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Progress in the Development of Guidance Strategies For the Landing Flare Manoeuvre Using Tau-based Parameters

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Airline transport operations can be carried out in a wide range of visual and instrument meteorological conditions. For all but the most limiting of degraded visibility situations, however, the pilot can choose to land the aircraft manually, using the visual cues available through the cockpit windshield. The answer to the question - how is this achieved? – may seem rather obvious but has actually challenged researchers for some time. The optical flow theory of visual perception offers a possible solution in terms of the way pilots pick up motion on the surfaces over which they move. In its most recent incarnation, flow theory transforms motion into its associated temporal space, based on the time-to-contact parameter tau, defined as the time to close on a surface at current closure rate. Research conducted at Liverpool has already applied this theory to low-level helicopter flight. This paper reports on the progress made in a project established to apply the theory to fixed wing aircraft to provide an engineering basis to the design of novel display technology. Analysis of a number of aircraft manoeuvres is presented in the tau domain. The results of the tau analysis of the landing manoeuvre suggest that both a constant rate of change of tau strategy and an intrinsic tau-guidance strategy will yield benefits in terms of touchdown descent rate if presented as display symbology. Potential uses of these results are presented in terms of the application to pilot vision aids, which is the planned next stage of this work, and also flight training and flight safety.

Nomenclature

c	=	constant rate of change of tau
k	=	constant of proportionality between the taus of two gaps being coupled
τ	=	time to contact or close on a surface (s)
t	=	current time during gap closure (s)
T	=	total elapsed time of gap closure manoeuvre (s)

I. Introduction

PRESENT day airline transport operations can be, and often are, highly automated. Given a suitably equipped aircraft and departure and destination aerodromes, an airline pilot is able to 'fly' the entire journey automatically. Of course, not all aircraft and aerodromes are suitable equipped. Even if suitable equipment does exist, the pilot may elect to fly the aircraft manually or indeed, may be forced to because the required equipment is unserviceable. Such phases of manually controlled flight can take place in all but the most limiting of visibility conditions. In this case, the pilot must rely on the information received from the aircraft instrumentation, his/her vestibular system and the view from the cockpit window. Flying an aircraft can be divided into three sub-tasks – navigation, (flight path) guidance and (attitude) stabilization. When flying an aircraft close to the ground the pilot is concerned with the latter two tasks and relies significantly on the outside world cues. This paper will deal with the use of the theory of visual perception. It is therefore the view from the cockpit window and how this is transformed by the pilot into control inputs that is of most relevance.

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Many natural species rely primarily on optical information to follow a safe path through the cluttered environment near the Earth's surface. In a similar way, pilots must use visual perception of motion to create a mental model of where their aircraft will be in the future, to fly a safe path through their surroundings. The reliability of this model is particularly critical when flying close to the ground or near to obstacles. In a good visual environment, the pilot is usually able to pick up sufficient information from the available visual scene. As the visual environment degrades, for example, due to adverse weather conditions, the available visual information becomes less reliable. To counteract this degradation, the pilot will require some form of guidance vision aid; cockpit instruments provide information for stabilisation and raw flight path data but cannot guide the pilot safely close to the surface.

To provide such a vision aid, a complete reconstruction of the natural world from active/passive sensors coupled with terrain databases, while achievable in principle, would be a massively expensive endeavour in the short term. This begs the question: what is the minimum necessary and sufficient visual information required by a pilot to develop a reliable mental model, rather than a dangerous illusion, that will allow safe flight through the surrounding environment? A project, entitled Prospective Sky Guides (PSG), has been under way at The University of Liverpool (UoL) to try to answer this question by: (1) establishing a coherent engineering basis for the methods of (visual) motion perception and control to inform the design of pilot aids that will support flight in degraded visual conditions, particularly when close to the ground and (2) constructing and evaluating synthetic displays that recover the visual cues necessary to allow flight in degraded visual conditions for a range of manoeuvres. This paper reports on the progress made during the course of the PSG project, a sample of the results achieved to date and the planned next steps to achieving a guidance vision aid.

II. Civil Transport Safety Review

The ultimate aim of the PSG project is to provide a vision aid concept appropriate to all phases of flight; from taxi to the runway, through take-off, climb out and cruise to landing and then the taxi back to the stand. It was considered prudent, however, to expend most effort on those phases of flight where a vision aid would provide most benefit in terms of increasing flight safety. It is perhaps common sense that the most dangerous phases of flight are those conducted on or near to the ground. In order to verify such an assertion, a review of aviation safety statistics was carried out[1]. The key results are presented below.

Aviation safety statistics are available from a number of sources. In the U.K., the Civil Aviation Authority (CAA) produces both UK and global aviation accident statistics[2-4]. In the U.S., the National Transportation Safety Board (NTSB) performs a similar function[5]. Figure 1 shows an analysis of global fatal accidents to jet and turboprop aircraft with a Maximum Take Off Weight (MTOW) above 5,700kg by phase of flight[2]. Of the 621 fatal aircraft accidents that occurred during the period 1980 – 1996 (inclusive), 15% occur during the take-off and initial climb and 50% during the approach and landing phases of flight (including go-around).

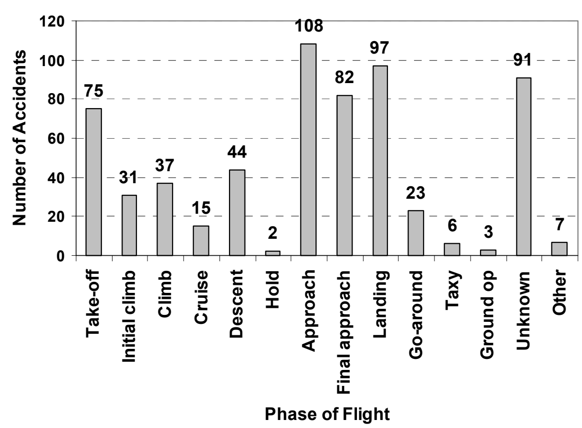

Figure 1. Global Fatal Accidents by Phase of Flight 1980 – 1996.

Each accident is assigned a causal factor and a consequence. The two most frequently identified causal factors are: (1) lack of positional awareness in the air and (2) the omission of an action or the carrying out of an inappropriate action. These translate to the aircraft crew not appreciating their proximity to the ground and descending below the (legal) safe altitude without a visual reference or when visual cues were lost[2]. The two most frequently identified consequences are collision with terrain/water/obstacle and controlled flight into terrain (CFIT). Updates to this data over subsequent years[3-4] show the same primary causal factors and consequences.

NTSB data show similar accident trends over the period 1983 – 1996 in terms of the phases of flight in which accidents occur. Furthermore, the NTSB data show that a greater number of accidents occurred on take-off in Visual Meteorological Conditions (VMC) than in Instrument Meteorological Conditions (IMC, 30 and 12 respectively) and that a similar number of accidents occurred in both VMC and IMC during the Approach and Land phases of flight (25 and 30 respectively).

Taking the findings of Refs. 2-5 together, it is considered that a vision guidance aid that recreates or provides the additional visual cues necessary to improve pilot situational awareness in flight has the clear potential to:

(i) improve pilot awareness of the proximity of the aircraft to the ground,
(ii) improve 'visibility' in degraded visual conditions/adverse weather and,
(iii) provide the pilot with improved information regarding the proximity of objects on the ground

All of these 'improvements' would contribute to the reduction of the number of global fatal aircraft accidents. The design of such a device would ideally provide enhanced visual cues for all phases of flight. However, to gain the greatest reduction in fatal accidents from a device that provides enhanced/synthetic visual cues, the Take-off, Initial Climb, Approach and Landing phases of flight should be targeted as a priority. An additional important aspect of such a display that derives from the NTSB data is that it be both useable and useful in both good and degraded visual conditions (i.e. VMC and IMC in the context of the preceding discussion). It is this task that has guided the project execution to date.

III. Review of Current and Near Future Civil Transport Guidance Technology

The pilot of a modern civil transport aircraft already has a number of systems at his/her disposal to provide guidance information of the aircraft through the environment. To avoid 're-inventing the wheel', it is useful to consider both the state-of-the-art guidance display technology available in the airline transport industry today and the displays that are already being explored for the future. Relatively up-to-date treatments of modern display technology can be found in Refs. 6 and 7. The information pertinent to the PSG project is summarized below.

A. Current Guidance Display Technology

Before continuing the discussion, the term 'guidance' needs to be elaborated upon. Classically, as noted previously, there are three tasks that a pilot must carry out during a flight: navigation, guidance and stabilisation[8]. The navigation task deals with the pilot knowing the current and next desired position of the aircraft with respect to the Earth's surface, with timescales measured in minutes and distances measured in miles. Stabilisation of the aircraft, at the other extreme, involves the continuous correction of small localized errors in the desired flight path or aircraft attitude induced by, for example, atmospheric conditions. Much of this task is automated for large transport operations but will still be required for example, during a manual approach and landing in gusty conditions. The stabilization task involves timescales of the order of a second and rotations of a few degrees. The guidance task falls between the stabilization task and navigation task in terms of both the timescales and spatial measures with which the pilot is concerned. It deals with, for example, the avoidance of obstacles when close to or on the ground and involves timescales of several seconds and distances of several hundreds of feet. It is the aircraft guidance function for which the PSG project seeks to develop novel vision aids.

Modern transport aircraft are fitted with 'glass-cockpits' to provide the pilot with flight information. That is, flight data are displayed using software-generated displays using cathode ray tube (CRT) technology. At present, the instruments displayed, in many cases, are similar to the analogue devices that they replace. This is considered to be a positive advantage in that this replication reduces the need for flight crew re-training.

Typically, there are two CRT displays per flight crew member mounted side-by-side: a Primary Flight Display (PFD) and a Navigation Display (ND). The PFD provides the following information to assist guidance and stabilisation: aircraft attitude information; speed and altitude information (including trends for projected speed at current power setting in 10 seconds); flight path deviations obtained from, for example, an Instrument Landing System (ILS), flight director command bars, lateral acceleration, a flight path vector (FPV, shows the aircraft horizontal and vertical flight path angles) and a flight path target (the desired aircraft horizontal and vertical flight path angles). The ND provides the pilot with either a plan view of the aircraft position with respect to the planned track or an electronic version of the Horizontal Situation Indicator (HSI). Due to their positions in the cockpit, the PFD and ND are sometimes referred to as Head-Down Displays (HDD).

Although in use with the UK military since 1961, it is only in the last decade that Head-Up Displays (HUDs) have begun to appear on the flight decks of civil transport aircraft[9]. The HUD derives its name from the fact that flight information is displayed using a glass 'combiner' that sits between the pilot and the outside world. Key features of such a display image are (1) some symbology can be conformal and (2) it is displayed at infinity or collimated. A conformal display element is one where angles are preserved between the display and the outside world. For example, the FPV on a HUD shows the pilot where the aircraft is heading in real world space. So, by placing and maintaining the FPV on the touchdown markers of a runway, the pilot can ensure that a steady approach will be achieved. Providing flight information displayed at infinity means that the pilot can maintain his view out of the cockpit window and does not have to continually refocus on the instruments on the HDD. This is particularly advantageous in poor visibility on the approach when the flight crew needs to maintain station on an approach profile and look for visual cues to allow them to land within legal requirements.

A number of manufacturers produce HUDs for civil aircraft. One example of a civil HUD is the BAE Systems 2020 Visual Guidance System (VGS)[10]. The VGS provides all of the usual flight information in a standard conformal format. Its 'look and feel' is based upon HDD symbology. In addition however, the VGS is capable of providing the pilot with: a clear touchdown point, even at airfields where precision approach equipment does not exist; acceleration cues to assist with total energy management; a guidance cue to assist with making precise corrections to flight path, the flare and ground roll-out; precision take-off guidance in the form of runway centre-line cueing and a mode to provide cues to support recovery from unusual attitudes. This display has been designated the current 'state-of-the-art' for the PSG project. It is to be used as a baseline against which novel displays developed during the course of the project will be tested and compared.

B. Emerging Advanced Guidance Displays

The primary sense utilized by humans to guide through their environment is sight. Sight has evolved into a precision system that enables light rays impinging on the 2-dimensional retinal surface to be interpreted instantly ('at-a-glance'), intuitively and in three dimensions. The displays described in the previous section provide an entirely two dimensional representation of the information required for flight. The pilot must assimilate the data presented to him and construct a mental picture of the flight path of the aircraft in three dimensions from rather limited information. This may not be intuitive and will certainly not be instant, particularly in unfamiliar situations. The research being conducted into the next generation of flight deck displays is attempting to address these issues.

In order to relieve some of the burden of recreating the vertical aircraft situation in relation to surrounding terrain, Boeing have developed the Vertical Situation Display (VSD)[6]. The VSD depicts a side view of the local terrain and current aircraft flight path to the pilot. It is a corollary in the vertical plane to the existing plan view representations of the aircraft position that is presented on a typical ND. This is a step forward but is still not intuitive, and certainly not conformal, as the vertical display is presented perpendicular to the actual direction of travel. The pilot must adjust the display direction to the 'forward' direction of flight.

In an attempt to make flight-deck guidance displays more intuitive, three-dimensional representations of the outside world overlaid with the pre-planned route have been in existence within the research community for some time. The pre-planned route can take the form of a tunnel, a channel or even a pavement[11-13]. The termed 'highway in the sky' (HITS) has been used to describe such displays. In addition to the pre-planned route, some researchers have experimented with the addition of a flight path predictor symbol that illustrates where the aircraft will be at some future time. With the addition of this time-based symbology, these displays are sometimes referred to as being four dimensional[14-15].

The VSD and HITS symbology is presented to the pilot on a HDD. They are still two-dimensional representations of a three dimensional world. The merits of HUDs have already been briefly discussed. One of the major drawbacks of a traditional HUD, however, is that their symbology has to be restricted to line drawings to limit the amount of the outside view that is obscured. They also tend to be monochrome. This limits any image to a strictly two-dimensional representation of a three-dimensional world. In an attempt to address this issue, a stereoscopic HUD has been developed and integrated into a fixed-base flight simulator[16]. This offers a number of claimed advantages such as: (1) improved perception of information in the outside view; (2) a decluttered display as information is spatially separated so is less likely to merge; (3) flight-path, terrain and obstacles can be seen in their spatial position and (4) new 3D symbology can be introduced to enhance spatial awareness and motion perception.

A third class of 'novel' display technologies has also been experimented with over the years (see, for example, Ref. 17). These provide the pilot with data to allow aircraft flight path control in a more abstract/symbolic manner than those displays mentioned thus far. A more extensive description of these displays is beyond the scope of this paper and the reader is encouraged to consult the reference if so inclined.

With all of the above in mind, the PSG project is exploring display concepts that are primarily 'head-up'. Both command and prospective flight path information will be utilized in the display.

IV. Transport Aircraft Mission Definition

In order to be able to assess the utility of any new vision guidance aids and to provide a useful comparison with that of the BAE Systems VGS baseline display, it is necessary to construct a set of repeatable tests. To that end, the project has taken its lead from the rotorcraft developments in Refs. 8, 18 and 19. A set of Mission Task Elements (MTEs) have been created as follows.

The operation of an aircraft can be broken down into the 'Missions' for which it will be used e.g. Transport Mission. Each mission can be further broken down into a number of distinct 'Phases' e.g. Take-Off, Climb, Approach etc. A mission phase can be described as a portion of the aircraft mission where a specific objective has to be achieved. The final step is to divide each phase up into a series of MTEs. An MTE is an individual component of a mission phase that has a distinct start and end condition (usually trimmed), has a specific piloting requirement and exercises the aircraft's flight or ground-handling characteristics. The definition of an MTE should include the operational objectives of the task (including the performance requirements) and the piloting requirements (including those needing special attention). Reference 20 provides the results of a mission analysis conducted for the PSG project for a civil transport aircraft. Space constraints preclude the inclusion of the results in this paper, but suffice to say that the typical transport mission was deconstructed into 16 MTEs; the near Earth MTEs are of most, although not exclusive, interest in the present study.

V. Ecological Approach to Motion Perception Theory

Despite all of the automation available to the transport pilot of today, there are still phases of flight that are mandated to be flown with reference to the visual cues obtained from the outside world. In such cases, the pilot has to rely on aircraft motion information received through the windscreen to guide the aircraft on the desired trajectory. The question arises as to how such a feat is achieved. The answer may seem obvious to some but has challenged researchers for some time[21-24]. A number of theories exist in the field of psychology, or perhaps more specifically, psychophysics, that provide a framework to explain how an animal perceives, and is thus able to control, its motion through the environment. The work on the PSG project has been guided by the ecological approach to motion perception using optic flow as a starting point.

The roots of ecological psychology are based in the aerospace field. J.J. Gibson investigated the use of pictures, both static and motion, for the selection of aircrew for the USAAC[25]. He was particularly attracted to the motion picture as a training aid due to the additional information that was available to the observer due to the movement of objects in the film. Gibson later hypothesized that this extra information came from the optic flow field – the way in which individual points in the scene move from moment to moment – that the motion caused. In his later work, Gibson cites the approach and land phases of flight as examples of how a pilot uses the optic flow available to him to control aircraft motion[26,27]. It has been shown that optic flow rate can provide the pilot with information about ground speed in eye-heights per second[28] or surface slant[29].

A student of Gibson's, David Lee, further developed the theory of optic flow and introduced an optical parameter tau, (τ), defined as the time to contact or close on a surface, see e.g. Refs 30-31. The earliest hypothesis that used tau concerned the controlling of a gap during the deceleration phase of an approach to an object ahead. The hypothesis stated that during such a manoeuvre, the rate of change of tau, would remain constant i.e.

$$\dot{\tau}_x = c \tag{1}$$

Research conducted at The UoL has shown that when helicopter pilots fly stopping manoeuvres close to the ground, a constant tau-dot strategy is adopted until the final moments of the manoeuvre[32]. The work suggests that the tau model of pilot perception is correlated so well with experimental results that it is suitable for extension to other flight manoeuvres. It further indicates that optical tau and tau-dot should be key variables used to guide and design vision augmentation systems. The PSG project picks up this challenge for fixed-wing aircraft.

In order to proceed further, there are a number of key principles on which tau theory is based that need to be raised. First, the control of tau is concerned with the closure of gaps (be they spatial or otherwise). A key method of closing gaps is by coupling the taus of different gaps[33], as shown in Eq. 2.

$$\tau_x = k\tau_y \tag{2}$$

where 'x' and 'y' are two variables that represent the values of the gaps being closed and 'k' is the coupling constant. τ_x and τ_y vary with time whilst 'k' is constant over time. Second, any gap closure must be prospective i.e. concerned with the future motion as well as the current motion. For example, a tennis player must learn to judge where to place the racquet to come into contact with the moving ball at some future time in order to return a shot.

The coupling of taus to close gaps can be extrinsic or intrinsic. An extrinsic coupling closes two externally perceived gaps. Where there is no obvious second gap available, it is hypothesized that an internally generated bodily process, e.g. electrical charge flowing in the brain, creates an intrinsic tau guide with which to couple. A *General Intrinsic* tau guide, designated τ_G, has been theorised as per Eq. 3[34].

$$\tau_G = \frac{t(T+t)}{T+2t} \tag{3}$$

So, to couple this guide onto an external gap, 'x', Eq. 4 must apply:

$$\tau_x = k\tau_G \tag{4}$$

When coupled onto such a guide, an object in motion will follow one of the normalised motion profiles shown in Figure 2, taken from Ref. 34. Inspection of these profiles reveals that the value of 'k' selected will provide differing responses when approaching a target surface or object (from time to go -0.5 to 0.0). A value of k<1.0 results in an acceleration - deceleration motion. As k approaches 1.0, the deceleration phase of the motion starts at an increasingly later time. If k=1.0, the resulting motion is performed under constant acceleration. The body under motion reaches the target with some residual velocity. If a value of k>1.0 is selected, then the object continues to accelerate towards the target. The profiles described by Eq. 4 can be used as a template when identifying motions that are potentially guided using a tau strategy.

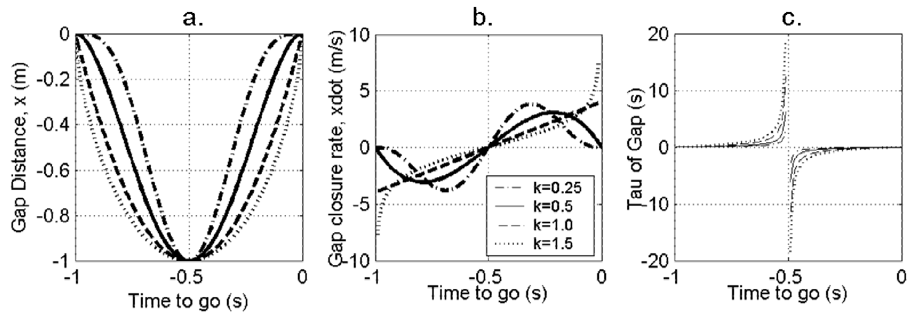

Figure 2. Normalised motion profile of a 1kg mass coupled to the General Intrinsic Tau Guide for varying values of coupling constant, k: (a) distance of mass from target; (b) instantaneous velocity of mass and (c) tau of distance for the mass.

VI. Experimental Results

To build on the rotary wing work already conducted at Liverpool, a number of experimental analyses have been carried out on a fixed-wing large transport aircraft simulation model. The first is a survey of gaps that the pilot closes during the civil transport MTEs was carried out to establish evidence for whether or not tau-based strategies are employed in these manoeuvres. The second is a more detailed tau-domain analysis of a series of approach and land manoeuvres performed in both real and simulated flight tests.

A. Survey for Tau-Based Relationships

A flight trial was conducted in the Bibby Flight Simulation Laboratory[35] primarily to verify the flight characteristics of a generic large transport aircraft simulation model constructed for the project[36]. This trial also provided the opportunity to perform an initial tau-domain analysis for the range of manoeuvres performed. All manoeuvres were carried out in a (simulated) good visual environment (GVE) and nil wind conditions. Typical examples of gap closures that were considered are: (1) pitch angle closure to a nominal target value during rotation for take-off and (2) the height of the aircraft during an approach/flare/touchdown manoeuvre. The latter case will be dealt with in more detail in the next section so a small sample of representative results for the first case is presented in Fig. 3.

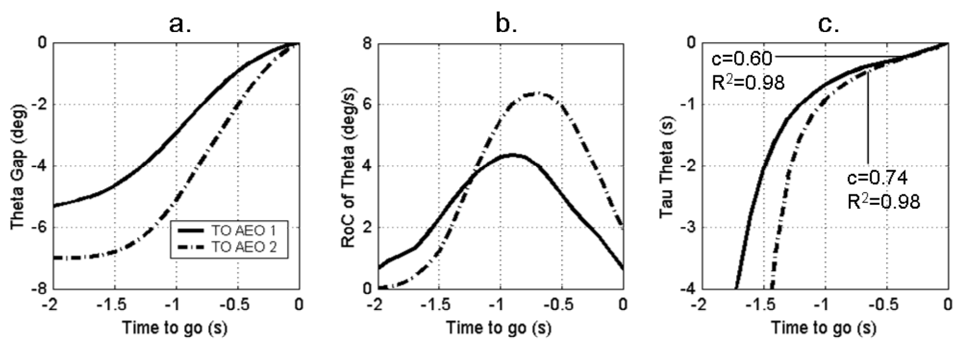

Figure 3. Analysis of Tau of Aircraft Pitch Angle for two take-offs with All Engines Operating (AEO): (a) closure of gap to selected pitch angle; (b) pitch rate over gap closure and (c) resultant tau of pitch angle.

Fig. 3 (a) shows the closure of the gap between the aircraft pitch angle on the ground and the initial pitch angle selected by the pilot during the rotation to unstick attitude for the take-off MTEs. An approximately constant tau-dot is observed over the final portion of the manoeuvre in Fig. 3(c). Inspection of Fig. 3 (b) reveals strong similarities in the shape of the curves with those of the latter half of Fig. 2(b). They were therefore considered as suitable candidates for manoeuvres that demonstrate coupling with the General Intrinsic Tau guide of Eq. 2. Fig. 4 shows the results of an analysis into what such a coupling would look like.

It can be seen from Fig. 4 that a well correlated coupling exists with τ_G over the final second or so of the pitch-up manoeuvre. The coupling constant observed in Figs 4 (a) and (b) would suggest that the initial pitch angle selected was captured successfully. This is indeed what is observed in the trial data.

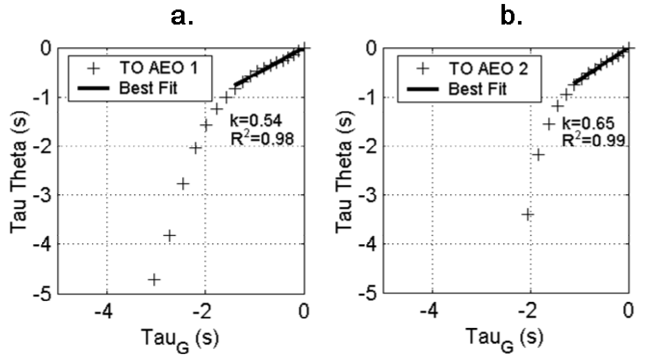

Figure 4. Coupling analysis between tau of height and general intrinsic tau guide for two take-off manoeuvres

Ref. 32 reported on the results of rotary wing accel-decel manoeuvres which are primarily concerned with the pitch axis of the vehicle and the control of longitudinal position. Tau analyses of these manoeuvres demonstrate good correlation between both constant tau-dot and tau-guided flight strategies. The results of the take-off MTE suggest that pilots utilize a similar strategy in the pitch axis for fixed-wing aircraft.

B. Landing and Flare

As the title of the paper suggests, of particular interest to the project are manoeuvres that are carried out during the approach and land phases of flight. Once the aircraft has left the ground, it must be brought safely back to earth using a suitable landing technique - the pilot must bring the aircraft height above ground to zero as the vertical velocity approaches zero. The pilot must do this by transforming the perceived aircraft motion from the optical frame of reference to the inertial frame of reference and by then applying feedback regulation to minimize errors between the commanded and perceived motion[32]. As a prelude to capturing and analysing data recorded within the project, previously reported flight test data for the approach and flare from pilots transitioning to the DC-10 aircraft[37] have been analysed in the tau domain. Fig. 5 illustrates two techniques adopted by pilots during the final phase of the approach, through the flare to touchdown. The first technique (Pilot 441) involves a continuous deceleration all of the way to touchdown. This results in a constant rate of change of height tau (τ_h) over the last few seconds of the manoeuvre. The second technique (Pilot 429) involves the pilot flaring the aircraft to a constant vertical speed a couple of seconds prior to touchdown. This rate of descent is maintained down to the runway surface. Such a manoeuvre results in an approximately constant height tau during the deceleration to the selected vertical speed. The descent to touchdown is then characterised by a constant tau-dot of approximately 1.0. The techniques identified were not pilot-specific i.e. individual pilots used both techniques for different touchdowns. Identical piloting techniques were observed in simulated flight trials at Liverpool in varying levels of degraded visual environments (DVE)[38].

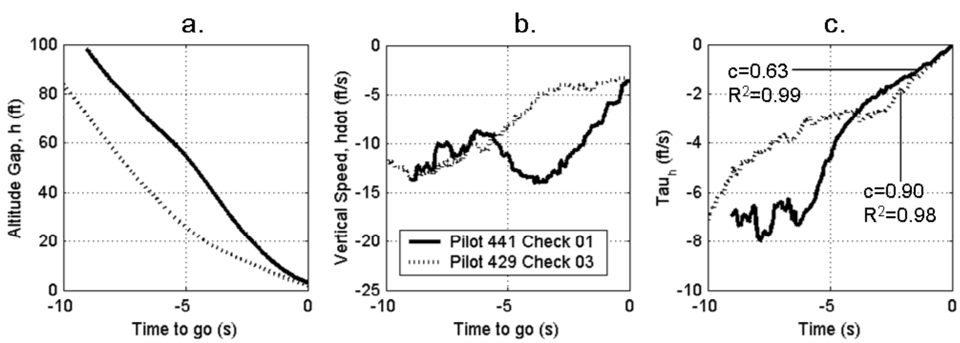

Figure 5. Two techniques used for flare and touchdown illustrated in the tau domain: (a) altitude gap closure; (b) vertical descent rate and (c) tau of height above runway.

From the beginning of training, pilots are taught to recognise the moment that they should commence the flare. This, of course, will vary from aircraft type to aircraft type (amongst other things). The cues available to the pilot to allow such a decision to be made will differ depending upon the airfield environs and the visual conditions on the day. A pilot will initially learn this technique at a familiar home airfield but must then apply it further afield.

Fig. 5(b) is interesting as the descent rate profile exhibited by Pilot 441 is similar to the velocity profile 'template' for motion guided by an intrinsic tau guide in Fig. 2(b). It was therefore hypothesized that the 'training' allowed pilots to calibrate an intrinsic guide onto which they could couple the optical height-gap perceived from the visual field. An analysis was therefore carried out to ascertain the value of the coupling constant, k (Eq. 4) for the tau of the height of the aircraft coupled with the General Intrinsic tau guide (Eq. 3) for the flight test data of Ref. 37 and the simulated flight test data of Ref. 38. Only those cases where the velocity profile of the descent had a character similar to that of Pilot 441 of Fig. 5(b) were selected for this analysis.

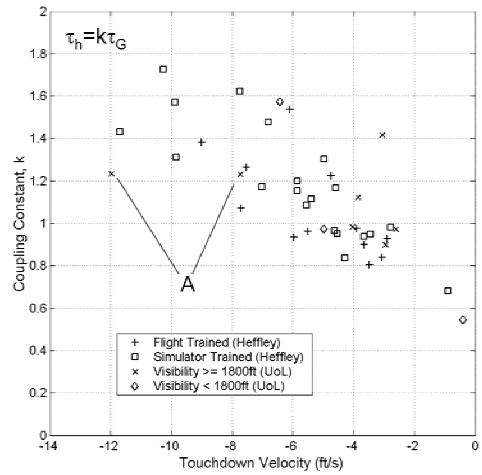

Figure 6. Variation of General Intrinsic Tau Guide coupling constant, k, with vertical descent rate at touchdown.

Fig. 6 shows the results of this analysis. There is an approximately linear correlation between coupling constant and touchdown velocity. Generally speaking, the higher the coupling constant, the higher is the touchdown velocity. Simulator trained pilots from Ref. 37 exhibit higher coupling constants and hence higher touchdown rates than their flight-trained colleagues (which is consistent with the findings of the referenced report).

The Liverpool test points are consistent with this trend. They show that reasonable touchdown rates (< 5 ft/s) were achieved in all levels of visual environment. On a few occasions, high touchdown rates and coupling constants are observed. The data appear to show that high touchdown rates were achieved more often in good visual environments (visibility >= 1800ft) then in degraded environments. These test points (marked 'A') were actually conducted in a simulated night scene where the only cues available to the pilot were the runway lights. The visual scene, in this case, was highly degraded (but with good visibility, there just wasn't much to see). It is believed that, in these instances, the cues from the outside world visual scene were insufficient to allow the pilot to detect the high sink rate that had developed.

Overall, the data of Fig. 6 suggests that control of touchdown velocity may be achieved by providing the pilot with a means of coupling the aircraft motion onto the General Intrinsic Tau Guide with a suitable value of the coupling constant, 'k'.

VII. Discussion

The results presented a number of interesting possibilities for the design of displays for use in airline operations generally. There are many gaps that a pilot must close during a flight. For example, the gap between the current and desired pitch angle during the rotation to take-off, the gap between the required glide slope and the actual glide slope angle or the gap between aircraft landing gear and runway surface. In each case, there is the intriguing possibility that the closure of this gap can be guided by a simple, time to contact/close parameter, tau. Indeed, the evidence presented in this paper suggests that, for two manoeuvre examples at least, this is the natural mechanism by which gaps are closed. Tau could be used in two ways. Firstly, it could be used as a measure of the quality or sufficiency of a display. Baseline tau profiles can be defined for each manoeuvre of interest in a GVE. One measure of the effectiveness of any new display can then be defined as how closely the manoeuvres flown in a DVE using the display match the baseline. The second option is, rather than tau being a passive measure of display effectiveness, it could be used as a parameter to actually drive display symbology. Using the approach and landing as an example, during the approach, the display would command that the pilot fly a profile where the rate of change of the tau of height = 1. As the flare needs to be initiated, the display could then command a reduced rate of change of height tau to ensure an acceptable descent rate at touchdown. Alternatively, a touchdown descent rate could be commanded using a display that couples the aircraft motion to a General Intrinsic tau guide with a suitable choice of coupling constant.

Flight safety is another area that the optical flow variable tau might well find application. Major airlines already monitor their operations using sensors onboard the aircraft. These sensors trigger 'events' when a particular condition is met e.g. for one UK-based operator, a high rate of descent below 2000 feet triggers a monitoring event. In the context of the current research, examples of events that might trigger an alert event are the use of a height-tau coupling constant above a pre-defined value or a height tau-dot of, say, between 0.75 and 0.95.

A third potential use of the parameter tau would be in flight training. The landing of an aircraft is perhaps one of the more difficult manoeuvres to achieve and the progress of a student's ability to perform it well could be measured in terms of the height-tau couplings achieved or the height tau-dot values used.

VIII. Next Steps

At the time of writing a number of display concepts are under development for testing in simulation at Liverpool. Their performance will be measured against the BAE VGS baseline display. Important factors in these trials will be the simulation of 'real' atmospheric conditions and the use of several pilots. The simulation results reported in this paper have all been conducted in 'ideal' atmospheric conditions i.e. no wind, no gusts, and where the pilot has only had to close vertical motion gaps. In a real landing, the pilot will have many gaps to close. Further work needs to be performed to establish what a tau-based display would look like to assist in this procedure. The results of this work and future trials will be reported at a later date.

IX. Concluding Remarks

Despite the great efforts of all of those involved in the aerospace industry to provide a safe means of travel, fatal accidents do still occur. Statistics show that the two primary causes of these accidents relate to flight crew having a poor appreciation of their proximity to the ground and/or making a decision to proceed below a safe altitude. Display technology is evolving to provide flight crews with increased spatial and situational awareness to try to prevent such accidents in the future and to improve operational effectiveness in degraded visual conditions. A project initiated at the University of Liverpool is contributing to this effort using ecological psychology as its guide. This branch of psychology provides a time-based theory (designated tau) regarding the manner by which animals guide themselves through the environment. Analysis of actual and simulated flight test data suggests that tau is being used by pilots to close various gaps during flight manoeuvres. Research at Liverpool has concentrated primarily on the tau of aircraft height during the approach and landing manoeuvre. This appears to follow either a constant rate of change of height tau or intrinsic tau guide law over the final few moments of the touchdown. This information will be used to inform the design of display formats that assist in the approach and land manoeuvre in both good and degraded visual environments.

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