for this comparison. The strategy involves increasing the collective gradually, and well beyond the steady state value, and then decreasing as the target rate of climb is approached. This overshoot may not be possible when operating with a low power margin, of course. As *k* increases, the peak collective lever position occurs later in the manoeuvre, until the limiting case where it is reduced as a down-step in the final instant to bring $\dot{\overline{\gamma}}_a$ to zero. The control strategy is far from the abrupt, open loop character associated with a step input. A comparison of normalised collective inputs and flight path angles with the τ-coupled predictions for the different cases are shown in Fig 16. The large peak for the 240m fog-line case resulted in the overshoot to 10 degree flight-path angle discussed earlier and could be argued is a case where the pilot has lost track of the cues that enable the τ-coupling to remain coherent. The actual pilot control inputs appear more abrupt than the predicted values but it again could be argued that the pilot needs to stimulate the flow-field initially with such inputs. There is good agreement for the flight path angle variations.

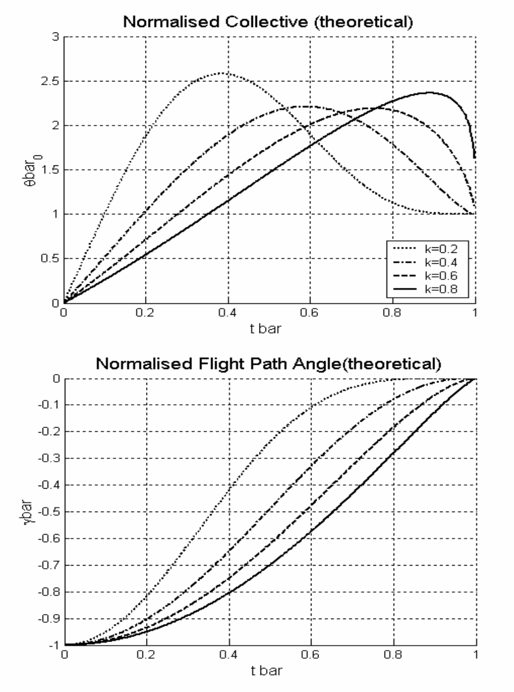


Fig 15 Normalised collective pitch and flight path response following a constant acceleration τ guide

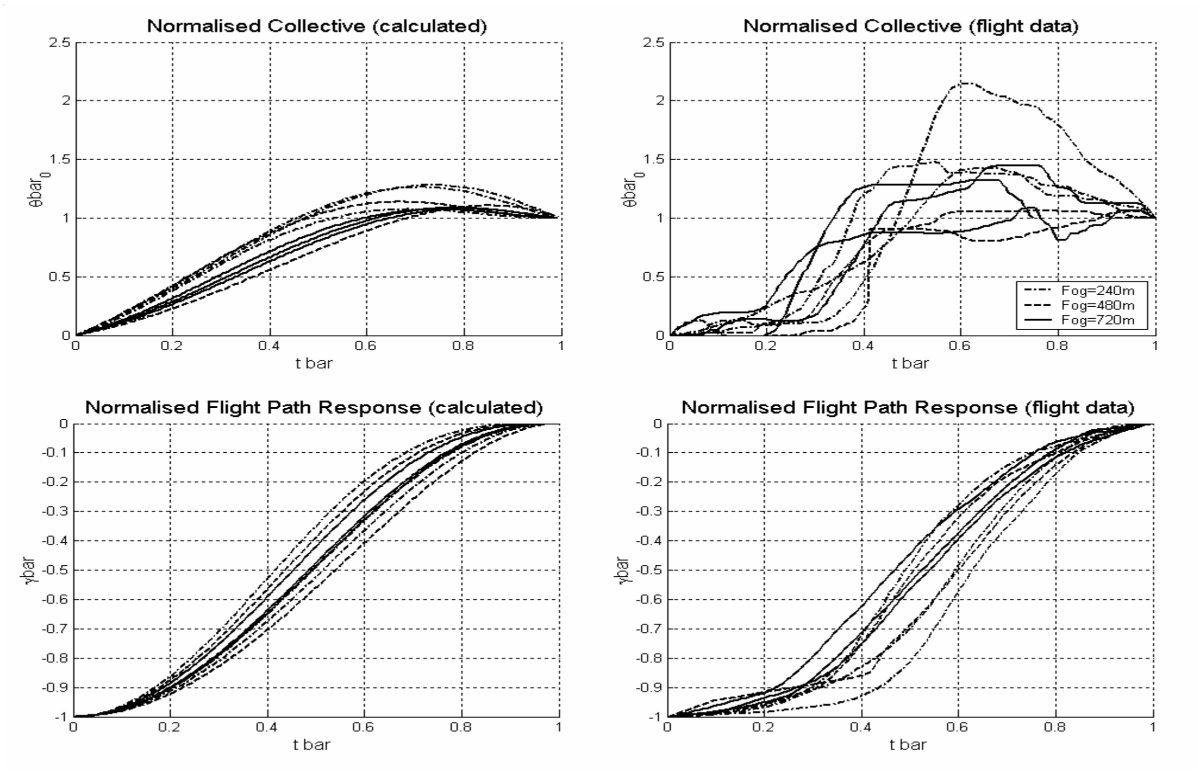


Fig 16 Comparison of normalised pilot control activity and flight path with τ-following strategy

Discussion

In Ref 10, the notion was put forward that "*the overall pilot's goal is to overlay the optic flow-field over the required flight trajectory – the chosen path between the trees, over the hill or through the valley – thus matching the optical and required flight motion*". This concept can be extended to embrace the idea that the overlay technique can happen within a temporal as well as spatial context. The results presented in this paper convey a compelling impression of pilots coupling onto a natural τ-guide during the 3-5 seconds of the climb phase of the terrain-hugging manoeuvre. As in the accel-decel. manoeuvre, it has also been shown that pilots appear to pick up their visual information from about 12 eye-heights ahead of the aircraft, with a corresponding look-ahead time of about 6 seconds. As height is reduced, so the pilot slows down to maintain velocity in eye-heights, and corresponding look-ahead time, relatively constant. The manoeuvre is typically initiated when the $\tau_{surface}$ reduces to about 6 seconds and takes between 4-5 seconds to complete (T). Of course, the manoeuvre time must depend on the heave time constant of the aircraft being flown. For the FGR, t_a varies between 3 seconds in hover and 1.3 seconds at 60kts, reducing to below 1 second above 100kts. Much stronger interference between the aircraft and task dynamics would be expected with aircraft that exhibited much slower heave response (e.g. aircraft featuring rotors with high disc loadings).

The temporal framework described in the paper offers the potential for developing more quantitative UCE metrics. For example, from the present tests, the UCE 3 case was characterised by the distance to visual obscuration coming within about 20% of the 12 eye-height point (≈1 second). For the UCE 1 case, the margin was more than 6 seconds. Sufficiency of visual information for the task is the essence of safe flight and τ envelopes can be imagined that relate to the terrain contouring and associated mission task elements. These constructs can then be used to define the optimum speed and height to be flown in given terrain and visual environment. This theme then develops naturally into the requirements for artificial aids to visual guidance. Visual information that provides clear cues to the pilot to enable coupling onto the natural τ guides could then form the basis of such aids.

The continuing research collaboration between Liverpool and ONERA is addressing these topics, building on the current work and extending to examine visual information requirements in the temporal world for other low speed mission-task-elements relevant to helicopter flight in the nap-of-the-Earth.

Concluding Remarks

The paper has reported results from collaborative research between The University of Liverpool and the French Research Agency, ONERA. The work aims to develop a quantitative framework for defining the requirements for artificial vision aids based on improved understanding of how pilots rely on natural mechanisms in their visual perception system. Within this context, the research also aims to develop quantitative metrics associated with the ADS-33 Usable Cue Environment, which can be used in assessment.

The question, "*how long do pilots look forward*?", and related human-centred research questions, are being addressed through analysis supported by a series of piloted flight simulation experiments. The tests reported have examined the effects of visual obscuration (in this case fog) on the UCE degradation and a pilot's ability to negotiate a terrain-hugging manoeuvre. The optic flow-field and its temporal incarnation using the time to contact variable, τ, supported by body-scaled distances and speeds referenced to eye-heights, form the framework for a fresh description of the DVE and quantification of the UCE. Within this framework, intrinsic motion guides are introduced as components of the pilot's repertoire of natural mechanisms to direct their actions.

The main conclusions derived from the present study are;

a) The optic flow emanating from an unstructured but rich micro-textured surface provides insufficient information to the pilot for controlling absolute speed and height; these variables are prone to drift upwards while the eye-height forms stay constant.

b) With the rich texture used in the simulations, pilots initiated climb manoeuvres when the sloping surface approached the 12 eye-height point, corresponding to about 6 seconds look-ahead time. The results are consistent with those from other manoeuvres (e.g. quick-stop) suggesting a minimum temporal envelope for safe flight for low speed manoeuvring.

c) The UCE degraded as the obscuration increased, from 1 (720m fog line) to 2 (480m fog line) and 3 (80<fog-line< 240m). In UCE 3, the pilot was still able to maintain the 12 eye-heights and 6 seconds look-ahead, but with only a margin of 1 second (handling qualities were Level 3). This suggests a UCE temporal metric related to the margin beyond the point where the pilot naturally picks up visual information.

d) As an aircraft approaches rising ground, analysis conducted shows that the test pilot appeared to use a prospective flight-path control strategy, based on following the natural (constant acceleration) intrinsic τ guide. The correlation between the flight path τ and the τ–guide was very strong over the 3-4 second transient as the new flight path was captured. The coupling constant k varied across the runs (power law coefficients 2 to 3) but no systematic trends were observed with UCE.

e) Finally the reconstructed control strategy and flight path variations (from the τ-following model) show remarkably good agreement with the test data.

The full suite of low speed mission task elements will be explored in the continuing research aimed at drawing up a more complete picture of the visual requirements for flight in the cluttered, undulating nap-of-the-Earth. This will lead on to the development of the τ-envelope concept that will be used to inform the design of more intuitive vision aids and associated UCE metrics.

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References

1. Padfield, G.D., Helicopter Flight Dynamics: The Theory and Application of Flying Qualities and Simulation Modelling, Blackwell Science, Oxford, 1996
2. Padfield, G.D. et al Where Does the Workload Go When Pilots Attack Manoeuvres? - An Analysis of Results from Flying Qualities Theory and Experiment, *Proceedings of the 20th European Rotorcraft Forum*, Amsterdam, Oct 1994
3. anon., Aeronautical Design Standard-33E-PRF, Performance Specification, Handling Qualities Requirements for Military Rotorcraft, US Army AMCOM, Redstone, Alabama, March 21, 2000
4. Lee, D.N., The Optic Flow-field: the Foundation of Vision, *Phil. Trans. R. Soc. London*, B 290, 169-179, 1980
5. Gibson, J.J., The Perception of the Visual World, Houghton Mifflin, Boston, 1950
6. Perrone, John A., The Perception of Surface Layout during Low-Level Flight, NASA CP3118, 1991
7. Lee, D.N., Davies, M.N.O., Green, P.R., Van Der Weel, F.R., Visual control of velocity of approach by pigeons when landing, *J.exp. Biol.* 180, 85-104, 1993
8. Lee, D.N., Young, D.S., Rewt, D., How do Somersaulters land on their Feet ? *Journal of Experimental Psychology, Human Perception and Performance*, 18, 1195-1202, 1992.
9. Lee, D. N., Simmons, J. A., Saillant, P. A., & Bouffard, F., Steering by Echolocation: a Paradigm of Ecological Acoustics. *J. Comp. Physiol. A* 176, 347-354, 1995.
10. Padfield, G.D., Lee, D., Bradley, R., How do pilots know when to stop, turn or pull-up? Developing guidelines for the design of vision aids, *J. American Helicopter Society*, April 2003
11. Padfield, G.D., White, M.D., Flight Simulation in Academia; HELIFLIGHT in its first year of operation, *The Aeronautical Journal of the RAeS*, Sept 2003
12. Jump, M., Padfield, G.D., Progress in the Development of Guidance Strategies for the Landing Flare Manoeuvre Using Tau-based Parameters, *1st International Conference on Innovation and Integration in Aerospace Sciences*, 4-5 August 2005, Queen's University Belfast, Northern Ireland, UK.
13. Jump, M., Padfield, G.D., To Tau or not to Tau?, that is the question: developing guidelines for an approach and landing skyguide, *AIAA Atmospheric Flight Mechanics Conference*, San Fransisco, August 2005
14. Lee, D.N., Guiding movement by coupling taus, *Ecological Psychology*, 10(3-4), 221-250, 1998

Appendix A

Pilot Control Strategy when Following a τ Guide

The equations for modelling the control strategy when the pilot follows a constant acceleration τ guide are developed below. Firstly, recasting the motion (equation 1) in terms of the flight path angle γ and introducing the new variable γ_a and normalising gives equations A1-A5, with the variable definitions given in A6.

$$\gamma = -\frac{w}{V} \qquad \text{(A1)}$$

$$\gamma_a = \gamma - \gamma_f \qquad \text{(A2)}$$

$$\dot{\gamma}_a - Z_w \gamma_a = Z_w \gamma_f - \frac{Z_{\theta 0}}{V}\theta_0 \qquad \text{(A3)}$$

$$\gamma_a(t=0) = -\gamma_f \qquad \text{(A4)}$$

$$\bar{\gamma}'_a + \frac{1}{\bar{t}_a}\bar{\gamma}_a = -\frac{1}{\bar{t}_a}(1-\bar{\theta}_0) \qquad \text{(A5)}$$

$$\bar{\gamma}_a = \frac{\gamma_a}{\gamma_f} \qquad \bar{t}_a = \frac{t_a}{T}$$

$$\gamma' = \frac{d\gamma}{d\bar{t}} = T\dot{\gamma} \qquad \text{(A6)}$$

$$\bar{\theta}_0 = \frac{\theta_0}{\theta_{0f}} \qquad \theta_{0f} = \frac{V Z_w \gamma_f}{Z_{\theta 0}}$$

The instantaneous time to reach the goal of $\gamma = \gamma_f$ is given by the expression,

$$\tau_{\gamma a} = \frac{\gamma_a}{\dot{\gamma}_a} \qquad \text{(A7)}$$

Following a τ guide such that $\tau_m = k\,\tau_g$ results in motion that follows the guided motion as a power law,

$$x_m = C\,x_g^{1/k} \qquad \text{(A8)}$$

where C is a constant.
The constant acceleration guide has the forms given in (A9) and (A10).

$$\tau_m = k\,\tau_g = \frac{k}{2}\left(t - \frac{T^2}{t}\right) = \frac{kT}{2}\left(\bar{t} - \frac{1}{\bar{t}}\right) \qquad \text{(A9)}$$

$$x_g = \frac{a_g}{2}T^2(\bar{t}^2 - 1) \qquad \text{(A10)}$$

a_g is the constant acceleration of the guide. The motion begins and ends with the guide, but initially overtakes before being caught up by the guide at the goal.

The equations for the motion and its derivatives can then be developed from (A10) and (A8) (see Ref 14). In terms of the flight path variable, these can be written in the normalized form,

$$\bar{\gamma}_a = -(1-\bar{t}^2)^{(1/k)} \qquad \text{(A11)}$$

$$\bar{\gamma}'_a = \frac{2\bar{t}}{k}(1-\bar{t}^2)^{(\frac{1}{k}-1)} \qquad \text{(A12)}$$

Using (A5) the collective control can finally be written in the general form,

$$\bar{\theta}_0 = 1 + \bar{t}_a\,\bar{\gamma}'_a + \bar{\gamma}_a \qquad \text{(A13)}$$