How Do Helicopter Pilots Know When to Stop, Turn or Pull Up?
(Developing guidelines for vision aids)

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Abstract

The title of this paper, posed as a question, reflects the current interest in gaining an improved understanding of visual perception in flight control to inform the development of design guidelines for future pilot vision aids. The paper develops the optical flow theory of visual perception into its most recent incarnation, tau-coupling, where tau is the time to closure to surfaces at current velocity. General tau-theory posits that the closure of any type of gap, using any form of sensory input, is guided by sensing and constantly adjusting the tau of the gap. According to the theory, and contrary to what might be expected, information about the distance to obstacles or the landing surface, for example, and about the speed and deceleration of approach, are not necessary for precise control of landing or stopping. Analysis is presented that supports the importance of tau-coupling in flight control. Results from simulation trials conducted at DERA and at The University of Liverpool demonstrate the considerable power of what we describe as tau-guides, that lead the pilot to adopt a prospective flight control strategy.

Introduction

Helicopter pilots make use of nap-of-the-Earth (NoE) flight to increase stealth and mission security. Such tactical flight, close to the ground and amongst the surrounding obstacles, is characterised by the pilot making continuous corrections in speed, height and heading, guided by a mental model of where his or her aircraft will be in the future. The pilot uses what can be described as 'prospective control' to evolve a safe trajectory, or skyway, based on perception of the aircraft's changing velocity and direction from instant to instant. How far into the future this mental model needs to project is a central question for research into vision aids, the answer to which depends on the task being flown and, critically, on the aircraft's performance and handling qualities. For NoE tasks suggested by the title of this paper - turning through a terrain-gap, stopping in a clearing or climbing over a hill - the question reflects the requirements for an adequate flight safety margin.

In engineering terms, the positional states and motion velocity and turn rate describe the flight control task. The pilot effectively transforms perceived motion in the optical frame of reference into relative motion in the inertial frame-of-reference and applies feedback regulation to minimise errors between the commanded and perceived motion. In an alternative, active psychophysics framework, flight control can be described in terms of pilots picking up information generated by motion over terrain and around obstacles, through variables in the optical flow-field from the surfaces in their field of vision (Ref 1). Optical flow rate can, for example, provide the pilot information on ground speed in eye-heights per second (Ref 2) or surface slant (Ref 3). Differential motion parallax can guide way-finding in a cluttered environment (Ref 4). Another optical variable, introduced by Lee (Ref 5), is that which specifies time to contact or close to an obstacle or surfaces at the current closing rate - tau. Tau provides a temporal scaling of the external environment and, like other flow-field variables, provides pilots with instinctive information about their motion relative to external surfaces. More recent developments of tau theory have hypothesised that purposeful motion is guided by couplings arising from either external or internal sources (Ref 6). This hypothesis features as a central theme in the paper and suggests a major new paradigm for safe flight, to be discussed later.

In terms of a visual guidance strategy we can say that the overall pilot's goal is to overlay the optical 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. With this approach, it is argued that the pilot has no requirement to 'transform' the flow variables into motion variables, as such. The pilot's perception system works directly with the raw optical flow variables.

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Learning to fly close to the ground and in a cluttered environment, a pilot naturally uses the same rapid and efficient processes that he or she uses every day to walk, run or jump. However, ultimately a pilot has to effect control of the aircraft through the flight motion variables in an inertial frame of reference (e.g. when landing). When there are consistent, unambiguous, one-to-one mappings between the frames of reference, accurate flight control will follow from the direct perception of the optical variables. When the relationships, the mappings, become blurred, then the pilot may experience flight control problems through a degraded spatial awareness. The blurring, in a general sense, defines a degraded visual environment (DVE). A key question relating to the design of pilot vision aids is how best to represent the world when the natural optical information begins to degrade.

At first sight the engineering and active psychophysics approaches can appear conflicting and yet they surely must overlap and ultimately be complementary descriptions of the same control function, viewed from different perspectives. Making the link between the two approaches should improve our understanding of both and ultimately stimulate ideas on how to provide effective aids to pilots when the prime source of information for flight control, through optical variables, begins to degrade. The amount and form of what is necessary to be displayed for the pilot to be able to fly safely is the driver for vision system requirements. The prospect of enhanced and synthetic vision systems calls for a re-examination of the design guidelines for primary flight display formats, and the stimulus for exploring the efficacy of more natural optical flow components. This is the subject of the present paper and is derived from research conducted by the authors in collaboration with scientists at the Defence Evaluation and Research Agency.

The paper is structured as follows. First, the nature of visual perception in flight control is discussed and the key optical variables used in the paper are introduced in the context of NoE helicopter manoeuvring. Second, the concept of tau-coupling is introduced and applied to test data captured on the DERA and Liverpool Flight Simulators. Some thoughts on the implications of the current research for the design of vision aids are then discussed before the paper is brought to a conclusion.

Visual Perception in Flight Control; Optical Flow

The use of the term *prospective control* emphasises that flight tasks are essentially temporal, within a spatially ordered environment. When flying close to the ground or obstacles, the reliability of the pilot's mental model of the future is particularly critical. In a good visual environment the pilot is able, arguably by definition, to pick up sufficient information to make sense of motion from the optical flow-field on the surfaces in the visual scene. The optical flow-field defines the way in which points in the visual scene move from instant to instant relative to the pilot's viewpoint. The visual perception system that picks up and organises this information has, necessarily, to be very robust and efficient. Figure 1, derived from Ref 3, illustrates the optical flow-field seen by the pilot when flying horizontally over a surface at 3 eyeheights per second. The figure shows the projection onto a plane perpendicular to the direction of flight. This corresponds to fast NoE flight - about 50kn at 30 feet height, giving the same visual impression as experienced by a running person. The eye-height scale is useful in visual perception research because of its value to deriving body-scaled information about the environment during motion. Each optical flow vector in Figure 1 represents the angular change of a point on the ground during a 0.25 second snapshot. Inter-point distance is one eyeheight. The scene is shown for a limited field-of-view window, typical of current helmet-mounted-displays. A 360deg perspective would show optical flow vectors curving around the sides and to the rear of the aircraft. The centre of optical expansion is on the horizon.

The length of the optical flow vectors in Fig 1 gives an indication of the motion information available to a pilot; they decrease rapidly with distance. If we consider the median plane, the angular velocity, $\frac{d\theta}{dt}$, of a point on the ground distance x in front of the pilot is given by,

$$\frac{d\theta}{dt} = -\frac{dx}{dt}\left(\frac{z}{x^2 + z^2}\right) \qquad (1)$$

where θ is the elevation angle, $\frac{dx}{dt}$ is the horizontal velocity, and z is the height of the observer. Velocity (i.e. the length of the vector) is seen to fall off as the square of the distance from the observer. In Ref 3, Perrone suggests that a realistic value for the threshold of velocity perception in practical complex situations is about 40 min arc/sec. According to eqn 1, this corresponds to information being sub-threshold at about 15-16 eyeheights distant from the observer for the case shown in Figure 1. To quote from Ref 3, "*This is the length of the 'headlight beam' defined by motion information alone. At a speed of 3 eye-heights/sec, this only gives about 5 seconds to respond to features on the ground that are revealed by the motion process.*"

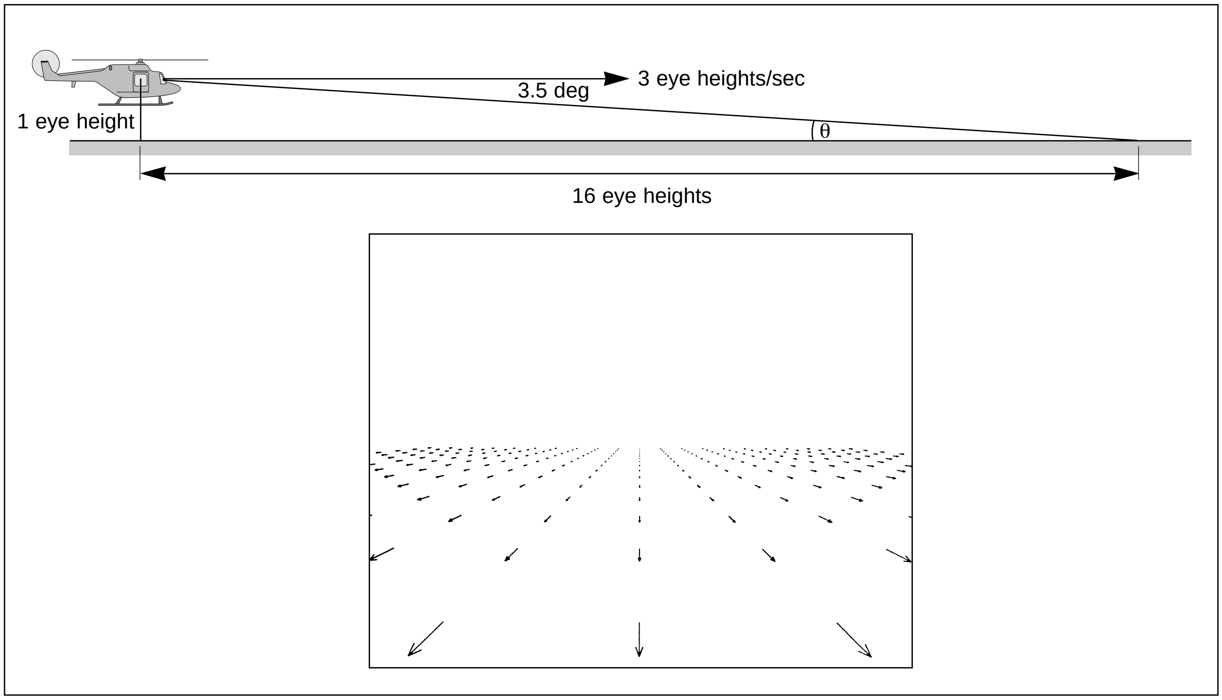

Fig 1 Optical Flow-field for Motion over a Flat Surface

The velocity in eye-heights per second is given by,

$$\dot{x}_e = \frac{dx}{dt}\frac{1}{z} \qquad (2)$$

Transforming eqn (1), we can write,

$$\frac{d\theta}{dt} = \frac{\dot{x}_e}{1 + x_e^{\,2}} \qquad (3)$$

where x_e is the pilot's viewpoint distance ahead of the aircraft scaled in eye-heights. When $\dot{x}_e$ is constant, then the optical angular velocity is also constant; they are in effect measures of the same quantity. However, the simple linear relationship between $\dot{x}_e$ and the ground velocity given by eqn (2), is disrupted by changes in altitude. 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. Generalising eqn (1) to the case where the aircraft has a climb or descent rate ($\frac{dz}{dt}$) relative to the ground we can write;

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

We can see from eqn (4) that the relationship between optical flow rate and the motion variables is not straightforward. Flow rate and ground speed are uniquely linked only when flying at constant altitude.

A related optical variable comes in the form of a discrete version of that given by eqn (2) and occurs when optically specified edges within the surface texture pass some reference in the pilot's field of vision. This optical edge rate is defined as (Ref 2);

$$e_r = \frac{dx}{dt}\frac{1}{T_x} \qquad (5)$$

Here, T_x is the spacing between the surface edges. A pilot flying at 50 ft/sec over a network of 50ft square grids would therefore experience an edge rate of 1/sec. Flying over a uniform surface the simple linear relationship between the flight motion and optical variables holds. Unlike optical flow rate, edge rate is invariant as altitude changes. However, as noted in Ref 2, when ground speed is constant, edge rate increases as ground texture becomes denser, and decreases as it becomes sparser.

Time to Contact; Optical tau

When x_e >>1 (or x>>z), we can simplify eqn (1) and (3) to the form;

$$\dot{\theta} = \frac{\dot{x}_e}{x_e}\theta = \frac{\dot{x}}{x}\theta \qquad (6)$$

The ratio of distance to velocity is the instantaneous time to reach the viewpoint, which we designate as $\tau(t)$, hence,

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

This temporal optical variable is important in flight control. A clear requirement for pilots to maintain safe flight is that they are able to predict the future trajectory of their aircraft far enough ahead that they can stop, turn or climb to avoid a hazard. This requirement can be interpreted in terms of the pilot's ability to detect motion ahead of the aircraft. In his explorations of temporal optical variables in nature (Refs 5-7), David Lee makes the fundamental point that an animal's ability to determine the time to pass or contact an obstacle or piece of ground does not depend on explicit knowledge of the size of the obstacle, its distance away or relative velocity. The ratio of the size to rate of growth of the image of an obstacle on the pilot's retina is equal to the ratio of distance to rate of closure, as conceptualised in Fig 2, and given in angular form by eqn (7). Lee hypothesised that this 'looming' is a fundamental optical variable that has evolved in nature, featuring properties of simplicity and robustness. The brain does not have to apply computations with the more primitive variables of distance or speed, thus avoiding the associated lags and noise contamination. The time to contact information can readily be body scaled in terms of eye-heights, using a combination of surface and obstacle $\tau(t)$'s thus affording animals with knowledge of, for example, obstacle heights relative to themselves.

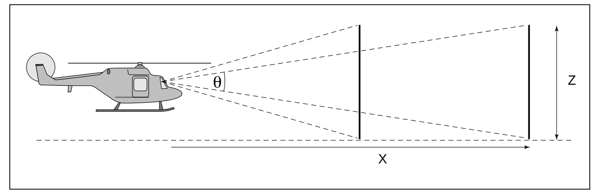

Fig 2 Optical Looming when approaching an Object

Tau research has led to an improved understanding of how animals and humans control their motion and humans control vehicles. A particular interest is how a driver or pilot might use τ to avoid getting into a crash state (or animals alight on objects). A driver approaching an obstacle needs to apply a braking (deceleration) strategy that will avoid collision. One collision-avoid strategy is to control directly the rate of change of optical tau, which can be written in terms of the instantaneous distance to stop (x), velocity and acceleration in the form;

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

With x<0, then $\dot{\tau} > 1$ implies accelerative flight; $\dot{\tau} = 1$ implies constant velocity, while $\dot{\tau} < 1$ corresponds to deceleration. With constant deceleration, $\ddot{x}$, the stopping distance from a velocity $\dot{x}$ is given by,

$$x = -\frac{\dot{x}^2}{2\ddot{x}} \qquad (9)$$

Hence a decelerating helicopter will stop short of the intended hover point if;

$$\frac{-\dot{x}^2}{2\ddot{x}} < -x \qquad or \qquad \frac{x\ddot{x}}{\dot{x}^2} > 0.5 \qquad (10)$$

Using eqns (7) and (8) this condition can be written more concisely as,

$$\frac{d\tau}{dt} < 0.5 \qquad (11)$$

A constant deceleration results in $\dot{\tau}$ progressively decreasing with time and the pilot stopping short of the obstacle, unless $\dot{\tau}$ = 0.5 when the pilot just reaches the destination. The hypothesis that optical τ and $\dot{\tau}$ are the variables that evolution has provided humans and animals with the ability to detect and rapidly process, suggests that these should be key variables to guide the design of vision augmentation systems. In Ref 8, Lee extends the concept to the control of rotations (angular τ) related to how athletes ensure they land on their feet after a somersault. For helicopter manoeuvring, this can be applied to control in turns, providing a direct connection with the heading component of flight motion. With heading angle and turn rate, we can write the angular tau as,

$$\tau(t) = \frac{\psi}{\dot{\psi}} \qquad (12)$$

A combination of angular and linear tau's, associated with physical gaps, needs to be successfully picked up by pilots to ensure flight safety. The requirement for combining tau's to perform more complex manoeuvres has led to the development of a more general theory of tau-coupling.

Tau-Coupling in Helicopter Flight – a Paradigm for Safety in Action

General tau theory posits that the closure of any type of gap, using any form of sensory input, is guided by sensing and constantly adjusting the tau of the gap (Ref 6). The theory shows, for example, that information solely about $\dot{\tau}_x$ is sufficient to enable the gap *x* to be closed in a controlled manner, as when making a gentle landing. According to the theory, and contrary to what might be expected, information about the distance to the landing surface and about the speed and deceleration of approach are not necessary for precise control of landing.

The theory further shows how a pilot might perceive τ of a motion gap by virtue of that τ being proportional to the τ of a gap in a sensory flow-field. The example of decelerating a helicopter to hover over a landing point on the ground serves to illustrate the point. The τ of the gap in the optic flow-field between the image of the landing point and the centre of optical outflow (which specifies the instantaneous direction of travel) is equal to the τ of the motion gap between the pilot and the vertical plane through the landing point. This is always so, despite the actual sizes of the optical and motion gaps being quite different (see Fig 3). The same applies to stopping at a point adjacent to an obstacle (Fig 4).

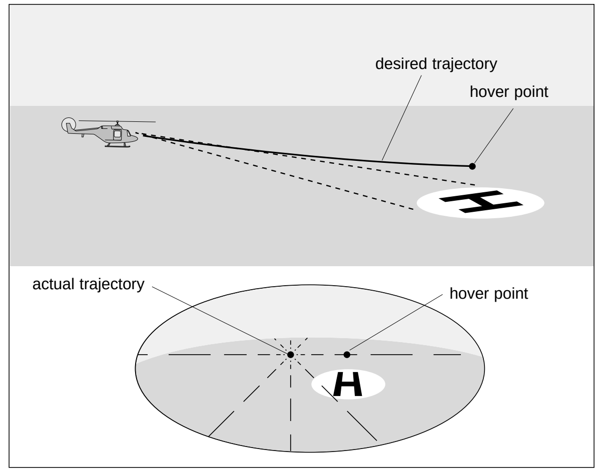

Fig 3 Tau-gaps for Helicopter approaching a Hover point above Landing Pad

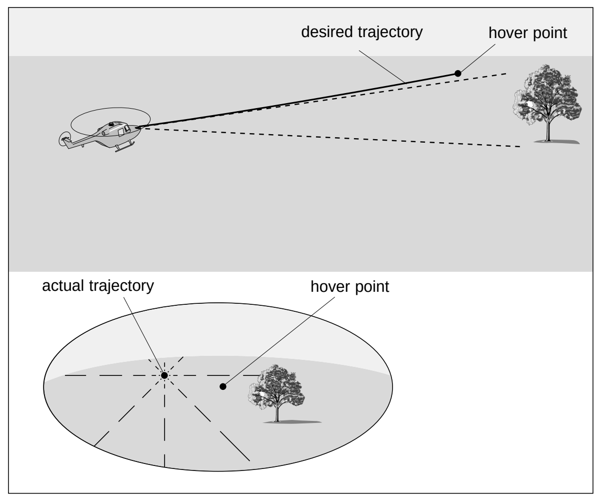

Fig 4 Tau-gaps for Helicopter approaching a hover point adjacent to an Object

Often movements have to be rapidly co-ordinated, as when simultaneously making a turn and decelerating to stop at a goal position or flying parallel to a line feature. This requires accurate synchronising and sequencing of the closure of different gaps. To achieve this, sensory information about several different gap closures has to be picked up rapidly and continuously and applied to guiding the action. Tau theory shows how such movement co-ordination might be accomplished in a simple way by τ-coupling, that is, by keeping the τ's of gaps in constant ratio during the movement.

Evidence of tau-coupling in action is presented in Refs 8 and 9 for experiments with echo-locating bats landing on a perch and infants feeding. In the present context, if a helicopter pilot, descending (along z) and decelerating (along x), follows the tau-coupling law,

$$\tau_x = k\tau_z \qquad (13)$$

then the desired height will automatically be attained just as the landing pad itself is reached. The kinematics of the motion can be regulated by appropriate choice of the value of the coupling constant *k*.

General tau-guidance principles can also be used to hypothesise how pilots might perceptually guide their craft through the other two manoeuvres of current interest – turning and terrain following. To simplify the analysis, and without losing much generality, we consider planar motion only. Turning to fly parallel to a vertical feature (e.g. line of trees) might follow the guidance rule of coupling tau for the heading with tau for the distance to the line feature. However, since the heading itself may be difficult to perceive, an alternative would be to follow the principle of keeping,

$$\tau_x = k\tau_y \qquad (14)$$

where x and y are the distances respectively to the centre of outflow (instantaneous direction of travel) and to a point ahead where the pilot naturally directs his or her gaze (Fig 5). Manoeuvring around an obstacle on the inside of the turn could be guided by controlling tau of the angle between the instantaneous trajectory and the direction of the tangent to the obstacle (Ref 6).

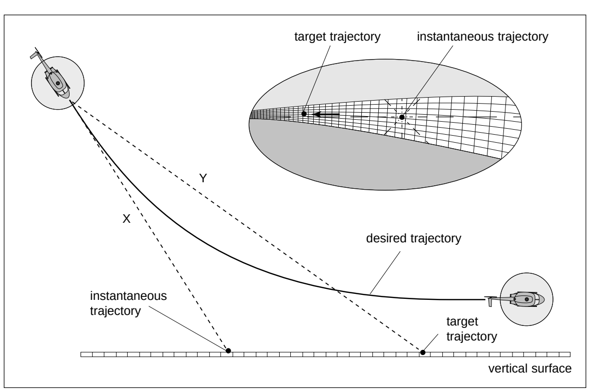

Fig 5 Tau-gaps for Helicopter Turning along a Line Feature

The scenario in Fig 5 could equally well apply to control of motion when approaching a horizontal surface (e.g. the ground). The visual cues available from the cockpit are different in the horizontal and vertical cases, of course, determined partly by the different orientation of the pilot's head to the outside world. Obscuration of visual cues by the cockpit frame, and the potential complexity introduced by the orientation of the optical frame of reference to the inertial frame, both clearly influence the available optical tau's.

Fig 6 illustrates the final case of interest with the scenario of a helicopter approaching rising ground and manoeuvring up and over a crest. As for the previous case, the pilot can potentially couple the tau's associated with a point on the ground along the instantaneous direction x (centre of optical expansion) with a point further up the hill moving at a rate consistent with the required climb rate.

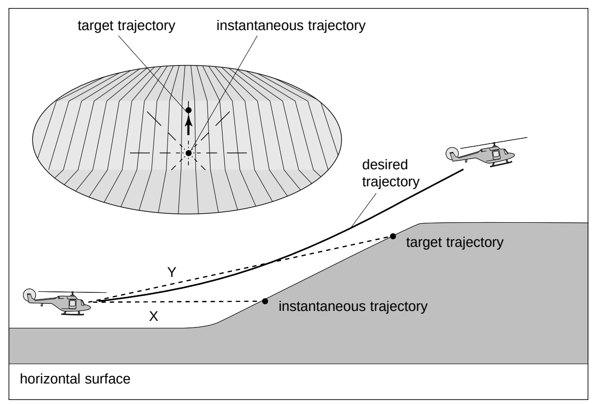

Fig 6 Tau-gaps for a Helicopter approaching Rising Ground

The basis of the general hypothesis for the 'turning' manoeuvres described above certainly needs to be tested, but there is evidence that such coupling can be exploited successfully in vision aids. For example, the system reported in Ref 10 exploited such tau-coupling through the matching of a cluster of forward directed light beams with different look-ahead times. Such a system was designed as an aid in situations where the natural optical flow was obscured.

Intrinsic Motion Guides

In the above examples, the tau's of two *motion* gaps are coupled to achieve the overall action. However, in many movements such as drumming a rhythm and self-paced reaching, there is only one motion gap basically to control (e.g., between the hand and drum). And yet the kinematics of controlled closure of motion gaps is similar, whether there are two coupled motion gaps or just one. Such findings led to the hypothesis that the closure of a single motion gap is controlled by keeping the tau of the motion gap (e.g., between hand and drum) coupled onto an intrinsically-generated tau-guide τ_g (Ref 6). It may be assumed that simple, robust control processes have evolved, rather than unnecessarily complex ones. Therefore it is reasonable to hypothesise that the simplest form of intrinsic tau-guide will have evolved that is adequate for guiding movements, such as reaching, through the normal phases of acceleration followed by deceleration. In the context of helicopter NoE flight any of the classic hover-to-hover re-positioning manoeuvres fit into this category of motions. The hypothesised intrinsic tau-guide corresponds to a time-varying quantity, perhaps related to the flow of electrical energy in neurons, that changes in value from a rest or constant velocity level to a goal level at a constantly accelerating rate. It should be noted, however, that tau-coupling onto this intrinsic guide does *not,* in general, generate a motion of constant acceleration, but rather generates one with a (non-constant) accelerative phase followed by a (non-constant) decelerative phase. The equations describing the changing τ_g take the form:

$$\tau_g = \frac{1}{2}\left(t - \frac{T^2}{t}\right) \qquad \dot{\tau}_g = \frac{1}{2}\left(1 + \left(\frac{T}{t}\right)^2\right) \quad (15)$$

where *T* is the duration of the aircraft or body movement and *t* is the time from the start of the movement. Coupling a motion-gap tau, τ_x (e.g., from hand to drum or hover to hover) onto an intrinsic tau-guide, τ_g, therefore involves following the equation,

$$\tau_x = k\,\tau_g \qquad (16)$$

for some coupling constant *k*. The intrinsic tau-guide, τ_g, has a single adjustable parameter, *T*, its duration. The value of *T* is assumed to be set by the nervous system, either to fit the movement into a defined temporal structure, as when moving the hand in time with a musical rhythm, or in a relatively free way, as when reaching for an object. In the case of a helicopter flying from hover to hover across a clearing, we can hypothesise that time constraints are mission related and the pilot can adjust the urgency through the level of aggressiveness applied to the controls. The kinematics of a movement can be regulated by setting the coupling constant, *k* in eqn (16), to an appropriate value. For example, the higher the value of *k*, the longer will be the acceleration period of the movement, the shorter the deceleration period, and the more abruptly will the movement end. We describe situations with *k* values > 0.5 as hard stops (i.e. where peak velocity is pushed close to the end of the manoeuvre) and situations with *k* < 0.5 as soft stops.

When two variables (e.g. the motion x_m and the motion guide x_g) are related through their tau-coupling in the form of eqn (16), then it can be shown that they are also related in one of the most prevalent ways in nature, through the power law,

$$x_m = C\,x_g^{1/k} \qquad (17)$$

where *C* is a constant. Reference 5 expands on the implications of this relationship in terms of the overall kinematics of the motion and the associated motion gaps. We continue this paper with an application of tau-analysis during helicopter stopping manoeuvres.

Tau in Action during Stopping Manoeuvres

A common manoeuvre used by helicopter pilots to fly from cover to cover across open ground is colloquially known as the acceleration-deceleration or quick-hop (Ref 12). As part of an exercise in simulation validation, 'accel-decels' were flown both in flight and on the DERA Advanced Flight Simulator (AFS) using a Lynx helicopter (Ref 13). The layout of the manoeuvre, showing the basic ground markings, is sketched in Figure 7. Pilots were required to fly the manoeuvre according to prescribed performance standards in terms of track, height, level of aggressiveness and terminal position constraints.

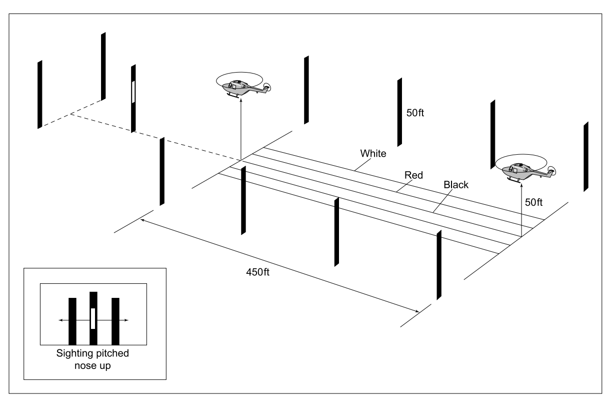

Fig 7 Course Layout for CONDVAL Acceleration-Deceleration Manoeuvre

A typical set of results from the AFS simulation trial for three levels of pilot aggressiveness is shown in Fig 8. The pilot accelerates the aircraft by commanding a nose down pitch attitude, accelerates to a maximum speed (approximately 40, 50, 65 ft/sec for the three aggression levels), reverses the pitch to initiate a deceleration, coming to a stop at a range of about 450ft (150m).

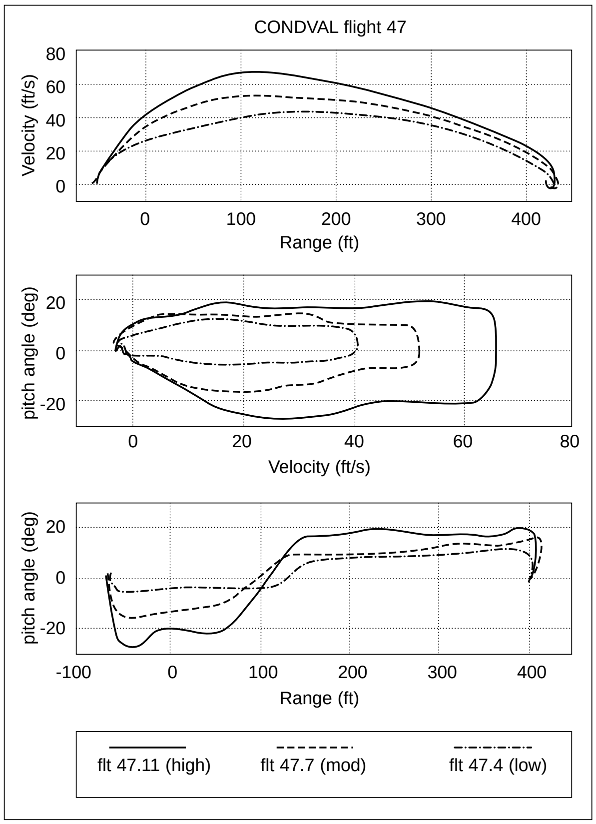

Fig 8 Typical set of Accel-decel results from the AFS CONDVAL Trial

The course markings on such manoeuvres are designed to provide sufficiently good visual information that the pilot can perceive whether the achieved performance is within the desired or adequate standards. Fifteen accel-decels were flown by three test pilots, at three levels of aggressiveness – low, moderate and high.

In the following analysis the relationship between the motion of the aircraft and the intrinsic guides introduced above is explored. The basic modelling technique adopted will establish the linear correlation between the motion tau, τ_m , the time t, and the guide tau, τ_g . Fig 9 shows a typical profile for the velocity and displacement as a function of manoeuvre time (36.2 = Flight 36, run 2). For the correlation analysis, the manoeuvre was assumed to begin when the velocity reached 10% of the peak velocity and to end when it had subsided to 10% of peak. The distance along the track is designated as X_s, to differentiate with the distance to go, X.

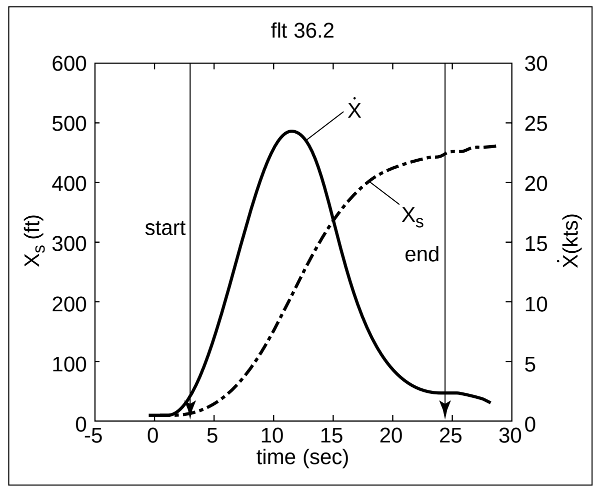

Fig 9 Typical Displacement and Velocity Profiles in the CONDVAL Accel-Decel (Flt 36.2)

Constant $\dot{\tau}$ Guides; Building on the previous tau-analysis for stopping scenarios, we begin with a study of the deceleration phase of the manoeuvre and an examination of the strength of the motion coupling with the constant $\dot{\tau}$ intrinsic guides. Figs 10a, b and c show the regression fit of the motion tau with time for flight cases, 47.4, 47.7 and 47.11, corresponding to pilot O flying with low, moderate and high aggressiveness.

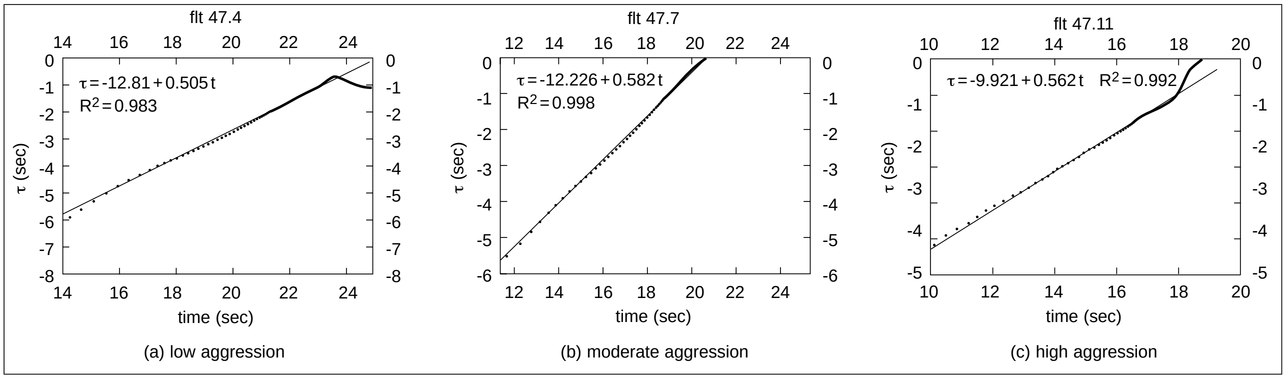

Fig 10 Regression fit of Motion Tau vs Time – Deceleration Phase

The values of the coupling, in this case corresponding to the guiding $\dot{\tau}$, are 0.51, 0.58 and 0.56, with the correlation coefficients R^2 of about 0.99. In all three cases the fit degrades during the final few moments of the stopping. As a guide to interpreting these results, Fig 11 illustrates the deceleration profile against time (normalised by initial τ under constant velocity) for a general tau guide moving with constant $\dot{\tau}$ (Ref 8).

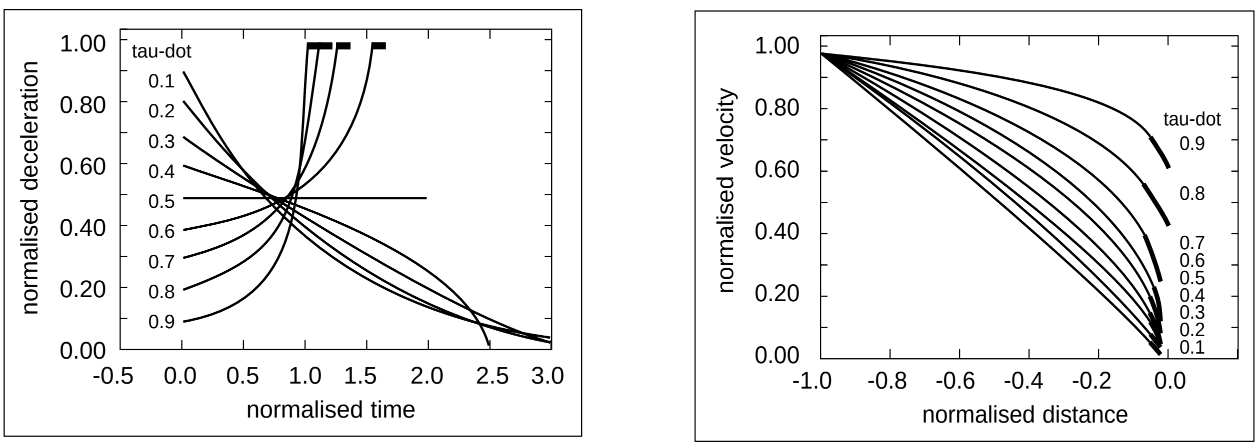

Fig 11 Kinematics of the Constant $\dot{\tau}$ guide (from Ref 8)

All three cases in Figure 10 follow a profile for $\dot{\tau}$ between 0.5 and 0.6, showing how the deceleration (or pitch attitude) of the aircraft increases as the stopping point is reached. The degraded match close to the hover is hypothesised to arise from the need for the pilot to fly the final positioning with a reduced pitch attitude and different control strategy. The close correlation of the motion tau and guide tau during the deceleration phase suggests that the pilot is able to pick up visual information from the course layout that enables this close coupling to be maintained until close to hover, despite the high nose-up pitch attitude.

Constant Acceleration Guide; Maintaining constant $\dot{\tau}$ will only work as a guiding strategy when performing a stopping manoeuvre. To treat the whole accel-decel we need to examine the efficacy of the constant acceleration guide described by eqn (15). If we normalise the kinematics, then a motion which couples onto this motion guide through the relation $\tau_m = k\tau_g$, will take the form given in Fig 12 (a) – (d) (from Ref 6).

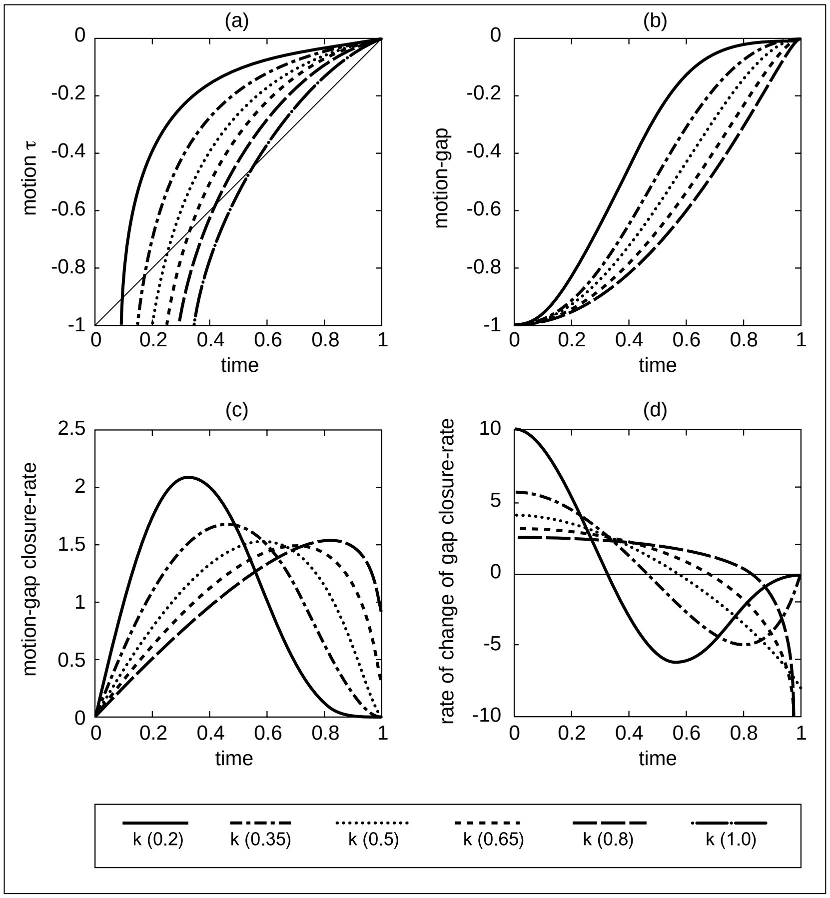

Fig 12 Kinematics of the Constant Deceleration Motion Tau (from Ref 6)

The bell-shaped profile of the velocity distribution and sigmoid profile of the displacement are reminiscent of the helicopter motion shown in Fig 9. The comparison of the helicopter motion tau and guide motion tau for the case Flt 36.2 is shown in Fig 13. Within a few seconds of the launch, the tau's show a consistent correlation through to the hover point. We can imagine the motion guide as a ball, initially at the same location as the helicopter and following the constant acceleration profile to the hover point, where it again meets the helicopter. The helicopter tau is always less than the tau of the ball. One can imagine the pilot developing the mental model of the aircraft motion as he or she rides in the ball, remaining behind the helicopter until they become one at the hover point.

Figures 14 - 16 show the graphs of τ_m vs τ_g and the comparison of the test data with the linear fit. Also shown are the velocity and displacement profiles of the test runs. For all 3 cases about 97% of the accel-decel data was used; only the first couple of seconds of the acceleration were truncated, when the pilot is settling into the manoeuvre (below 10% V_{max} threshold).

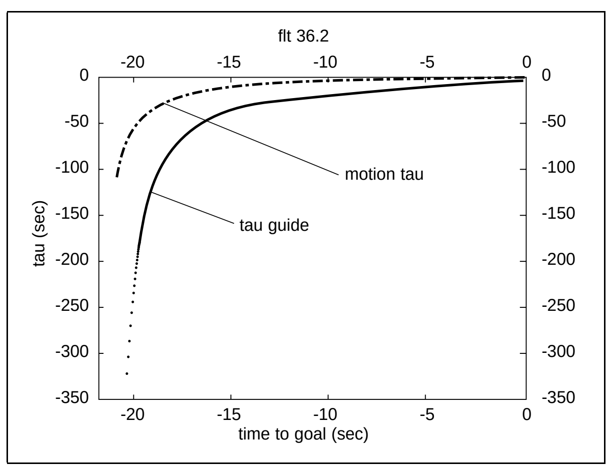

Fig 13 Comparison of Helicopter and Guide Tau's for Flt 36.2

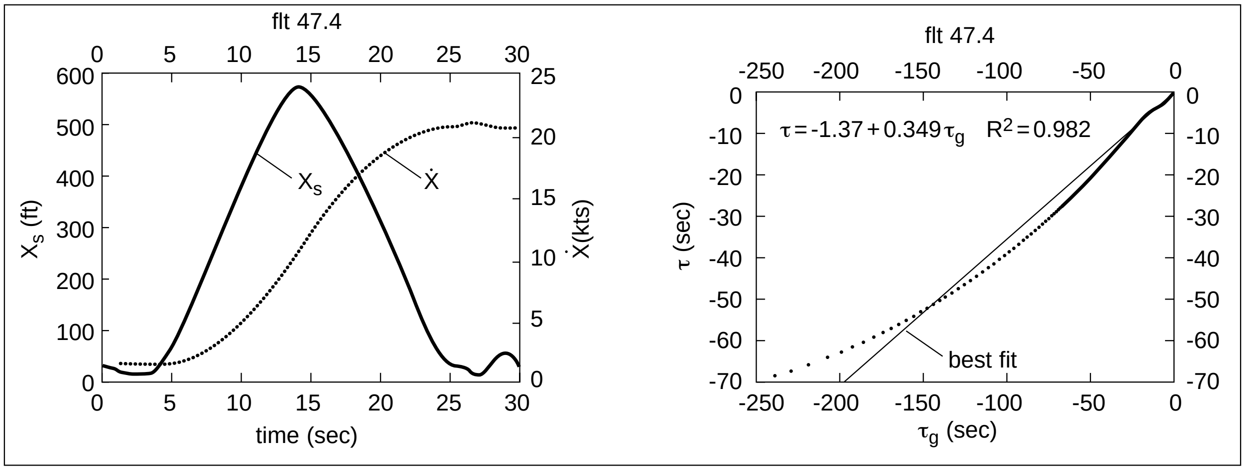

Fig 14 Correlation of Motion Tau with Guide tau; Flt 47.4 - low aggression

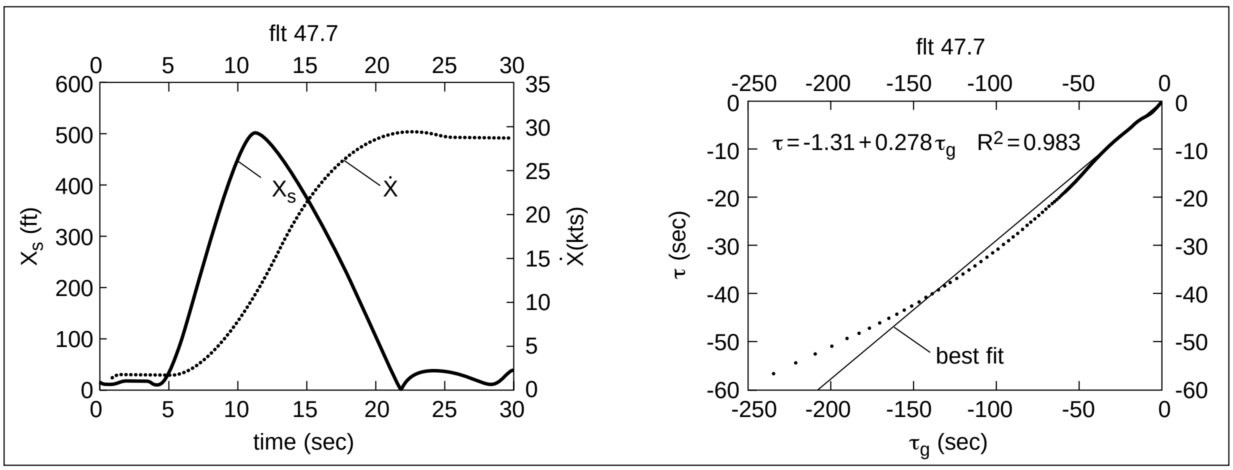

Fig 15 Correlation of Motion Tau with Guide tau; Flt 47.7 - moderate aggression

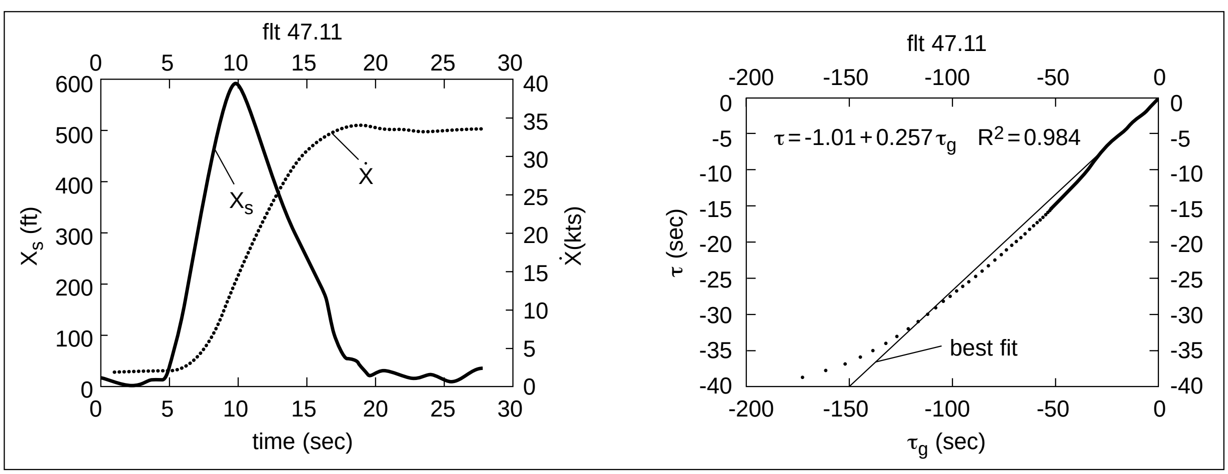

Fig16 Correlation of Motion Tau with Guide tau; Flt 47.11 – high aggression

The coupling constant *k* varies between 0.26 (high aggression case) and 0.35 (low aggression case). The correlation coefficient is greater than 0.98 for all cases and the velocity profiles show consistency with the general guide profile in Fig 12, i.e. the later the velocity peak, the larger the coupling constant. If we consider all 15 accel-decels then the mean values of *k* follow the expected trend (low aggression, *k*=0.381; moderate aggression, *k*=0.324; high aggression, *k*=0.317). As the aggression level increases, the pilot elects to initiate the deceleration earlier in the manoeuvre; low aggression at 10 sec (0.5T into manoeuvre); high aggression at 4 sec (0.4T into manoeuvre). The pilot is more constrained during the deceleration phase. Fig 8 shows the pilot limiting the nose up attitude to about 20 deg at high aggression, even though attitudes of greater than 30 deg were possible purely from a performance standpoint.

The tau-coupling principle hypothesises that the pilot seeks features in the visual flow-field that provide consistent and continuous information on motion and allow the intrinsic tau-guide to be activated. The results from the CONDVAL simulation trial provide fairly compelling evidence that such a coupling is present and that sufficient optical information was available on the test course for the pilot to fly the manoeuvres safely. The handling qualities results reported in Ref 13 indicate that the desired performance was achieved. Handling qualities ratings (HQRs) of 4/4/5 were given for low/mod/high aggression cases respectively by pilot O. The pilot commented on the task 'cues' (Ref 13); *"Overall visual cues were good but better in the acceleration compared to the deceleration phase. The tramlines gave good positional cueing and the poles gave good peripheral height cueing. The forward field of view was restricted compared to the Lynx, which might make the task a little easier in the real aircraft. At high nose up attitudes the large poles in the forward window provide a general idea of lateral and heading position and the poles in the side window gave a good indication of longitudinal position. However as aggression increased cueing was compromised by the degree of divided attention between the windows."*

As noted in passing above, task 'cues' are introduced in stylised course layouts to ensure that the pilot has an equivalent visual scene content to what would be expected in the real world when flying such a manoeuvre. The process at arriving at such equivalence needs to have a sound engineering basis. This, and the related fundamental question of what information a pilot needs to guide and stabilise the aircraft, is at the heart of developing guidelines for pilot displays and synthetic vision systems. We continue the paper on this theme.

Developing Guidelines for Vision Aids and Synthetic Vision Systems

The collaborative research described in this paper aims to inform the development of guidelines for the requirements-capture and design of future display systems for low level tactical flight. An important aspect of such requirements is the level of stability augmentation in the host aircraft. The handling qualities performance standard, ADS-33E introduced the Usable-Cue-Environment (UCE) as a construct from which the stability augmentation requirements to achieve Level 1 handling qualities can be established. The design of any vision aid influences the UCE and hence we have a clear and important link between display and control augmentation. The UCE scale is illustrated in extended form in Fig 17. To achieve Level 1 performance when flying in UCE 1, a conventional rate response type will suffice. As we move through UCE2 to UCE 3, so increased augmentation in the form of attitude and velocity response types are required to enable the pilot to focus on guidance, rather than the workload-sapping stabilisation tasks. UCE 3 corresponds to conditions where the pilot is unable to achieve precision when flying tasks with any level of urgency, but the conditions are not so degraded that the surface and surrounding obstacles are not visible.

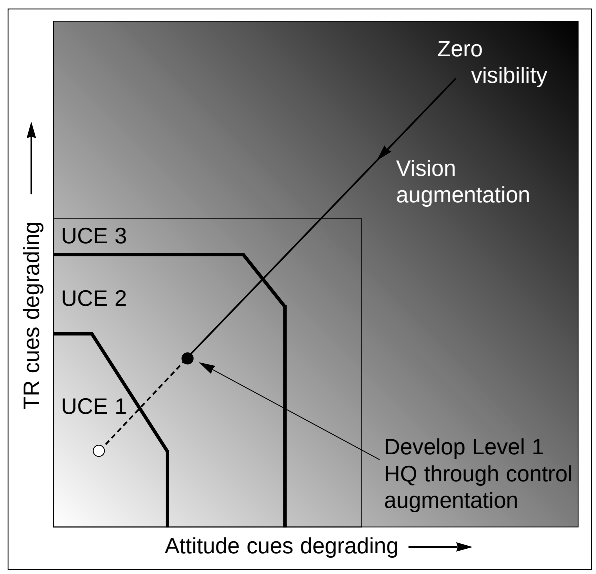

Fig 17 The Extended UCE Scale

The extended UCE scale in Fig 17 conceptualises that beyond UCE, conditions continue to degrade through to zero visibility. Free flight at NoE heights can only be conducted safely in these conditions through a synthetic vision system. Leaving aside the maturity of the technologies that will make such a system practicable, for it to be functional it must, arguably, provide a pilot with a consistent model of the outside world throughout the range from UCE2/3 to zero visibility. The vision augmentation system that brings the UCE into the 2/3 range on Fig 17, must essentially be complementary to any system that enhances the pilot's real outside world view with, for example, overlaid symbology. In addition, such vision augmentation needs to harmonise and be integrated with control augmentation. The fundamental requirement for such an integrated system is that it should allow the pilot to construct and maintain an accurate mental model of the future flight trajectory that is sufficiently prospective for safe flight. The nature of such an *integrated prospective flight control system*, its functions, failure modes and how it interfaces with the pilot needs to be investigated in research, and clearly there is considerable scope for innovation.

One of the conclusions from the exploratory analysis presented earlier in this paper is that tau-coupling offers a robust approach to the design of a synthetic vision system. The first stage in developing requirements for a tau-based prospective system is to quantify what visual information pilots use for performing manoeuvres like climbing, turning and stopping. Such a synthesis leads to a second stage where we examine how pilots cope when visual components are removed, through to conditions where insufficient information is available for safe flight, i.e. beyond UCE 3. Such degradation in spatial awareness and task performance will, in theory, be reflected in the correlation between the tau's of motion gaps or perhaps the pilot's inability to track an intrinsic motion guide through the poor visibility. A third stage takes us to the design of the re-constructed or synthetic world where the tau-coupling is restored and once again coherent. This 3-stage approach is being taken within the current UK research. In the first stage, a series of experiments have been initiated on the new moving base flight simulation facility at The University of Liverpool. The single seat cockpit pod is mounted on a 6-axis, hexapod, high-bandwidth motion system (Fig 18) and contains 5 outside-world visual channels presented to the pilot in the arrangement shown in Fig 19.

The first phase of this work included very simple tasks with limited flight degrees of freedom, guided to an extent by concurrent NASA research reported in Ref 15. Fig 20 illustrates the stopping area for a decel-to-stop manoeuvre over a flat surface. The task involves decelerating the helicopter from a defined initial speed to stop over the line, 2 grid squares in front of the vertical poles, which themselves were 2 grid squares ahead of a vertical wall. The visual information available to the pilot included the surface grid, and the vertical wall, poles and stop line. The grid size was either 50ft or 100ft. Flying at a speed of 50ft/sec at a height of 50ft over the 50ft grid gives exactly the same visual impression as flying over the 100ft grid at a height of 100ft and velocity of 100ft/sec.

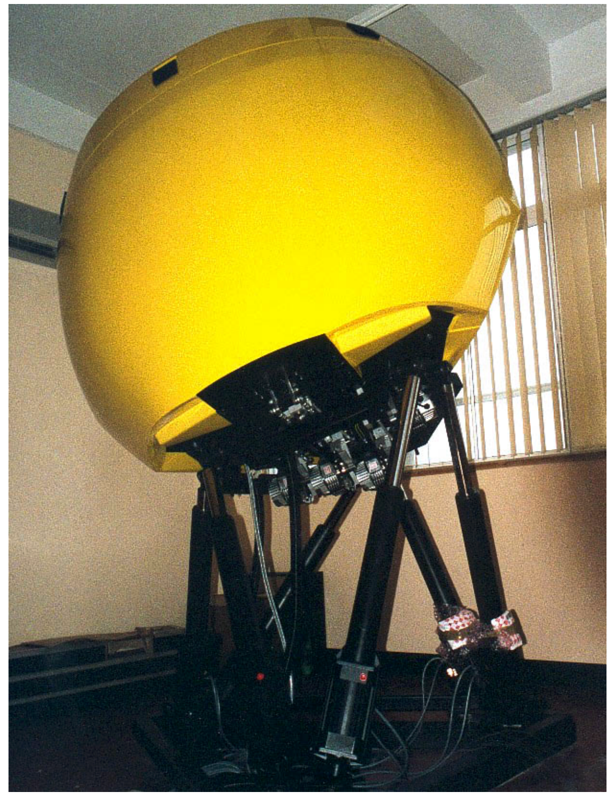

Fig 18 The Liverpool Flight Simulator

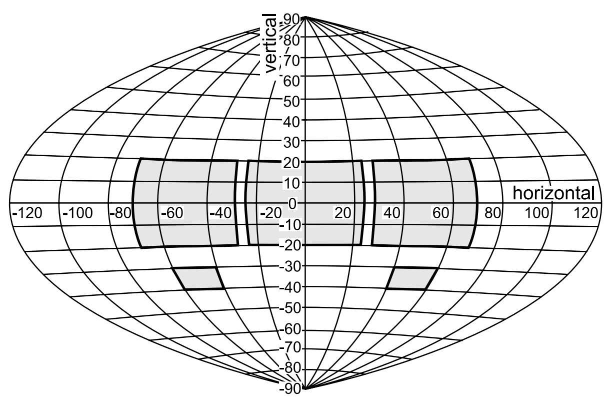

Fig 19 Cockpit Field of View in Liverpool Flight Simulator

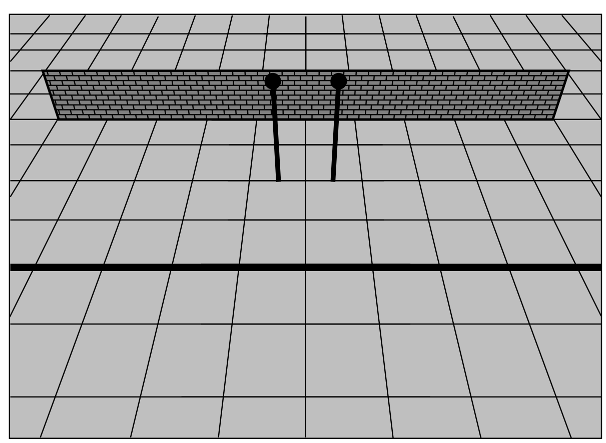

Fig 20 Stopping Area for Decel-to-Stop Manoeuvre

For these tests, the only degrees of freedom active in the simulation were pitch angle, controlled through conventional cyclic, and forward translation. All other motions were locked. The simulation model was the FLIGHTLAB generic articulated rotor helicopter, similar in configuration and dynamics (e.g. pitch rate response type) to the UH-60 Blackhawk. Six subjects, all non-pilots, were instructed to use the cyclic to decelerate the aircraft to a hover. Preliminary analysis of the data shows general consistency between subjects flying with various levels of aggressiveness, at different speeds and over different grid sizes. Figs 21 and 22 show a sample of results from 3 different subjects flying at three different initial speeds, 50, 75 and 100 ft/sec.

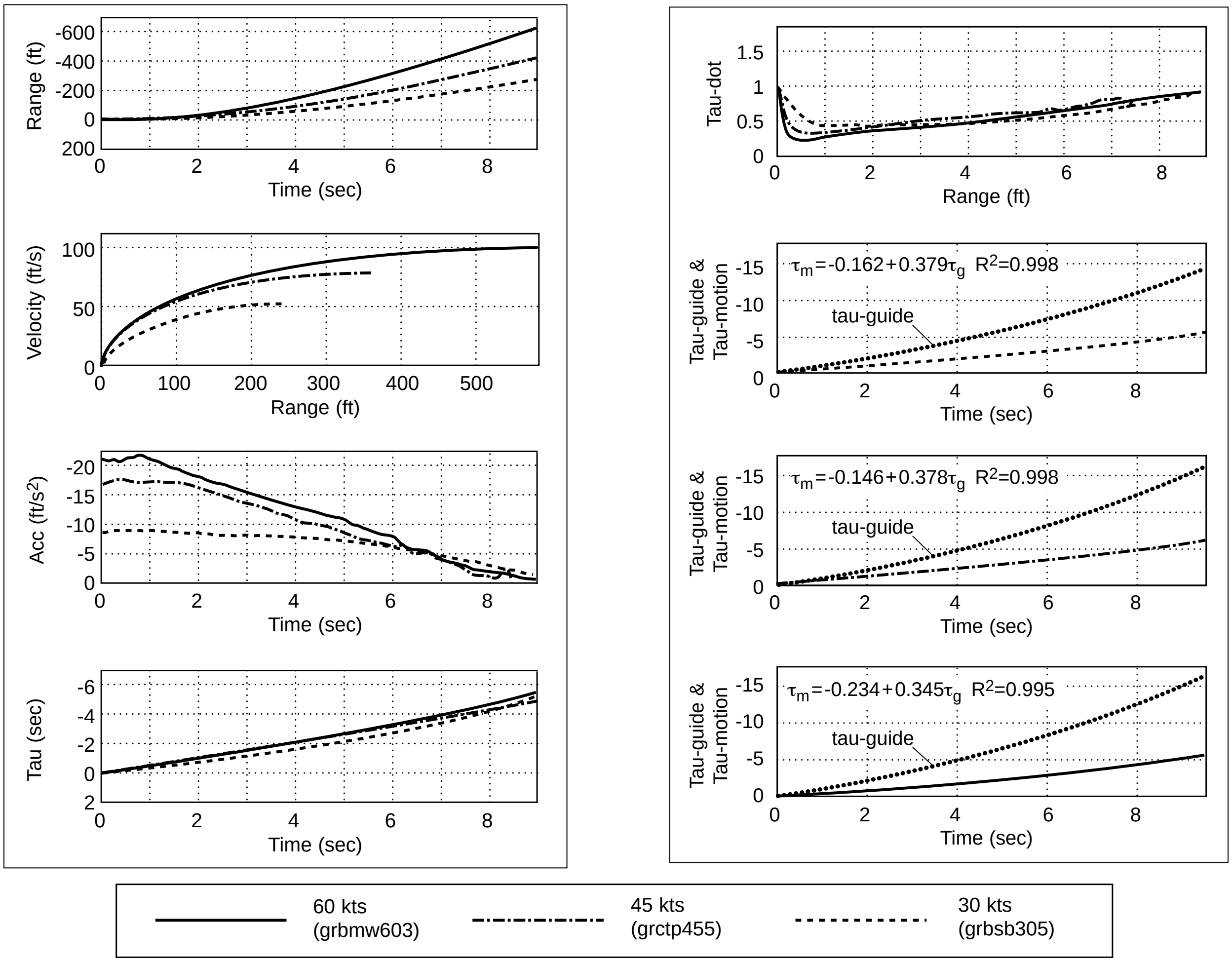

Fig 21 Decel-to-Stop Manoeuvre Results

Fig 22 Decel-to-Stop Manoeuvre Results (cont.)

Fig 21 shows the range, velocity, deceleration and tau profiles. Fig 22 shows the $\dot{\tau}$ profiles and a comparison of the motion tau (τ_m) with the constant acceleration guide (τ_g) according to equation 15. Also shown are the least squares fits of τ_m to τ_g. Note that the $\dot{\tau}$ values consistently increase to unity during the final 0.5 seconds of the manoeuvre, indicating that the subjects did not achieve a perfect stop. The coupling parameters are given by the slope of the fit function and are remarkably similar for the 3 cases. We can hypothesise that for such a simple, single axis, task the subjects pick up the same optical flow components from which the coupling strategy is activated. How to establish the value to prospective control of the various scene components is the subject of the continuing research, moving through to the second stage where 'scene-thinning' is carried out. Future simulation plans include examination of other simple manoeuvres, unlocking the secondary control axes for more complex manoeuvres (e.g. turn through gap, climb over rising ground) flown by helicopter test pilots, and different forms of scene content. Complementary to the piloted-simulation plans, a synthesis technique is currently under development whereby non-piloted 'constrained' simulations will be used to explore how pilot control strategies change when the available visual cues are changed. It is in the nature of such constrained simulation that the parameters of the pilot model reflect the changing task demands (Ref 16). In the current application we are developing a model that responds directly to errors in the tau-coupling; results will be reported on a future occasion.

Conclusions

This paper has presented the first application of tau-coupling to aircraft flight. The theory of tau-coupling has been considered within the context of helicopter flight close to the ground in a cluttered environment. Results derived from flight simulation tests conducted at DERA and The University of Liverpool have shown that when pilots fly stopping manoeuvres there is a close correlation between the motion-tau (i.e. instantaneous time to reach the stop point) and a pilot-generated tau-guide that can follow constant $\dot{\tau}$ or acceleration laws. The correlation is so tight that the inevitable hypothesis is that the tau-model of pilot visual perception and motion is eminently suitable for extension to other flight manoeuvres and forms a robust framework for the re-construction of visual information in pilot displays.

The answer to the question, 'how do pilots stop, turn or pull up?' is that they seek out the visual information from the optical flow on the surfaces, over and around which they fly, that provide for tau-coupling. When this information remains consistent and is sufficiently prospective, then the manoeuvres will proceed safely. When insufficient information is available to couple more than one motion tau, then the pilot creates a mental model of the prospective motion, from which a tau-guide is activated that leads the pilot along a safe flight path. Flight safety is only assured if the pilot has sufficient information for coupling motion tau's or following self-generated tau-guides. The tau-theory of visual perception provides a coherent framework for research into synthetic vision systems and, ultimately, the development of an integrated prospective flight control system.

Acknowledgements

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