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Executive Summary

This report first describes the development of a methodology to assess the handling qualities requirements for Vertical Take-Off and Landing-capable Personal Aerial Vehicles (PAVs). It is anticipated that such a PAV would be flown by a 'flight-naïve' pilot who has received less training than is typically received by today's general aviation private pilots. The methodology used to determine handling requirements for a PAV cannot therefore be based entirely on existing rotary-wing best practice – the use of highly experienced test pilots in a conventional handling assessment limits the degree to which results apply to the flight-naïve pilot. This report describes alternative methods based on both the subjective and objective analysis of performance and workload of flight-naïve pilots in typical PAV tasks. A highly reconfigurable generic flight dynamics simulation model that has been used to validate the methodology is also described. Results that highlight the efficacy of the various methods are presented and their suitability for use with flight naïve pilots demonstrated.

Secondly, this report describes research to develop handling qualities guidelines and criteria for a PAV. The objective has been to identify, for varying levels of flying skill, the response type requirements in order to ensure safe and precise flight. The work has shown that conventional rotorcraft response types such as rate command, attitude hold and attitude command, attitude hold are unsuitable for likely PAV pilots. However, response types such as translational rate command and acceleration command, speed hold permit 'flight naïve' pilots to perform demanding tasks with the required precision repeatedly.

Thirdly, this report describes research activities into the development of training requirements for pilots of PAVs. The work has included a Training Needs Analysis (TNA) to determine the skills that need to be developed by a PAV pilot and the development of a training programme that covers the development of the skills identified by the TNA. The effectiveness of the training programme has been evaluated using the first three Levels of Kirkpatrick's method. The evaluation showed that the developed training programme was effective, in terms of engaging the trainees with the subject, and in terms of developing the skills required to fly a series of PAV-mission related tasks in a flight simulator.

Fourthly, motivated by simulator test subjects expressing discomfort during taking the current constant-deceleration landing profiles, the report reports on progress made in the design and assessment of a "natural feeling" landing profile to guide PAV occupants from cruising flight, down an approach path, to bring the vehicle to a successful hover. The development of the new profile is motivated from the point of view that 'natural-feeling' cues are related to the physiological cues presented during a visual landing. As such, test subjects with little or no prior flight experience flew simulated approaches to a hover following limited instruction in the use of a vehicle model. It was found that the approaches were broadly similar and could be grouped into three distinct phases. Previous work in this field and tau theory phases were used to design an idealized approach profile based upon the simulation results. The report presents the final design and discusses a number of issues that arose from the simulator testing.

Finally, this report presents results from a study to investigate the use of novel control systems designed to provide a safe and reliable method for the control of a future PAV. The use of response and control characteristics derived from road vehicles is investigated. Objective and subjective techniques are used to quantify and qualify the applicability of automobile-like response characteristics using traditional helicopter control inceptors modified to behave somewhat like automobile controls, using foot pedals to control an Acceleration Command, Speed Hold system, for example. Additionally, the effects of eliminating vehicle pitch and roll dynamics are investigated to determine whether this allows a reduction in workload for non-professional pilots. Results suggest that, particularly for the most inexperienced of pilots, the automobile-like configuration is more suitable for control of a PAV than an augmented set of helicopter-style response types. This is shown through increased performance, and a reduction in subjective NASA Task Load Index (TLX) ratings. Improved Handling Qualities Ratings (HQRs) were also obtained in the automobile-like system for the tasks undertaken. Overall, removal of pitch and roll dynamics was not found to significantly affect task performance in the automobile-like system, but their absence resulted in a decrease in performance for the rotorcraft-style response type configurations tested.

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Notation and Glossary

a_x, a_z	Acceleration in the *x* and *z* axis, ft/s^2
c, C	Constant parameters
g	Acceleration of gravity, ft/s^2
h	Instantaneous height above the ground, ft
k	Coupling constant
K_g	Collective input to the command flight path angle
K_I, K_p	Proportional and integral gains
n	Constant parameter
t	Time, s
T_2	Period for the second phase manoeuvre, s
$\overline{t}$	Normalized by the first phase of the manoeuvre
u	Forward velocity in the body axis, ft/s
v	Body axis sway velocity [m/s]
V_x, V_z	Ground speed and vertical speed, ft/s
X_b, V_c	Longitudinal and collective inputs, inch
x, z	Pilot's viewpoint distance ahead of the aircraft and instantaneous height above the ground, ft
$\dot{x}$, $\ddot{x}$	Closure rate and acceleration to a boundary, ft/s, ft/s^2
Z_w, $Z_{\delta_{col}}$	Collective control and heave damping derivatives
z_τ	Instant gap to closure in the *z*-axis, ft
γ_a, $\dot{\gamma}_a$	Flight path angle gap to go and gap closure rate, deg, deg/s
γ_f	Final flight patch angle, deg
δ_{col},δ_{lon}	Collective and longitudinal control input, inch
η	Elevation angle, deg
ϑ	Pitch attitude, deg
τ	Instantaneous time to contact boundary in the optical field, *s*
τ_{U_p}	Time constant of surge response [s]
$\dot{\tau}$	Rate change of optical tau
ω	Eye height velocity, 1/s
A	Aptitude Test Score [-]
ACAH	Attitude Command, Attitude Hold
ACSH	Acceleration Command, Speed Hold
Alon	Turbulence Amplitude [-]
Apt.	Aptitude score
Exp.	Experience code
FoV	Field of View
HQs	Handling Qualities
HQR	Handling Qualities Rating
HUD	Head-Up Display
lat	Roll Response Natural Frequency [rad/s]
lat	Roll Response Damping Ratio [-]

lat	Lateral stick input [-1:1]
lon	Longitudinal stick input [-1:1]
lon,gust	Longitudinal stick input component from gust [-1:1]
lon,pilot	Longitudinal stick input component from pilot [-1:1]
lon,total	Longitudinal stick input from gust and pilot combined [-1:1]
cmd	Commanded Bank Angle [rad]
Klat	Lateral Control to Roll Attitude Gearing [rad]
Lw	Turbulence Scale Length Parameter [m]
MTE	Mission Task Element
P	Precision Metric [%]
PAV	Personal Aerial Vehicle
PPL	Private Pilot’s License
R2	Coefficient of Determination [-]
RC	Rate Command
TLX	Task Load Index
TPX	Task Performance Index
TRC	Translational Rate Command
TV	Thrust Vectored
U0	Mean Wind Speed [m/s]
W	Workload metric [1/sec]
Wmin	Theoretical minimum workload for an MTE [1/sec]
Wnoise	White Noise Input [-1:1]

1. Introduction

The development of aviation transport technology in the last half century has largely followed an evolutionary, rather than a revolutionary path. There is good reason for this; revolutionary developments carry much more risk. So, whilst the evolutionary approach has led to significant gains in performance, efficiency and safety, the fixed- and rotary-wing airframes of today, particularly in the civil transport arena, would be recognizable to the air traveller of 50 years ago. As a response to this perceived lack of revolutionary innovation in the air transport industry, the European Commission (EC) funded the 'Out of the Box' study of [1] to identify new and potentially disruptive concepts for air transport for use in the second half of the 21st century.

For ground transport, the problems are different. The volume of road traffic in and around the world's cities continues to increase (Refs. [2;3]). This results in serious congestion at peak times, which, in turn, seriously impacts on the output of global economies. For example, across Europe, delays due to road congestion have been estimated to cost approximately €100bn per year in [4]. A radical solution to this problem, proposed in [1], would be to move commuting traffic from the ground into the air using a Personal Aerial Transportation System (PATS). The results from the [1] were therefore used to inform the direction of some of the recent EC 7th Framework Programme (FP7) funding calls. One of the subsequent projects, funded by FP7, was *myCopter – Enabling Technologies for Personal Aerial Transportation Systems* (Ref. [5]). The aim of the four-year *myCopter* project was to develop some of the enabling technologies to allow a PATS to be realized.

For a PATS to be successful, it would be necessary to combine the benefits of conventional road transportation (door-to-door, available to all) and air transportation (high speed, comparatively free of congestion), whilst simultaneously avoiding the need for costly infrastructure such as airports, roads etc. The PATS would have to be capable of supporting air traffic flow volumes that are much higher than the present day (which, of course, may conflict with the need to avoid new infrastructure) whilst mitigating any environmental impact (both in terms of fuel efficiency and noise footprint) and ensuring appropriate levels of safety.

A key part of any PATS would be the Personal Aerial Vehicles (PAVs) that the travelling public would occupy. PAVs (as distinct from General Aviation (GA) aircraft) have existed for over half a century. Since the 1950s, a number of vehicle designs claiming to combine the benefits of the car and the aircraft have been produced. These have included 'roadable aircraft', vehicles which can be driven on the road and are also capable of conventional fixed-wing flight, such as those found in [6-8]. Similarly, a number of rotary-wing designs, such as [9-12] have reached at least the prototype stage for personal transportation purposes. To date, none has achieved mass production. There are many possible reasons for this. One is that the start point for each of these projects has been the vehicle design. The method by which it would be operated and how it would integrate with existing road and air transportation has not always been given due consideration. For example, roadable aircraft still require long runways to operate to and from, reducing their utility for relatively short commuter journeys. Another is that all of the vehicles would still require the user to obtain a pilot's license, creating possible financial and skills barriers to mass-adoption.

The *myCopter* project approached the challenges of personal aviation from a different perspective. The idea was to first identify how such a system would work and then how PAVs would operate within a PATS. The actual design of the PAV, which was not part of the *myCopter* project, could then follow. However, to inform the direction of the research, it was necessary to draw up a broad specification for a potential PAV configuration early in the project (Ref. [13]). It was envisaged that a

PAV would take the form of a small (1-2 seat) Vertical Take-Off and Landing (VTOL) vehicle capable of cruising at 80-120kts over a range of 50-60 miles. The *myCopter* PAV would not have road-going capabilities but should be accessible to anyone that can drive a car.

This report documents those tools and techniques used by the *myCopter* project team for these purposes for Work Package 2. It is structured as follows. In Section 2, an introduction to the methods developed during the project is presented. A Handling Qualities (HQ) approach was adopted to assess the candidate vehicle response types and the corresponding occupant training requirements for phases of flight that might require some form of human closed-loop control input. In Section 3, the previously described methodology is applied to identify, for varying levels of flying skill, the response type requirements to ensure safe and precise flight of a PAV. Section 4 considers the quantity and type of training that would be required by prospective PAV pilots in order to be qualified to operate a manually-piloted aircraft. A PAV training syllabus has been developed, and used to train a group of volunteers who had no previous flying experience. Section 5 focuses on the development of nature-inspired guidance trajectories for the visual landing of a PAV in a good visual environment. Section 6 describes the research involved in the creation, tuning and assessment of a PAV simulation configured to be representative of driving a car. The conclusions from this work are then drawn at the end of this report.

2. Methods to Assess the Handling Qualities Requirements for Personal Aerial Vehicles

To meet the requirement for general access to a PATS, it will be necessary to make significant reductions in the costs associated with traditional GA, including training, operating and maintenance costs. In order to try to reduce the cost of training, two approaches have been considered by *myCopter*. The first of these would be to implement autonomous capabilities on the PAV such that the occupant is not required to fly manually. This, however, implies software and hardware designed to very high safety assurance levels. In turn, this implies expensive testing and certification processes which will add to the development and hence acquisition costs of the vehicles. An alternative option (perhaps for early PAV adopters as the traffic densities would almost certainly have to be lower) is therefore to ascertain the required PAV HQs such that the degree of 'skill' associated with piloting the vehicle is significantly reduced compared to that required for a traditional GA rotorcraft. While very high levels of safety assurance will also be required for the flight control systems associated with delivering these excellent HQs, the process to achieve this should be more straightforward for manual flight than for fully autonomous flight.

Methods for HQ assessment of conventional military rotorcraft have become widely accepted using standards such as ADS-33E-PRF (Ref. [14]). These have been developed for use by professional test pilots who are assessing the vehicle's capabilities as a proxy for a well-trained and well-motivated professional pilot. The much broader spectrum of potential PAV occupants means that it was considered unlikely to be the case that these methods on their own would be directly applicable or even useable for PAV HQ assessments. It was therefore considered necessary, using the existing body of knowledge as a basis, to develop additional methods to support vehicle HQ analysis when the intended pilot is not a professional (termed 'flight-naïve' in the remainder of the report).

2.1. Test Environment

This Section describes the creation of the test environment used throughout the PAV HQ assessment process.

2.1.1. HELIFLIGHT-R Simulator

The main facility employed for the PAV HQ evaluations has been the HELIFLIGHT-R flight simulator at the University of Liverpool (UoL) as described in [15]. The crew station's instrument panel features a pair of reconfigurable 'glass cockpit' style Primary Flight Displays (PFDs, Fig. 1). For the *myCopter* HQ evaluations, the instrument panel displays were configured to show a slightly modified (through the addition of a radar altimeter and Height and Direction Hold engaged indicators (HH and DH respectively) representation of the Garmin G1000 GA glass cockpit PFD (Ref. [16]). It was anticipated that the clear presentation of the PFD symbology would permit the flight-naïve pilots taking part in the *myCopter* trials to learn to interpret the display quickly.

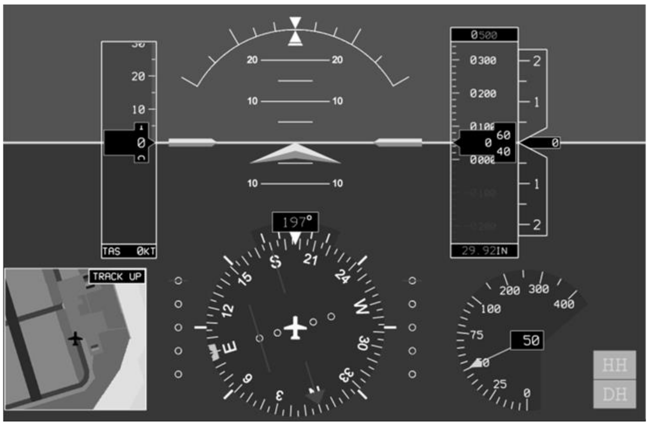


Fig. 1 Garmin G1000 PFD as Implemented at the University of Liverpool

In addition to the head-down display symbology offered by the G1000 panel, a set of basic Head-Up Display (HUD) symbology has been developed (Fig. 2). The HUD symbology includes: a Malcolm horizon line (Ref. [17]) spanning the full field of view of the simulator (rendered in orange-brown); a flight path vector symbol (white); an attitude indicator (green); numerical readouts of current airspeed (and, for the longitudinal acceleration-rate-based response type, described in the following Section, commanded airspeed), heading and height above the terrain (green apart from the commanded airspeed, which is red); and during decelerating flight, a conformal display indicating the ground position above which the vehicle will stop, assuming a constant deceleration rate (cyan).

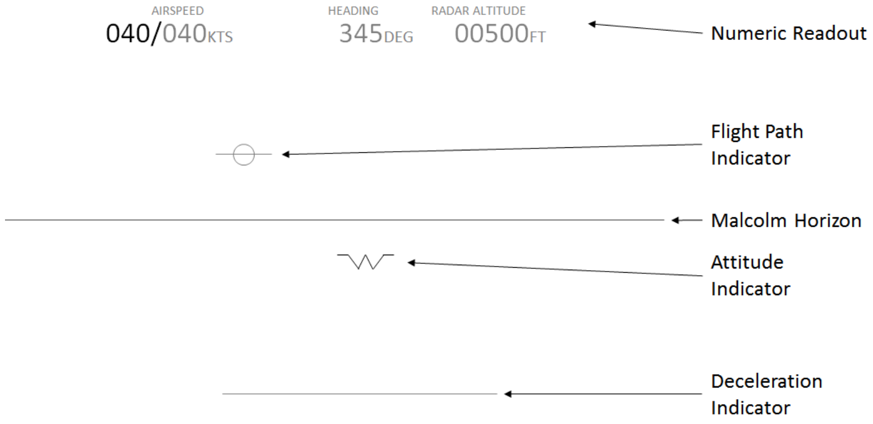


Fig. 2 Schematic of Head-Up Display Symbology

The HUD symbology has been kept deliberately simple and sparse so as to facilitate easy assimilation and interpretation by flight-naïve pilots. The exact requirements for such a display are one of the other areas of study for the *myCopter* project (Ref. [18]) and it is not claimed here that this is a final or optimum set.

2.1.2. PAV Model Configuration

The flight dynamics model used for the study was the General Purpose Dynamics Model (GPDM) created for the project. The underlying response types offered by the GPDM are either Rate Command (RC) or Attitude Command, Attitude Hold (ACAH) in the pitch and roll axes, and RC in the yaw and heave axes. These responses are created through 1st order (RC) or 2nd order (ACAH) transfer functions using the method of [19]. Equation (1) illustrates this method; it shows how the roll axis dynamics are specified for the ACAH response type.

$$\frac{\phi_{cmd}}{\delta_{lat}} = \frac{K_{lat}}{\frac{1}{\omega_{lat}^2}s^2 + \frac{2\zeta_{lat}}{\omega_{lat}}s + 1} \tag{1}$$

The use of transfer functions for the rotational motion permits the vehicle dynamics to be tuned rapidly to obtain precise predicted HQs, facilitating evaluation of multiple configurations easily. This approach does not lend itself to a direct physical interpretation of the individual elements of the vehicle, but this was considered to be acceptable for this project (an actual *myCopter* PAV does not yet exist). In the heave axis, the collective lever controls a vertical 'lift' force, which, when tilted via pitch and roll control, creates longitudinal and lateral accelerations through standard rigid body dynamics.

The basic responses can be augmented through 'outer loop' feedback to create, for example, a Translational Rate Command (TRC) response type for pitch and roll, or a flight path angle response type (γC) in the heave axis.

Three baseline vehicle configurations have been developed to facilitate the *myCopter* HQs research. Each configuration can be considered as being representative of a different level of 'augmentation' of a vertical flight vehicle's responses. The three configurations are as follows:

1. *Configuration 1: 'Rate Command'*

RC responses in pitch and roll are combined with RC in heave. In yaw, the response type in the hover is RC, but as the speed increases, directional stability is introduced through sideslip angle feedback, providing a sideslip angle command (βC) response type at forward flight speeds greater than 25kts. In forward flight, turn coordination inputs are applied to the roll, pitch and yaw controls to ensure that the vehicle performs smooth turns without additional pilot activity. Apart from these coordination inputs, inter-axis coupling is not present in the model. This is on the basis that such a coupling would be highly undesirable in a PAV. The dynamics of this configuration have been tuned to offer predicted Level 1 HQs for the 'All Other MTEs' category of tasks of Ref. [14]. The rate-based response types of this configuration may be considered as being approximately representative of a current light GA helicopter, albeit one with excellent HQs.

2. *Configuration 2: 'Attitude Command, Attitude Hold'*

The second configuration may be considered as being approximately similar to a modern, augmented helicopter. It is configured as described above for the RC response type. The difference is the primary response in the pitch and roll axes, where an ACAH response type is used rather than the RC response type of Configuration 1. Again, the dynamics of this configuration have been tuned to offer predicted Level 1 HQs according to Ref. [14].

3. *Configuration 3: 'Hybrid'*

The 'Hybrid' configuration has been designed to allow the dynamics in each axis to be more closely matched to the demands of a particular task than is the case with configurations 1 and 2. For the tests described in this report, response types for hover and low speed manoeuvring (at speeds up to 15kts), and for forward flight manoeuvring (at speeds above 25kts) have been created. Smooth blending occurs between the hover response types and the forward flight response types as the speed increases from 15kts to 25kts and vice versa. The response characteristics of the Hybrid configuration in each airspeed region are summarized in Table 1. The selection of response types for the Hybrid configuration has been made, where possible, on the basis of minimizing the number of control inputs required to perform a manoeuvre.

Table 1 Summary of Hybrid Configuration Response Types

Speed Range	Pitch	Roll	Yaw	Heave
<15kts	TRC	TRC	RC	VRC
blend	Instantaneous at 15kts (accel) and 0kts (decel); internal logic to eliminate transients	Smoothed transition between 15-25kts	Smoothed transition between 15-25kts	Smoothed transition between 15-25kts
>25kts	ACSH	ACAH	βC + TC	γC

Worthy of note is that in the hover and low speed segment of the flight envelope, in the pitch axis, the response type changes to Acceleration Command, Speed Hold (ACSH). The ACSH response type generates, for a fixed displacement of the longitudinal controller, a constant rate of change of airspeed; releasing the controller to the zero force position results in the currently commanded airspeed being held. The transition between TRC and ACSH modes during deceleration does not follow the general pattern of blending between 15kts and 25kts. Instead, the ACSH mode is maintained throughout the deceleration until the vehicle comes to a halt. The response type is then switched back to TRC, ready for the next pilot input. The Hybrid configuration is also equipped with pilot selectable Height Hold (HH) and Direction Hold (DH) functions.

As with the other configurations, the dynamics of the Hybrid configuration have been tuned to offer predicted Level 1 HQs for 'All Other MTEs' according to Ref. [14]. For the response types not covered by ADS-33E-PRF (such as the ACSH mode), subjective tuning has been performed to create a satisfactory response. This tuning was conducted based upon feedback from the first group of Test Pilots (TPs) and flight-naïve Test Subjects (TSs) to fly the GPDM using the Hybrid configuration.

4. Comparison of responses of PAV configurations

It is instructive to consider the way in which the various configurations behave when a pulse control input is applied to a specific axis of motion. Inputs such as these form the basis for many of the ADS-33E-PRF predictive analyses. Fig. 3 shows the different response-type responses in the pitch axis, which are typical also of the roll axis. Fig. 4 shows the responses in the yaw axis. In the case of Fig. 3, the magnitude and duration of the pulses for each response type have been selected to generate rate and attitude responses of comparable magnitude. The progressively increasing stability of the responses as the response type progresses from RCAH through ACAH to TRC is evident in the velocity traces for this axis.

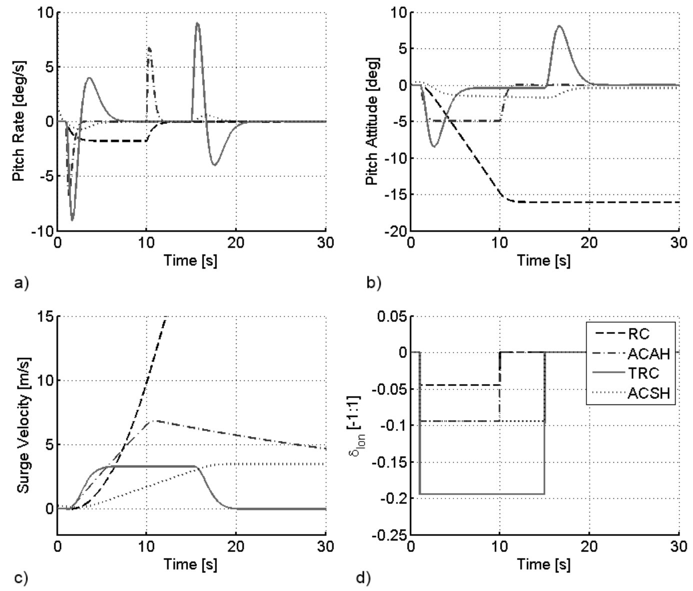


Fig. 3 ***myCopter*** **PAV Model Pitch Axis Responses to Pulse Inputs**

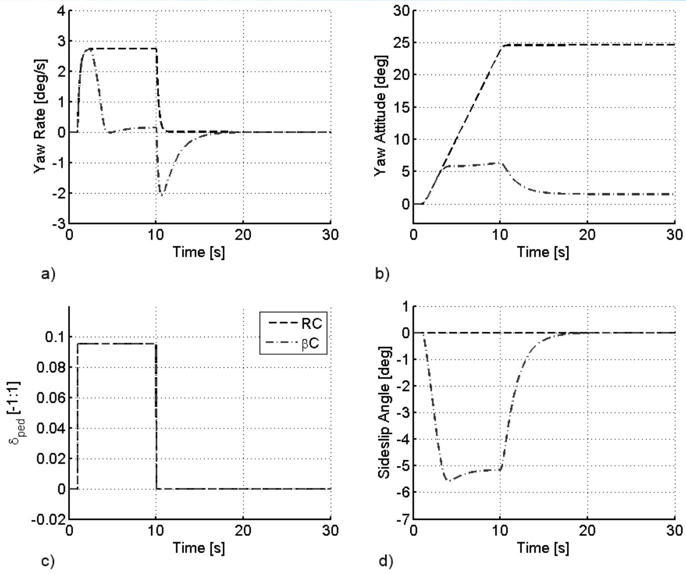


Fig. 4 ***myCopter*** **PAV Model Yaw Axis Responses to Pulse Inputs**

2.1.3. Mission Task Elements

As part of the wider *myCopter* project, a commuting scenario was developed, whereby the PAV flight would begin with a vertical take-off from a rural or suburban region (Ref. [13]). The PAV would accelerate and climb into a cruise towards its final destination, typically the central business district of a major city. Upon arrival at the destination, the PAV would descend and decelerate to hover at a designated PAV landing point, before executing a vertical landing. From this general commuting scenario, a series of Mission Task Elements (MTEs) appropriate to the PAV role have been identified and a subset of 5 hover and low speed MTEs were selected for use in the investigations reported in this report. The 5 MTEs used were the Hover, Vertical Reposition, Landing, Decelerating Descent and Aborted Departure. Where possible, the outline of the task has been drawn from ADS-33E-PRF; some of the task performance requirements have, however, been modified (generally relaxed) to reflect the nature of the PAV role. Additional details relating to the MTEs can be found in Supplemental Data S1 (Appendix 1). The key points are summarized in the following.

1. Hover MTE

The hover manoeuvre was conducted as described in Ref. [14] using the same MTE performance requirements for maintenance of longitudinal and lateral position as well as heading and altitude for the cargo/utility class of aircraft in a Good Visual Environment (GVE).

2. Vertical Reposition MTE

The vertical reposition manoeuvre starts in a stabilized hover at an altitude of 20ft with the aircraft positioned over a ground-based reference point. A vertical climb is initiated to reposition the aircraft to a hover at a new altitude of 50ft within a specified time. Overshooting the end point is not permitted. The manoeuvre is complete when a stabilized hover is achieved. Longitudinal and lateral position had to be maintained within ±5ft (desired) or ±10ft (adequate) whilst heading had to be maintained within ±5° (desired) or ±10° (adequate) of the initial heading. The new height had to be captured within ±2ft (desired) or ±4ft (adequate) and the manoeuvre had to be completed within 10s (desired) or 15s (adequate).

3. Landing MTE

The landing manoeuvre starts with the vehicle in a stable hover at a height of 20ft, offset laterally and longitudinally from the prescribed landing point. Following a repositioning phase to place the vehicle in a hover directly above the landing point, an essentially steady descent to the landing point is conducted. It is acceptable to arrest sink rate momentarily to make last-minute corrections prior to touchdown. The performance requirements used for the landing manoeuvre were as per those for a GVE in Ref. [14].

4. Decelerating Descent MTE

The decelerating descent manoeuvre begins with the aircraft in a stable cruise at 60kts at a height of 500ft above the ground. Once a specified ground marking has been reached, the pilot initiates a descent and decelerates towards a target hover point and a height of 20ft. The approach was configured to give a mean glideslope angle of 6 degrees. The manoeuvre is complete when the aircraft has been stabilized over the marked manoeuvre end point. Overshooting the approach beyond the front longitudinal adequate tolerance, or the lower vertical adequate tolerance was not permitted. Lateral position had to be maintained within ±20ft (desired) or ±50ft (adequate) whilst heading had to be maintained within ±10° (desired) or ±15° (adequate) of the initial heading. The aircraft model had to be stabilized in the hover at the target height within ±5ft (desired) or ±10ft (adequate) and longitudinally within ±10ft (desired) or ±20ft (adequate) of the target hover position.

5. Depart/Abort MTE

The Depart/Abort MTE departure begins in a stabilized hover at an altitude of 50ft. A normal departure is initiated by accelerating the aircraft longitudinally along a target track. When the groundspeed has increased to 40kts, the vehicle is decelerated to a hover as rapidly and as practicably as possible. The acceleration and deceleration phases should each be accomplished in single, smooth manoeuvres. The manoeuvre is complete when control motions have subsided to those necessary to maintain a stable hover. The performance requirements for the Depart/Abort MTE were as specified in Ref. [14] for a Cargo/Utility aircraft in a GVE for lateral position, heading and time to complete. An extra constraint for height maintenance (desired = ±10ft; adequate = ± 20ft) was also introduced for this study.

2.1.4. Simulating a Harsh Environment

1. Introduction to Harsh Environments

A newly-qualified GA pilot is typically restricted to operating in daylight hours when the visibility is good (greater than 4500ft, [20]). However, the three main airports in the North West of England, Liverpool, Manchester and Blackpool, have recorded an average of 21.7 days with fog (visibility less than 3000ft) per year over the period 1993-2013 (Ref. [21]). A comparable figure for three airports in the North Eastern United States and Eastern Canada (New York John F. Kennedy; Chicago O'Hare; and Montréal Dorval) is 33.0 days with fog per year (Ref. [21]). If a PAV was unable to operate in these or other degraded visibility conditions, it would be a significant impediment to its utility in the commuter role. It is therefore important that the impact on PAV HQ requirements of degrading the visual environment be considered.

Ref. [14] defines the minimum acceptable response types for various stages of degradation in the Useable Cue Environment (UCE). For UCE=1 (excellent task cueing available), a basic rate response type is all that is required for Level 1 handling. In UCE=2 conditions (some degradation in either attitude and/or translational rate cueing), a more strongly stabilized ACAH response type is required to maintain Level 1 handling, while in UCE=3 conditions (severe degradation in attitude and/or translational rate cueing), a TRC response type is required. These requirements were developed on the basis that the pilot flying the helicopter would be a well-motivated professional pilot, with extensive training in the skills required to control the helicopter. For the potentially flight-naïve PAV pilot, the relationship between UCE and required response type needed to be established.

Atmospheric disturbances can occur in either free stream conditions or as a result of the air passing around obstructions such as trees or buildings (Ref. [22]). It is expected that PAVs will operate into and out of the central business districts of major cities in their commuting role. Thus, it is important that the PAV pilot is able to perform precision take off, landing and low speed manoeuvring tasks in the presence of disturbances that may typically be found in these locations.

2. Degraded Visual Conditions

Degradation in the UCE was achieved by restricting the visibility range of the UoL HELIFLIGHT-R simulator's Vega Prime image generation system. Vega Prime employs an atmospheric illumination model to automatically darken the scene and provide a 'natural' fog onset in response to limiting the visibility. In this context, visibility is measured as the maximum range from the observer at which no further world features can be seen. In the simulated 'benign environment', the visibility range was set to be a sufficiently large value such that there were no apparent reductions in scene contrast and no obscured features within the regions visible to the pilot. For the investigation into the effect of degraded UCE, the visibility range was reduced to 800ft. This range just provided the pilot with visibility of the task cues from the starting point for each of the hover and low speed MTEs. All natural horizon references were obscured together with many of the vertical features of the terrain database. Additionally, the micro-contrast of the textures used on the ground was significantly reduced.

The effect of the introduction of the fog model was assessed by a test pilot who awarded Visual Cue Ratings (VCRs, Ref. [14]) to determine the UCE level of the environment. With reduced visibility and micro-contrast, the VCRs were increased as shown in **Fig. 5** (where: MTE 1 = Hover; MTE 2 = Vertical Reposition; MTE 3 = Landing and MTE 4 = Depart/Abort), creating a Degraded Visual Environment (DVE).

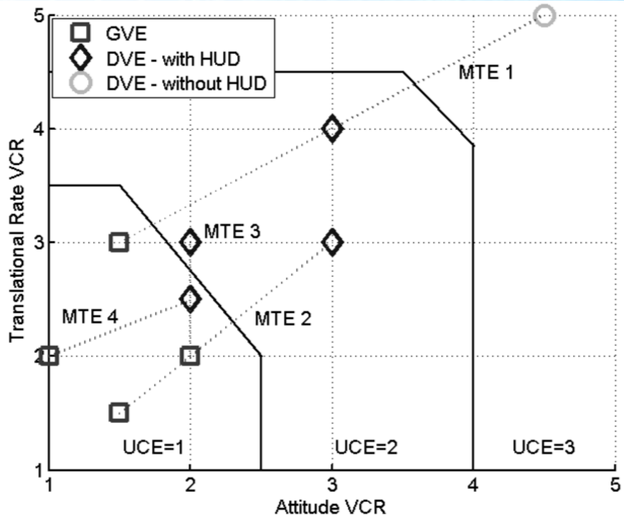


Fig. 5 Determination of UCE for Hover and Low Speed MTEs

The flight-naïve TSs were not, however, asked to fly the MTEs in UCE=3 conditions. As described above, the PAV simulation is equipped with a HUD (**Fig. 3**). Two features of the HUD in particular provide enhancements to the UCE. The first is the wide field of coverage Malcolm horizon. This, together with the attitude indicator, provides the pilot with a strong reference for vehicle attitude and attitude rate in any external visual conditions. The second key HUD feature is the flight path indicator. This symbol can be used to augment cueing of the ratio of longitudinal to lateral translational movement.

In general therefore, the harsh environment evaluations were conducted in UCE=2 conditions. The exception was the Depart/Abort MTE, where the very strong task cueing provision meant that even in the presence of the simulated fog, sufficiently strong cues were provided to still achieve UCE=1. In addition, the Decelerating Descent MTE was not conducted suing the harsh environment due to the strong reliance placed on distant visual cues in this task. In the GVE, UCE=1 conditions prevailed for this task.

3. Atmospheric Disturbances

Many different models of atmospheric disturbances have been created and applied to the simulation of helicopters (Ref. [23]). Among the most popular of these is the von Karman method (Ref. [24]). This method models continuous gusts with specified Power Spectral Density (PSD) characteristics in surge, sway and heave; angular gust components are also modelled. Due to the non-physical nature of the PAV simulation model, however, it was not feasible to generate disturbances using the von Karman method. Instead, the Control Equivalent Turbulence Input (CETI, Ref. [25]) method was adopted. The CETI approach uses a similar technique to the von Karman method, in that it passes white noise through appropriately designed filters to generate disturbance signals. However, rather than applying the output of the filters as changes to the atmospheric model around the aircraft, the outputs are applied as control inputs (lateral and longitudinal cyclic, collective and pedals) that generate 'equivalent' aircraft responses to those that would have been experienced by the vehicle when exposed to the originally-modelled gusts. The CETI technique is constrained relative to the von Karman method in that it can only create disturbances that are achievable using the controls of the aircraft, but it has the advantage that it can be realized in any simulation without the need to control the local atmospheric properties.

The structure of the CETI models used in this study was adopted from Ref. [25]. For example, the structure of the CETI model for the longitudinal cyclic is shown in Equation (2) below:

$$\frac{\delta_{lon,gust}}{W_{noise}} = A_{lon}\frac{1}{\left(s+\frac{U_0}{L_W}\right)} \tag{2}$$

Initial parameter settings for the turbulence filters were also drawn from Ref. [25]. However, as the PAV is considered to be a small air vehicle (mass ≈ 500kg), and the aircraft used to generate the parameters was considerably larger (an EC-135 helicopter, mass ≈ 2800kg), the parameter settings were subjectively tuned using the opinions of a current light helicopter pilot to create a turbulence response that was considered appropriate for a vehicle of the size of the PAV. Further detail on the frequency spectra for the transfer functions used in the harsh environment can be found in Supplemental Data S2 (Appendix 2).

For the RC configuration, the CETI signal is fed directly into each channel of the model, as shown in Equation (3) for the pitch axis:

$$\delta_{lon,total} = \delta_{lon,pilot} + \delta_{lon,gust} \tag{3}$$

This approach models a system where there is no closed-loop feedback of vehicle response into the flight control system – in other words, an unstabilised response.

For the ACAH and Hybrid configurations, the CETI signal in pitch and roll is firstly integrated to create a commanded attitude disturbance, and the integrated signal is fed into the appropriate control channel. It is assumed with these configurations that closed-loop feedback of vehicle attitude is present within the 'virtual' flight control system. Therefore, delayed feedback of the commanded attitude disturbance is also applied to each control channel. The resultant implementation is shown in Eq. (4):

$$\delta_{lon,total} = \quad \delta_{lon,pilot} + \left(\int \delta_{lon,gust}.\,\mathrm{dt}\right) - \left(e^{-\tau s}\int \delta_{lon,gust}.\,\mathrm{dt}\right) \tag{4}$$

The time delay of the 'sensor' (τ in Eq. (4)) was modelled as 100ms, this figure being representative of the measurement and associated digital data processing time that would be required in a real sensor feedback system. The turbulence implementation for the yaw and heave axes were also subject to closed-loop feedback in the ACAH and Hybrid configurations, meaning that, although the underlying vehicle response to a control input is identical to the RC configuration in these axes, the turbulence response is different.

The effect of the turbulence on the RC and ACAH configurations is shown in Fig. 6. The attitude response of the Hybrid configuration is similar to that of the ACAH configuration, shown in Fig. 6, but the translational response is more stable due to the additional closed-loop feedback of velocity present in the TRC control loop.

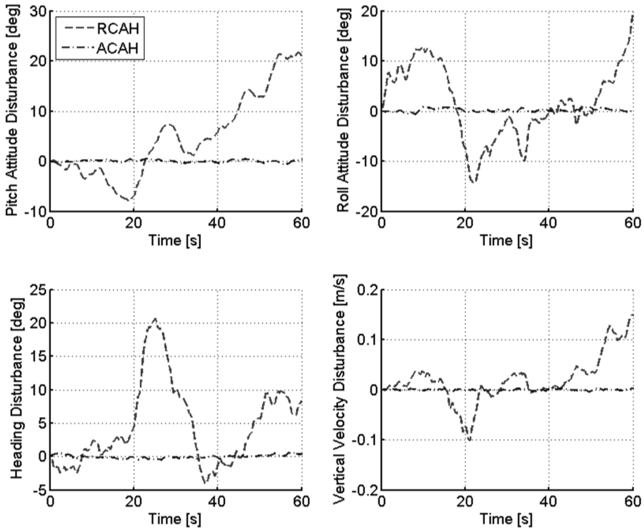


Fig. 6 Turbulence response of RCAH and ACAH configurations

The strength of the turbulence was assessed subjectively by a test pilot using the Turbulent Air Scale (Ref. [26]). For the 'unaugmented' RC configuration, a rating of 5, occasionally increasing to 6, was awarded, indicating moderate turbulence intensity.

2.2. Conventional Handling Qualities Evaluation

The three PAV configurations were assessed against the ADS-33E-PRF hover and low speed criteria for 'All Other MTEs' to provide a baseline against known standards. The results in this Section focus on vehicle responses in the hover, as this is the condition in which the majority of the piloted simulation tests have been performed. However, as the rotational dynamics of the GPDM are created through transfer function models, these predicted HQ values will remain constant across the flight envelope.

In the pitch axis, the bandwidth of the RC and ACAH configurations is as shown in Fig. 7, while the attitude quickness is as shown in Fig. 8. The bandwidths of the two configurations are quite different; this is a result of the configurations being tuned to exhibit similar attitude quickness properties. The different structures used to implement the RC and ACAH response types in the GPDM prevent an exact match, and additionally lead to different bandwidth results. For each criterion, the handling qualities are predicted to lie within the Level 1 region.

It should be noted that, for all of the bandwidth analyses shown below, the results incorporate a time delay of 80ms. This is representative of the inherent stick-to-visuals transport delay of the HELIFLIGHT-R simulator – with the exception of the 'sensor' delays described above, the GPDM itself does not include any additional delay elements.

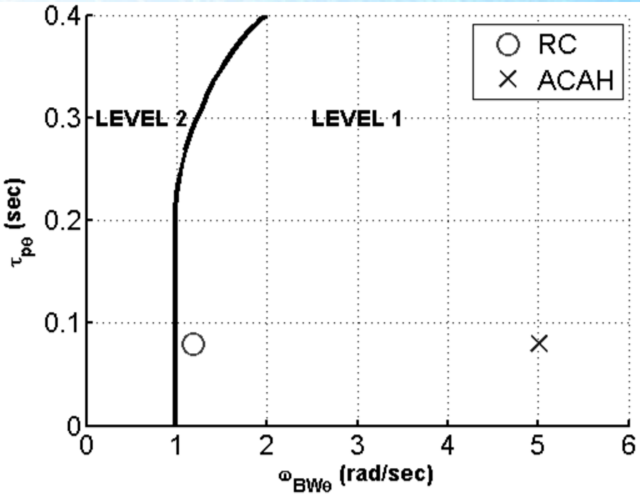


Fig. 7 Pitch Axis Bandwidth

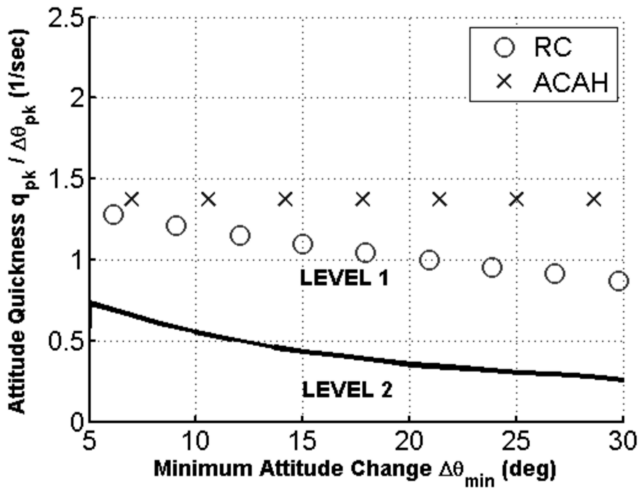


Fig. 8 Pitch Axis Attitude Quickness

In the roll axis, the bandwidth is shown in Fig. 9, and the attitude quickness is shown in Fig. 10. The attitude quickness results could not be matched so closely in roll as they were able to be matched in pitch – increasing quickness at smaller attitude changes (Fig. 10) for the ACAH configuration would have resulted in the bandwidth increasing to very high values, leading to an aircraft that was extremely sensitive to small control inputs. This was considered to be undesirable for flight-naïve pilots. Conversely, reducing the quickness for smaller attitudes with the RC configuration would have resulted in the bandwidth becoming unacceptably close to the Level 1/Level 2 boundary.

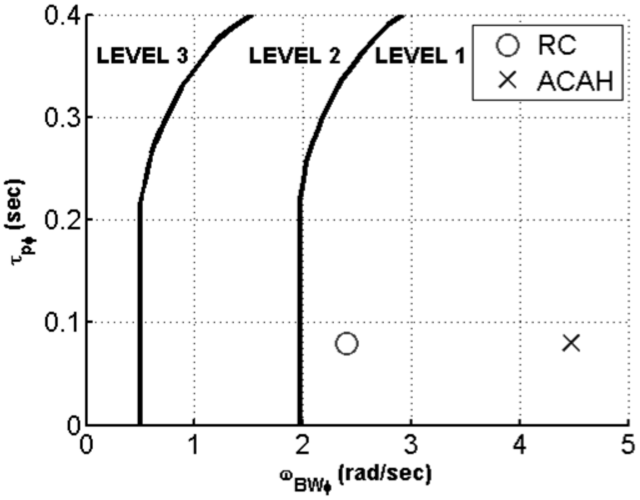


Fig. 9 Roll Axis Bandwidth

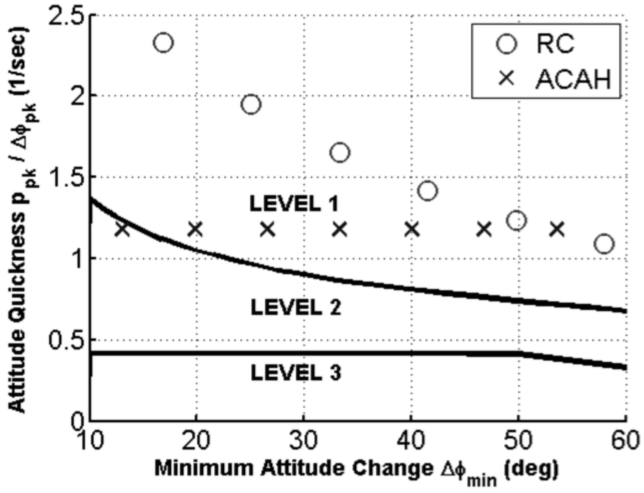


Fig. 10 Roll Axis Attitude Quickness

In yaw, all configurations employ the same RC response type in the hover. The bandwidth for this response is shown in Fig. 11, and the attitude quickness is shown in Fig. 12.

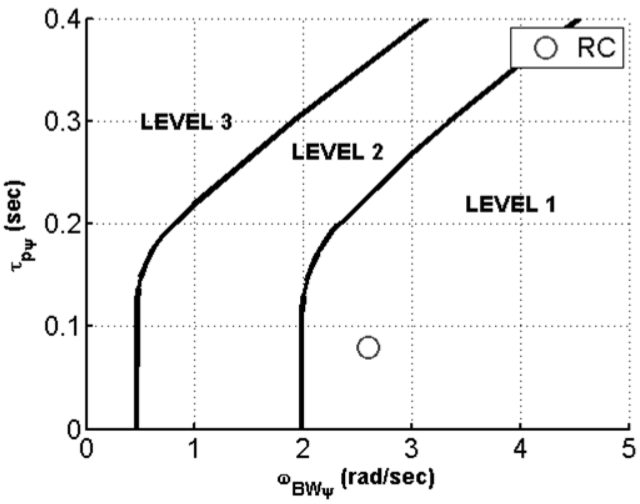


Fig. 11 Yaw Axis Bandwidth

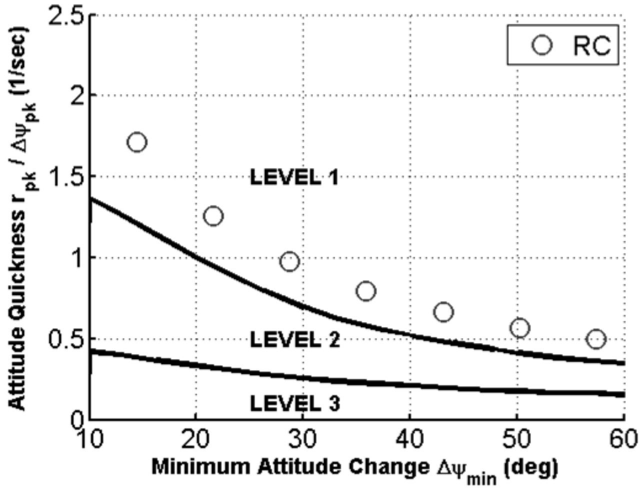


Fig. 12 Yaw Axis Attitude Quickness

The TRC response type of the Hybrid configuration is created using a velocity feedback loop around the ACAH dynamics described above. Therefore, the initial attitude response of the Hybrid configuration will be the same as that of the ACAH configuration. The velocity feedback loop has been configured to offer a rise time of 2.5 seconds in both the pitch and roll axes. The magnitude of the surge and sway velocity response for a given controller deflection is set as a constant 11ft/s/in for any deflection size. The rise times meet the ADS-33E-PRF Level 1 requirement for a TRC response type. The velocity gradient is somewhat higher than that required for Level 1 handling for low velocities, but is acceptable for higher velocities (ADS-33E-PRF recommends a non-uniform velocity gradient to improve sensitivity around hover). The constant velocity gradient has been adopted for this study to increase the predictability of the vehicle response to a change in control position for flight-naïve pilots.

Fig. 13 shows the HQRs (Ref. [27]) awarded in each of the five MTEs for the different PAV configurations. The ratings were awarded by a single TP over the course of a one day simulation trial.

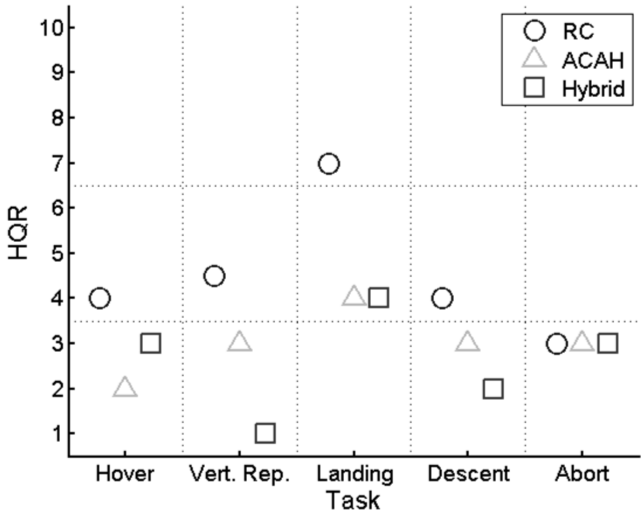


Fig. 13 PAV Handling Qualities Ratings

Despite all three configurations offering predicted Level 1 handling in Fig. 13, a number of Level 2 HQRs and a single Level 3 HQR were awarded to the RC configuration. The TP found that, although desired performance could generally be achieved in all tasks apart from the Landing MTE, the workload associated with achieving this was higher than desired. The pilot commented on a number of occasions about a PIO susceptibility with the RC configuration – note the marginally Level 1 attitude bandwidth shown in Fig. 11 and Fig. 12 above, and hence a requirement to modify his control strategy to avoid exciting oscillations.

In terms of HQRs, the Hybrid configuration was shown to be as good as, or better than, the RC and ACAH configurations in all MTEs. The only exception to this was in the Hover MTE, but it should be noted that the HQR=3 awarded to the Hybrid configuration was during the TP's first exposure to this configuration, and it is possible that a lack of familiarity with its responses may have played a part in this rating.

The Landing MTE generally resulted in poorer HQRs than would be desired. The TP found the requirement to control the PAV's position within ±1ft longitudinally and ±0.5ft laterally to be demanding, even in the ACAH and Hybrid configurations. In the RC configuration, this level of accuracy could not be attained, resulting in the touchdown being made outside the position limits of the task. Note in **Fig. 5** that the VCRs place the UCE close to the UCE=1/UCE=2 boundary for the Landing MTE. As the RC configuration will be more susceptible to UCE degradation than the other configurations (Ref. [14]), this may explain the larger difference in HQRs observed here compared to the other tasks.

The Level 1 HQRs suggest that the Hybrid configuration would be highly suited for use by a typical helicopter pilot of today. Further, with the exception of the RC configuration, the results also show that there is generally a good agreement between the predicted HQs according to ADS-33E-PRF and the assigned HQRs, serving to validate the GPDM and the wider simulation. In the case of the RC configuration, the TP was generally able to meet each task's desired performance standards, indicating that high precision was attainable, albeit at the expense of higher than desired workload. The improvement in HQRs as the response type is changed from RC through ACAH to TRC is as expected given the stability improvements accorded by the changes from rate to attitude, and from attitude to translational rate response types.

Although the results presented in Fig. 13 are from a single TP, a total of five other TPs have also taken part in HQ assessments during various stages of the development of the PAV simulation (Refs. [16;28]). While these TPs were not flying the final versions of each configuration as described in this report, the results from these assessments show good correlation with the results for the final configurations presented in Fig. 13. The results of Fig. 13 indicate that the Hybrid configuration would be suitable for current helicopter pilots. However, the same cannot be said with regards to its suitability for use by flight naïve pilots.

2.3. PAV Handling Qualities Assessment Procedure

In order to determine HQ requirements for potential PAV 'flight-naïve' PAV pilots (i.e. non-professional pilots with a potentially broad spectrum of previous experience), it is necessary to look beyond the traditional TP evaluation. As the 'pilots' who took part in the flight trials did not possess training in HQ evaluations, alternative approaches to those described above for the assessment of conventional rotorcraft with TPs had to be employed. Workload in each task was assessed subjectively through the TLX rating (Ref. [29]). Task performance was then evaluated through a quantitative analysis of the precision with which the task was completed and the amount of control activity required to perform the task. With this data in place, the suitability of the different candidate vehicle configurations could be assessed in terms of the skill required to meet various levels of performance, and hence also infer the amount of training required to be capable of operating the PAV safely and precisely. While it is possible to broadly categorize these 'pilots' via their level of prior experience, it is to be expected that considerable variations in skill level would be evident within an experience tier. Therefore, each participant in the evaluations undertook a series of psychometric tests to determine their underlying aptitude towards flying before attempting the PAV tasks. This Section of the report describes the development of the various methods utilized to evaluate PAV handling requirements.

2.3.1. Aptitude

The suite of psychometric tests was used to determine a subject's aptitude to pilot a PAV. These consisted of nine separate computer-based tests examining different aspects of the piloting task. The tests were created at UoL using elements from the US Air Force Basic Attributes Test (Ref. [30]) and standard psychometric tests (Ref. [31]) to produce a broad assessment of an individual's aptitude for the skills required to fly the PAV. Additional information regarding the tests used can be found in Supplemental Data S3 (Appendix 3). Generally, the 9 psychometric tests can be categorized as assessing the following: hand-eye coordination i.e. the ability to apply appropriate control inputs relative to visual stimuli (e.g. positional errors); visual (including pattern recognition, and spatial reasoning) i.e. the ability to develop spatial awareness; decisiveness i.e. the ability to make rapid decisions regarding the correct course of action; memory i.e. the ability to remember task instructions; and problem solving i.e. the ability to work out the correct control inputs for a given response type.

The theoretical maximum achievable score from the nine tests was fifteen; scores closer to the maximum indicate a greater aptitude for the skills needed to successfully complete the PAV flight tasks. Fig. 14 shows the test scores achieved by 22 subjects (19 male, 3 female with an age range of 19-43, the mean of which is 25) who have taken the aptitude tests. The TSs were also broadly categorized by their prior flight experience:

- No Experience – these TSs have no prior experience of flight, either real or simulated;
- Simulator Experience – these TSs have experienced flight simulation, either on a desktop using PC-based flight simulation games, or in a full flight simulator such as HELIFLIGHT-R.
- Flight Experience – these TSs have undergone some elementary flying training, and have generally achieved solo flight;
- Flight Qualified – these TSs have completed some form of elementary flying training (either military or civilian), and are qualified pilots. The most experienced pilot in this group has just over 200 hours flight time.

The Figure shows that each category of pilot contains a reasonably broad range of aptitudes. However, as might be expected, the trend is for a higher aptitude amongst those with increasing flight experience but with an overlap between the aptitudes demonstrated between groups. Aptitude here means the innate ability of a subject to perform a task. It is entirely possible that someone with a good aptitude for a subject has little experience in it (the former does not imply the latter), they simply have not yet been able to obtain any experience in it. For those with flight experience, the categorizations above make no distinction between those with fixed-wing experience and those with rotary-wing experience. The vast majority of the TSs came from a fixed-wing background. It is, however, interesting to note that the two pilots with a rotary-wing background achieved the two highest aptitude scores in the 'Flight Qualified' category. Their high scores and the trends previously described therefore provide confidence that the aptitude tests used return an appropriate and useful grading of the test subjects.

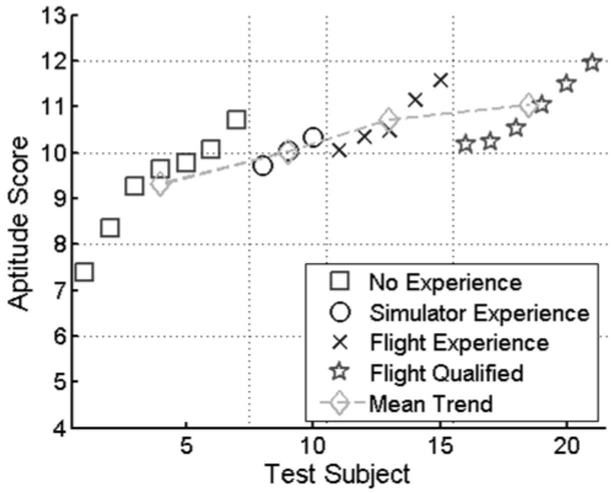


Fig. 14 Aptitude Test Scores

The impact of TS aptitude on flying ability can be seen in Fig. 15. This Figure shows the average time spent within the desired performance boundaries of the five MTEs defined above, for a number of TSs of varying aptitude (each point represents an individual TS) flying the RC-configured GPDM. It is clear that increasing aptitude closely correlates with increased ability to complete the PAV MTEs more precisely. The result the TSs with A = 10.3 does fall above the notional trend line for the other TSs. This TS has considerable previous simulator experience with vehicles which exhibit RC-like responses, which possibly helped the TS to understand the demands of this particular exercise. This TS aside, the results provide further evidence that the aptitude assessment process used is an effective discriminator for the flying ability of flight-naïve TSs.

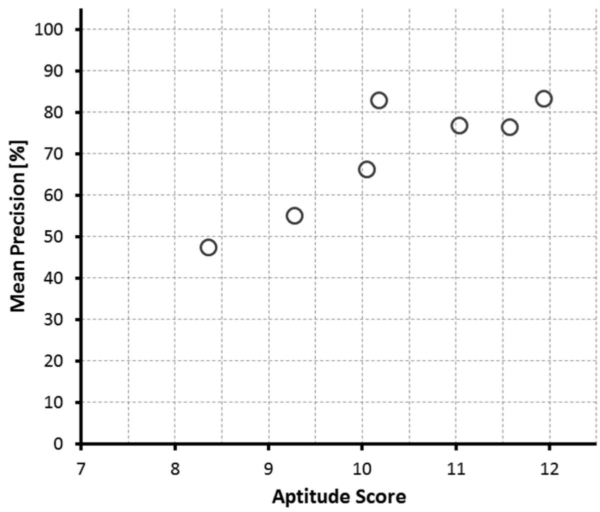


Fig. 15 Improvement in Attained Precision with Increased Aptitude for RC Configuration

2.3.2. Task Load Index

The Task Load Index [29] is a workload rating system developed by NASA. It was designed to be applicable to the assessment of the workload involved in any task and to be straightforward such that new users could easily understand the concepts and processes involved. The TLX rating assesses six aspects of workload – mental, physical and temporal demand; performance; effort and frustration. The ratings for each of these are combined using a weighting system, whereby the TS compares each of the workload elements to the others, deciding in each case which represented the greater contribution to the overall task workload. This results in a single TLX workload score for each task in the range $0 < TLX \leq 100$, where lower numbers indicate a lower workload.

Fig. 16, shows the mean TLX rating awarded by a group of TSs flying the ACAH configuration for the five PAV MTEs. It can be seen that there is a close relationship between the aptitude of a given TS and the workload that they associate with the tasks – the higher the aptitude, the more straightforward the TS is likely to find this configuration. As with Fig. 15, outlying data is present in Fig. 16 in the A=10.3 region. Again, this is likely to be a result of previous exposure of these TSs to ACAH-like response characteristics.

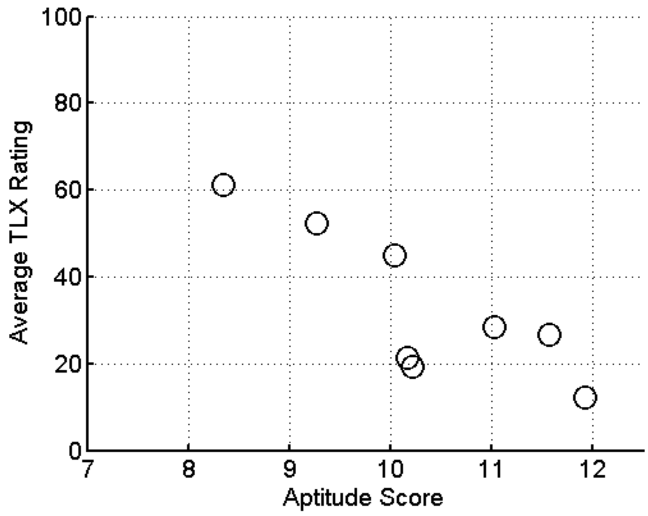


Fig. 16 Effect of Aptitude on Awarded TLX Ratings with ACAH Configuration

2.3.3. Task Performance Assessment

For the quantitative assessment of task performance, two key parameters have been identified. The first of these is the accuracy with which a given MTE could be performed. This has been measured as the percentage of time spent within each of the MTE's desired performance boundaries. The results for each performance requirement are averaged to produce an overall precision rating (*P*) for an MTE. Higher *P* values correspond to more accurate performance in the task and have a range $0\% \leq P \leq 100\%$.

The second is a quantitative measurement of task workload (*W*), in terms of the amount of control activity required to complete an MTE. While this can be measured in many ways (for example cut-off frequency analysis (Ref. [32]), attack analysis (Ref. [33] etc.), the technique in this report was to count the number of discrete movements of the controls and to average them against the task completion time. Only inputs 0.5% above or below full stick deflection are counted to prevent measurement noise from affecting the analysis). This gives the average number of control inputs made per second in each axis. This metric has been found to be sensitive to pilot control strategy and reflective of pilot subjective opinion of the physical workload associated with a task (Ref. [32]). The control input rate is averaged across the four control axes to produce a single value for each MTE. It follows that fewer control inputs are preferred to complete a task, as this implies lower pilot effort. For flight-naïve pilots, reducing the required control effort is expected to be key for safe, reliable PAV operation. Typical workload measurements fall in the range 0.1/sec < W < 1/sec depending on the task, the GPDM configuration and the pilot's control strategy.

It is acknowledged that there can be cases where a low amount of control activity correlates to a high workload (e.g. where a large time delay is present in a system – the pilot then has to apply considerable mental effort to reduce their control activity to prevent pilot induced oscillations). However, the benefit of having a single metric to capture a basic representation of the workload outweighs this disadvantage, provided that the subjective workload assessments are also taken into consideration to ensure that the correlation between low workload and low control activity holds.

It is then possible to combine the metrics used to assess precision and workload to represent the overall performance achieved in a given MTE. Here, the ability to achieve an MTE's desired performance requirements was considered to be of greater importance than achieving a minimal workload for a given task. The relative weighting of the precision and workload metrics was therefore adjusted to be:

$$\text{performance} = \frac{P^2}{\sqrt{W}} \tag{5}$$

Finally, it is possible to define a theoretical maximum value for each of the precision and workload metrics for each MTE, and hence a maximum value for the overall performance metric. Maximum precision should be 100% time spent within the desired performance requirement in every case. Theoretical minimum workload (W_{min}) can be computed by determining the lowest number of control inputs required to complete a given MTE. These theoretical maximum performance values for each MTE are then used to normalize the values of the performance achieved. This has been called the Task Performance Index (TPX):

$$\text{TPX} = \frac{P^2\sqrt{W_{min}}}{100^2\sqrt{W}} \tag{6}$$

With the TPX, a rating of 1.0 means that the pilot was able to achieve maximum precision in the task through the use of the minimum possible control effort. TPX ratings of less than 1.0 indicate that either the control effort was higher, or the precision lower, than would be ideal. To improve the statistical reliability of the TPX scores, average values of P and W are calculated using the final three attempts at a given task by each TS. The TPX is therefore representative of the overall 'experience' of flying a given task, rather than a snapshot of the events of a single run.

Figure 22 shows a comparison of the measured TPX scores and awarded TLX ratings taken during the HQ assessment process in the *myCopter* project. A total of 209 individual test points, flown by 13 flight-naïve TSs, are shown. Notwithstanding the comments above regarding the W component of the TPX score, a coherent relationship between the TPX scores and the TLX ratings is apparent. Plotting the computed TPX scores on a logarithmic scale yields a reasonably linear relationship with the subjectively awarded TLX ratings. The exponential best-fit to the data (the dashed line on **Fig. 17**) is described as:

$$\mathrm{TPX} = 0.54\mathrm{e}^{(-0.033\times\mathrm{TLX})} \tag{7}$$

where the coefficient of determination (Ref. [28]), R^2 = 0.988. A greater scatter in the points is visible in Fig. 17 at higher TLX ratings. This is partly due to the logarithmic presentation of the TPX scores and partly due to higher TLX scores being associated with TSs struggling to achieve the task. Here the returned ratings may not truly reflect their performance in the task.

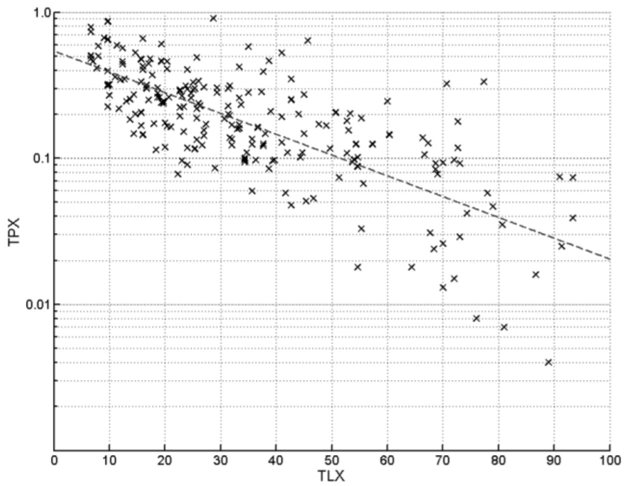


Fig. 17 Comparison of TPX Scores with TLX Ratings

The TLX rating is predominantly intended to function as a measure of the workload experienced when completing a specified task. However, the presence of 'performance' as one of the six contributory factors to the overall workload means that the evaluator is considering the level of success attained in a task as part of the process of awarding a TLX rating. The incorporation of both *P* and *W* into the TPX means that the metric is evaluating similar factors to the TLX rating (albeit with an increased emphasis placed on performance relative to workload). The coherent relationship demonstrated between TLX and TPX indicates that TPX is an effective measure of the performance of a TS in a given flight task.

Fig. 18 shows the scores achieved by a group of flight-naïve pilots flying the Hover MTE using the ACAH configuration in DVE conditions with turbulence. It can be seen that there was a progressive increase in achieved performance as the aptitude of the TSs increased. As previously mentioned, the two TSs in the A=10.3 region achieved a higher level of performance and this is likely to be due to their previous simulator experience with vehicles similar to the ACAH configuration.

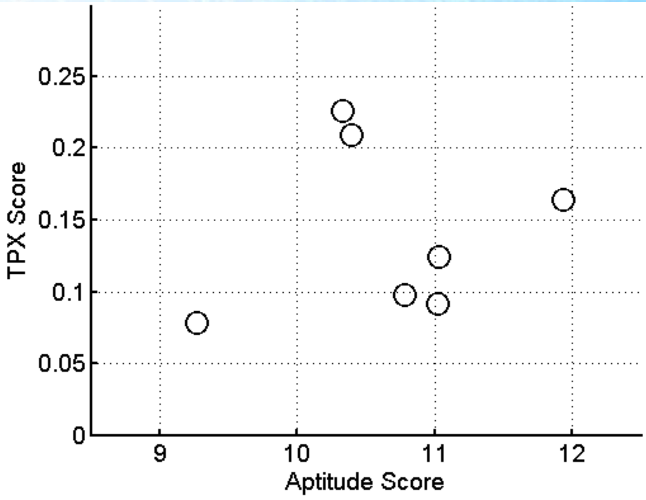


Fig. 18 Sample TPX Scores for Hover MTE with ACAH Configuration in Harsh Environment

2.3.4. Determination of the Suitability of Candidate PAV Configurations

The results presented above indicate that, despite the generally good HQRs awarded by the TP to the PAV configurations, all of the flight-naïve TSs were not able to complete the MTEs to an acceptable standard. The low level of achieved precision and the high reported workload for some TSs do not concur with the HQRs awarded by the TP. The methods described in the preceding Sections can be used to compare the different configurations. By considering the relationship between aptitude and the various metrics (TLX, *P*, TPX), it is possible to determine the range of *A* across which a given configuration can be flown 'successfully' i.e. safely and repeatably perform the PAV MTEs to the required level of precision. As the suitability of a given configuration for use in a PAV increases – in other words, the more straightforward and intuitive the response characteristics are for flight-naïve pilots to learn and master – TSs with progressively lower *A* will be able to operate the PAV with similar levels of performance as the TSs with high *A*.

3. Handling Qualities Requirements for Personal Aerial Vehicles

Section 2 presented the development of a methodology through which HQ requirements for PAVs using flight-naive pilots might be assessed. The methodology is applied in this Section to identify, for varying levels of flying aptitude, the response type requirements in order to ensure safe and precise flight.

The response type (Ref. [14]) describes the way in which a vehicle responds when a cockpit control is moved. Most GA helicopters exhibit a 'Rate' (RC) response type – following the application of a step control deflection from trim, the vehicle will pitch, roll or yaw at an approximately constant rate. As vehicle complexity increases, helicopters equipped with a Stability and Control Augmentation System (SCAS) may exhibit an 'Attitude Command, Attitude Hold' (ACAH) response type. Here, the pitch or roll rate following the application of a step control deflection will return to zero over a period of a few seconds, with the aircraft held at a constant perturbed attitude from trim. A more sophisticated SCAS may exhibit a 'Translational Rate Command' (TRC) response type – here, the velocity of the aircraft over the ground is proportional to the magnitude of the control deflection.

According to the requirements of [14], it is only necessary for a helicopter to possess a rate response type for Level 1 HQs (that is, the most desirable level of HQs) to be achieved in a good visual environment (GVE). As the visual conditions degrade (e.g. at night or in the presence of fog), an ACAH response type is required whilst in the most severely degraded visual conditions, a TRC response type is then required to maintain Level 1 HQs [1]. This report will assess whether this requirement for increasing augmentation with degraded environmental conditions also exists for PAVs.

3.1. Handling Qualities Requirements in a Benign Environment

3.1.1. Results

Nine TSs took part in the handling assessments in the benign environment. The lowest aptitude score was 7.4, while the highest was 11.9 (out of a theoretical best aptitude score of 15 points). The results from the testing in the benign environment are reported in two stages. Firstly, the subjective TLX workload ratings are shown. These are followed by objective analysis in the form of the TPX.

3.1.1.1. Analysis of Task Load Index in the Benign Environment

Fig. 19 shows the TLX ratings, averaged across the five MTES, awarded by each TS for each of the three PAV configurations under assessment.

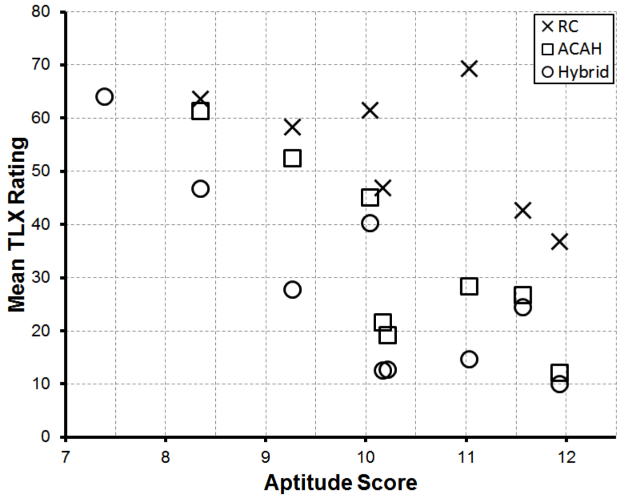
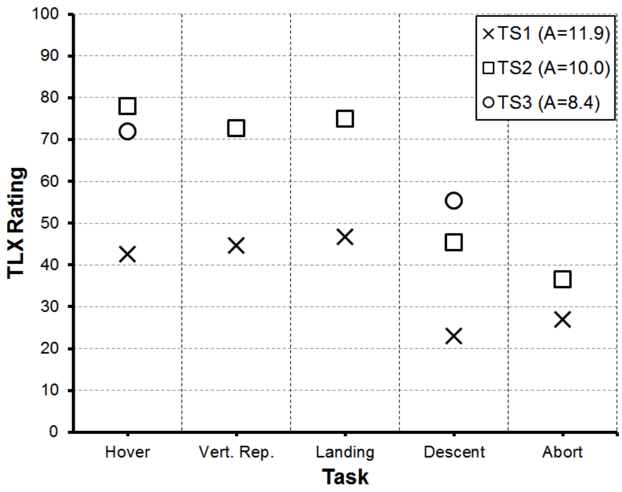


Fig. 19 Average TLX Ratings for Three PAV Configurations

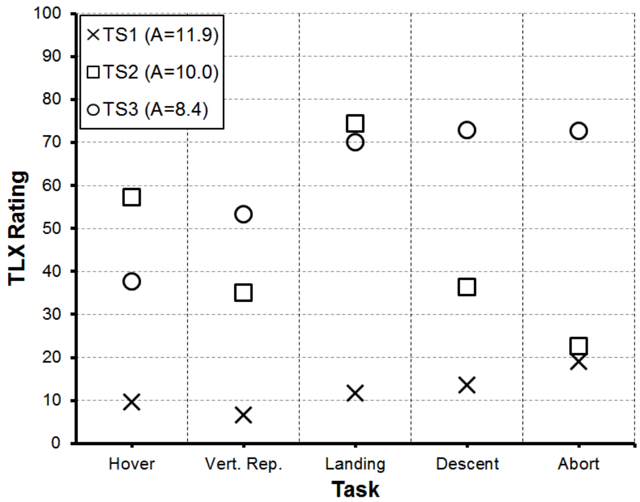
For each configuration, there is an observable reduction in perceived workload as the pilot's aptitude increases. It is also clear that as the configuration changes from RC to ACAH to Hybrid, there is a significant reduction in the reported workload. The exception here was some of the TSs with high aptitude scores, who rated the ACAH and Hybrid configurations as requiring similar, low levels of workload to fly.

Whilst reported workload reduces as aptitude increases for all three configurations, the way in which this reduction occurs is different in each case. For the RC configuration, there is considerable scatter in the results, with some TSs finding this configuration extremely high workload. For the ACAH configuration, the scatter is much lower – there is a steady reduction in perceived workload as aptitude increases. Finally, with the Hybrid configuration, there is a trend for a rapid reduction in perceived workload at low levels of aptitude, with little change in the TLX ratings for aptitude scores between 10 and 12.

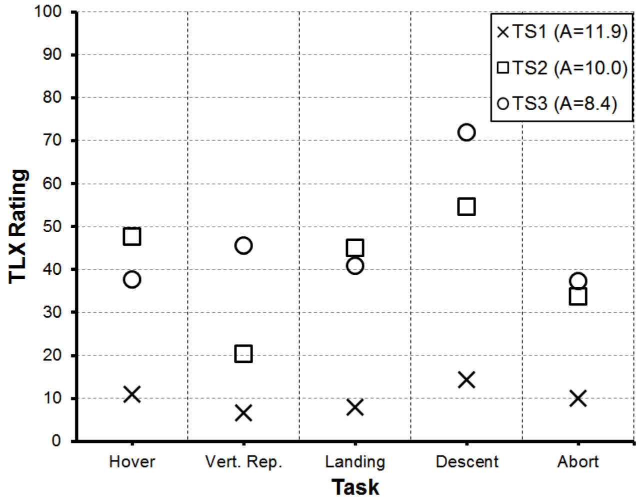
For the individual MTEs, Fig. 20(a) shows a sample of typical results (for high, medium and low aptitude TSs) for the RC configuration, Fig. 20(b) the results for the ACAH configuration, and Fig. 20(c) the results for the Hybrid configuration. Results from the same TSs have been used to construct all three Figures.



a) RC Configuration



b) ACAH Configuration



c) Hybrid Configuration

Fig. 20 Sample of TLX Ratings - Individual Tasks

In Fig. 20(a), a clear difference can be seen between the pilots' reported workload for the hover, vertical reposition and landing tasks, and their reported workload for the decelerating descent and aborted departure tasks. For the former group of MTEs, there is a requirement for a continuous, precise flying. For the latter tasks, a somewhat more 'open loop' control strategy for large periods of the task is required. The relatively low level of stability offered by the RC response type means that, for the precision tasks, there will always be a higher workload demand than would be the case for a more 'open loop' task.

For the ACAH configuration, Fig. 20(b) shows a smaller variation in TLX rating between the tasks for each TS. There is no clear pattern connecting all of the TSs – with this configuration, some TSs found the precision tasks more demanding, other pilots found the more 'open loop' tasks more demanding.

For the Hybrid configuration of Fig. 20(c), there are no clear differentiators between tasks. In general, the TSs found all five tasks to be equally demanding with the Hybrid configuration. There are exceptions to this rule, for example, the decelerating descent task. For the Hybrid configuration, the decelerating descent task requires the pilot to coordinate the application of control inputs on two separate inceptors simultaneously (longitudinal cyclic and collective). In every other task, when the HH and DH functions are employed, the pilot is only ever required to apply inputs on a single inceptor at a time. While the higher aptitude pilots did not find this to be a significant challenge, the lower aptitude pilots reported that their workload increased significantly. *This result highlights the importance of minimizing or eliminating unnecessary secondary or off-axis control activity in a future PAV.*

3.1.1.2. Analysis of Task Performance in the Benign Environment

The TLX results presented above have shown that the Hybrid configuration offers subjectively the lowest workload of the three configurations tested. In this Section, a quantitative assessment of each manoeuvre will be presented.

Fig. 21 shows the precision (percentage of task time spent within the desired performance boundaries) achieved by each TS in each of the PAV configurations, averaged across the final three attempts by a TS for 5 MTEs. A value of 100% precision indicates that the TS was consistently able to achieve 100% of the manoeuvre time within desired performance in every task.

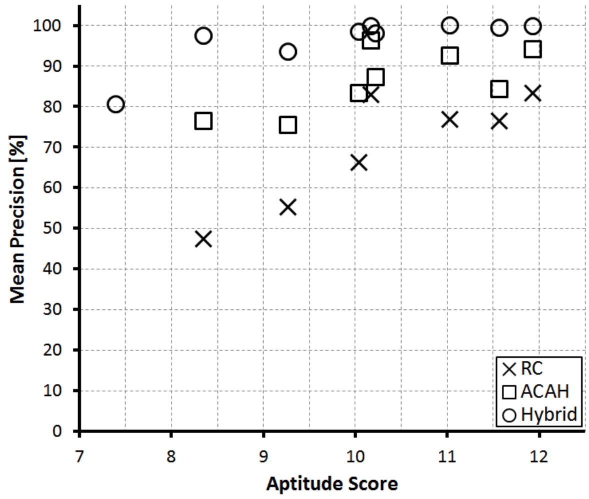


Fig. 21 Precision for PAV Configurations

While the highest aptitude TS was able to perform very well (> 90% time spent within desired performance) in the ACAH and Hybrid configurations, and only slightly less well (> 80% time spent within desired performance) in the RC configuration, the same cannot be said of the lower aptitude TSs. It can be seen in Fig. 21 that precision was generally lower (<70% time spent within desired) for the lower aptitude TSs flying the RC configuration. Precision improved progressively as the aptitude score increased. A similar pattern is evident in the data for the ACAH configuration. However, the rate of decay of precision with reducing aptitude was significantly lower. Finally, with the Hybrid configuration, the majority of the TSs were able to achieve an excellent level of precision (>98% time spent within desired performance). Only the TS with the lowest aptitude was not able to consistently achieve the desired task performance requirements. At A=10.2, it can be seen that one TS managed to perform to a significantly higher standard than other, comparable TSs in both the RC and ACAH configurations. It is believed that this is a result of significant previous exposure to PC-based flight simulation games for this TS.

Fig. 22 shows the TPX score achieved by each of the TSs for each PAV configuration. As above, the scores represent an average of the final three attempts at an MTE, and have been averaged across the five MTEs.

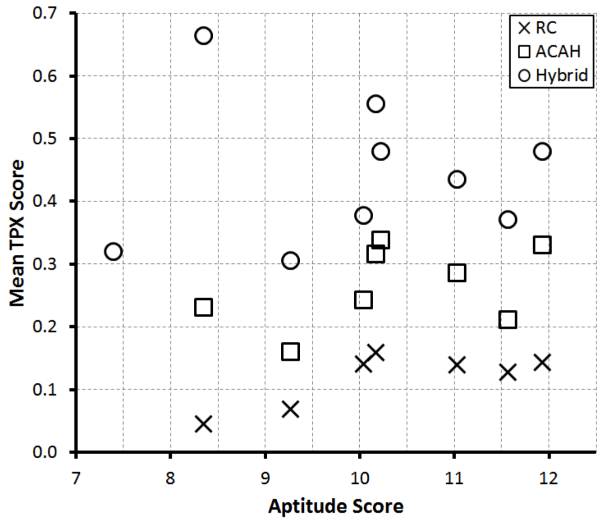


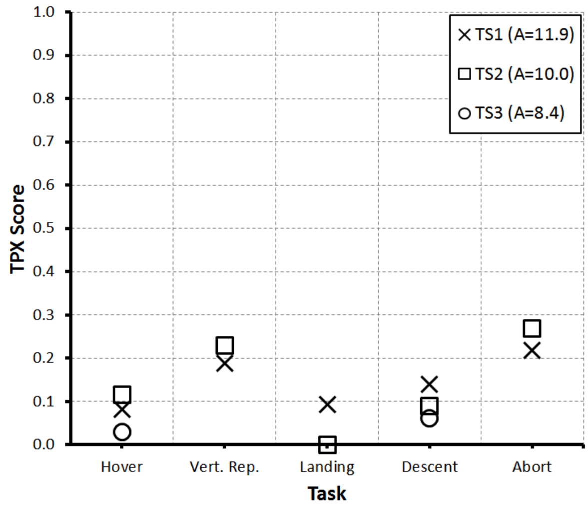
Fig. 22 TPX Scores for PAV Configurations

A similar trend can be seen in the quantitative analysis. There is a steady improvement in achievable TPX moving from the RC configuration, through the ACAH configuration to the Hybrid configuration. It is of note that nearly every TS achieved a better TPX score with the Hybrid configuration than the best-performing TSs did with the ACAH configuration. The same can be seen in the ACAH-RC comparison. Also of note is the low aptitude TS (A=8.4) who achieved an extremely high mean TPX score. As was seen in Fig. 21, this TS achieved comparable precision to the other TSs. The high TPX score is a result of the development of a very low frequency control strategy – actually closer to the theoretical ideal than any of the other TSs managed. Although this TS generally flew the MTEs with slightly lower aggression (lower accelerations, lower peak translational velocities) than the higher aptitude TSs, this shows that it was possible for TSs across the aptitude range to develop effective strategies to successfully fly the Hybrid configuration.

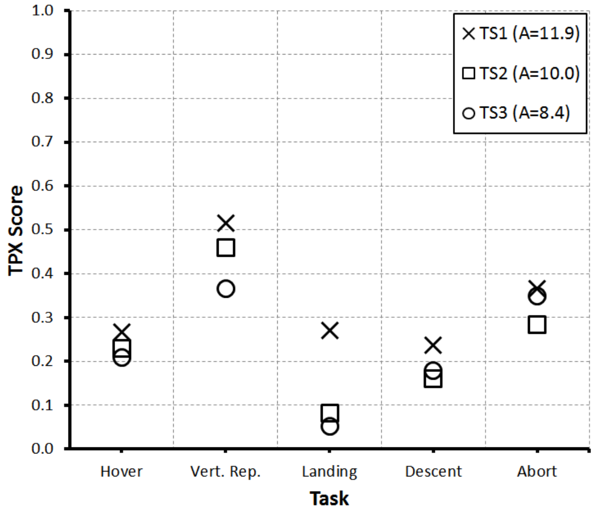
Although there is some scatter in the results, the trends evident in Fig. 22 provide an indication of how pilots of differing aptitude performed with the three PAV configurations. Starting with the RC configuration, all TSs performed to a much lower standard than with the other configurations. There was an improvement in performance from low aptitude to moderate aptitude, but increasing the aptitude beyond this point did not significantly affect the results achieved. With the ACAH configuration, a slight improvement in task performance with increasing aptitude is visible. Finally, with the Hybrid configuration, all TSs, regardless of aptitude, were able to achieve a good TPX score for each task. Increased scatter is evident in the results for the Hybrid configuration. This is a result of differing levels of 'acceptance' of the positional stability offered by the TRC response type. This allowed some TSs to minimize their level of control activity and allowed the system to do most of the 'work' for them. In contrast, other TSs felt the need to apply continuous closed-loop control inputs to the vehicle, even when trying to maintain a constant position; hence reducing their TPX scores.

The contrast between the performance scores shown in Fig. 22 and the subjective workload ratings shown in Fig. 19 should be noted. While all pilots were able to achieve a good TPX score with the Hybrid configuration, there was a definite trend of increasing subjective workload as the aptitude score reduced. This difference reflects the inherent limitation of the TPX calculation method – it can only consider the control movements for the workload component of the score. The mental processing required to determine what those control movements need to be is also an important element in the overall workload for a task, and this appears to be an increasingly important element as the pilot's aptitude reduces.

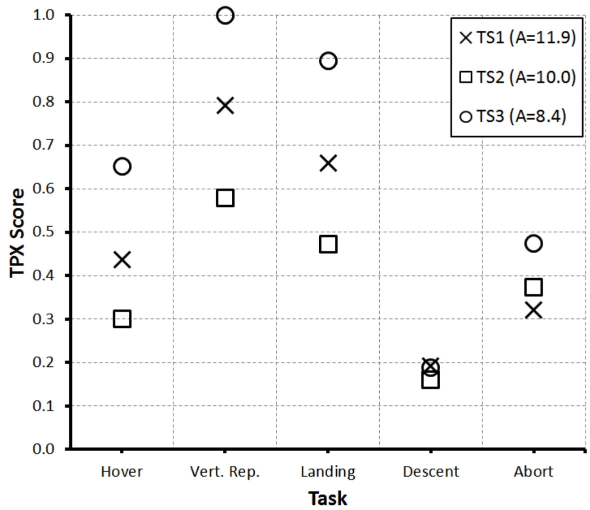
Fig. 23(a) shows the individual TPX scores for each MTE for a sample of the TSs. The TSs used are the same as those used in the presentation of Fig. 20. Fig. 23(b) provides the same analysis of the ACAH configuration, with Fig. 23(c) for the Hybrid configuration.



a) RC Configuration



b) ACAH Configuration



c) Hybrid Configuration

Fig. 23 Sample of TPX Scores - Individual Tasks

Generally, there is a considerable spread between the scores for each task for any one TS and it was not the case that one TS consistently performed better than the others across the tasks; this is true for all configurations. The differing comparative levels of performance across the five MTEs are likely to be a result of the differing demands of each task (e.g. precision station keeping, flight path control etc.) being more or less suited to each TS. The trend of which tasks offer high scores and which offer low scores is roughly similar across all three configurations. The variation of TPX scores between tasks is a result of the different nature of each of the tasks (e.g. duration, number of axes requiring control inputs) making the achievement of the theoretical minimum number of control inputs easier or more difficult in relative terms.

To illustrate the point, the examples of two tasks with the Hybrid configuration (Fig. 23(c)) – the vertical reposition and the decelerating descent – will be used. In the vertical reposition task, the pilot is required to align the PAV in front of a lower hover board – the task is started with the aircraft offset to the left of, and back from, the correct position (this ensures that the aircraft is not started in a 'perfect' trim ready to climb, and therefore, the pilot must accommodate all of the handling characteristics of the aircraft). The movement into the correct position requires a pair of longitudinal cyclic inputs (one to accelerate and one to decelerate) and a pair of lateral cyclic inputs. Once in position, the TRC response type will hold the vehicle in the correct position. The only remaining control activity to complete the task is for the pilot to raise the collective lever, to initiate the climb, and then lower it to capture the new height. A minimum of six control inputs is therefore required to perform this task.

When it comes to actually flying the vertical reposition task, it is relatively straightforward to get close to this theoretical minimum – the translation into position in front of the lower board can be done slowly (there is no aggression requirement on this element of the task), and the availability of good heave dynamics makes it possible to capture a new height precisely and without overshoots. This is also facilitated by the collective lever inceptor force-feel characteristics that are used – a return-to-centre spring is applied, meaning that if the pilot judges the correct moment to commence the vertical deceleration, simply releasing the collective lever will ensure that the aircraft decelerates to a hover at constant altitude.

In contrast, the decelerating descent task is a longer manoeuvre (several minutes), but still only requires six theoretical control inputs to complete it. However, as the initial descending flight path angle and deceleration rate must be set up when still 0.75nm from the final hover point, it is difficult for the pilot to position the controls at exactly the correct locations, even with the enhanced visual cueing provided by the HUD. As the approach continues, the pilot is able to refine his control inputs to improve the accuracy of the final hover. This adds to the workload and reduces the TPX score. Further, if the theoretical minimum number of control inputs is to be achieved in this task, the pilot must hold a constant force on both the longitudinal cyclic and the collective for a period of several minutes. This is physically demanding and difficult for a pilot to achieve, leading to inadvertent control movements away from the desired position. Again, this reduces the TPX score for the task. The implication of this is that care is required when comparing TPX scores between different tasks.

Using the data in Fig. 23, it can be seen that for the vast majority of TS/task combinations, a move from the RC configuration to the ACAH configuration resulted in an improvement in performance, and likewise, a move from the ACAH configuration to the Hybrid configuration again resulted in an improvement in performance. The only general exception to this is the decelerating descent MTE, where the results for the ACAH and Hybrid configurations are very similar. This is due to the relatively 'open loop' nature of this task – at least until the very final stage where the pilot is required to capture a hover. The demands of controlling deceleration using an ACAH response type are similar in nature to those when using an ACSH response type. Given that it is difficult for the pilot to take full advantage of the ACSH response type's advantages for a task such as this one, it is perhaps unsurprising that the final performance is similar.

3.1.2. Discussion of Results

3.1.2.1. Effect of Test Subject Aptitude

The results presented above show a considerable difference between the performance achievable by high and low aptitude subjects with the RC configuration. This difference is illustrated in Fig. 24. The high aptitude TS (TS1) was able to maintain the precise hover position for the majority of the task but the low aptitude TS (TS3) was unable to engage with the hovering activity in this configuration. As soon as the vehicle had been moved away from its starting trimmed hover, TS3 was unable to apply appropriate control inputs to decelerate the vehicle back to the hover. Divergent longitudinal and lateral positional oscillations resulted. This level of performance was also reflected in the TLX rating of 72 for this task, the rating being dominated by the mental demand involved in the determination of the desired control inputs, and the frustration of being unable to achieve the task's goals. In contrast, TS1 awarded a TLX rating of 43 for the hover MTE, with a relatively even distribution of workload across the six components of the rating. Fig. 25 shows the control activity in the lateral (δ_{lat}) and longitudinal (δ_{lon}) axes. It can be seen that TS3 applied corrective inputs at a lower rate and smaller magnitude than TS1, particularly during the first 20 seconds of the manoeuvre (the translation and deceleration to hover). The variations in height and heading seen in the data for TS1 are a result of the greater confidence with which this subject approached the Hover MTE in the RC configuration, with attempts being made to actively engage with all axes of control. TS3, in contrast, focused purely on longitudinal and lateral control, and was content to allow height and heading to drift during the task.

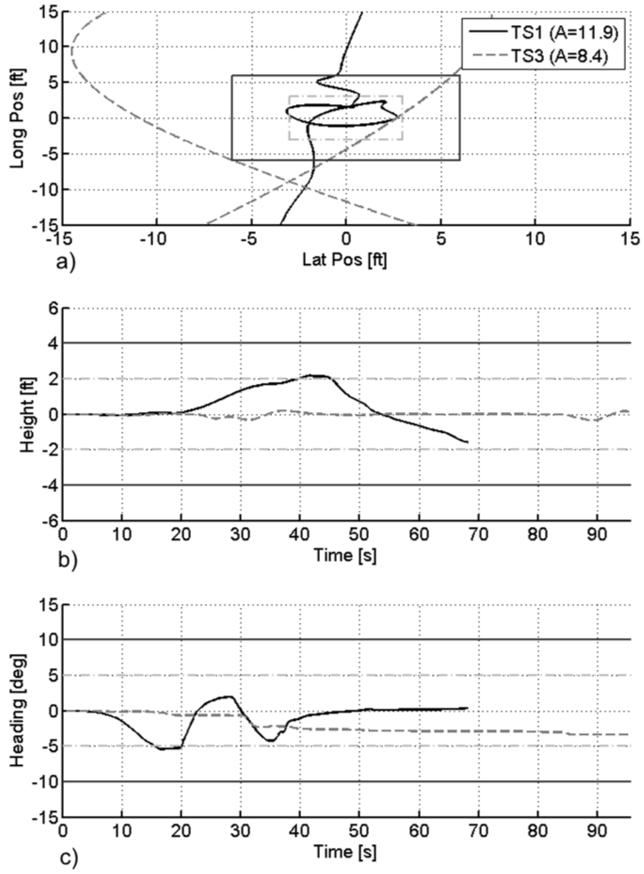


Fig. 24 Comparison of High and Low Aptitude Test Subjects in Hover MTE with RC Configuration

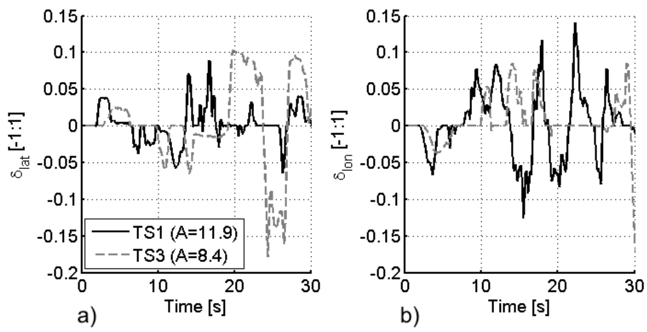


Fig. 25 Control Activity in Hover MTE with RC Configuration

Fig. 26 shows performance in the Hover MTE, for the same two TSs flying the Hybrid configuration. The difference between the two subjects here is much less noticeable. Again TS1 brought a greater level of confidence to the task, decelerating the vehicle to a hover from a higher initial velocity (this can be seen in the larger initial control inputs applied by TS1 in Fig. 27). Both TSs were, however, able to bring the vehicle to a hover within the MTE's desired performance requirements. The HH and DH functionality of this configuration was employed, allowing both subjects to focus purely on the longitudinal and lateral position control elements of the task. Once the vehicle had been decelerated to a hover, neither TS found it necessary to apply further corrective inputs to maintain position – the TRC response type functioned effectively to command zero velocity with the cyclic stick cantered.

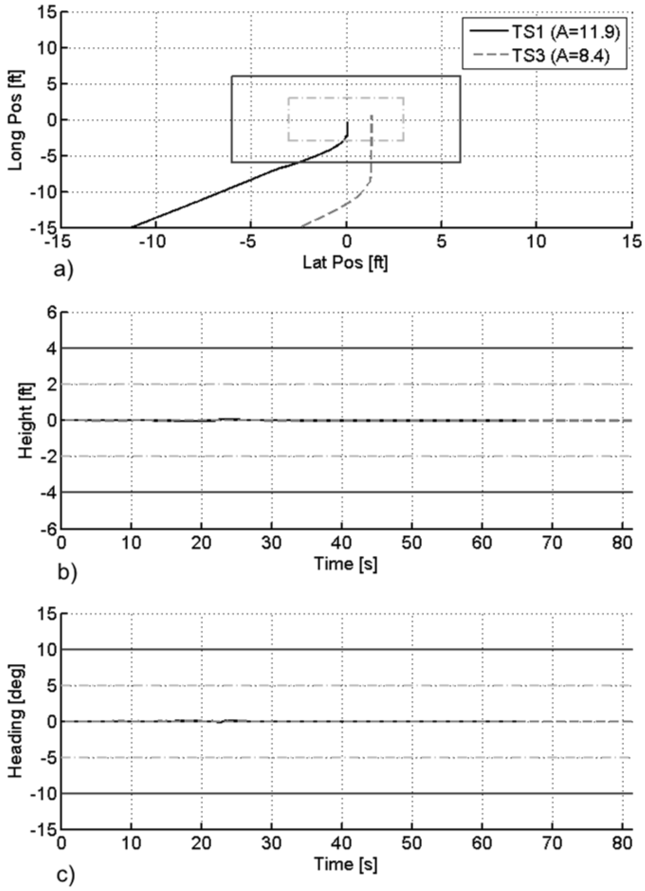


Fig. 26 Comparison of High and Low Aptitude Test Subjects in Hover MTE with Hybrid Configuration

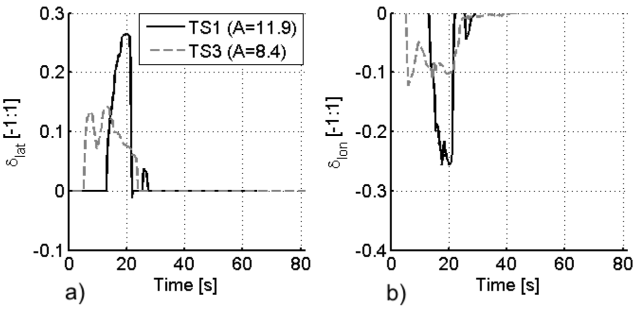


Fig. 27 Control Activity in Hover MTE with Hybrid Configuration

The TLX ratings awarded by the two TSs reflected the greater achievable precision and reduced control activity of the Hybrid configuration, with much lower ratings than were awarded for the RC configuration. For TS1, the TLX rating reduced to 11. The most significant component of this workload was the mental effort associated with determination of the correct location at which to begin the deceleration phase of the MTE to bring the vehicle to a hover in the correct position. For TS3, the TLX rating for the Hybrid configuration was 38. Again, the mental demand of the task was the most significant component of the workload.

3.1.2.2. PAV response type requirements in the Benign Environment

Examination of the results presented in the preceding Sections reveals a consistent picture of the way in which vehicle response type affects the way TSs with differing levels of aptitude for flight-based tasks can perform a range of hover and low speed PAV manoeuvres.

The RC configuration is clearly inappropriate for use in a future PAV. There was a very rapid reduction in achievable task precision and TPX as a pilot's aptitude reduced. Without extensive training, the range of pilots that would be able to safely fly the RC configuration would be small relative to the overall population of potential PAV users. Additionally, if the TLX ratings are considered, although the workload typically reduced as the aptitude increased, workload for all aptitude levels was relatively high.

For the ACAH configuration, precision and TPX were increased compared to the RC configuration, while TLX ratings were lower. If a requirement for safe PAV flight was for a pilot to be able to remain within the desired performance tolerances of the tasks for 90% of the time, then PAV pilots would be required to demonstrate skills equivalent to an aptitude score greater than 10 before being permitted to fly. This aptitude level corresponds roughly to those who have had some prior flight experience, based on the pool of TSs evaluated to date. As with the RC configuration, this would prevent a large proportion of the pool of potential PAV users from doing so, although a moderate amount of conventional GA training might enable a wider population to perform well with this configuration.

Finally, the Hybrid configuration has allowed all but one TS (who recorded the lowest aptitude score of all – A=7.4) to achieve at least 95% of time spent within desired performance. The TPX scores for almost all TSs have been higher with the Hybrid configuration than the scores of all but the best-performing TSs with the ACAH configuration. There are individual cases where TPX scores for the Hybrid configuration have approached the theoretical maximum achievable score for a task. Applying the same criterion as above, (for TSs to be capable of achieving 90% time spent within desired performance), PAV pilots would need to demonstrate skills equivalent to an aptitude score of approximately 8 for the Hybrid configuration. This would open up PAV flight to a much broader pool of potential PAV users, or alternatively, reduce the amount of time (and cost) needed for PAV pilots to perform skills acquisition. As only one TS with an aptitude score less than 8 has been assessed so far, the precise location of this boundary is not certain.

In the predominantly forward flight-based Decelerating Descent MTE, the difference between the configurations was reduced in comparison to the hover-based MTEs. In particular, the ACAH and ACSH response types resulted in similar level of performance and comparable workload. This MTE did not, however, expose the benefits of the ACSH response type in terms of automatic trimming at any airspeed and linear airspeed changes. *The provision of airspeed hold functionality in particular is likely to be very important for flight-naïve pilots in general flight*.

The overall picture developed by the tests performed to date is one where the Hybrid configuration (TRC in hover, ACSH for pitch and ACAH for roll in forward flight) consistently allows both experienced pilots and flight naïve TSs to achieve a very high level of performance across a range of hover and low speed flight tasks with a low to moderate workload. *The Hybrid configuration is therefore considered as being the most suitable of those tested for use in a future PAV in benign environments*.

These results lead to further questions related to the utility of the Hybrid configuration's response types in less ideal environmental conditions. It was noted earlier that [1] anticipates an increased level of vehicle augmentation when the visual conditions degrade. The results in this Section indicate that a TRC response type is the minimum acceptable level of augmentation for a PAV even in good environmental conditions. The following Section therefore explores PAV requirements in harsh environmental conditions, and considers whether the relationship established in [14] for increasing augmentation for degraded environments holds true.

3.2. Handling Qualities Requirements in a Harsh Environment

3.2.1. Results

A total of 7 test subjects took part in the PAV HQ evaluations for the harsh environment. Their aptitude scores ranged from A=9.3 to A=11.9. Some of these TSs also took part in the evaluations for the benign environment, while others were newly recruited for the harsh environment assessments. The evaluations can be broken down into three phases. The first phase examined the impact of degrading the Usable Cue Environment (UCE) or introducing atmospheric disturbances individually on all of the PAV configurations in the Hover MTE. Three TSs took part in this phase of testing (TS1 – A=11.9; TS4 – A=10.33 and TS5 – A=10.39). In the second phase of testing, all of the TSs flew the Hover MTE in both a 'benign' environment – one with good visual conditions and no turbulence, and in the harsh environment – with degraded visual conditions coupled with atmospheric disturbances. All configurations were again used in this phase of testing. The phase of testing involved all of the TSs flying the Hybrid configuration in all of the MTEs (apart from the Decelerating Descent MTE, where the reliance on far-field visual cues to perform the task precluded its use in the DVE) evaluations.

3.2.1.1. Effect of Degraded UCE and Atmospheric Disturbances on Hover MTE

Fig. 28 shows TLX ratings awarded by the three TSs for the three PAV configurations in the Hover MTE. Four datasets are presented, showing subjective workload evaluations for a benign environment with neither DVE nor disturbances (GVE, no turb), the two cases which introduce the DVE or atmospheric disturbances individually (GVE, turb and DVE, no turb) and finally, the full harsh environment which combines both the DVE and the atmospheric disturbances together (DVE, turb). Fig. 29 shows TPX scores for the same set of test points.

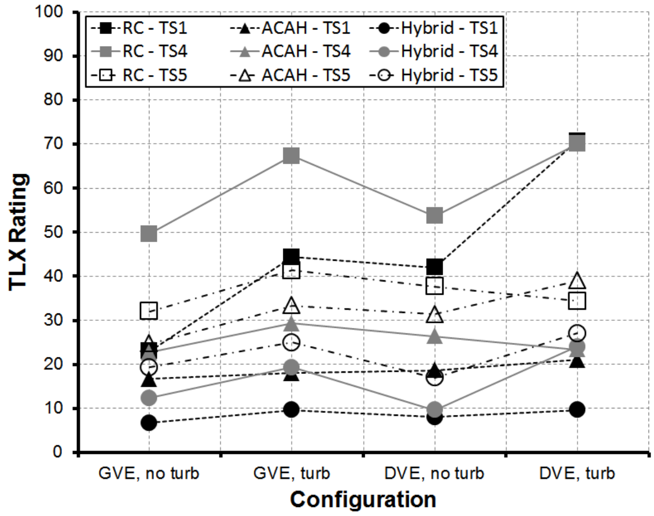


Fig. 28 TLX Ratings for effect of DVE and turbulence in Hover MTE

Although there is considerable variation in the subjective workload interpretation between the three TSs, it can be seen in Fig. 28 that each TS reported a reduced workload transitioning from RC to ACAH and from ACAH to Hybrid. This confirms the findings reported above for the benign environment. Further, Fig. 28 shows that the TSs generally reported greater increases in workload due to the introduction of turbulence than they did due to degradation of the UCE. Subjectively rated workload in the DVE was generally only slightly higher than workload in the GVE, whether or not turbulence was present. The exception was the RC configuration, where two of the TSs found similar workload was required in the DVE without turbulence to that in the GVE with turbulence. This finding is in agreement with the statement in [14] that ACAH and TRC response types are suitable for operations in degraded visual conditions.

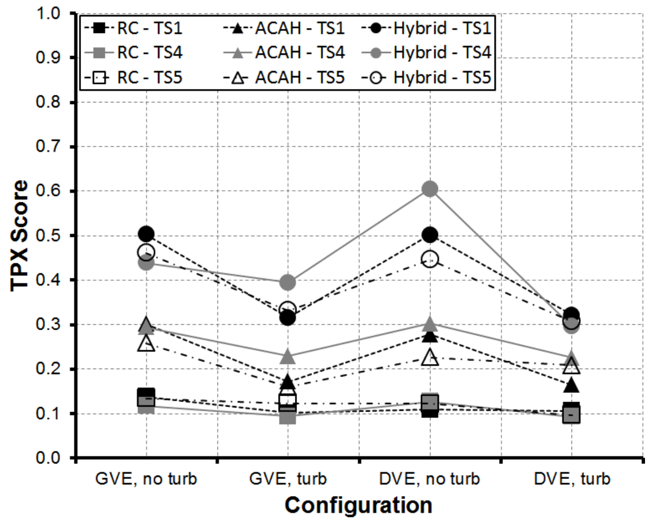


Fig. 29 TPX Scores for effect of DVE and turbulence in Hover MTE

For the quantitative analysis of these tests, Fig. 29 shows a more consistent picture of the behaviour of the three configurations in the various environmental conditions. The Hybrid configuration clearly allowed the best performance to be achieved, followed by ACAH, with the RC configuration resulting in the poorest performance. This was the case in all conditions. Indeed, the TSs were able to achieve better performance in the harsh conditions with the Hybrid configuration than they were able to achieve in the most benign conditions with the ACAH configuration. Similar patterns can be seen in the data for the Hybrid and ACAH configurations – similar levels of performance were achieved in GVE and DVE conditions, whilst introducing turbulence caused a reduction in the TPX score. For the Hybrid configuration, this was primarily a result of an increased level of control activity rather than a reduction in the precision with which the TSs were flying the task (see below). For the ACAH configuration, the reduction in TPX was due to a simultaneous reduction in precision and an increase in control activity. With the RC configuration, the picture is somewhat different. Here, the TPX score is lower in the DVE than is the case in the GVE, being similar to the TPX scores achieved when turbulence was introduced in the GVE. Together, these results confirm the UCE measurements for the test database, as the degraded visual conditions adversely affected the RC configuration, but not the ACAH or Hybrid configurations.

One interesting result that can be seen in Fig. 29 is that one of the TSs achieved a significantly higher level of performance in the DVE (without turbulence) than they did in the GVE. In both cases the TS achieved 100% precision in the Hover MTE; the improvement in the TPX resulted from a reduction in the applied control activity. While this is likely to be in part due to the effect of learning (the DVE case was flown shortly after the GVE case), the degraded UCE may have also had the effect of limiting the cueing of small translational rate errors, and therefore slowed the rate at which the TS applied corrections (Fig. 30).

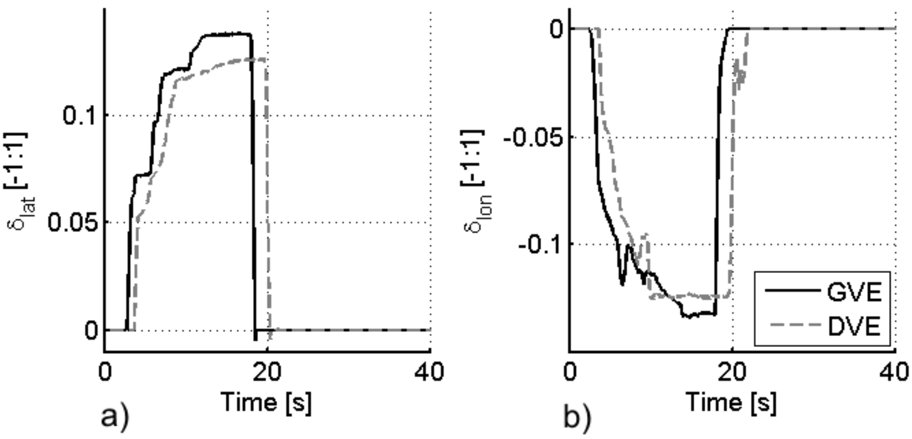
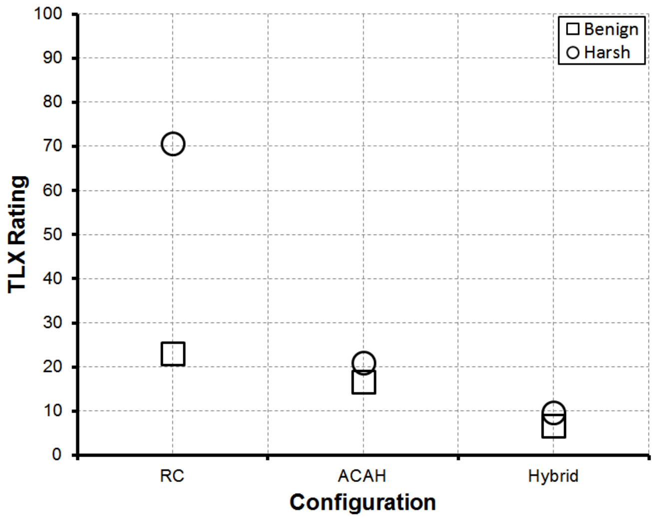


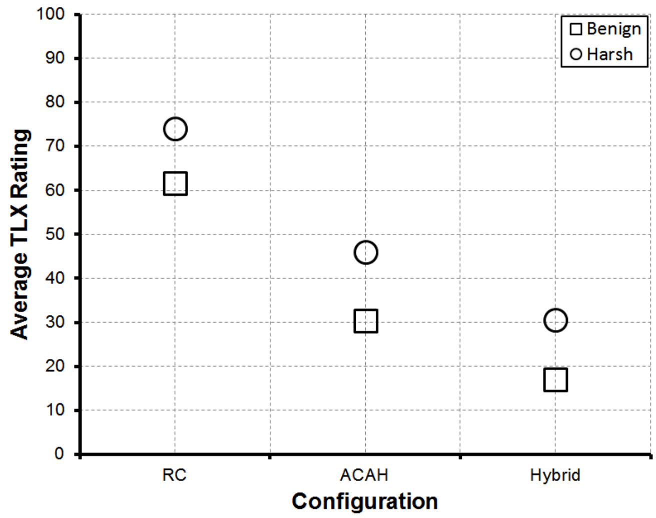
Fig. 30 TS4 control activity in good and poor visual conditions

The key question to be answered by these tests relates to the level of degradation experienced by the pilot in moving from the fully benign condition (GVE, no turbulence) to the harsh environment (DVE, turbulence). **Fig. 31**(a) shows the TLX ratings awarded by TS1 for these two conditions. This TS achieved the highest aptitude score and holds a PPL (H). Nevertheless, the results shown provide a very clear picture. A slow increase in workload can be observed in the benign environment moving from Hybrid to ACAH to RC. In the harsh environment, the rate of change is faster, especially transitioning between the ACAH and RC configurations. These results show that the closed-loop disturbance rejection features of the ACAH and Hybrid configurations can be effective at minimizing the additional workload required to perform the Hover MTE in the harsh conditions, and that the DVE does not necessarily adversely affect workload, given the correct response characteristics.

Not all of the TSs, however, achieved the same results as TS1. **Fig. 31**(b) shows the average TLX rating for each configuration given by the 7 TSs who took part in the harsh environment testing. It can be seen that the difference in average TLX ratings between the benign and harsh environments is fairly similar for all three configurations.



a) TS1



b) All TSs

Fig. 31 Average TLX ratings for Hover MTE

For the Hybrid configuration, some of the TSs reported applying corrective control inputs as the PAV was displaced by the atmospheric disturbances, even if the disturbance would not cause the aircraft to move outside the desired performance boundaries. At the other end of the scale, many of the TSs who were less experienced found the RC configuration extremely challenging to fly in the benign environment, meaning that they were already working at close to their maximum rate. The addition of further challenges, in the form of atmospheric disturbances and restriction of the visual cueing, could not, therefore, lead to a significant increase in workload.

A picture that is more consistent with that seen in Fig. 31(a) can be observed if the task precision achieved by all of the TSs is considered. Fig. 32 shows the average percentage of time spent within the Hover MTE's desired performance boundaries for each of the PAV configurations in the benign and harsh environments. Across all of the TSs, there was a very small reduction in the precision achieved with the Hybrid configuration (3%) in the harsh environment, compared to a larger reduction with the ACAH configuration (7%), and a larger still reduction with the RC configuration (12%). The small reduction in precision with the Hybrid configuration provides confidence that this remains a suitable option for implementation in future PAVs, even in the presence of atmospheric disturbances and a DVE. The analysis of the tests in the benign environment indicated that the ACAH and RC configurations were unsuitable for use in PAVs due to the relatively low levels of precision achievable, and the results seen in Fig. 32 confirm this conclusion, with even lower levels of precision achieved in the harsh environment.

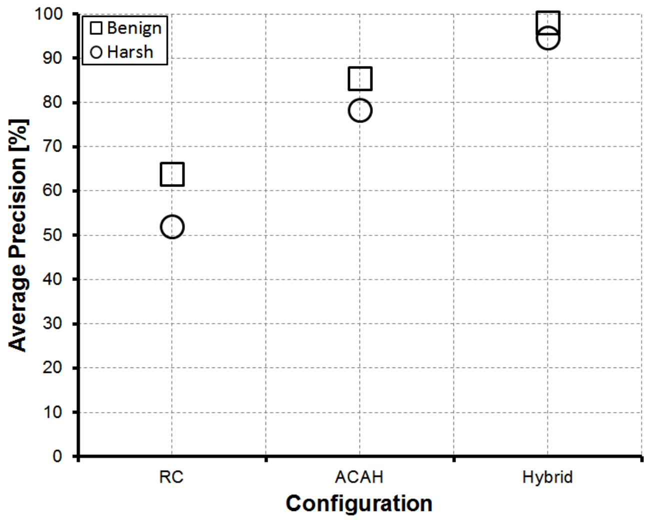


Fig. 32 Average precision from all TSs for the Hover MTE

3.2.1.2. Suitability of Hybrid Configuration for Operations in Harsh Environment

The results presented above suggest that the Hybrid configuration remains suitable for use on a PAV operating in a harsh environment, albeit with an increased workload. However, this is based on just one of the four MTEs used for the assessments. Fig. 33 shows the average TPX score achieved by each TS across all four MTEs.

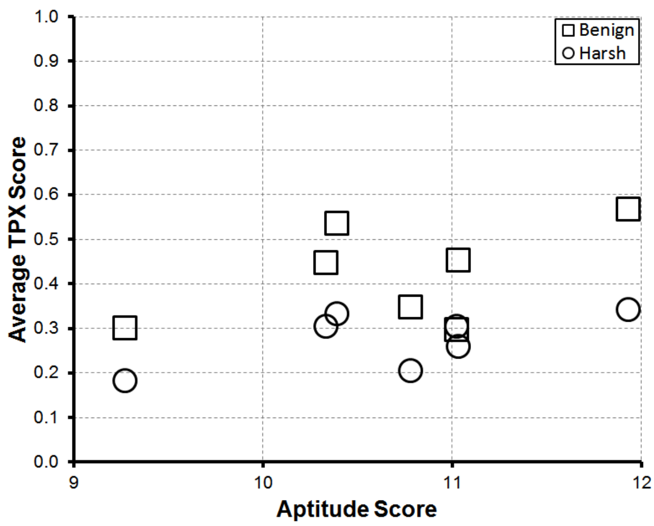


Fig. 33 TPX scores from all TSs averaged across all MTEs

It can be seen that, when all MTEs are considered, there is a considerable drop in the TPX score when moving from the benign to the harsh environment – somewhat more so than was seen in Fig. 29 for the Hover MTE alone. Generally, the reason for this reduction in performance is the same as for the Hover MTE – an increased level of control activity, rather than a reduction in the level of precision achieved in the tasks. An example is shown in Fig. 34. It can be seen that there was an increased number of corrective control inputs required to establish and maintain the 45° translation in the first 20 seconds of the task when flown in the harsh environment. However, in both cases, the TS was able to judge the deceleration phase of the MTE correctly, bringing the PAV to a hover inside the task's desired performance boundaries. Thereafter, the PAV maintained its position inside the desired performance boundaries without requiring additional corrective inputs from the pilot.

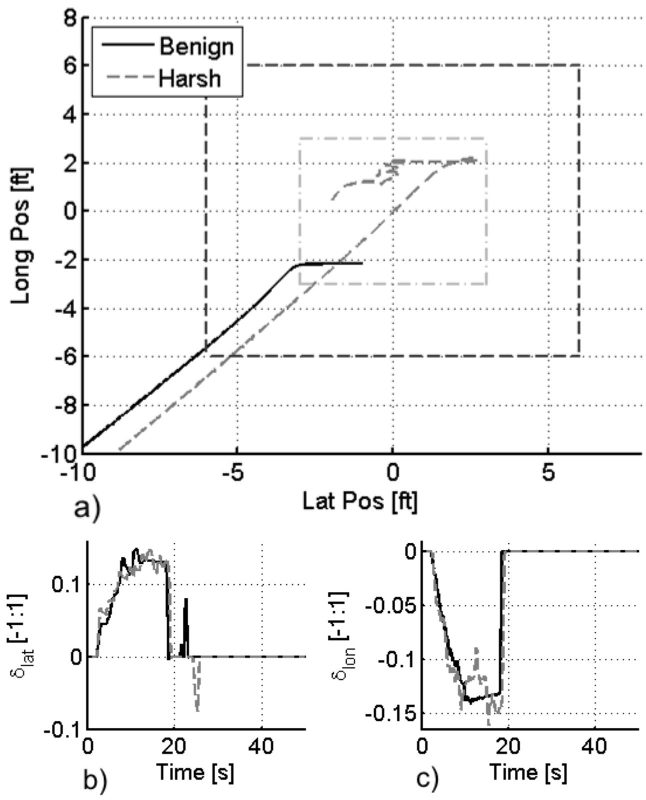
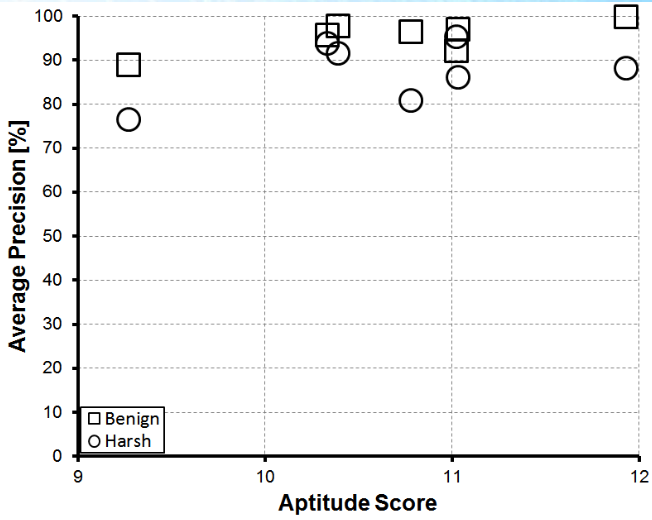
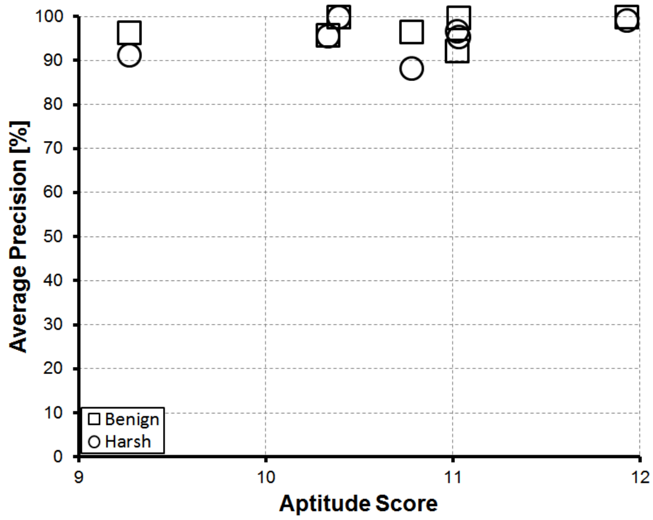


Fig. 34 Plan position and control activity in Hover MTE

There was, however, one notable exception to the trend described above, and that was the Landing MTE. To achieve desired performance, the PAV pilot must touch down inside a target box measuring 2ft longitudinally by 1ft laterally. It proved difficult for the flight-naïve TSs to achieve this very high level of accuracy consistently in the presence of atmospheric disturbances. The impact of this is shown in Fig. 35(a) (showing average precision across all four MTEs) and **Fig. 35**(b) (showing average precision across the Hover, Vertical Reposition and Aborted Departure MTEs).



a) All MTEs



b) All MTEs bar Landing

Fig. 35 Precision achieved by all TSs

When comparing precision in the benign and harsh environments across all four MTEs (**Fig. 35**(a)), there is typically a 10-15% reduction for each TS in the harsh environment. If the Landing MTE is excluded, however (**Fig. 35**(b)), the reduction in precision is much smaller (generally <5%), with several of the TSs able to achieve the same, or better, level of precision as they could achieve in the benign environment. When excluding the Landing MTE, in only one case did the level of precision achieved in the harsh environment fall below the 90% threshold used to measure success in the benign environment analysis.

3.2.2. Discussion of Results

The results presented show that, with the Hybrid configuration, the TSs were largely able to maintain their level of precision in degraded environmental conditions. This was not the case with the ACAH and RC configurations, which both showed significantly larger reductions in precision. An exception to this, was, however, found in the Landing MTE, where the TSs were not able to consistently achieve the very high level of accuracy demanded of this task. The velocity hold with velocity beep (the ability to make small velocity commands by pushing a 4- or 8-way 'hat' switch in the desired direction of travel) functionality incorporated into the Hybrid configuration is sufficient for this level of accuracy in the benign environment, but not in the harsh environment. *The addition of position hold functionality (combined with a position beep system) would be recommended for this type of task*.

Despite the demonstrated capability of the Hybrid configuration to maintain precision in the harsh environment in most of the investigated tasks, the workload experienced by the TSs did increase (both qualitatively and quantitatively). This was, in part, due to occasional corrections being required (or perceived as being required) to maintain plan position within the desired tolerances. Again, incorporation of position-hold functionality would be of benefit here. However, workload also increased due to additional effort being required to establish and maintain translational rates in the desired direction (e.g. in the Hover and Aborted Departure MTEs), and in interpreting the more restricted visual cues. In these scenarios, the elevated level of workload may have to be accepted as a consequence of operating manually in the harsh environment. A question would therefore exist regarding the duration of time that a PAV would be expected to operate in such conditions, and hence the expected level of pilot fatigue that would occur. In terms of high precision tasks, such as those employed in this report, it would be expected that these would form only a small part of a complete PAV mission. The majority of the flight would take place at higher altitudes and away from ground obstacles (Ref. [13]). However, assuming that all phases of the flight would be controlled manually, an elevated level of workload would still be likely in the cruise phase. This was beyond the scope of the current study.

In terms of the precision achieved in the MTEs, there was generally a very small (<5%) reduction in the harsh environment compared to the benign environment (excluding the Landing MTE). In all but one case, the TSs were able to maintain their level of precision at greater than 90% of time spent inside the task's desired performance tolerances. Notwithstanding the comments above regarding the elevated level of workload and possible requirement for a position hold system for very high precision tasks in turbulent conditions, *it is apparent that the Hybrid configuration remains, generally speaking, as being as suitable for operations in the harsh environment as it is in the benign environment*. *This is an interesting contrast to the military rotorcraft specifications in* [14]. For the flight-naïve PAV pilot, it appears that the same (highly augmented) response type is acceptable for UCE 1 and 2 conditions.

4. Guidelines for Improved Training Effectiveness through Use of New Control and Information Systems

HQ requirements for a notional set of PAV dynamic have been examined in the previous Sections. The work has included the identification of response types (i.e. the manner in which the vehicle responds following a cockpit control input) that permit 'flight-naïve' pilots (those with little or no previous flight experience) with a broad range of aptitudes for flight tasks to rapidly develop the skills required to operate a PAV simulation safely and repeatedly with a high degree of precision [34-36]. This work showed that a vehicle that offered a TRC response type (i.e. the vehicle moves at a constant velocity over the ground for a constant stick deflection) in hover and at low speeds could be operated by a wide range of test subjects, with minimal instruction. This was found to be the case in both good environmental conditions, and in the presence of atmospheric disturbances and a degraded visual environment.

This Section extends the previous work to consider the quantity and type of training that would be required by prospective PAV pilots in order to be qualified to operate a manually-piloted aircraft with a Hybrid response type. The development of the syllabus, based on a Training Needs Analysis [37] for PAV flight is described, taking into account current 'best practice' for the training for the acquisition of both private pilot licenses (PPL, for both helicopter, PPL(H) and aeroplane, (PPL(A)), and car drivers. Whilst current PPL training may be thought of as being more directly applicable to the PAV, in the scenario of mass adoption of the PAV, many trainee PAV pilots would already have some knowledge and experience of car driving, and so commonality (where feasible) would permit more effective transfer of this knowledge to the PAV training.

Further, this Section presents the results of trials conducted using the University of Liverpool HELIFLIGHT-R flight simulator [38] in which the volunteers were trained using the syllabus developed for that purpose. The aims of the trials were to study the effectiveness of the training syllabus and to explore the likely length of time required to complete the training for a range of test subjects.

Many methods have been developed for the assessment of training programmes, but perhaps the most widely-used is Kirkpatrick's Four Level model [39;40]. The four levels of evaluation allow the effectiveness of the training to be evaluated in terms of the trainee's engagement and satisfaction (Level 1), immediate demonstration of the learning that has been achieved (Level 2), longer-term application of the learning to the trainee's job (Level 3) and finally the benefit to the organisation from the trainee's new skills (Level 4).

In the context of the evaluation of the PAV training syllabus, the first level was accomplished using questionnaires that were completed by each participant at the end of their training. For the second level evaluation, the participants undertook a final 'skills test', in which they flew a series of manoeuvres related to the PAV's role. The third level evaluation took the form of a 'real-world' PAV flight that the participants were asked to fly. For both the second and third level evaluations, the measurement of the precision achieved and level of control activity allowed the degree of success to be measured. A fourth level evaluation could take the form of long-term assessment of the PAV pilot while flying the real aircraft. As the scope of current PAV research is limited to simulation only, it was not feasible to conduct the fourth level evaluation during the project.

The structure of the evaluation of the training can take several forms [40]. These generally involve a period of training followed by a post-training test to measure final performance. A pre-training test can also be included to measure initial performance prior to training. More complex evaluation structures can involve the use of control groups who do not receive training, in order to evaluate the impact of external factors on the evaluation.

For the PAV training evaluation, time restrictions in terms of the availability of the simulator prevented the use of a control group. Pre-training testing of role-specific tasks (i.e. actual flying in the simulator) would have significantly impacted on the outcomes of the evaluations due to the (intended) highly intuitive nature of the system being trained – i.e. the participants would have been able to self-learn to a considerable extent while completing the pre-training test, which would affect the quantity of training required while following the syllabus. Hence, evaluation of the efficacy of the PAV training syllabus has been performed on the basis of post-training performance only. The ability to successfully complete a 'skills test' and a 'real-world' evaluation has been taken as the means to show that the participant has acquired the necessary skills for to fly a PAV. Whilst the enforced absence of a pre-training test evaluation does impinge upon the ability to directly measure the skills gained during the training programme, the use of an aptitude test to assess natural flying ability (e.g. hand-eye coordination) allowed the performance of each participant to be placed in context [35]. Furthermore, as none of the participants in these tests possessed any previous flying experience (all had some driving experience, this is discussed in further detail in the Results Section), and hence none had pre-existing directly-relevant knowledge, it has been assumed that all of the participants started the training programme from an equivalent level of relevant knowledge and skill.

4.1. Training for Drivers and Pilots – Existing Requirements and Practice

This Section describes the current requirements, and typical practice, associated with training car drivers and private pilots in the UK today. The primary sources for the information discussed on actual practice in this Section are interviews conducted with highly experienced driving and flying instructors – each with more than 15 years of practical training experience.

4.1.1. Driver Training in the UK

UK car drivers are expected to be able to meet certain standards in terms of their actions on the road and their knowledge of the 'Highway Code' – the rules that govern their driving behaviour. These standards are set out by the UK's Driving Standards Agency (DSA) [41]. The DSA also publishes a national driving syllabus [42] that covers all points of learning – including the development of skills and abilities and the acquisition of knowledge and understanding, required to meet the published standards. The national syllabus is not, however, compulsory, and many driving instructors have developed their own methods by which to train their students in the required skills. This often involves breaking down the learning process into separate, grouped, components – for instance basic vehicle control, road skills, interacting with other road users and so on. Within each of these groupings, there might be 10-20 individual skills or knowledge items to be covered. These might include, changing gear, steering, braking and clutch control etc. in the basic vehicle skills category and signalling, road markings and junctions in the road skills category.

For each item of learning, an instructor will typically introduce the concept using graphical aids (typically report-based, but increasingly using electronic means such as videos), and will then ask the student to attempt the task relating to a particular skill. Progress is monitored according to the amount of guidance that the instructor needs to supply to the student. At the beginning, this would consist of comprehensive guidance of every stage of a given task, with the instructor telling the student exactly what they need to do. As the student develops their skills, the instructor will be able to reduce their input to prompts only, and eventually the student should be able to complete the task independently.

The judgement as to when a learner driver is performing to an acceptable standard is typically a subjective decision made by an instructor. Anecdotally, this may be performed on the basis of whether or not the instructor would be happy for the learner to drive with members of the instructor's family in the car.

The UK driving examination takes place in two stages. The first of these is a computer-based theory test, which assesses the candidate's knowledge of the Highway Code. The second, the practical driving test, has a duration of 40 minutes. During this time, the examiner will ask the student to conduct a set of 'standard' manoeuvres (such as reversing around a corner, hill starts and so on) in addition to general driving, as directed by the examiner. Recently an 'independent driving' element has been introduced to the test in order to check on a student's driving ability whilst following traffic signs and making their own driving decisions. The examiner will judge (again, relatively subjectively) whether the candidate is performing to an acceptable standard. Minor driving faults do not directly result in test failure, but an accumulation of a sufficient number (either overall or within a single category) will result in a failure. More serious faults, or indeed dangerous manoeuvres, will result in immediate failure of the test.

4.1.2. Pilot Training in the UK

Pilot training in the UK is standardised to a much greater extent than is the case for driver training. For fixed-wing aircraft, nineteen standard 'lessons' (although they may take more or less than one actual flying session) have been specified by the UK Civil Aviation Authority (CAA), and are taught by all flying schools. For helicopters, there are 27 'lessons', the additional sessions being focussed on hover and low speed operations. Each lesson covers a particular subject (e.g. the effect of the controls, straight and level flight, turning flight etc.). Each lesson begins with a pre-flight briefing in which the subject will be introduced, and the appropriate terminology defined. In the air, the instructor will generally demonstrate the correct procedure, and then hand control to the student to allow them to make their own attempt. By subsequently coaching the student through the procedure (i.e. providing detailed, step-by-step instructions), appropriate behaviours are instilled and refined until an acceptable standard has been achieved.

Unlike driver training, where progress is largely judged subjectively, pilot training involves the use of some objective measures with associated tolerances – in height, heading, airspeed etc. (e.g. ±150ft in height, ±15kts in airspeed during cruising flight etc. [43]) – to judge whether a student pilot has attained an acceptable level of performance. A subjective element remains however, with the instructor making judgements regarding the appropriateness of the student's actions in terms of ensuring the safe operation of the aircraft (for example, having an appropriate mental approach (e.g. keeping 'ahead' of the aircraft), the ability to multi-task etc.). In addition to these checks, during the course of a lesson, three 'Progress Tests' are defined in the PPL syllabus. These are designed to verify that the student pilot is able to demonstrate the techniques that have been learned during the lessons.

As with learning to drive, becoming a licensed pilot involves the completion of both theory and practical exams. A PPL student must pass nine theory exams, covering subjects such as Air Law, Human Performance and Navigation. The practical flying skills test includes navigation, circuits and dealing with a simulated engine failure, in addition to general handling. The examiner will use both the quantitative tolerances of height, heading and airspeed, and subjective judgement to determine whether or not a student has successfully passed the practical test.

4.1.3. Discussion of Existing Training Paradigms

It is evident from the commentary above that there are a number of similarities in terms of the methods used to train pilots and car drivers – particularly, in terms of the way in which new techniques are introduced to a student, and in which progress is assessed. In both scenarios, learners are introduced to new concepts progressively, and are not expected to master control of all aspects of their vehicle simultaneously. Similarities also exist in the methods used to examine competency – with theory exams and practical tests in both cases.

While there are common elements to the methods described above for car driving and flying instruction and examination, a number of additional limitations are imposed on a PPL student. Firstly, it is a legal requirement that a trainee pilot must accumulate a minimum quantity of 'hands-on' learning prior to being able to acquire a license. This is a minimum of 45 hours, which must include at least 25 hours of 'instructed' flight and 10 hours of 'solo' flight, and should also include at least 5 hours of 'cross-country' flying – which requires the student to exercise their navigation skills. PPL students are also required to meet more stringent medical standards, although a discussion of these is beyond the scope of the current report.

Secondly, a newly-qualified driver can drive any four-wheeled vehicle with a total mass of less than 3.5 tonnes, in any environmental conditions. A newly-qualified PPL(A)-holder is limited to basic Single Engine Piston (SEP) aircraft. Any additional features that complicate the operation of the aircraft (for example retractable undercarriage, multiple engines etc.), require separate 'type ratings' for that particular aircraft. With the PPL(H), aircraft types are even more restricted – every individual helicopter type is covered by its own type rating. Further, basic PPL-holders are allowed to fly only during daylight hours and in Visual Flight Rules (VFR) conditions. To fly in more adverse conditions, pilots require additional training and further qualifications (the Night Qualification and IMC Rating, respectively).

4.2. Proposed PAV Training Syllabus

4.2.1. Key Skills for PAV Pilots

At an early stage in the *myCopter* project, an outline 'commuting' scenario was developed to inform the subsequent research [13]. This scenario requires the PAV to perform a vertical take-off from a residential location, climb and accelerate to cruising flight. Upon reaching the destination in the Central Business District (CBD) of a city, the PAV must descend and decelerate to a hover above the landing point, following which the landing is performed vertically. Using this description as a basis, a list of manoeuvres that would need to be performed by a PAV pilot was developed. These, in turn, were used to identify the skills that the PAV pilot would need to demonstrate for manual flight, based on the ideal PAV response characteristics identified in the earlier *myCopter* research [34-36].

In total, 24 key skills have been identified that relate to manual PAV handling. These are as follows:

1. Use of longitudinal inputs in hover to control forward speed (TRC response type);
2. Use of lateral inputs in hover to control lateral speed (TRC response type);
3. Combined use of longitudinal and lateral inputs to control horizontal flight path angle;
4. Use of pedals in hover to control heading and yaw rate (Rate Command (RC) response type);
5. Use of the collective lever in hover to control height and vertical rate (Vertical Rate Command (VRC) response type);
6. Combined use of pedals and lateral inputs at low speed (<25kts) to improve turn coordination;
7. Use of longitudinal inputs in forward flight to control speed (Acceleration Command, Speed Hold (ACSH) response type);
8. Use of lateral inputs in forward flight to control heading (Attitude Command, Attitude Hold (ACAH) response type);
9. Use of the collective lever in forward flight to control vertical flight path angle (flight path angle command (γC) response type);
10. Function of the pedals in forward flight (sideslip angle command (βC) response type);
11. Combined use of lateral inputs and collective in forward flight to perform climbing and descending turns;
12. Combined use of lateral and longitudinal inputs in forward flight to perform accelerative and decelerative turns;
13. Combined use of longitudinal inputs and collective in forward flight to perform accelerative and decelerative climbs and descents;
14. Combined use of longitudinal and lateral inputs and collective in forward flight to perform accelerative or decelerative climbing or descending turns;
15. Longitudinal transition from TRC to ACSH;
16. Lateral transition from TRC to ACAH;
17. Collective transition from VRC to γC;
18. Pedals transition from RC to βC;
19. Longitudinal transition from ACSH to TRC;
20. Lateral transition from ACAH to TRC;
21. Collective transition from γC to VRC;
22. Pedals transition from βC to RC;
23. Use of secondary 'automation' functions (such as height hold, direction hold etc.) and
24. Use of instrumentation – including HUD symbology for guidance and navigation

It is acknowledged that additional knowledge and skills would be required in terms of cockpit procedures, navigation, communications etc., although it is anticipated that training requirements here would be minimised by effective cockpit design optimisation [44] and by the provision of automatic functionality for route-planning etc. Due to the uncertainty related to these issues, the study of their training requirements was considered to be beyond the scope of the current work.

4.2.2. Construction of PAV Training Programme

The 24 skills identified above were grouped into four 'lessons', each focussed on a specific part of the PAV flight envelope. The lessons were set out as follows:

Lesson 1: Hover and Low Speed Flight – this lesson covers skills (1)-(6), and introduces the student PAV pilot to all that is required to operate the vehicle at air speeds below 15kts.

Lesson 2: Cruising Flight – this lesson covers skills (7)-(14), and introduces all of the requirements for flight at speeds greater than 25kts

Lesson 3: Transition – this lesson covers skills (15)-(22), covering the changes in response characteristics between hover and low speed flight (< 15kts) and cruising flight (> 25kts)

Lesson 4: Advanced Functions – this lesson covers skills (23)-(24), which focus on the 'automation' functions of height and direction hold, and the visual symbology provided by a Head-Up Display for attitude and flight-path and navigation using a Highway-in-the-Sky.

In addition to these 4 lessons covering the basic skills required to fly the PAV, a fifth lesson was created that focussed specifically on the conduct of typical PAV manoeuvres – such as precision hovering, vertical landings and descending approaches to hover [35]. These manoeuvres might be considered as being the equivalent of the 'reverse around a corner' or 'parallel parking' manoeuvres associated with driver training, or standard flying manoeuvres such as performing 'circuits' around the airfield.

For each skill within a lesson, a series of exercises designed to introduce and subsequently refine the skill were taught. For example, from the first lesson, for the skill of forward speed control, the exercises were:

1) Use longitudinal stick input to set a desired forward speed
2) Accelerate/decelerate from one forward speed to another forward speed
3) Decelerate to hover
4) Control deceleration to hover at a specific point above the ground

A complete listing of the training exercises for all skills is included as Appendix 4 at the end of this report.

For each exercise, a 'briefing' was conducted, introducing the purpose of the exercise and what would be attempted. A demonstration was provided by the instructor (a member of the *myCopter* project team who was very familiar with the characteristics of the simulation), with the required control inputs and visual observations (i.e. the outside world features that the trainee should be monitoring) highlighted. The student then attempted the exercise, and through repeated practice with coaching from the instructor in terms of how to modify their technique to ensure safe and precise control of the PAV, improved until a good, repeatable standard was attained (as with driver and flying training, this was judged subjectively based on correct use of the controls and the trainee's apparent confidence in the control inputs being made along with the subsequent responses of the vehicle). This was tracked using record sheets (see Appendix 4) that allowed improvements in competency to be followed and for the length of time spent on each skill to be recorded. Progression to the next exercise was not permitted until at least 'acceptable' performance had been achieved – in other words, the student was able to operate the vehicle safely (without large overshoots of position, for example), repeatably and to a reasonable level of precision.

4.3. Results

Five TSs undertook the PAV training syllabus. Their ages ranged from 22 to 45. Four of the TSs were male, one female. All were car drivers, with driving experience levels that corresponded to their age (the least experienced had been driving for 5 years, the most experienced 25 years). None of the TSs had any previous flying experience.

4.3.1. Training Duration

Fig. 36 shows the total amount of time required by each TS to progress through the syllabus, broken down into the individual lessons. It can be seen that four of the five TSs were able to complete the syllabus in less than 300 minutes/5 hours. TS5, however, progressed at a much slower pace, and failed to complete all 5 lessons in the time available. It is interesting to note that the aptitude test taken prior to the start of the training identified this TS as being more likely to struggle with the demands of the training than the other TSs (aptitude score of 0.56 for TS5, compared to scores in the range 0.74-0.82 for the other TSs; higher scores indicating greater aptitude). TS5 also reported that they had always required a lot of time and practice to become proficient with new 'manual' skills – for example, when learning to drive a car.

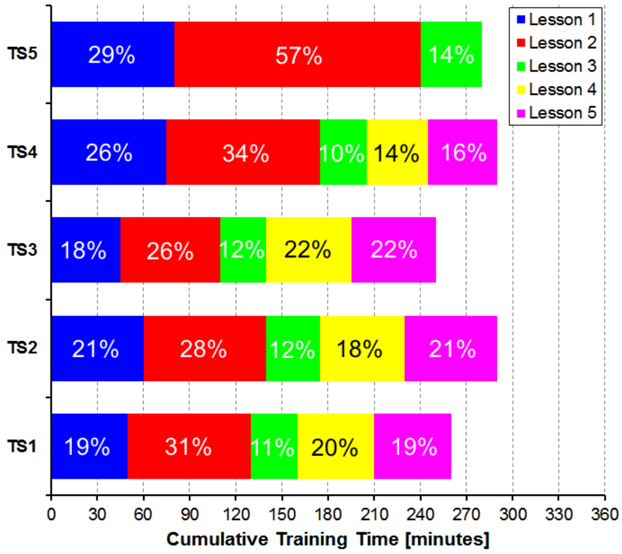


Fig. 36: Training Time for Individual Test Subjects

It can be seen in Fig. **36** that the individual lessons required different amounts of time. There was, however, a good level of consistency between the TSs in terms of which lessons required more or less time (the percentages on Fig. **36** show the proportion of time spent by each TS on each lesson). The lesson that demanded the greatest amount of time was Lesson 2 – covering control of the aircraft in forward flight. Whilst the characteristics of the individual control axes could be learned quite quickly, all of the TSs found that more time was required to reach the 'acceptable' standard when simultaneous, coordinated multiple control inputs had to be made (skills 11-14). As with the single-axis tasks, the process of physically moving the controls to start the PAV moving in the correct sense was not demanding for the TSs. The main complexity introduced by the exercises for these skills was the requirement to regularly monitor two or more of the controlled vehicle states (e.g. airspeed, heading, altitude). The requirement to share attention across a number of information sources required all of the TSs to spend time developing their instrument scan patterns, and to build sufficient confidence in their knowledge of the vehicle's responses. Prior to reaching this point in the syllabus, the TSs had generally only been asked to apply control inputs in a single axis, allowing them to focus on the way in which the controlled parameter was changing. For the multi-axis exercises in Lesson 1, more readily available outside visual cues allowed the TSs to assimilate flight information without the requirement for the comprehensive scan that was demanded in Lesson 2.

Lesson 3, in contrast, was straightforward for all of the participants. The subjects for this lesson – transitioning between the low speed regime and the high speed regime, did not require the demonstration of large amounts of skill or significant practice by the TSs. Rather, the key outcomes from this lesson were the acquisition of theoretical knowledge and understanding by the TSs of the expected behaviour of the aircraft during the transition stage. A short period of practice to reinforce the theoretical knowledge was then all that was required to complete the objectives of this lesson.

4.3.2. Level 1 Evaluation – Participant Satisfaction

Each of the participants who completed all five lessons was asked to complete a questionnaire that explored their satisfaction with the training that they had received. The questionnaire contained five questions with quantitative answers, plus a number of 'open' questions for the participant to explain the reasons for the answers that they had given. The five quantitative questions were:

1) To what extent do you feel that you have learned the skills necessary to fly a PAV from the programme?
2) Was the programme stimulating?
3) Was the pace of the programme appropriate for you?
4) Was the programme sufficiently flexible to meet your needs?
5) Was the programme challenging?

In each case, the participant was asked to respond on a scale from 1 to 8. A score of 8 indicated strong agreement with the statement, while a score of 1 indicated strong disagreement. In the case of question 3, a score of 8 indicated a pace that was too rapid, while a score of 1 indicated a pace that was too slow.

Fig. **37** shows the average score given by the participants for each question, together with the upper and lower bounds of the ratings awarded. It can be seen that the participants found the training programme to be effective at teaching them the skills they felt they needed (based on the requirements of the final evaluations conducted following the training phase), was stimulating and flexible. The participants found the pace of the training to be neither too fast nor too slow. The participants generally found the training to be moderately challenging, indicating that the characteristics of the PAV were relatively straightforward to learn, but that there remained sufficient challenge to engage and stimulate the participants.

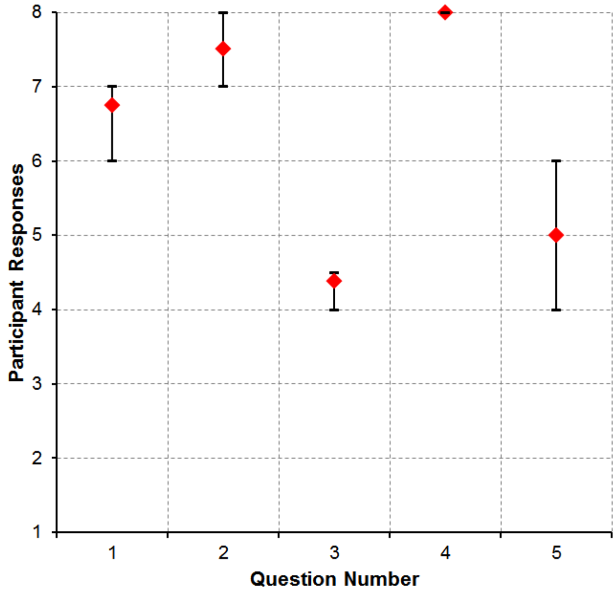


Fig. 37: Participant Responses to Satisfaction Questionnaire

4.3.3. Level 2 Evaluation – Skills Test

Following completion of the training programme, each of the TSs who reached this stage took part in a skills test. The test consisted of five MTEs, used in earlier stages of the *myCopter* research [35]. The MTEs are representative of various elements of the *myCopter* commuting scenario. The five MTEs are as follows:

1) Hover – aircraft is accelerated to a speed of 6-10kts along a track aligned at 45° to its heading. The aircraft is then decelerated in a single, smooth action to hover at a prescribed point. The positioning accuracy with which the hover can be maintained is monitored. Height and heading are maintained constant throughout.
2) Vertical Reposition – the aircraft performs a hovering climb of 30ft while maintaining plan position and heading. A time limit of 10s is imposed on the climb.
3) Landing – the aircraft must perform a vertical touch down within a tightly constrained area. A 10s time limit is imposed on the final stages of the landing (height above ground < 10ft).
4) Decelerating Descent – the aircraft begins in cruising flight at a height of 500ft above the ground, at 60kts. When a marked position is reached, the aircraft descends and should begin to decelerate. The manoeuvre is complete when the aircraft has been brought to a hover at a height of 20ft above the marked end point.
5) Aborted Departure – the aircraft accelerates from hover to 40kts, and then decelerates back to hover. Height, heading and lateral track are held constant during this manoeuvre. A time limit of 25s is imposed on this task, making the level of aggression significantly higher than the other tasks.

For each task, a set of 'desired' performance boundaries have been identified (for the Hover for example, in height (±2ft) and heading (±5°) deviation, and in plan position (±3ft either laterally or longitudinally) during the steady hover phase of the task). These are identified to the pilots using reference objects placed in the outside world visual scene. The TSs were asked to attempt to stay within these boundaries whilst flying the MTEs.

Fig. 38 shows the average time spent within the desired performance boundaries for each MTE across the TSs who completed the skills test. Also shown for comparison is data from earlier *myCopter* testing [35] in which the TSs were asked to attempt the MTEs without having had any formal training. The TSs for this data were different to those being studied in this report, and had a mixture of previous experience – from no flying or driving experience at all to holders of PPL(A)s and PPL(H)s. It can be seen that those TSs who received training in the characteristics of the PAV simulation were consistently able to achieve an excellent level of precision (>98% time spent in the desired performance region) in all five MTEs. Although the 'untrained' TSs were able to achieve good precision (confirming the highly intuitive nature of the response characteristics of the PAV simulation), the precision achieved by the 'trained' TSs was better than the average precision achieved by the 'untrained' TSs in every task (between 1% and 5% improvement in time spent within the desired performance boundaries). This was particularly true in the Landing and Decelerating Descent tasks. These two tasks, perhaps more so than the others, demand the application of developed technique by the pilot, particularly in terms of use of the 'advanced' functions (such as the use of a 'hat' switch to command small velocity perturbations for fine positioning in the Landing MTE) and Head-Up Display symbology (flight path vector indicator and deceleration rate indicator to judge the approach to hover in the Decelerating Descent MTE). The training received by the TSs has clearly been beneficial in terms of allowing the target level of accuracy to be achieved.

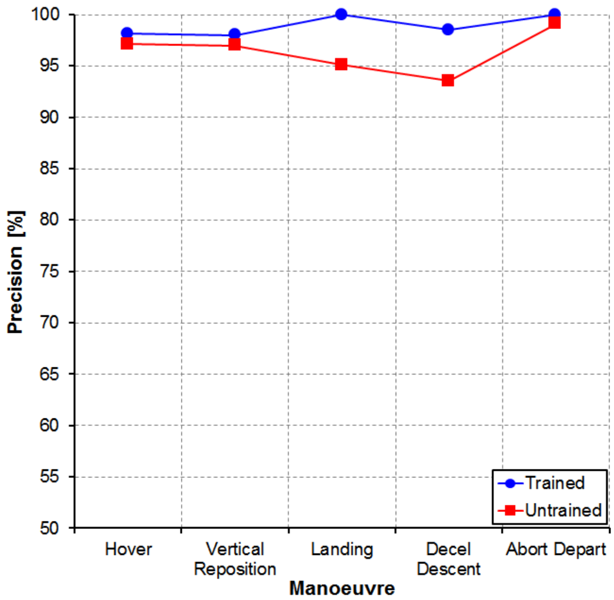


Fig. 38: Improvement in Task Precision Following Training

4.3.4. Level 3 Evaluation – Real-World Commute

To judge whether the participants in the training programme had developed the skills required to fly the 'real-world' task of the commute, a simulation scenario was developed whereby the PAV pilot would fly from the village of Kingsley Green to the south-east of Liverpool into the city centre. The course that the participants were asked to follow is shown in Fig. 39. It can be seen that this was not a direct route – as Liverpool's international airport is located directly between Kingsley Green and the city. Hence, a deviation inland from the direct route was incorporated, with the PAV avoiding the airport's GA circuit patterns. The en-route planned altitude was 800ft. It was assumed for the virtual scenario that all required airspace clearances were in place. The route follows the River Mersey as Liverpool city centre is approached. This was to simulate noise abatement procedures for the more densely populated regions being over flown. These deviations from the direct path also provided an opportunity to incorporate manoeuvring elements into the evaluation, rather than having a long, straight flight track. The total flight duration for this task was approximately 11 minutes. The visibility was good, and there was no wind or other atmospheric disturbance introduced to the simulated environment. Similarly, no other air traffic of any kind was introduced into the scenario.

Fig. 39: Route of Complete Commute (Map Data Copyright © Google)

At the start of the route, in Kingsley Green (Fig. 40), the PAV begins on the ground in the centre of a grassy area. A vertical take-off is performed, with the PAV climbing to a height of 75ft above the ground so as to be clear of the surrounding buildings and trees. The PAV is then accelerated towards the cruise whilst simultaneously climbing to the cruising altitude of 800ft and turning onto the course for the first leg of the route. When the PAV nears the city centre, this process is reversed, descending and decelerating, and eventually coming to a hover above an open area close to the city's financial centre. The PAV was then repositioned to a marked parking position, onto which a vertical landing is performed.

Fig. 40: Start of Commute in Village Location (Map Data Copyright © Google)

The participants in this study used a Highway-in-the-Sky (HITS) [45;46] display to navigate along the planned route (Fig. 41). The HITS is attractive for PAVs due to its intuitive (i.e. visually straightforward to determine appropriate control inputs to follow the correct route) and conformal (i.e. is directly related to real terrain features) nature. The size of the boxes that form the HITS informed the pilot as to the allowable discrepancy between planned and actual routing. It is anticipated that PAVs would operate at considerably higher traffic densities than existing commercial or private aviation. This leads to a requirement for precise positioning, and rigour in the maintenance of position in order to avoid conflicts with other PAV traffic.

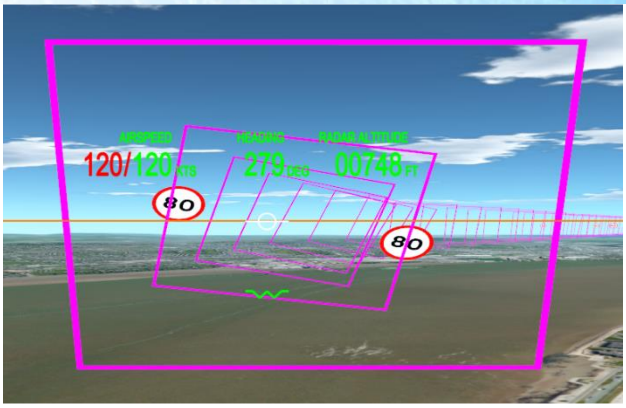


Fig. 41: Highway-n-the-Sky used for PAV Navigation

The HITS also provided airspeed limit indications to the pilots. These was presented in the form of UK-style road speed limit boards, albeit displaying limits as knots rather than miles per hour (airspeed readouts for the PAV were also displayed in knots).

All of the TSs were able to fly the PAV along the HITS without incident, remaining well within the boundaries throughout. Fig. 42 shows a typical example of deviation measured from the centre of the HITS boxes (which have dimensions of ±100ft). The larger spikes in deviation correspond to points at which the PAV was turning onto the next leg of the route. Additionally, the pilots were always able to adhere to the airspeed limits. This is illustrated in Fig. 43; the airspeed limits were sequentially 120kts, 80kts, 50kts and 30kts.

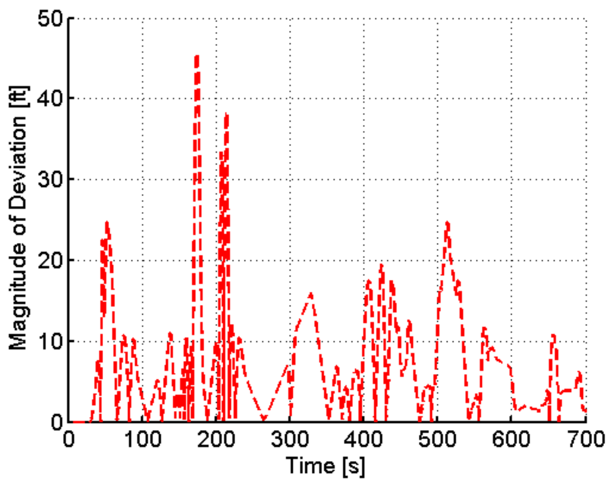


Fig. 42: Lateral Deviation from Centre of HITS during Commute

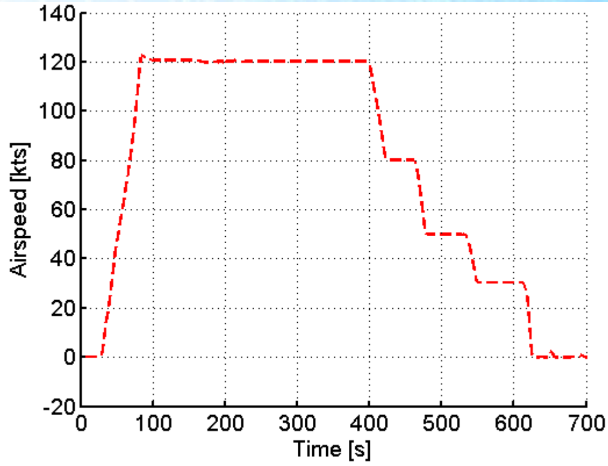


Fig. 43: Airspeed during Commute

Following completion of the commute scenario, each TS was asked to rate their workload using the NASA TLX rating scale [29]. This system asks a participant to evaluate workload using 6 factors – mental demand, physical demand, temporal demand, performance, effort and frustration. Each factor is then weighted by its relative contribution to the overall workload to create a single workload score between 0 and 100. A TLX of 0 indicates no workload at all, while a TLX of 100 indicates that the participant is at their maximum tolerable level in each area assessed.

The TSs returned an average TLX rating of 24 for the commute scenario, with a maximum of 30. They commented that the workload in general was very low, giving plenty of time for observation, monitoring etc. There were, however, occasions during the scenario where the workload increased. These were generally the points at which the route required the pilot to perform two or three actions simultaneously – i.e. airspeed change, heading change and/or altitude change.

4.4. Discussion

The results presented above indicate that the training syllabus developed as part of this research was an effective method by which to transfer the required knowledge and skills to the participants to allow them to operate a PAV safely (i.e. within tolerances) and reliably (i.e. repeatedly). The precision achieved in the manoeuvres used for the ‘skills test’ was improved in comparison to a dataset for a group of ‘untrained’ test subjects. While in absolute terms the magnitude of the improvement was not large, it should be noted that the ‘untrained’ subjects were already able to fly the PAV to a high level of precision, demonstrating the intuitive nature of the PAV’s responses. In this context, the improvement in achieved precision with the ‘trained’ subjects is useful. In none of the MTEs did the trained subjects average less than 98% of time spent inside the task’s desired performance boundaries.

The ‘trained’ test subjects were also able to complete the ‘real-world’ test – the commute scenario – with a good degree of accuracy and with low workload. To contrast with the results reported here, TLX ratings in the region of 55-60 have previously been reported for undistracted, qualified drivers operating a car in a simulated urban environment [47]. TLX ratings are, however, a subjective measure, meaning that it is not always possible to have complete read-across between different sets of results. Nevertheless, these results provide an indication that the PAV is not more difficult to fly in a typical role than a car is to drive. Given that all of the TSs were able to keep the PAV well within the boundaries indicated by the HITS, the low workload is perhaps the more important of these two metrics. Given the potential duration of a typical PAV flight (10-30 minutes), it would be unacceptable for the workload to be continuously high, as this would lead to pilot fatigue.

Based on the subjective questionnaire completed by the TSs, all found the training to be engaging and stimulating. This is an important consideration in training programme development, as without trainee engagement in the process, learning typically occurs at a much slower rate [48]. Given that one of the objectives of the *myCopter* project has been to determine the most effective methods by which to reduce the costs associated with a PAV, *a training programme that delivers high levels of participant engagement is an obvious requirement*.

The participants generally reported that they felt that they had received a comprehensive level of training for the tasks that they were asked to carry out in the final evaluations. Two main items were identified where the participants felt that additional training could have been delivered. The first of these was simply further time to practice the various skills that were taught during the training. Although all of the participants achieved a good level of performance in all of the exercises during the course of the programme, further practice and experience will always be of benefit in terms of developing a thorough understanding of exactly how the vehicle will respond to any given control input. This is a phenomenon that can also be found in driving and (current) flight training – with the expectation that newly-qualified drivers or pilots will need considerable time at the controls of their vehicle before they have fully matured into their role.

The second area where the participants would have liked additional training was in the procedures that would need to be followed in the case of something going wrong – either with the vehicle itself, or with external factors (such as encroachment by other aircraft). As noted above, training for these 'emergency' situations was deliberately excluded from this phase of the research.

Finally, it was reported above that four of the five TSs in this study were able to complete the training programme in less than five hours, while the fifth was slightly behind, having completed three of the five lessons in just under five hours. Although, as discussed above, certain aspects of the required training have been excluded from this study, and testing was exclusively simulation based (which might remove the 'startle' and 'fear' related to real-world operations), these numbers compare favourably with those typically expected for car driving (generally 20-40 hours) and flying (45-100 hours). For a 'real' PAV training programme, it would be desirable to conduct at least some of the training in simulation in order to minimise costs. The training would then progress to the actual aircraft. The impact of this multi-stage approach on total training time would need to be evaluated.

5. Development of a Visual Landing Profile with Natural-Feeling Cues

This Section describes of the research conducted at the UoL to develop nature-inspired guidance trajectories for the visual landing of a PAV in a good visual environment (GVE). The motivation for the study is as follows. If PAVs, within a wider PATS, were to become a widely-used transportation method, the expectation is that the 'piloting' of them should demand no more skill than that associated with driving a car today. In addition, it would also be expected that the number of hours of training received by a novice PAV 'pilot' would be lower than that currently required to gain and maintain a Private Pilot's License (PPL) – a level that might be termed 'flight naïve' (this is based upon the assumption that training costs need to be reduced compared to those of today's general aviation aircraft). It is not expected that the general public will all become private pilots, rather, that different 'modes' of PAV operation might be employed, ranging from 'highly augmented' to fully 'autonomous', leading to a new licensing category specifically for PAV pilots. For the former case, what might be termed partial authority manual flight modes could be made available. For the manoeuvres where such a mode were available, it is of interest to design a flight trajectory, perhaps indicated to the pilot by some kind of flight director, that provides the required "natural" physiological cues, as well as meeting the requirement to ensure that the PAV and its occupants follow the trajectory in a safe condition [14]. For the fully autonomous flight case, the occupant would be relieved of the need to manually fly the aircraft. In this case, if the manoeuvre profiles were not appropriately designed, the cues (e.g. visual and proprioceptive motion cues) sensed by the driver/pilot might be inconsistent with the PAV occupant's natural expectations. This inconsistency may impair the ability of the PAV occupant to satisfactorily monitor the manoeuvre [49;50]. For example, approaches to land at a constant deceleration (CD) rate conducted in the University of Liverpool's HELIFLIGHT-R simulation facility [38] appear to provide visual cues in the latter parts of the constant-deceleration manoeuvre that imply accelerative flight [51]. This leads to an increased level of discomfort for the cockpit occupants in terms of their confidence that the on-board guidance system will actually achieve the task that it is designed to do. Therefore, it is important to design trajectories that provide the PAV occupant with intuitive guidance cueing that is consistent with their expectations. It is anticipated that the more intuitive and salient the perceptual information provided to the pilot is, the greater will be their ability to make rational and correct decisions to control the aircraft. Numerous previous studies have been undertaken to understand pilot control behaviour during a visual landing task [49;51-55]. Some initial research was conducted by NASA to design a desired approach with "natural physiological" cues for the design of a flight director system by studying the characteristic shapes of various visual approach profiles [49]. 236 visual approaches using four helicopter types and nine sets of initial conditions were conducted for that study. The characteristic shapes of the altitude, ground-speed, and deceleration profiles of visual approaches were then mathematically determined. The results have been replicated during flight simulation trials at the University of Liverpool [49] and by Heffley's mathematical model based on the crossover model of the human operator [53].

The NASA Advanced General Aviation and Transportation Experiments (AGATE) to design Small Aviation Transportation System (SATS) also aimed to make aircraft avionics more intuitive so pilots require less training to stay safe [56]. More recently, the research in Ref. [55] proposed an improved deceleration guidance cueing system (a hybrid profile consisting of constant deceleration and constant optical flow phases) within the Brown-Out Symbology Simulation (BOSS) display to provide the pilot with intuitive guidance cues to enable the safe landing of a rotorcraft in brownout, zero-visibility conditions.

The research reported here consisted of two stages. The first stage in Ref. [52] focused on the development of the new landing profile, motivated from the point of view that 'natural-feeling' cues are related to the physiological cues presented during a visual landing. As such, test subjects with little or no prior flight experience flew simulated approaches to a hover following limited instruction in the use of a vehicle model. The first stage of the research found that the approaches were broadly similar and could be grouped into three distinct phases. Previous work in this field and Lee's optical tau theory [57;58] were used to design an idealized approach profile based upon the simulation results. The key results from the first stage of the work has been reported in Ref. [52].

The second stage of the work evaluated the "natural-landing" profiles designed in the first stage and compared it to other possible guidance profiles, such as a constant deceleration approach [55] and a constant optical-flow approach (OF) [23]. The results of this evaluation are the subject of this Section. For the initial stage of the research, the approach was flown purely with reference to outside world visual cues. However, for the second stage, the profiles were evaluated in two modes of operation; either using manual flight or automatic flight. For the manual case, the Test Subjects (TSs) flew the approach task using flight-path and speed guidance head-up symbology. For the automatic case, the TS was a passive passenger. As such, no guidance symbology was required and only outside-world visual cues were provided. The results from this research will help to determine an optimal profile for a future PAV landing approach descent profile.

5.1. Introduction of Optical Tau Theory

The following Section summarizes the key elements of τ theory used in this report to design a descent profile with a "natural-feel".

Optical tau (τ), the time-to-contact variable, in the optical field is defined in Eq. (8),

$$\tau = \frac{x}{\dot{x}} \tag{8}$$

It has been constructed using the conceptual framework for understanding information used in detecting an upcoming collision [23;59-61], where x is the motion gap to be closed and $\dot{x}$ is the instantaneous gap closure rate. The term 'motion gap' refers to a perceived difference between the observer's current and desired target state. This information allows the rate of change of τ in Eq. (9) to provide prospective information as defined by:

$$\dot{\tau} = 1 - \frac{x\ddot{x}}{\dot{x}^2} \tag{9}$$

Here, $\ddot{x}$ is the instantaneous gap closure acceleration rate. Tau theory further hypothesizes that the observer's motion is guided using τ coupling. Here the tau of one motion gap is kept in constant ratio with the tau of another motion gap. In practice, there are often two or more gaps needed to be closed simultaneously, such as the coordination required between the lateral and forward motions, or forward and vertical motions, in order to achieve combined horizontal-vertical manoeuvres [58;62]. Two motions, $x(t)$ and $z(t)$, are said to be tau-coupled if the following relationship is satisfied,

$$\tau_z = k\tau_x \tag{10}$$

The coupling term k in Eq. (10) regulates the dynamics of the motions in the x and z directions. By keeping the tau's of motion gaps in a constant ratio, tau - coupling results in effective movement coordination through a power law (for $x < 0$, and $z < 0$),

$$y = C(-x)^{1/k} \tag{11}$$

If a second externally perceivable motion gap is not available, it is hypothesized that self-guided motion can still be achieved by coupled onto an intrinsic motion guide, τ_g. Intrinsic τ guidance is modelled using the relationship,

$$\tau_x = k\tau_g \tag{12}$$

in which τ_g can take the form of CD (with coupling term k_d) for deceleration-to-stop motions, (e.g., car braking [63] and prospective guidance in a fixed-wing aircraft flare manoeuvre [62]) or constant acceleration (with coupling term k_a) for acceleration-deceleration (accel-decel) motions (e.g., prospective guidance in a stopping manoeuvre [61]). The coupling term k regulates the kinematics of the motion. For a more complete description of tau theory in relation to flight control, see Ref. [64].

5.2. Experimental Setup

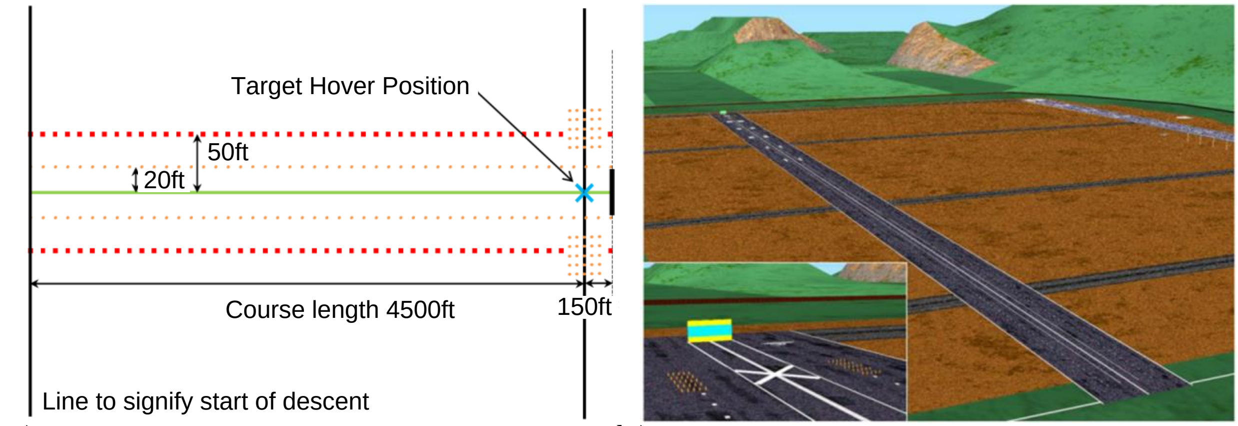
The development of the new landing profile in this report is motivated from the point of view that 'natural-feeling' cues are related to the physiological cues presented during a visual landing [50]. As such, test subjects with little or no prior flight experience flew simulated approaches to a hover following limited instruction in the use of a vehicle model to gather the dataset with the sufficient size that is the prerequisite for the current research. The experimental setup is detailed as follows.

5.2.1. Outline of the PAV Model

The PAV flight dynamics model used hereby is that reported in the document [63]. It is a decoupled system i.e. there are no couplings present between the collective, longitudinal, and lateral control channels. It is not anticipated that PAVs will exhibit any significant helicopter-like control cross-couplings by design. This will allow the PAV pilot to operate using a more instinctive piloting strategy than is possible in a conventional, strongly coupled helicopter [49]. Within the model, the PAV pilot commands flight path angle using the collective control and forward speed using the longitudinal cyclic.

5.2.2. Decelerating Descent Manoeuvre Description

The *myCopter* commuting scenario consists of the following flight phases: vertical take-off, acceleration, climbing, cruise, decelerating descend, and vertical landing [13]. The following subset of five hover and low-speed MTEs can be identified from these phases: Hover, Vertical Reposition, Landing, Decelerating Descent, and Aborted Departed, by following appropriate outlines given in ADS-33E-PRF [14]. Among these MTEs, the decelerating-descent manoeuvre is of most interest due to involving more potential pilot control activities resulting from requiring the three-dimension coordinated control and dynamic transition between the forward flight modes and the hover modes. Therefore, this manoeuvre is chosen for study in this report and is illustrated in Fig. 44*a* as well as the implemented simulation visual database in Fig. 44*b* [14;49].



a.) b.)

Fig. 44 **General arrangement for decelerating descent manoeuvre**

The task performance specified in Fig. 44*a* have been modified to reflect the nature of the PAV role. The manoeuvre begins with the aircraft in a stable straight and level cruise at 60kts at a height of 500ft above ground level (AGL). At a pre-defined point, the aircraft is placed into a descent and decelerated towards a hover condition. This descending approach is configured to give a mean glide slope angle of 6 degrees. The original lateral track and heading should be maintained during this process. The manoeuvre is completed once a stabilized hover is achieved at a height of 20ft AGL within pre-defined lateral and longitudinal ground positions (see inset on Fig. 44*b*).

5.2.3. Test Performed

The test campaign was conducted in the HELIFLIGHT-R simulator as used for the previous Sections. Moreover, the test campaign involved 11, what have been termed, "flight naïve" subjects, i.e. not professional pilots (10 male, 1 female, with an age range of 20-43 and a mean age of 26). The test subjects were broadly categorized by their prior flight experience: No Experience, Simulator (Sim) Experience, and Flight Experience. In addition, for this purely visual landing, the subjects were instructed to fly the vehicle at their discretion to complete the manoeuvre to comply with the requirements in Fig. 44*a*. Each subject was required to repeat each test manoeuvre at least three times. Test runs were only conducted following a number of familiarization runs conducted by each test subject. The number of familiarization runs used was subjectively varied based upon both the participant's previous flight experience and observed aptitude/competence on the day. For those TSs with limited experience, limited instruction was made available to them e.g. effects of controls etc.

5.3. Development of Tau-Based Landing Profile

The main objective of this study was to design a landing profile with natural-feeling cueing. The start point for this exercise was to observe how the flight-naïve test subjects undertook the landing manoeuvre using only the outside - world visual cues available to them. Fig. 45 shows the velocity and flight path angle information achieved by the 11 subjects against both time (left-hand column) and the longitudinal distance along the test course (right-hand column).

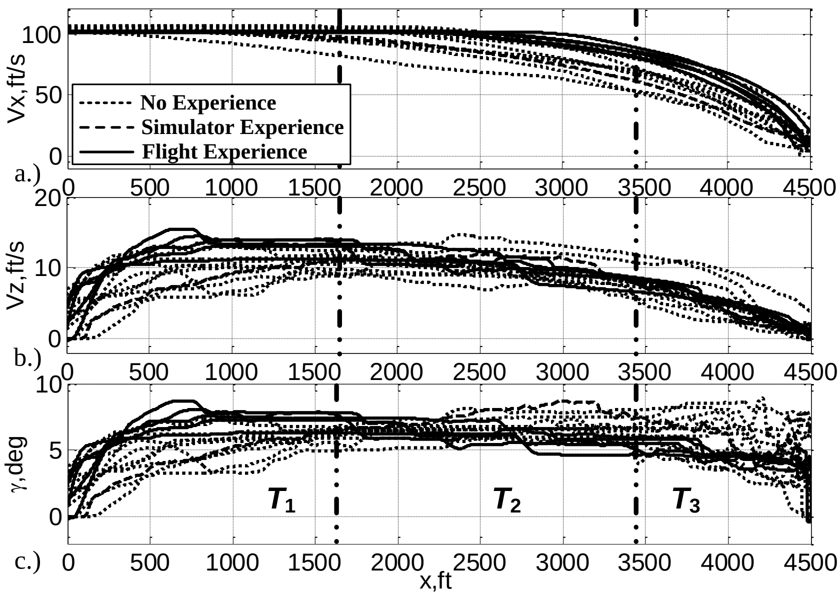


Fig. 45 **Body velocity and flight path angles achieved by 11 flight-naïve test subjects**

Three phases are discernible for each of the test subject's descent profiles in Fig. 45. The initial phase (T_1) of the manoeuvre only involves flight path control. This can be seen from the almost constant forward velocity (V_x) in Fig. 45*a* and the sharp change of the flight path angles in Fig. 45*c* during this period. The second distinct phase (T_2) of the descent profile is distinguished by a change in both the forward and vertical body velocities (downwards). The test subjects attempt to maintain the flight path angle profiles for a certain period before initiating the deceleration phase for the remaining part of the manoeuvre. This indicates that the subjects adopt constant flight path control during this part of the manoeuvre. Finally, Fig. 45*c* shows that as the landing point is approached, constant flight path control is no longer used as the approach strategy.

The next step is focused on modelling these profiles based on these observed features. The procedure used is described in what follows.

5.3.1. First Phase - Flight Path Angle Control

As can readily be appreciated from the above discussion, an important feature in the early stage of the landing process is that flight path angle control is performed with the collective only, with only minor longitudinal control inputs being performed to maintain the desired speed. In general, as the descent manoeuvre begins, the pilot can either apply separate cyclic/collective controls to reduce the forward speed and height or a combination of the two controls simultaneously. The results above indicate that all of the tested subjects preferred to control flight path angle with the collective alone. This is likely to be due to the fact that the longitudinal control of the PAV model used in this project is completely decoupled from the collective. Given that the test subjects are not professional pilots, it is possible that all of the operators naturally prefer to focus on only one control axis at a time for the landing manoeuvre. In addition, the test subjects commented that, due to the length of the test course (the landing point is 4500 ft away from the test start point), the final landing marker is barely visible, and they preferred to maintain their initial forward speed to avoid having to make abrupt cyclic control inputs to correct errors introduced at an early stage later in the manoeuvre. This kind of operation is consistent with normal helicopter operational procedures for the final approach to a runway [23;58;61;62;65] whereby the descent is commenced by selecting a recommended vertical speed.

In relation to τ theory then, there is only one motion gap to be closed – the flight path angle which starts with a zero value and ends with some fixed value. This suggests that the flight path motion gap is closed using an acceleration-deceleration type velocity profile [66]. Therefore, for this stage of the descent, flight path control was coupled onto the intrinsic constant acceleration guide as described by Eq. (12).

For the τ analysis in this report, the flight path angle gap (γ_a) is defined as follows,

$$\gamma_a = \gamma - \gamma_f \tag{13}$$

in which γ_f is the final flight patch angle (≈ 6.7 deg). The γ_a and associated time rates of change ($\dot{\gamma}_a$) are plotted in Fig. 46.

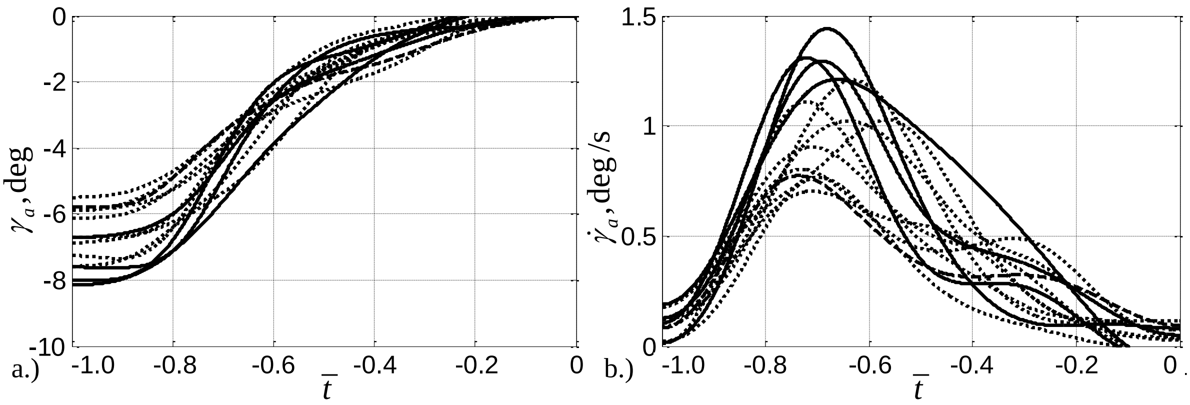


Fig. 46 **Flight path motion gaps and closure rates in the initial phase of the approach manoeuvre**

In Fig. 46, the time ($\bar{t}$) is defined as time to go (to the end of the manoeuvre) and has been normalized by the manoeuvre duration (T_1) of the first phase. The final flight path angles used in Fig. 46 were chosen as the value when $\dot{\gamma}_a$ first becomes zero. The same rule also was used to define the value T_1. Moreover, as mentioned above, the period is achieved with the constant acceleration guide, with the relationship described in Eq. (12) or

$$\tau_{\gamma a} = \frac{\gamma_a}{\dot{\gamma}_a} = k_r \tau_g \tag{14}$$

The T_1, γ_f, and k_r values determined for the 11 subjects as well as their mean values (with the bar symbol) from the experiments are shown in Fig. 47.

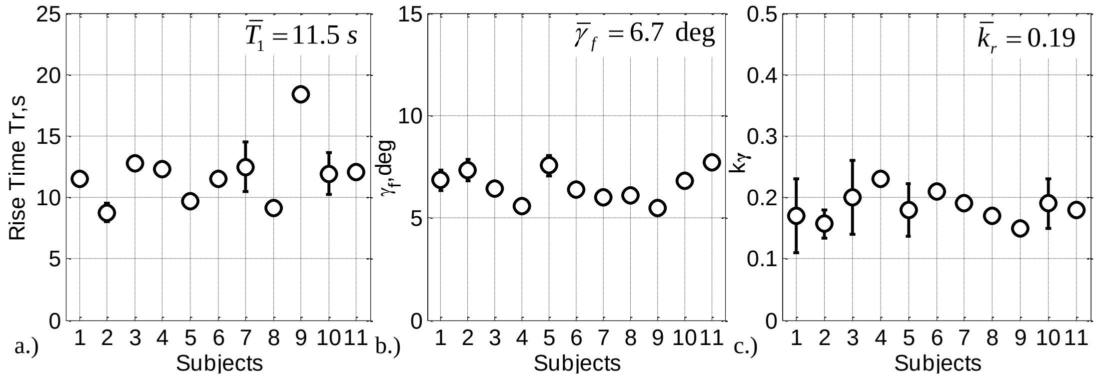


Fig. 47 **Rise time, final flight path angle and coupling term values obtained from the simulated flight trials**

The rise-time values in Fig. 47 range from 9 to 13s, with the exception of Subject 9 (the only female) where the value is 18 s. The γ_f values vary from 5.4 to 8.2 deg. The k_γ values were calculated using the Positive Wavelet Approach in Refs. [58;64] and range from 0.13 to 0.26. This indicates that all of the subjects initiate the deceleration to the desired flight path angle early on in the flight path control period, as can be seen by inspection of Fig. 47*b* (a value of 0.5 corresponds to a symmetric manoeuvre).

The mean values obtained are indicated in Fig. 47 using a bar. They were used to determine the γ_a and $\dot{\gamma}_a$ profiles, based on Eqs. (15) and (16) derived from Eq. (12), using the intrinsic constant acceleration guide.

$$\gamma_a = C(\bar{T}_r^2 - t^2)^{1/\bar{k}_r} \tag{15}$$

$$\dot{\gamma}_a = \frac{2Ct}{\bar{k}_r}(\bar{T}_r^2 - t^2)^{1/\bar{k}_r - 1} \tag{16}$$

in which C is a constant parameter. The resultant γ_a and $\dot{\gamma}_a$ profiles of Eqs. (15) and (16) are shown in Fig. 48.

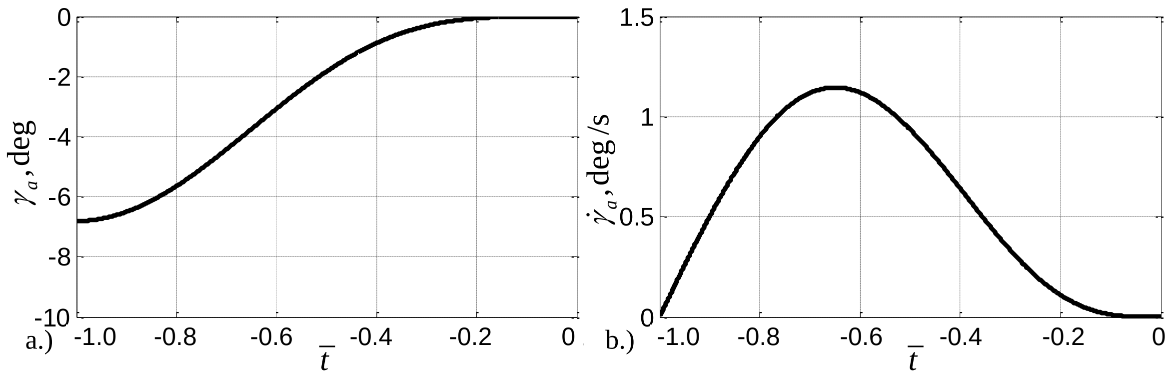


Fig. 48 γ_a and $\dot{\gamma}_a$ profiles derived with the intrinsic constant acceleration guide

The γ_a and $\dot{\gamma}_a$ information can be validated by a comparison of the derived τ-coupled collective inputs and the actual subject inputs. To accomplish this validation, the simplified flight path control loop used in the PAV model is illustrated in Fig. 49.

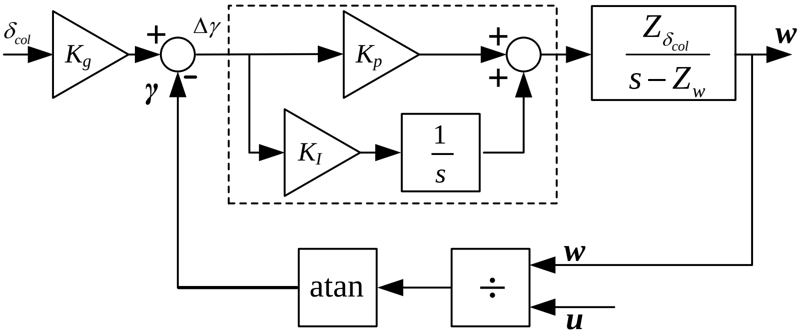


Fig. 49 **Flight path angle loop with collective control (V_x > 25 kts)**

in which K_g (= 30) is the control gearing from the collective input to the command flight path angle, K_p (= 0.30) and K_I (= 0.25) are proportional and integral gains of the introduced proportional and integral controller for the flight path feedback. The symbols $Z_{\delta_{col}}$ (= 18.47) and Z_w (= –1.20) are the collective control and heave damping derivatives, respectively. The described control loop flow in Fig. 49 has ignored the Coriolis forces due to their negligible contribution.

The following collective to flight path transfer function can be modelled from Fig. 49 (the initial surge speed $u = u_0 = 60\ kts$).

$$\gamma \approx \frac{-309.3}{s+10.7}\delta_{col} \tag{17}$$

From Eq. (17), the collective control can then be written in the following form,

$$\delta_{col} \approx \frac{-1}{309.3}(\dot{\gamma}_a + 10.7(\gamma_a - \overline{\gamma}_f)) \tag{18}$$

By replacing the γ_a and $\dot{\gamma}_a$ in Eqs. (15) and (16) into Eq. (18), the derived collective input can then be compared to those made by the test subjects. This comparison is performed in Fig. 50.

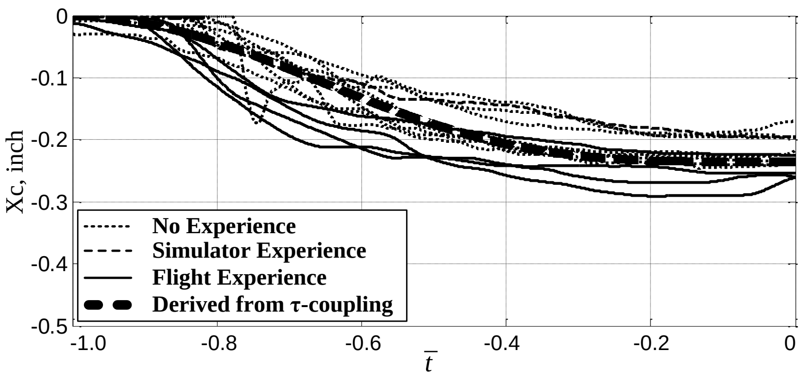


Fig. 50 The derived τ-coupled collective inputs compared with the actual subject inputs

The results in Fig. 50 show that the derived collective control provides a reasonable 'best fit' with the experimental measurements, which in turn validates the γ_a and $\dot{\gamma}_a$ values of Fig. 48. Compared to the actual inputs, the derived input profile is generally smoother. Notably absent are the oscillations observable on the actual input signals which are primarily a characteristic of the pilot's higher-frequency stabilization control activities [67]. The guidance activity only consists of low-frequency control inputs. Furthermore, the control strategies undertaken by all subjects, is reflected in the large rise time ($\overline{T}_r = 11.5\,s$) and are far removed from the abrupt, open-loop characteristic theoretically associated with the large pole of Eq. 20 (–10.7) that gives an effective time delay ≈ 0.1s. It could therefore be argued that, besides, the augmented stability loops shown in Fig. 49, the test subjects formed an additional outer feedback loop in the vehicle's control system.

5.3.2. Second Phase- Constant Flight Path Control

Before the characteristics of the second phase can be considered in more detail, the altitude, speed, and deceleration profiles in the *x* axis need to be first assessed in conjunction with the previous results from the UoL and NASA investigations into a large number of visual approaches (simulated and actual flight data) to the hover at a helipad [64;67].

236 visual approaches with four types of helicopters from nine sets of initial conditions were conducted by a NASA study to determine an approach profile that had "natural physiological" cues. The aim of this study was to design a flight director system by studying the characteristic shapes of various visual approach profiles. The following kinematic relationship for the deceleration phase in the *x*-axis resulted from the analysis of the flight-test results by using parametric and graphical techniques:

$$\ddot{x} = \frac{c\dot{x}^2}{x^n} \tag{19}$$

in which *c* and *n* are constants. The similarity between Eq. (9) and Eq. (19) has been discussed in Ref. [23]. Moreover, the findings of the NASA flight test trials were replicated in the Liverpool flight simulator with an almost identical test setup in a good visual environment (GVE) [50;52]. It is therefore of particular interest to investigate the applicability of the formula given in Eq. (19) to the results conducted in the current research.

An analysis was first conducted to determine the conditions necessary for the application of Eq. (19). Ref. [52] outlined the details of the implementation of Eq. (19) and this can be summarized as follows. First, the initial deceleration level $\ddot{x}_0$ and value for *n* are estimated with regard to the initial forward speed from the charts given in Ref. [50]. They are determined approximately to be: $\ddot{x}_0 = 0.024g$ (*g* is the acceleration of gravity, ft/s^2) and $n = 1.56$. Second, the NASA research points out that 80% of the deceleration phase usually occurs within the last 2800ft of the landing manoeuvre. Therefore, the initial position x_0 is chosen to be 1700ft and $\dot{x}_0 = 101$ ft/s for the current investigation. Based on these initial values, the constant *c* can be solved for as follows:

$$c = \frac{x_0^n \ddot{x}_0}{\dot{x}_0^2} \tag{20}$$

The derived longitudinal-speed profile from Eq. (19) with Eq. (20) is compared in Fig. 51 with those recorded results during the experiments.

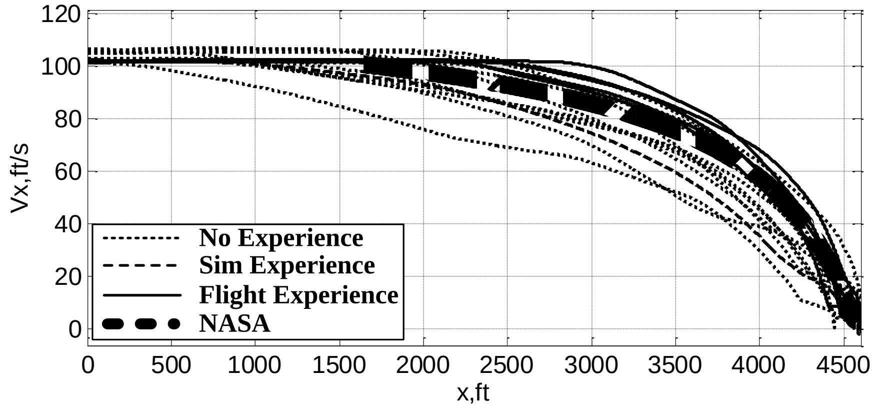


Fig. 51 Comparison of ground speed profiles between the actual data and NASA results

As shown in Fig. 51, the correlation between the NASA results and actual recorded data are reasonably good. Again, the computed trajectory forms a reasonably good 'best fit' line for the experimental data. This result seems to indicate that the NASA formula is applicable to the PAV experiment test subjects during the deceleration period. This study shows that regardless of it being a different vehicle model, the non-professional pilot subjects appear to conduct the visual landing by following the natural approach profile derived from the helicopter trials in Eq. (19) performed by professional pilots. Therefore, Eq. (19) was adopted to design the remaining parts (T_2 and T_3) of the position and velocity profiles in the *x* axis for the current study.

The second-phase of the approach profiles, which is a phase characterized by constant flight path control, can be characterized even more explicitly by plotting V_z against V_x, as shown in Fig. 52.

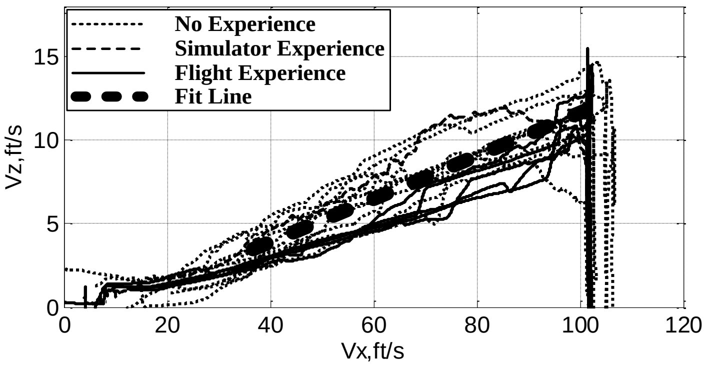


Fig. 52 Illustration of constant flight path angle in phase 2 of the approach manoeuvre

The slope of the V_z -V_x curves is, of course, the flight path angle. As can be appreciated from Fig. 52, these plots constitute a shape that has fairly well defined lower and upper boundaries within the V_x range from 20 ft/s to 100 ft/s. It should be noted that each case shown in Fig. 52 generally follows a linear profile in this range. The line there with the slope $\bar{\gamma}_f = 6.7 \deg$, determined from the analysis above, appears to capture the 'average' of these curves within this V_x range. As such, the constant flight path control finding, described in Eq. (21), was used to develop the desirable profile for the third phase of the approach as follows,

$$V_z = k_f V_x \tag{21}$$

in which k_f is equal to the tangent value of 6.7 deg. With this relationship, the only open question that remains is when the constant flight path control phase should terminate. This will be considered in connection with the beginning of the third phase of the profile in the next Section.

5.3.3. Third Phase: Final Approach to the Landing Point Using τ-Coupling

Although there is good agreement with the best fit line shown in Fig. 52 over a broad range of velocities (> 40 ft/s), the fit degrades somewhat below around 40 ft/s. The velocity profile changes to a concave-like form when approaching the final landing spot. This is posited to be the subjects adapting their control strategy from the constant flight path control during the second phase to 'something else' during the third, final approach phase. The determination of the switching point between the second and third phases as well as the control strategy used in the third phase gives rise to two questions: how the transition timing point from the second phase to the third should be determined, and the reason for the subject's control behaviour adaptation or change. The first point is addressed here and the second will be explained at the end of this Section.

The moment of transition, from the second to third phase, determines the required control inputs to be made by the subjects to guide the vehicle successfully to the hover point whilst maintaining an adequate safety margin. The studies in Ref. [50] reported that pilots typically need 12 eye-heights, which corresponds to about six seconds look ahead time, to initiate a manoeuvre (e.g., terrain hugging and deceleration) from a series of piloted flight simulation experiments [59;60]. The methodology used for these studies are adopted for the current problem. To determine the final deceleration point, the number of eye heights of the 11 subjects during the manoeuvre is plotted in Fig. 53.

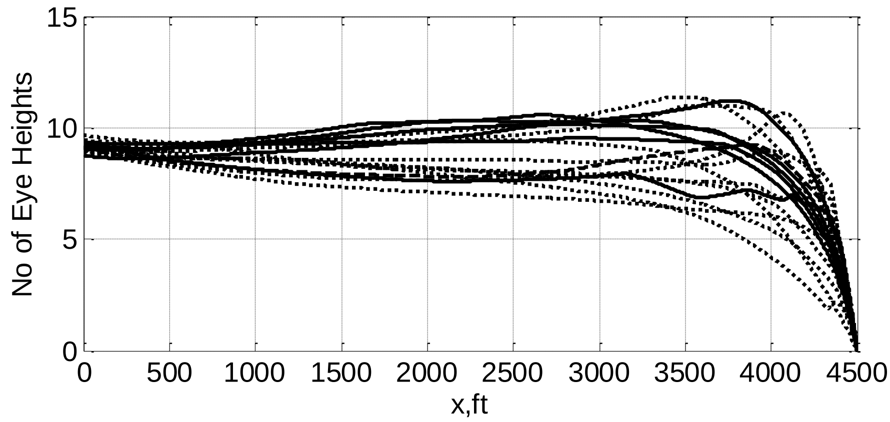


Fig. 53 **Illustration of eye height profiles for all subjects**

A clear result from Fig. 53 is that the subjects maintain a relatively constant number of eye heights as they fly lower and slower, until the distance to the landing point is around 700ft. The subjects then fairly rapidly decrease their number of eye height to approach the target. The point at which the subjects adapt their control strategies averages out to be 8 (± 2) eye-heights, which is used as the transition point between the second and third phases.

The number of eye heights for the profile designed in the previous Sections is plotted in Fig. 54.

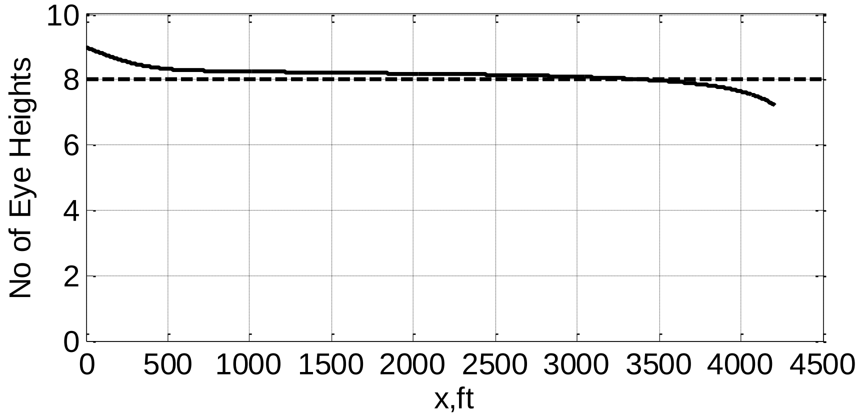


Fig. 54 **Determination of the transition point between the second and third phases**

Fig. 54 shows that the eye-height curve holds almost constant up to the distance (1000ft) to the landing point. Moreover, the selected 8 eye-heights (marked as the dashed line) generally captures the turning point of the curve that initiates the final approach stage.

The remaining problem was now to design the profile for the final stage of the manoeuvre. The first open question is to find what mechanism guided the subjects during this stage. Although the landing manoeuvre in Fig. 44 is conducted in an unrestricted environment allowing for movement in three axes, the simulation results indicates that the motions of the vehicle's inertial *x* (longitudinal) axis and the *z* (vertical) axes are dominant in this stage of the task, which is to be expected in the absence of any atmospheric disturbances. Moreover, compared with the first two stages, more rapid coordinated control activities between the *x*- and *z*-axis are required due to the more rapid required changes of V_x at the end of the manoeuvre as shown in Fig. 51. To achieve this level of coordination of the vehicle motion in the two axes, accurately synchronizing and sequencing of the closure of the motion gaps in the *x*- and *z*-axes, respectively is required. Tau theory has shown that this coordination can be accomplished by the maintenance of the dynamic relationship described in Eq. (10) [64]. As these two gaps closely follow this τ-coupling law, the desired hover can be automatically achieved just as the PAV arrives at the landing point.

Therefore, τ coupling between multiple axes may also be applicable to the modelling of the coordinated motion of the final landing stage. To test this hypothesis, the τ-information for the final approach was calculated from the simulation results and is illustrated in Fig. 55.

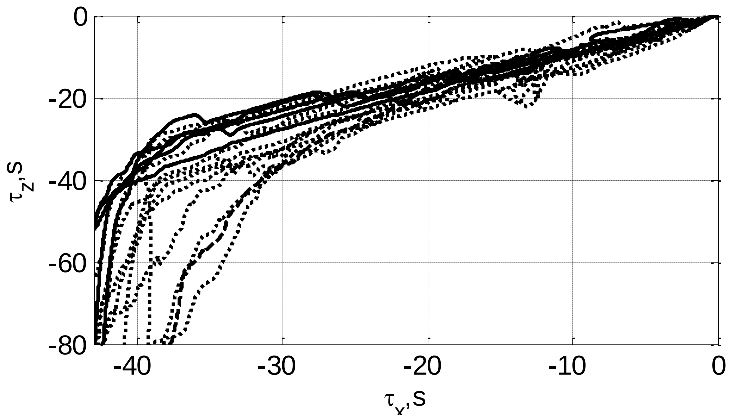


Fig. 55 **Plot of τ_z vs τ_x during the final approach**

As shown in Fig. 55, there is a strong linear correlation between τ_x and τ_z, regardless of the subject, during the final 30 seconds (time to closure) of the manoeuvre. Based on the gap closure relationship described in Eq. (11), their velocity and acceleration information can be derived in the following.

$$\dot{z} = C(1/k)(-x)^{1/k-1}(-\dot{x}) \tag{22}$$

$$\ddot{z} = C(1/k)(-x)^{1/k-2}[(1/k-1)\dot{x}^2 - x\ddot{x}] \tag{23}$$

The final gap, gap closure rate, and acceleration profiles of the gap closure in the *z*-axis are determined in conjunction with the good fit shown in Fig. 51 that shows a good agreement between NASA's Eq. (19) and the simulation results in the *x*-axis. Therefore, using Eq. (19) for the *x*-axis trajectory profile, the corresponding profile in the *z*-axis is naturally determined from Eqs.(11), (22), and (23).

The determination of *k* used in Eq. (10) requires some discussion. The *k* value can be approximately estimated to be 0.90 from Fig. 55. However, to assure the smooth and continuous connection between the second and third phases, the end conditions of the second phase must be used for the initial conditions of the third phase. Therefore, based on these predetermined initial conditions, the *k* value can be derived from either of Eq.(22) or Eq. (23) and was found to be 0.89. This value indicates that the rate of the gap closure in the *z* axis is faster than the one in the *x*-axis, which is consistent with the concave shapes of the profiles in Fig. 52 (V_x < 30 ft/s).

5.3.4. Fit with the Piloted Simulation Results

The first question associated with the performance of the designed profile is whether it has an overall good agreement with those recorded from the piloted-simulation tests. The comparison between them is shown in Fig. 56.

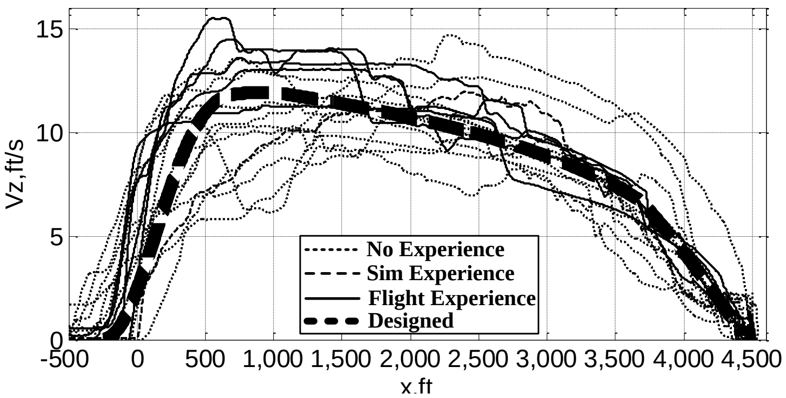


Fig. 56 **Profile comparisons between the designed and piloted simulation results**

As expected, Fig. 56 shows that the designed velocity profile in the *z*-axis reflects the simulation results reasonably well and it is generally located within the extremes formed by the test data. Besides the good fit of the first flight path phase that has been validated in Fig. 50, Fig. 56 shows that the designed version reaches good agreement with both the second and third phases of the simulation results. Moreover, the designed profile captures tightly the feature of the majority of the test data at the final phase, which indicates the applicability of τ coupling used in the previous Section.

5.4. Experimental Setup for Evaluating the Designed Profile

The second stage of the work evaluated the "natural-landing" profile designed in the first stage and compared it to other two popular guidance profiles: a constant deceleration approach (CD) [54] and a constant optical-flow approach (OF) [23]. The results of this evaluation are the subject of this remaining report.

5.4.1. First Phase - Flight Path Control with Tau Guidance

For the initial stage of the research, the approach was flown purely with reference to the outside world visual cues. However, for the second stage, the profiles were evaluated in two modes of operation; either using manual flight or automatic flight. For the manual case, the TSs flew the approach task using flight-path and speed guidance head-up symbology. For the automatic case, the TS was a passive passenger. As such, no guidance symbology was required and only outside-world visual cues were provided. The TSs were provided with head-up guidance symbols as illustrated in Fig. 57 for the assessment of the flight profiles conducted manually.

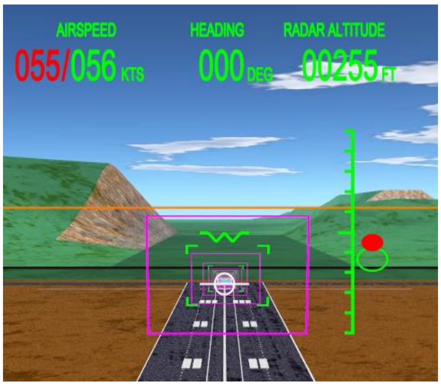


Fig. 57 **Head up display used for PAV manual landing**

The Head Up display (HUD) shown in Fig. 57 provides the following information. First, the airspeed, heading, and radar altitude can be readily observed. The velocity indicated in red is the current commanded velocity. The velocity indicated in green shows the current actual velocity. Second, there are two new symbols also implemented specifically for the research reported in this report in Fig. 57. The red ball and green circle symbols, to the right of the display, are used to indicate the correct position for the longitudinal cyclic stick to the PAV pilot. The green circle shows the required position of the cyclic for the current descent profile, whilst the red ball indicates the current actual position. The TSs were required to place the red ball within the green circle which moved up and down the vertical green bar. The information (a_{xd}) used to drive this symbology is given by,

$$a_{xd} = a_{xc} e^{\tau_d s} + k(V_x - V_{xc}) \tag{24}$$

in which a_{xc} and V_{xc} are the longitudinal commanded acceleration and velocity respectively. V_x is the current PAV forward velocity. The first term on the right-hand side of Eq. (24) provided the acceleration information to drive the green circle symbol. The term τ_d was introduced to account for the time delay between the cyclic input and acceleration response to increase the symbol tracking accuracy. The second term on the right-hand side of Eq. (24) contains the difference between the actual and commanded velocities. This term removed the observed velocity drift that simply following the acceleration command alone induced. This configuration worked effectively with the human-in-the-loop being part of a PI feedback control loop.

The second symbol-set adopted in this report is the graphical highway-in-the-sky (HITS) flight path display system [68]. This intuitive cockpit display shows the virtual path that the aircraft must follow to maintain the desired Earth-referenced lateral and vertical positions. The inner green brackets define the desired performance and the outer pink brackets define the adequate performance tolerances for the manoeuvre. The TSs were only required to use the collective lever to alter their vertical position within this virtual tunnel. After three attempts at each profile, the TSs were again asked to provide subjective assessments by following the Comfort and Presence questionnaire in Appendix.

5.4.2. Feature Summary of Landing Profiles

Based on the information provided in the previous Section, the forward velocity and the vertical position of the three profiles used in this report are illustrated in Fig. 58. Moreover, a simple pilot model, modelled as a pure gain, was implemented to "fly" the three profiles adopted here to derive the required inputs that are shown in Fig. 59.

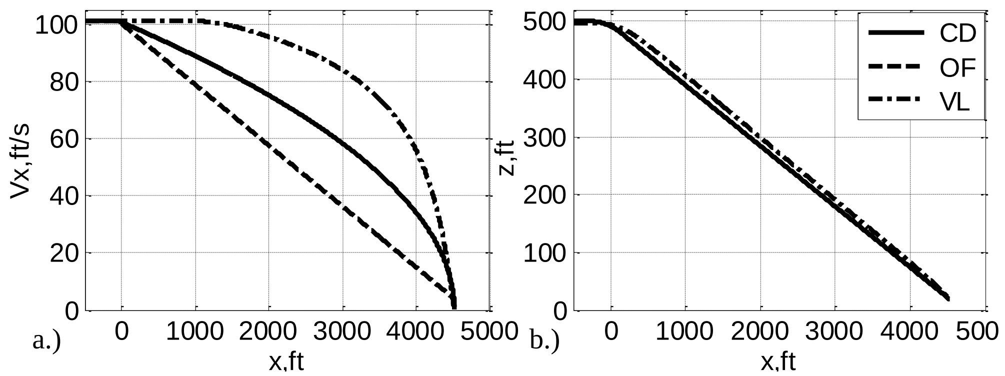


Fig. 58 **Comparison of profiles used for investigation**

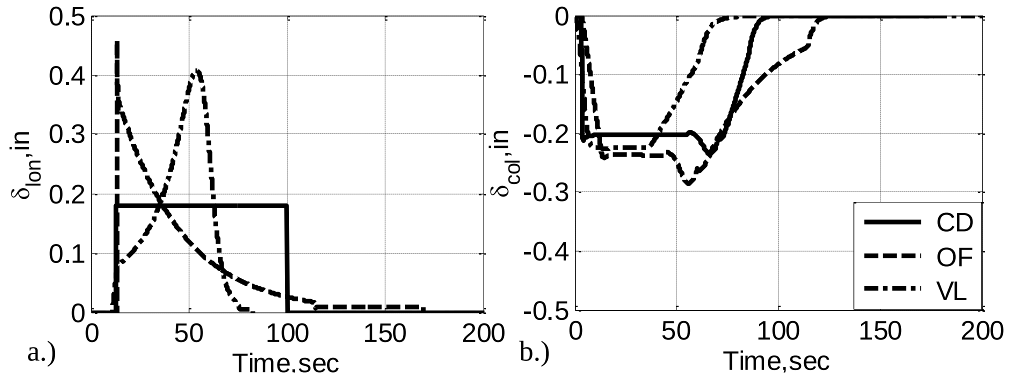


Fig. 59 **Pilot model inputs for each of the designed profiles**

The term “VL” in the above figures corresponds to the designed profile under the visual landing condition. The altitude profiles in Fig. 58 that are used to drive the HITS flight path display system all appear to be reasonably similar for all of the profiles with the exception of slightly larger value of VL.

It is noticeable that the forward speeds in Fig. 58 (note, these are plotted against along-track distance) are quite different for the CD, OF, and VL profiles. The acceleration features of these four profiles are reflected in the longitudinal control input shown in Fig. 59 (note that these are plotted with respect to time) due to that the acceleration command is used as this response type for this channel. A review of these in Fig. 59 indicates that the VL profile has the majority of the deceleration in the later stages of the task. In contrast, the CD profile has a constant deceleration profile (as expected) and the OF profile has an exponentially reducing deceleration throughout the whole manoeuvre. It should be noted that, by inspection of Fig. 59, the lower average speed of the OF case results in a significantly extended manoeuvre time when compared to the other cases used (170 sec, whereas VL is around 80 sec, and CD is around 100 sec).

The forward speed difference is reflected in the required control effort in Fig. 59. As shown, the CD profile requires a constant longitudinal cyclic input for the acceleration command response type of the vehicle model. Conceptually, this might be the easiest to achieve for a flight naïve pilot, with the assistance of some form of guidance. This potentially represents a lowest workload configuration since no additional control inputs are required to accomplish this profile. The constant optical flow profile requires an exponentially decreasing stick deflection, as expected from rest, which might be harder to achieve for a TS. However, the small control deflection changes following the initial large input and the low speed at the final approach may make this profile the 'safest' approach for a flight-naive pilot. Moreover, it is acknowledged that the initial spike associated with the OF's longitudinal input is due to the numerical issue relating to the model inversion process. However, the OF profile may suffer from the long-time spent at low speeds when approaching the stop point. For the VL profile, they require the highest peak control deflections and the most rapid control movements during the manoeuvre, but may be intuitive for flight naïve subjects in mimicking their natural operational mode discussed in Ref. [53].

5.5. Evaluation Results

The results from the experimental test campaign are presented in this Section.

5.5.1. Ranking of Subjective Rating Scale Values

The subjective rating scale values from the 6 TSs are presented in Fig. 60 for each assessment point based on the scales of Appendix 5.A and 5.B, respectively. It should be noted that, for those questions where a high score indicates a positive outcome, the score has been modified to reflect the opposite i.e. a negative outcome. For example, the score awarded for Question 3 in Appendix 5.A would be subtracted from 100 before being included in the results of the Figures. Therefore, the final results presented that have a high value indicate a more negative outcome.

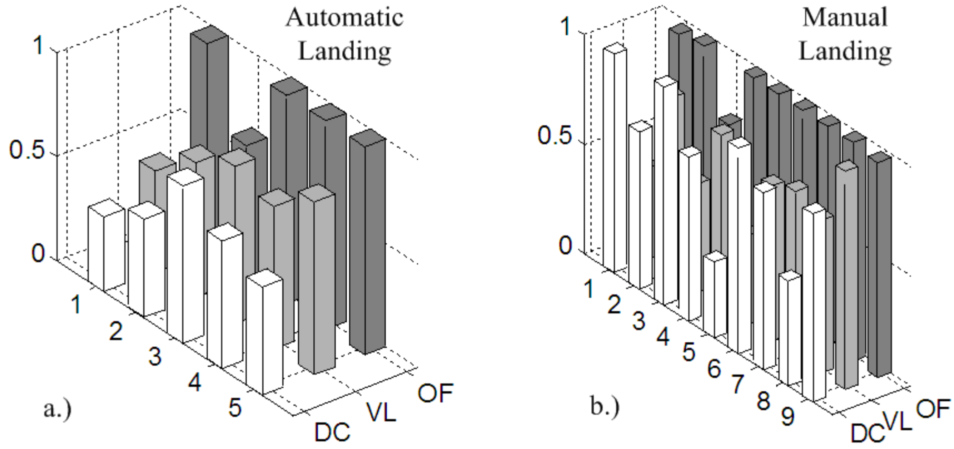


Fig. 60 **Illustration of normalized summed rating values for all test subjects**

Each bar ($\bar{x}_p$) in these two figures has been normalized by the maximum value of the corresponding summed assessment item across the profiles, as shown in Eq. 9;

$$\bar{x}_p = \frac{\sum_{j=1}^{m}\sum_{i=1}^{n} x_{i,j}}{\max\left\{\sum_{j=1}^{m}\sum_{i=1}^{n} x_{i,j}\right\}_{p=1,\cdots,4}} \qquad (25)$$

where *n* is the number of ratings for each TS, *m* is the number of TSs, *p* relates to the current profile, and x_i is the rating value.

For the subjective rating values for the automatic landing cases, the first thing to notice is that the OF profile is ranked worst 4 times from the 5 assessment points (question 2 being the exception). This is interpreted to mean that the TSs felt the most uncomfortable and unnatural when being flown along the OF profile. On the contrary, the CD profile has been awarded the lowest comfort rating 4 times out of the 5 possible. This suggests that the TSs felt at their most comfortable during this manoeuvre. The rankings for the VL profiles exist in between these two extremes.

The distribution of the ratings for the manual landing cases, shown in Fig. 60, departs somewhat from the results of the automatic landing. First, although the OF profile is still rated most negatively for 6 out of the 9 assessment items, the CD profile has been indicated as the most uncomfortable manoeuvre overall by a small margin (Question 1 in Appendix 5.B). Second, the VL profile has been rated most favourably, having the least negative rating 5 times out of the 9 possible assessment items. This is interpreted to mean that the TSs generally felt at their most comfortable for this profile during this form of the experiment. On this basis, the VL profile is ranked the 2nd most favourable profile of the 4 tested.

Overall, these subjective results indicate that the OF is the least favourable profile among these four profiles for both automatic and manual landing cases. Moreover, the TSs prefer the CD profile for the automatic landing and the designed "natural-feeling" profiles for the manual landing, respectively. The latter may be due to that the designed profiles reflect the TSs' daily operation habits.

5.5.2. Analysis of Control Input Effort

The root-mean-square (RMS) control inputs of the longitudinal and collective channels from the 6 TSs are presented in Fig. 61. Moreover, a case conducted by TS 1 has been plotted in Fig. 62 for illustrative purposes.

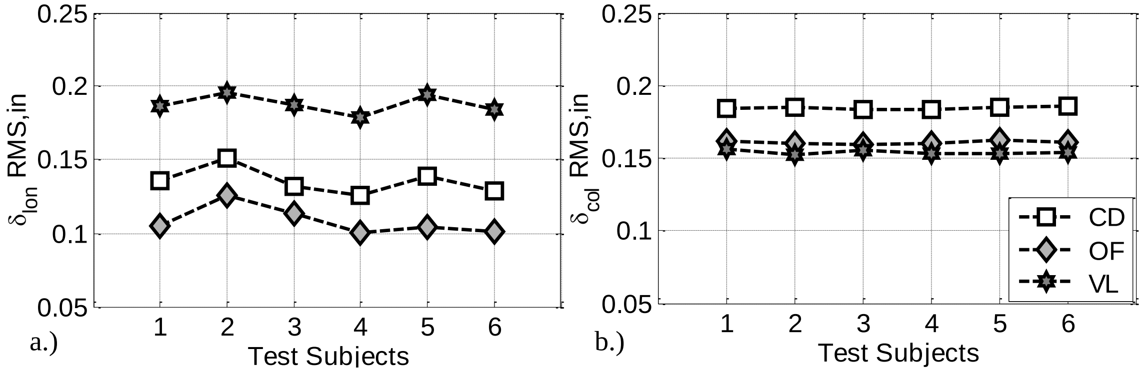


Fig. 61 **RMS values of control inputs (manual landing)**

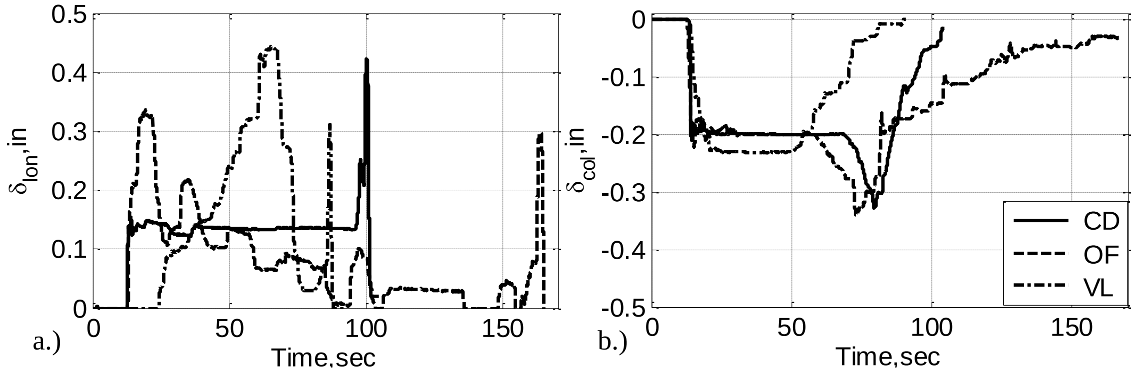


Fig. 62 **Illustration of control inputs of four profiles (TS 1)**

The difference between the three landing profiles in Fig. 61 is quite evident and consistent. For the longitudinal input, the designed profile has input amplitudes that is almost double the other two profiles. This may be due to the requirement to decelerate the PAV at the later part of these two profiles, as depicted in Fig. 59 and Fig. 62. For the CD profile, the TSs only needs to move the stick to a fixed position and hold it there. For the OF profile, the exponentially decreasing profile as well as the longest manoeuver period (170 sec) result in the smallest RMS value. As for the collective input, the three profiles have achieved generally similar levels of average control input.

However, the control input information shown in Fig. 61 cannot give the TS's level of compensation that is associated with the workload experienced during the manoeuver. This can be effectively addressed by calculating the control attack which measures the size and rapidity of a pilot's control inputs [69], defined as,

$$attack = \left|\frac{\dot{\eta}_{pk}}{\Delta\eta}\right| \tag{26}$$

where η is the pilot's control deflection and $\dot{\eta}_{pk}$ is the peak of the rate of control input. The number of times that a TS moves a particular control can be used to describe the TS's control activities (the attack number). In this report, one 'attack' is defined as being when a TS makes a control input of more than 2% of full travel. The attack number per second (ANPS) can then be used to describe the average number of control movements per second. The summed values of the ANPS, normalized by the whole manoeuver period, are illustrated in Fig. 63.

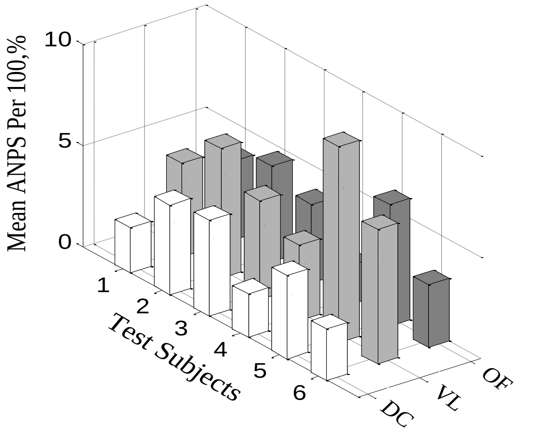


Fig. 63 **Mean attack number per second of longitudinal control input (manual landing)**

The results in Fig. 63 emphasize the lowest control activities associated with the CD profile. Four of the 6 TSs achieve the lowest ANPS for the CD approach from the four manual profiles flown. This is consistent with the theoretical prediction in Fig. 58 and Fig. 59 i.e. that the TS only need to hold the stick due to the acceleration command response type of the PAV system. The VL profile shows the largest attack number. This may be due to the less aggressive deceleration required (due to a smaller flight path angle when approaching the terminal phase of the manoeuvre, as reflected in Fig. 58 and Fig. 59).

5.5.3. Guidance-following Precision

As shown in Fig. 57, all three landing profiles for the manual flight were conducted by following the same form of guidance symbology. Therefore, it might be expected that the profile for which the TSs achieved the smallest deviations from the desired inputs might be considered to be the profile that is, in some way, 'easiest' to follow. The deviation errors for the forward speed and vertical position, normalized by the manoeuvre period, are plotted in Fig. 64.

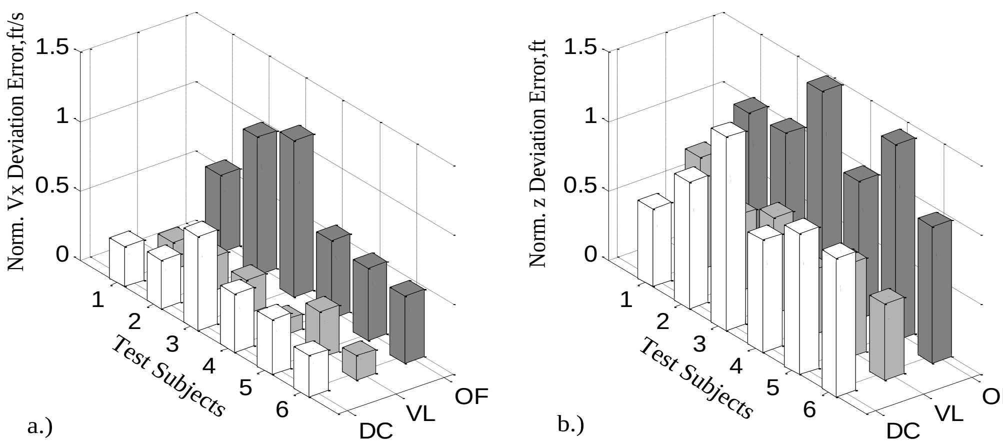


Fig. 64 **Illustration of the normalized *Vx* and *z-position* deviation**

The results in Fig. 64 show that the TS's achieved the best task performance with the designed profile than for the other two tested profiles. For the V_x channel, Fig. 64 shows that all of the TSs exhibited the worst adherence to the desired profile for OF case, followed by the CD profile. However, 5 of the 6 TSs showed the best performance for the VL profile and the remaining TS (no. 3) showed the best performance for the VL profile. For the vertical channel, the main difference from the V_x channel is that the VL profile was the one that was better adhered-to.

5.5.4. Result Summary

The following Section discusses a number of the issues of interest that arose during the investigation. The main thrust of the second-phase research was to answer the question as to which profile, amongst the three profiles tested was the most preferred by the TSs? The rankings (1 to 4 with 1 most favourable and 4 least favourable) of the three profiles with respect to the key features investigated above have been summarized in Table 2 (automated landing) and Table 3 (manual landing).

Table 2 Comparisons of key features associated with four profiles (auto landing)

Profiles	Discomfort	Natural Feeling	Whole Subjective Ratings
CD	1	1	1
OF	3	3	3
VL	2	2	2

Table 3 Comparisons of key features associated with four profiles (manual landing)

Profiles	Discomfort	Natural Feeling	Whole Subjective Ratings	Attack Number	Tracking Precision V_x	Tracking Precision z
CD	3	2	2	1	2	2
OF	2	3	3	2	3	3
VL	1	1	1	3	1	1

The results shown in the above two tables indicate that the answer to the research question is dependent on the point of interest. For example, the VL profile is ranked highest based upon the subjective ratings for the manual landing manoeuvre, but appears to require the highest workload based upon the attack number. However, there are still a few conclusions that can be drawn from these two Tables. First, based on the values in the Tables, the OF profile was the least favoured by the TSs. This profile is consistently ranked worst in Table 2 for the automated landing cases and worst for 5 of the 7 factors in Table 3 for the manual landing. Second, the preference for a profile is dependent upon the mode of operation i.e. automated or manual. *For the automatic landing, the CD profile is the most preferred*. It is ranked as being lowest in terms of discomfort and feeling the most natural. *However, for the manual landing, the VL profile was preferred*. It was rated as providing the most general subjective satisfaction and having most natural-feel by the TS. If the requirement is to achieve the highest tracking performance and the lowest physiological variation, then the VL profile would be the profile of choice for a manual descent. Overall, for the manual landing situation, taking into account all of the 7 factors listed in Table 3, the "natural-feeling" profile was generally preferred over the other two profiles.

6. Investigation of Novel Concepts for Control of a Personal Air Vehicle

As an extension to the previous investigations, an aim of the *myCopter* project is to investigate the use of 'novel' control methodologies for use in PAVs. The HQs requirements development process described thus far for the PAV has considered 'conventional' rotary-wing response types and inceptors; a cyclic handle for pitch and roll control, collective lever for heave, and pedals for heading. However, the majority of test subjects used in the investigations to date, and potentially representative of the level of skill and training of future PAV pilots, have more experience of driving cars than flying helicopters. A typical automatic transmission automobile features a steering wheel, an accelerator (gas) pedal, and a brake pedal. As such, the *myCopter* project also explored the implications of a PAV in which the response and inceptor characteristics were more akin to those found in an automobile than a helicopter.

Table 4 compares the response characteristics and training requirements for helicopters and cars in the UK. The automotive control consists of a single rotational (yaw/heading) and single translational axis (surge). Furthermore, the vehicle motions are linked; one cannot change heading without moving forwards or backwards.

Table 4: Comparison between traditional helicopter and automobile control

	Helicopter	Car
Translational Axes	Surge, Sway, Heave	Surge
Rotational Axes	Pitch, Roll, Yaw	Yaw
Controls	4 (Lateral Cyclic, Longitudinal Cyclic, Collective, Pedals)	3 (Accelerator, Brake, Wheel)
Experience and Testing (legal requirement) in UK	40 hour flight time, seven written exams, minimum 10 hours solo flight, two hour practical exam	One practical hour exam, One written exam
Approx. hours to obtain license in UK	60-90 hours (mixture of tuition and practice)	20-50 hours (mixture of tuition and practice)
Approx. cost in UK	20,000-30,000 GBP	500-1500 GBP

In a conventional helicopter, the pilot must control four independent axes, and, for longitudinal and lateral motion, must command pitch and roll attitude changes in the first instance. It is considered that a reduction in the number of controls could provide significant benefits in terms of reducing the workload of the pilot.

The report focuses primarily on the vehicle responses, using conventional helicopter inceptors that were configured to behave more like those of an automobile; the use of novel inceptors (such as a steering wheel) is part of a separate study. The next Section describes the methodology used, including the modelling of the car-like PAV and the tasks and analysis methods used. The results from a set of preliminary tests performed using the first version of the car-like configuration are described and analysed. This is followed by a description of a set of modifications made to the simulation model to improve the HQs of this vehicle. Finally, results of a comparison of the tuned car-like configuration and the existing 'Hybrid' configuration are presented and discussed.

6.1. Experimental Method

6.1.1. Implementation of an Automobile-Like Configuration

A novel control system, referred to as the 'Automobile' configuration, was developed by modifying the 'Hybrid' control system briefly mentioned above. In this new system, forward flight velocity is controlled through the Attitude Command, Speed Hold (ACSH) response type throughout the flight envelope. The response of the ACSH is similar to the Linear Acceleration Command, Velocity Hold (LACVH) response type assessed for use on the MH-47G helicopter [71]. When the pilot inputs and holds a 'forward' command, the vehicle accelerates at a constant translational rate. Returning the control to neutral will have the effect of holding the velocity, by arresting the acceleration. Velocity is reduced through the application of the opposite control, which will cause deceleration of the vehicle.

A full description of the development of the Hybrid configuration of the PAV is contained within [35]. The automobile configuration longitudinal control is formed as an outer loop system of the TRC response type used for low speed flight in the Hybrid configuration. The TRC system itself is an outer-loop control of an ACAH system.

The simulation facility used for this investigation, HELIFLIGHT-R, has been used for all previous *myCopter* investigations at UoL. A full description of the facility is contained within [38]. Fig. **65** shows the crew station contained within HELIFLIGHT-R which incorporates a 210º by 70º Field-of-View (FoV) projection system, dual controls, and reconfigurable instrument panels.

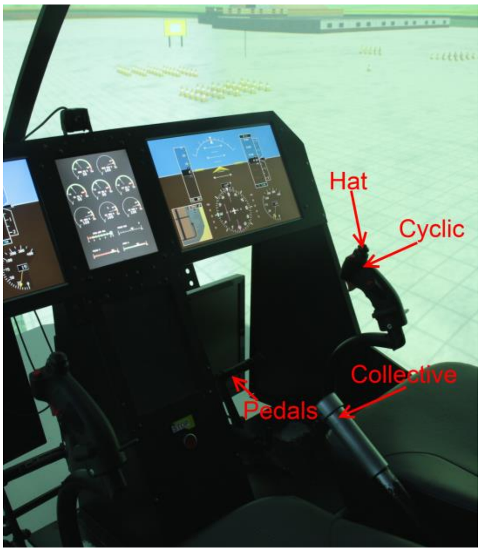


Fig. 65: Helicopter Control within HELIFLIGHT-R

The crew station is equipped with conventional helicopter-style inceptors. For the Hybrid control system, controls are operated as in a standard helicopter; heave motion is controlled through the collective lever, yaw is controlled through the use of pedals, and lateral and longitudinal translation are controlled through deflection of the central cyclic handle. Precision control of the vehicle can be achieved through the use of a `hat' switch on the cyclic handle, which functions as a four-way low-speed TRC velocity command inceptor.

The longitudinal ACSH response type of the 'Automobile' configuration investigated in this work was controlled using the pedals, functioning in a manner similar to those found in a car. Left and right pedals provide deceleration and acceleration commands respectively. To replicate the function of the car's steering wheel, lateral movement of the cyclic inceptor controls the heading of the PAV – commanding yaw rate at low speed (< 15 kts), and through bank angle control at higher speeds (> 25 kts). In addition, turn coordination is used to ensure that independent yaw control is not required in forward flight. A lateral TRC mode remains active (maintaining v = 0kts) at low speed to provide turn coordination throughout the envelope. Unlike an automobile the collective inceptor was retained to allow control of heave motion. With no direct control of roll at low speed, and no direct control over yaw at high speed, operation of the PAV is reduced to three axes of control (surge, heading/roll (the combined lateral directional control depending on airspeed) and heave).

6.1.2. Test Configurations

Traditional helicopters tilt their rotor thrust vectors in order to generate longitudinal and lateral forces, and hence translational accelerations. The associated body rotations (pitch and roll) are an additional complexity for the pilot to manage in comparison to the driver of an automobile. Particularly for test subject unused to flight motions in three dimensions, these can add a dimension of disorientation, potentially destabilizing the aircraft and increasing task workload. It was hypothesized that in future PAV concepts, it would be advantageous to remove the vehicle's pitch and roll motions, and hence make the PAV flight experience more similar to that of driving a car. This could be achieved through the use of a Thrust Vectoring (TV) system, for example. This type of control has been demonstrated in previous research aircraft, an example being the Vectored-thrust Aircraft Advanced Control (VAAC) Harrier [38].

The TV configurations were implemented by initially analysing the velocity response of the 'standard' versions of the Hybrid and Automobile configurations to step control inputs. The translational accelerations required to achieve these velocity profiles were determined, and used to configure longitudinal and lateral force generators placed at the centre of mass of the PAV. Hence, the longitudinal and lateral velocity responses of the TV systems were configured to be identical to those of the standard systems, except they did not require the aircraft to pitch and roll to generate those responses.

In order to investigate the individual impacts of changing the response configuration, and the mechanism used to generate accelerations, a total of four configurations were created for investigation within this study. The relationships between the configurations are shown in Fig. **66**. The two response types (Hybrid and Car), both flown with and without a TV system lead to a 2x2 matrix of configurations. The first configuration to be tested was the Hybrid system, used in the previously reported studies [35], identified here as Case I. This was used as a baseline for comparison with the more novel configurations. The second configuration to be tested was the 'automobile type' control, using the Pedal-based Automobile system (Case II). The second pair of models are those using the same method of control, but with the removal of rotational response through the notional use of TV. These configurations are shown in Table 5, alongside their designated case numbers.

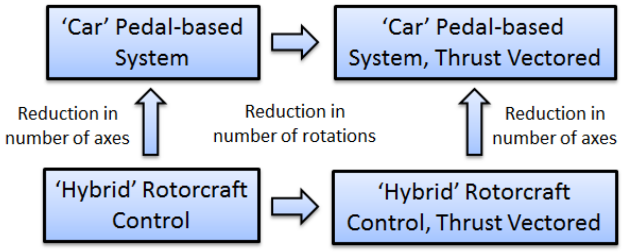


Fig. 66: Control Response Types Investigated (Car = Automobile)

Table 5: Test Case Numbers

Case	Control	Thrust Vectored	Rotation
I	Hybrid	No	Yes
II	Automobile	No	Yes
III	Hybrid	Yes	No
IV	Automobile	Yes	No

Two MTEs were selected for the investigation reported in this report; one task to explore control of the PAV in forward flight and one to explore control at low speed and in the hover; a Decelerating Approach task and a Hover Reposition task, both derived using similar principles to the MTEs included in [35]. The Decelerating Approach task has been used previously in the *myCopter* project during the evaluation of conventional response types [35]. The Low Speed Hover Reposition task was developed around the principles of the ADS-33E-PRF Hover task. This task involves repositioning the vehicle from and to a stabilized hover, with the final hover position constrained to have a high degree of accuracy.

As defined in ADS-33E-PRF [14], the translation phase of the Hover MTE is flown along a trajectory at a 45º angle relative to the heading of the aircraft, making the task suitable for the assessment of both longitudinal and lateral axis HQs. However, two of the configurations under investigation in this study (Cases II and IV) are not suited to the 45º approach, as these configurations do not allow the pilot to command lateral velocity directly. However, other aspects of the Hover task, such as repositioning and controlled deceleration of the vehicle to a hover at a fixed point, are applicable to PAV operations. Therefore, the task was modified to incorporate a curved route from the start point to the final hover point. For this reason it is referred to in this report as the 'Hover Reposition'. The layout of the MTE is shown in Fig. **67** . The cones indicate to the pilot the desired and adequate requirements for the final longitudinal position. The reference pole shown between the vehicle and the 'hover board' indicates height, heading, and lateral position deviation from desired when in the final hover. The task performance requirements are shown in Table 6.

Fig. 67: External View – Hover Reposition Task

Table 6: Hover Reposition Performance Requirements

Parameter	Desired	Adequate
Attain a stabilized hover within X seconds of reaching the target hover point	5	8
Maintain the longitudinal and lateral position within ±Xft of the ground reference point	3	6
Maintain heading with ±Xº	5	10
Maintain height within ±Xft	2	4

A typical ground trajectory for completion of the manoeuvre is shown in Fig. **68**. As the aircraft begins the MTE aligned with the final hover heading, the pilot must begin the manoeuvre by completing a heading change of 80º. Following the heading change, pilots were required to accelerate to a forward airspeed of between 6 and 10 knots. Simultaneously, the pilot must perform a turn, to bring the aircraft to the correct hover location defined by the visual references. There were no requirements placed on the turn radius, but pilots were asked to achieve a forward speed of at least 6kts prior to commencing the turn. Furthermore, pilots were expected to have completed their turn prior to arriving at the hover point.

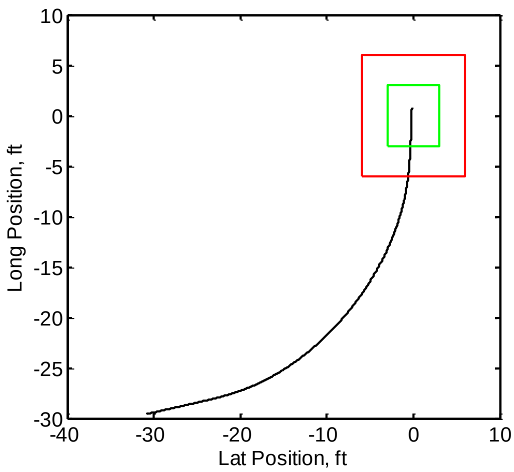


Fig. 68: Ground Trajectory for Hover Reposition Task.

The Decelerating Approach task was designed to investigate the transition from cruising flight to hover. The task investigates the deceleration of the vehicle to a defined hover point, from a speed of 60 knots and a height of 500ft. The descent associated with the task represents a flight path angle with an average of 6º [34]. The HUD symbology used is shown in Fig. **69**, and has been used in previously reported *myCopter* studies [34;35;49]. Although the subject was free to select their own descent profile, the HUD provided information to aid the pilot's selection of glide path angle and deceleration rate. The display features a flight-path vector (white circular symbol) indicator and a ground stop–position predictor (lower pale horizontal line) indicator, as seen in Fig. **69**. The stop-position predictor indicates where the aircraft will stop if the current rate of deceleration is maintained to the hover. Therefore, the combination of the flight-path indicator and the stopping position line can be used to bring the aircraft to a hover at the correct position (above the white cross seen in Fig. **69**). The HUD also features current (right-hand, green figure) and commanded (left-hand, red figure) airspeed, heading and height information, alleviating the need to refer to head-down displays. Throughout research reported in this report, MTEs were flown in benign flight conditions.

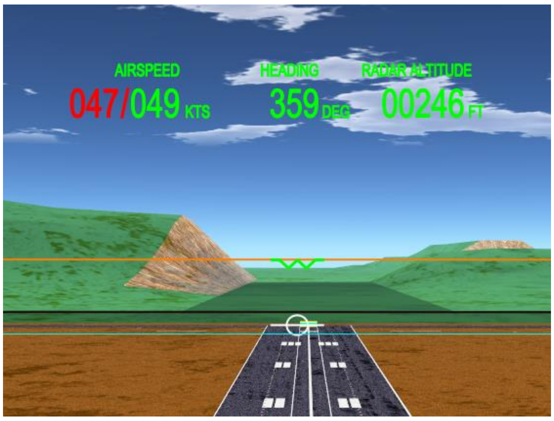


Fig. 69: HUD used during the Decelerating Approach Task

The test subjects used in this investigation were selected to cover a broad spectrum of aptitude and flying experience. Prior to beginning the flying tests, each subject completed a series of computer-based aptitude tests, examining different aspects of piloting. These were developed from elements of the United States Air Force (USAF) Basic Attributes Test [30] and a set of standard psychometric tests [31]. A full description of the nine tests included in the UoL aptitude evaluation is contained in [35].

In the present study, pilots are identified by their aptitude and additionally by 'experience codes'. Aptitude tests were designed to give an appreciation of the pilot's natural ability to complete the flying tasks. However, this does not convey their experience. Therefore, experience codes, shown in Table 7, were used to show whether the pilots have any experience of driving, flight simulation, or actually piloting aircraft. It should be noted that the categories are broad and act only to indicate the pilots' experience. They represent the 'levels of training' the pilot has previously received.

Table 7: Flight Experience Codes.

Exp. Code	Flight Exp.	Sim Exp.	Driving Exp.	Additional
1	X	X	X	-
2	X	X	O	-
3	X	O	O	-
4	O	O	O	+ No Flying License
5	O	O	O	+ Private Pilot License (PPL)
6	O	O	O	+ Helicopter Private Pilot License (H-PPL)
7	O	O	O	+ Commercial Pilot License (CPL)
8	O	O	O	+ Test Pilot

A number of tools were used to both objectively and subjectively assess each subject's performance during the simulations. As in previous *myCopter* investigations at UoL, the NASA Task Load Index (TLX) workload rating system [72] was employed, to quantify the subjective workload of the participants. To objectively assess the novel response types, the TPX mentioned in the previous Section was used.

6.2. Results from Preliminary Investigations

Prior to commencing the main body of the simulation trials, a preliminary study was performed to gain some initial insight into the HQs of the various configurations. Each configuration shown in Table 5 was tested using four test subject pilots, of varying experience and aptitude. These pilots flew the Hover Reposition manoeuvre nine times in each configuration. Due to the limited number of participants in the trial, and to ensure consistent comparisons were made between the configurations, each pilot flew the four configurations in the same order. This test methodology introduces the potential disadvantage that learning (of both task and vehicle HQs) could occur. Experience gained during the early cases during the testing process could impact upon the results of later cases, potentially leading to workload and performance comparisons showing bias towards those tests carried out later in the assessment process.

For each Case (I-IV), each pilot awarded two TLX ratings. The first was taken after the 6th run, and the second after the 9th and final run. The aim here was to observe the learning behaviour of each pilot, and to try and capture whether the participants were or were not proficient in the task after the first 6 runs, or whether learning continued to the 9th run. If the TLX ratings were similar, it indicated that the pilot had managed to achieve repeatable performance following no more than 6 runs. However, if the ratings were different, it indicated that either the pilot was not maintaining consistent task performance (through either variable workload or task completion strategy), or was continuing to learn how to optimize their performance through to the end of the tests. In HQ investigations, involving qualified test pilots, 3-4 runs of each vehicle configuration are usually considered sufficient before ratings are awarded, and further repeats may skew the results by allowing the pilot to subconsciously adapt to a vehicle's deficiencies. However, it was considered that the test subjects used were likely to find it more challenging to achieve consistent performance than professional test pilots, and were therefore allowed a longer period of time to familiarize themselves with each task.

Fig. **70** shows the TLX ratings awarded by the four initial subjects. Test numbers are a combination of Case number and run number. For example, I.6 is the 6th run of Case I. The test subjects' flight experience is indicated via the 'Exp' code (Exp.) and Aptitude (Apt.). The general trend shown in Fig. **70** is that workload is lower in the 'Car' configurations (Cases II and IV) than in the Hybrid configurations. The overall lowest workload ratings were found for Case IV. The highest average workload for each pilot, with the exception of the pilot with the lowest Exp., was found for Case III. One observation for this case was the increase in workload for the pilot with the highest experience. For this case, the pilot awarded TLX ratings significantly higher than for Case I. It is likely that, due to his experience, this pilot is more familiar with the rotational cueing than other pilots used during the study.

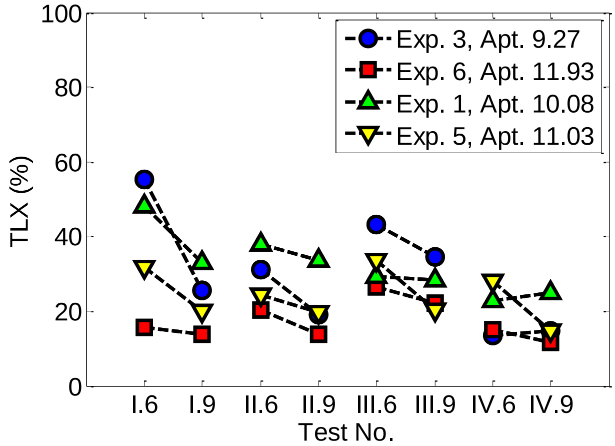


Fig. 70: TLX Ratings awarded during Hover Reposition task

For the majority of cases, pilots generally awarded a lower TLX rating for the 9th run than they did the 6th run, suggesting that for all four configurations, the pilots were still learning how to optimize their performance in the final three runs.

At this stage, the main problem reported by the test subjects for the Automobile configurations (both with and without TV) was a lack of precision during the hovering phase of the task. All pilots successfully managed to navigate to the hover position with relative ease. However, when approaching the target position, pilots found it more difficult than expected to stop the vehicle in the correct position. This was due to a lack of sensitivity offered through the deceleration inceptor (left pedal). Overshooting the target required the pilot to engage a 'reverse' mode, with little cueing offered in this condition due to the limited rearwards FoV within the simulator. The cones of the test course did provide cueing laterally but, of course, this is not usually the method employed by drivers to reverse – they would more likely be looking in rear-view mirrors or out of the rear windscreen. The lack of precision control meant that pilots often overshot their intended stopping position whilst trying to make small reversing or creeping position adjustments. The result of these difficulties was an increase in 'Workload' and/or a decrease in 'Precision' for the Automobile systems. Figure 71 and Fig. **72** show 'Precision' with respect to 'Workload' for all tests completed for Case I and Case II respectively. For Case I (Figure 71) the results suggest a relationship between overall 'Precision' and the individual pilot's aptitude. The pilot with the highest aptitude achieved 100% 'Precision' on all tests completed in this configuration. Furthermore, it can be seen that greater than 95% 'Precision' was achieved in the majority of runs, even by the lower aptitude pilots. For Case II (Fig. **72**), there is a general reduction in P, for all pilots. Although pilots were still able to achieve P=100%, the proportion of cases for which this was achieved was reduced compared to Case I. However, an increase in workload was not shown by the TLX ratings awarded, suggesting that the decrease in Performance (shown through P) and increase in control activity (shown from W) were not a function of increased subjective workload.

The reduction in P was attributed, at least in part, to the lack of lateral control in the Case II configuration. If pilots arrived at the target hover point with a lateral position offset, the only way to reposition the vehicle was to move out of the desired hover region, and reposition using a combination of longitudinal and heading control (as would be the case in an automobile). This process proved cumbersome, leading to poor performance, and in particular significantly lowered the associated TPX ratings. In most cases however, the additional repositioning did not significantly increase subjective workload, as evidenced by the TLX ratings.

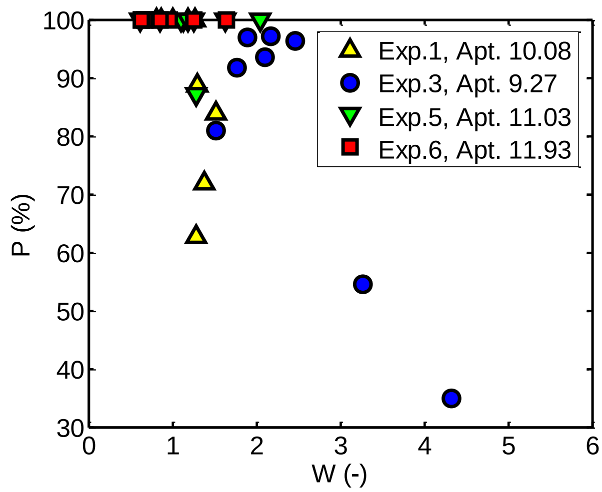


Figure 71: Workload vs. Precision for Case I (Hybrid)

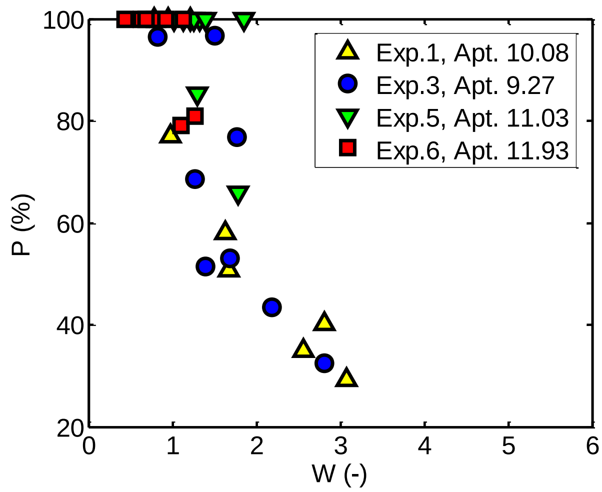


Fig. 72: Workload vs. Precision for Case II (Automobile)

6.3. Model Modifications

The four pilots used in the study were all able to complete the Hover Reposition task using both control systems, but were frustrated by a number of aspects of the Automobile configuration. Following the results of the preliminary tests, the characteristics of the simulation were tuned to improve its suitability for the Hover Reposition MTE. There were four main 'user requests' suggested for the Automobile configuration. These were:

- Control Stiffness: Increase the stiffness to provide force-feedback akin to that experienced when driving an automobile – particularly on the 'brake' pedal.
- Control Sensitivity: Increase sensitivity to reduce the required stopping distance when performing the deceleration.
- Quicker Response: Ability to perform rapid changes in forward velocity, to assist in making appropriate corrections during deceleration.
- Introduction of Precision/Lateral control: Provide a method for low-amplitude repositioning for use during low-speed flight.

In order to investigate theses requests further, a small sensitivity study was performed with one of the subjects (*Exp.=6, Apt.=11.93*). For this study, 'Raw' TLX ratings [73], where the six aspects of workload are given equal weighting), was used in preference to the traditional TLX method. This method was adopted due to time constraints during the testing.

6.3.1. Control Stiffness

Pilots commented in the preliminary tests that they felt that there was a lack of feedback from the pedal controls during the simulation. It was felt that the primary problem was the lack of 'resistance' in the pedals and hence a lack of 'feel' for how much braking was being applied. In an automobile, reasonably high forces can be experienced when depressing the pedals, particularly when using the brake pedal. Applying maximum or excessive braking requires one to apply significant force, limiting the use of such control to situations where it is entirely necessary. In the small sensitivity study, the test subject completed the MTE on two occasions with 'light pedals' and three occasions with 'stiff pedals', awarding lower TLX ratings for the latter configuration. The introduction of stiffer controls lead to the reduction of average workload from TLX = 15.99 to TLX = 7.78. The 'stiff' pedals featured a much larger spring force of 86 N/in (compared to just 8 N/in with the 'light' pedals), and a higher breakout force of 25 N (compared to 15N). It was decided that the stiff pedals were more suited to the task and were therefore implemented within the simulation for future tests involving the Automobile configuration.

6.3.2. Control Sensitivity

It was identified during the initial tests that control sensitivity was a limiting factor with regard to the stopping distance of the PAV when in the Automobile configuration. Consistently, pilots applied maximum control deflection in their attempt to stop the vehicle at the desired point. By applying very early deceleration inputs, pilots were able to avoid maximum pedal deflection, but this resulted in an increased reported workload for the task. The large stopping distance was one of the largest contributors to pilot frustration in the initial tests. In the sensitivity study, tests with the same control gain were repeated with the `stiffer' control configuration.

As shown in Fig. **73**, the increase in pedal stiffness did not entirely prevent the subject from applying full control inputs. However, it did increase the physical workload when using that configuration due to the higher control loads experienced. As part of the tuning process, the control gearing was doubled. Two cases were completed using this higher gearing, with results shown in Fig. **74**. It can be seen that, in both cases, the pilot did not use full pedal travel, but still came to a smooth stop in the desired position without any overshooting. It is also evident that far fewer control inputs were required to complete the manoeuvre. As a result of these findings, the control gain was doubled from the value used in the initial tests. This complemented the increase in stiffness, and allowed for suitable control margins during the task. All subsequent tests in the sensitivity study were performed with this control gearing.

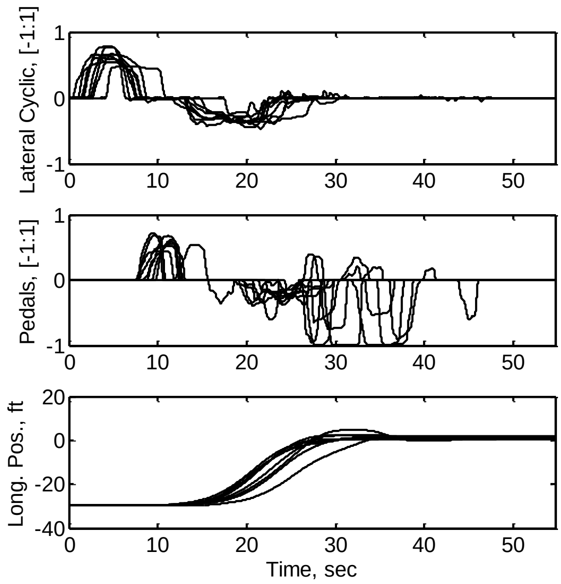


Fig. 73: Hover Reposition Task completion using nominal longitudinal control gain.

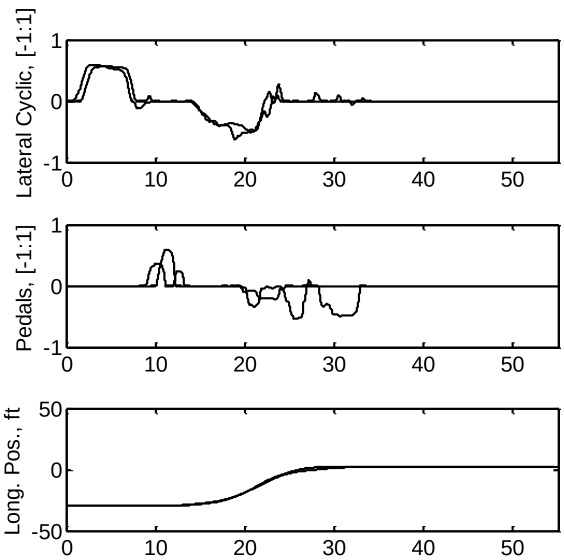


Fig. 74: Hover Reposition Task completion using double longitudinal control gain

6.3.3. Sharper Response: Velocity Response Time Constant

The problems encountered in stopping at the correct position in the preliminary study can also be related to the time taken for the system to respond following a control input. The time constant of the system's velocity response to a pedal input was modified by altering the properties of the inner TRC feedback loop. A first order low-pass filter with time constant τ_{U_p} is used to smooth the pilot's inputs and reduce pitch attitude overshoots. Control damping is increased as τ_{U_p} decreases. This provides a faster response to a control input, resulting in a higher system bandwidth. In the initial model, τ_{U_p} was set as 0.7s, a result of the requirements of the Hybrid control system for Level 1 HQs [49]. This value, alongside two other values of 0.4s and 0.1s were used in this sensitivity study.

It was found that there were no major differences between the subjects' performance with each of the time constant values. For the Hover Reposition MTE, when τ_{U_p} = 0.7 sec, the objectively measured Workload (*W* in Eqn. 1) was found to be higher than for the other two cases. With smaller time constants, the subject stated that they had more precise control of the vehicle, and likened performance of the configuration when τ_{U_p} = 0.1 sec to that of a 'sports car'. However, the subject commented that they felt the translational motions were quite harsh, and may be uncomfortable in-flight.

For the intermediate case of τ_{U_p} = 0.4 sec, the subject reported that the aircraft still offered a useful improvement in manoeuvrability over the baseline setting, and attitude excursions did not feel unnecessarily large. The subject's individual preference was for the configuration with τ_{U_p} = 0.1 sec, as they had the ability to make the most precise corrections in the system if required.

While the test subject expressed a preference for the lower time constant in the Hover Reposition MTE, the opposite proved to be the case for the Decelerating Approach MTE. In this task, the vehicle was over-sensitive with the lower time constant values, leading to difficulty setting and maintaining a steady deceleration to the hover. To proceed, different τ_{U_p} values were selected for each MTE, providing a degree of optimization of the configuration towards each task. In future testing, it is recommended that further research is undertaken to determine the characteristics that would suit the complete flight envelope, to aid in the generation of generic PAV control configuration. The resultant model parameters used are shown in Table 8.

Table 8: Optimized 'Car' Controls

Parameter	Before	After
K_{pedal}	0.15	0.30
τ_{U_p}, sec	0.7	0.1 (Hover) 0.7 (Decel Approach)
Spring Stiffness, N/in	8	86
Breakout Force, N	15	25

6.3.4. Implementation of Low-Speed TRC Response

The final optimization was the addition of a low speed longitudinal and lateral TRC function using the hat switch on the cyclic handle. During the initial tests, one of the largest frustrations reported by the pilots was the inability to translate laterally without the need for forward or aft vehicle motion. This, coupled with the difficulties experienced with precision control in the Automobile configuration made it very challenging for the subjects to reach the specified target positions. In many cases, pilots were only a few feet from the correct location, but had to forfeit all task performance requirements to get to the correct position. It was decided that, in order to improve this aspect of the vehicle's capability, an additional corrective TRC controller should be added. The purpose of the control was to provide a means to perform low-speed, precise repositioning, in both the lateral and longitudinal axes. It was not however implemented to replace the primary responses of the Automobile configuration at low speed. As a result of its intended used, it was set to command a maximum steady-state translation of 1 knot in both lateral and longitudinal directions.

6.4. Results from Tuned Models

Following the tuning process, a further group of six test subjects were tested, completing both the Hover Reposition and the Decelerating Approach MTEs. Most of the pilots involved in the preliminary tests completed further investigations using the tuned models. The following Sections outline some of the key findings.

6.4.1. Test Pilot Evaluation

Prior to the evaluations by the non-professional pilot test subjects, all four configurations were evaluated by a test pilot, to determine their handling qualities. The pilot awarded Handling Qualities Ratings (HQRs, [27]), as recorded in Table 9. It was found that, whilst the removal of rotational motion through TV significantly affected the Hybrid configuration, there was little affect shown for the Automobile system. The Hybrid system with rotations (Case I) was awarded HQR=4, suggesting 'minor but annoying' deficiencies within the system (as a point of reference, the test pilot awarded the Hybrid configuration HQR = 2 for a standard ADS-33E-PRF [14] Hover MTE). However, with the TV system, the pilot awarded HQR = 7. In this case, the pilot struggled to maintain translational position throughout the manoeuvre, and found that the lack of rotational cueing affected both their ability to maintain position and to perform a smooth translation.

Table 9: Handling Qualities Ratings

Hover Reposition	**Rotation**	
	NO	**YES**
Hybrid	4	7
Car	3	3
Decel. Approach	**Rotation**	
	NO	**YES**
Hybrid	-	2
Car	1	1

Fig. **75** and Fig. **76** show the difference ground trajectories achieved by the test pilot for the Hybrid configuration with and without the TV system. Both the smoothness of the transition phase and final positional accuracy are degraded when the pitch and roll axis rotations are removed. The test pilot's performance when using Case II was found to be worse than that of all the test subjects used in the preliminary study. One possible reason for this is the large difference between the response of this configuration, and that of a traditional helicopter. From their experience, the test pilot expects to be cued through rotational motion of the vehicle. With the lack of rotations, the pilot struggles to 'fly' the vehicle as expected. As the test subjects used have less experience, they are less affected by the lack of rotational cueing, as they can quickly adapt to using other cues available within the environment.

In contrast to the Hybrid system, the HQs of the Automobile configurations appeared to be unaffected by the removal of pitch and roll rotations. Both configurations (Case II and Case IV) were awarded HQR=3. The pilot found coordination of the turn to the hover target the most challenging element of the manoeuvre, but favoured this system to both of the Hybrid configurations. For the test pilot, one of the key difficulties was remembering to control the aircraft `like a ground vehicle', as they were so familiar with the operation of conventional fixed- and rotary-wing aircraft. Despite this, the test pilot believed that the Hover Reposition MTE was easier to achieve with the Automobile configuration.

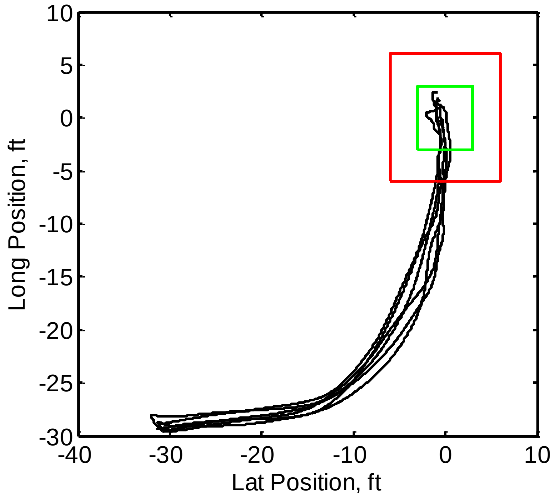


Fig. 75: Ground Position during Hover Reposition – Case I

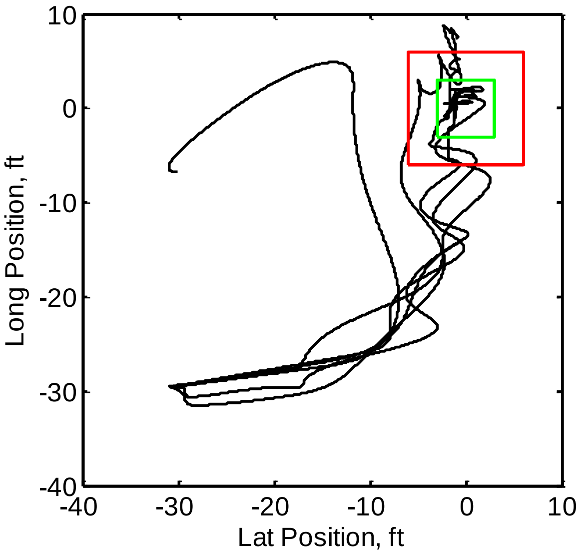


Fig. 76: Ground Position during Hover Reposition – Case III

Unlike the Hover Reposition manoeuvre, the test pilot reported very little difference in the HQs of any of the configurations in the Decelerating Approach task. All HQRs awarded, and the supporting pilot comments, suggested that this task was easier to complete than the Hover Reposition for both Hybrid and Automobile configurations. The pilot marginally preferred the Automobile configurations, awarding HQR=1 for both. However, a rating of HQR=2 for the Hybrid configuration showed that, for this task, there were no significant deficiencies.

6.4.2. Hover Reposition MTE with Non-Professional Pilot Test Subjects

The results obtained with the tuned configurations in the Hover Reposition manoeuvre supported the test pilot's finding that the Automobile configuration offered benefits for low speed repositioning manoeuvres over the Hybrid configuration. With the tuned system, the test subjects were able to complete the task much more successfully than in the preliminary investigations. The increase in control gearing, system bandwidth, and control forces appeared to aid subjects in controlling their stopping distance. Selection and control of stopping distance was previously one of the main drivers of poor performance in this task. As in the preliminary tests, each subject (6 in this case) performed the manoeuvre 9 times in each configuration. They were asked to award TLX ratings following the 6th and 9th attempts. In addition, the test pilot used to assess the HQs of the vehicle models was also asked to provide TLX ratings. These were given following the 6th attempt at the task.

Table 10 to Table 13 display the TLX ratings collected during the Hover Reposition MTE. With the exception of a few cases, TLX ratings awarded for the Automobile configurations were lower than for the Hybrid systems. This was the case for both the 1st and 2nd TLX ratings awarded by each of the pilots. The large difference in magnitude of TLX ratings for a given Case seems to be a result of individual pilot interpretation of what constitutes very low and very high workload. For this reason, the TLX ratings do not necessarily give an insight into the comparative workload experienced by each pilot. Despite large differences in the individual ratings awarded by each pilot for a particular configuration, the trend of the TLX results was predominantly consistent across pilots for the different configurations.

Table 10: TLX Ratings for Hover Reposition Manoeuvre – Case I

Aptitude	Exp. Code.	1st	2nd	Average
-	8	38.66	-	38.66
9.27	3	32.66	32.66	32.66
10.08	1	29.00	48.55	38.78
10.39	4	17.33	18.00	17.66
10.78	2	82.66	78.33	80.50
11.03	5	16.00	17.00	16.50
11.93	6	11.66	9.66	10.66
		31.55	34.03	32.79

Table 11: TPX Ratings for Hover Reposition Manoeuvre – Case II

Aptitude	Exp. Code.	1st	2nd	Average
-	8	21.33	-	21.33
9.27	3	27.66	24.00	25.83
10.08	1	23.33	26.33	24.83
10.39	4	17.00	16.00	16.50
10.78	2	67.33	65.60	66.47
11.03	5	19.00	18.00	18.50
11.93	6	9.00	9.00	9.00
		27.22	26.49	26.85

Table 12: TPX Ratings for Hover Reposition Manoeuvre – Case III

Aptitude	Exp. Code.	1st	2nd	Average
-	8	82.33	-	82.33
9.27	3	-	-	-
10.08	1	41.33	33.00	37.17
10.39	4	29.00	33.00	31.00
10.78	2	86.66	76.33	81.50
11.03	5	29.00	24.00	26.50
11.93	6	15.66	18.00	16.83
		40.33	36.86	38.60

Table 13: TPX Ratings for Hover Reposition Manoeuvre – Case IV

Aptitude	Exp. Code.	1st	2nd	Average
-	**8**	17.66	-	17.66
9.27	**3**	-	-	-
10.08	**1**	23.66	25.66	24.66
10.39	**4**	20.66	17.00	18.83
10.78	**2**	59.00	57.33	58.17
11.03	**5**	22.66	20.66	21.66
11.93	**6**	11.00	13.00	12.00
		27.40	26.73	27.07

The mean and spread of the TLX ratings awarded for the Hover Reposition task are shown in Fig. **77**. Despite the large range of TLX ratings awarded for each configuration, both the extreme and mean results indicate a lower workload for both Automobile configurations than either of the Hybrid configurations. For three of the four cases, TLX ratings awarded by the test pilot were similar to the mean of the sample population of the test subject pilots. However, for Case III, the test pilot's rating was found to be much higher. In this case, as discussed above, the test pilot encountered several major deficiencies with the vehicle that were not necessarily encountered by the test group.

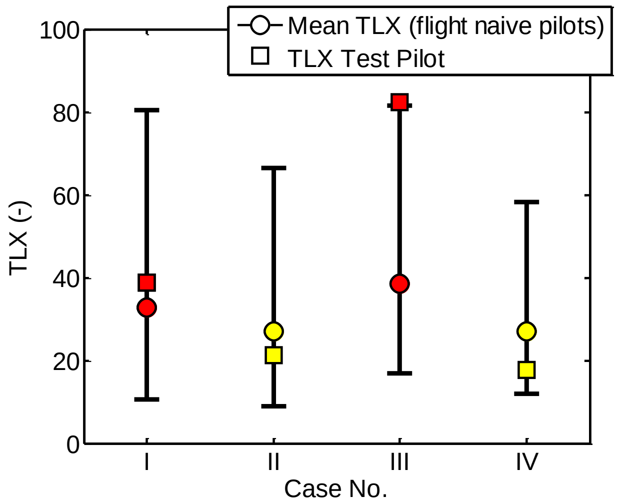


Fig. 77: Comparison between TLX Ratings for the Hover Reposition Task

The results shown in Fig. **77** are of limited use, due to the large spread of results. It is difficult to determine which control method individual pilots preferred. The TLX ratings were normalized in order to observe the difference between each of the vehicle control configurations. Each pilot's TLX ratings were normalized against the rating that they each awarded for Case I, to give a relative difference between Case I and all other configurations. Using this normalization process, a value greater than unity denotes higher workload than the initial Case I TLX rating. Values less than unity denote a lower workload. Fig. **78** shows the normalized TLX ratings from the Hover Reposition manoeuvre.

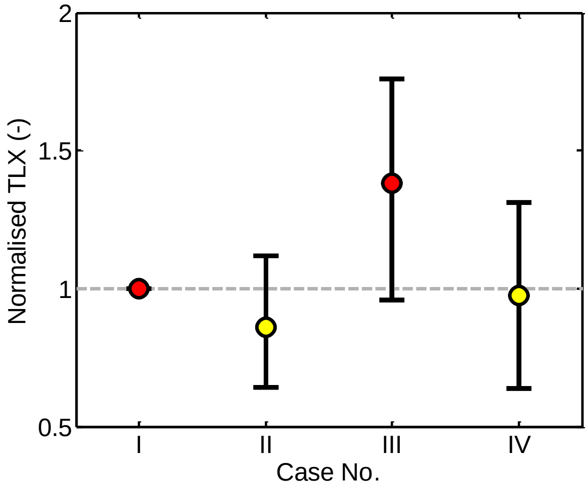


Fig. 78: Comparison between Normalized TLX Ratings

These results show that workload was generally highest for Case III, the Hybrid TV system. Additionally, this configuration resulted in the largest spread of results, indicating a lack of consistency in the way the configuration performed with differing flying styles. This matches the finding of the test pilot (Table 9). Both Car systems (Case II and Case IV) were on average found to require lower workload than the initial Case I, confirming the initial impression from Fig. **77**.

Observing the variation in TPX with respect to run number helps to explore the ability of pilots to learn successful and repeatable control techniques for each configuration. Fig. **79** shows the TPX scores achieved by a pilot with very low experience across their 9 runs in each configuration. Fig. **80** likewise shows the TPX scores of the highest experience pilot in the sample group. As shown, both were able to achieve better performance (higher TPX) with the Automobile configurations than with the Hybrid configurations. Furthermore, the less experienced pilot was able to achieve a consistent level of performance within fewer runs with the Automobile configurations. This effect was less marked with the more experienced pilot, who was able to perform at close to their maximum level from the first run in each configuration

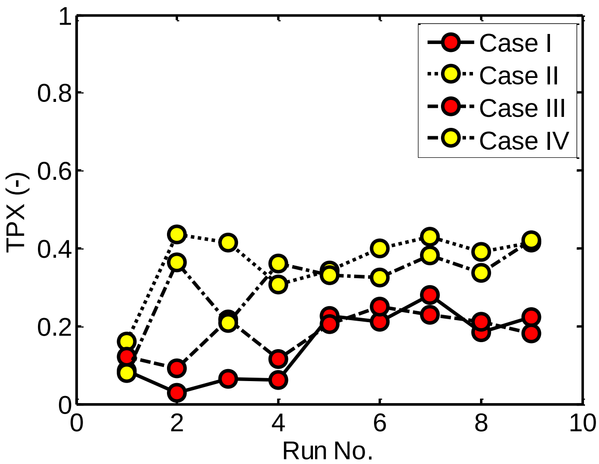


Fig. 79: Variation in TP with respect to Run No. Exp. = 2, Apt. = 10.78

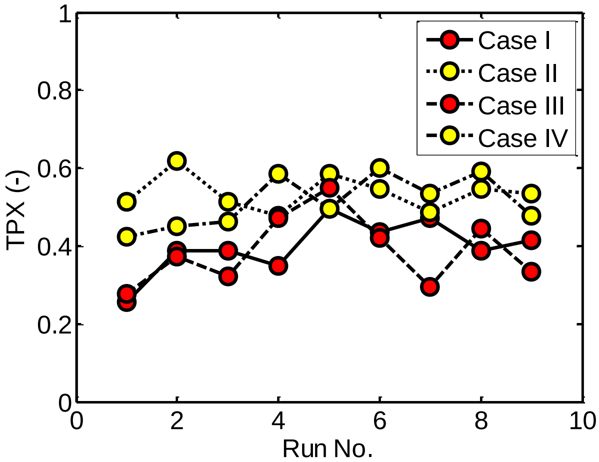


Fig. 80: Variation in TP with respect to Run No. Exp. = 6, Apt. = 11.93

Fig. **81** and Fig. **82** show the spread (shaded regions) and mean (circular markers) TPX scores for Case I and II across all of the non-professional test subject pilots who took part in these tests. One observation is that a relatively consistent spread of TPX scores exists across all runs for Case I (Hybrid), whereas there is a narrowing range with respect to run number for Case II. Not only were higher overall TPX scores achieved with Case II than Case I, but all subjects were able to achieve performance close to that of the best subject by the 5th or 6th run, no matter their aptitude. A larger dependence on aptitude appears to exist for Case I, with a considerable gap remaining between the highest performing and lowest performing subjects, even after all 9 runs.

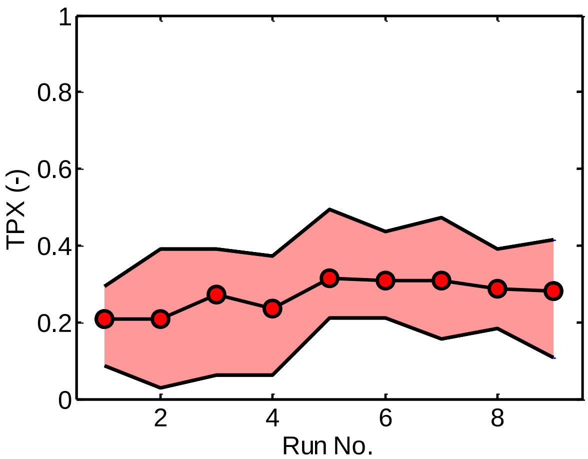


Fig. 81: Spread and Mean of TPX Ratings for all test subjects with respect to Run No. – Case I

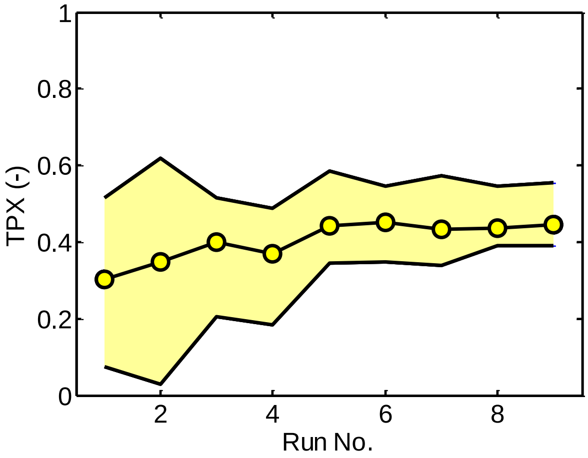


Fig. 82: Spread and Mean of TPX Ratings for all test subjects with respect to Run No. – Case II

Fig. **83** displays how TPX for Case I and Case II varied with pilot experience. This figure shows TPX scores for the final four runs completed by each of the test subjects. The shaded regions show the spread of results obtained for each case, and the markers indicate the average of the four runs.

For Case I, a relationship between TPX awarded and pilot experience was observed. TPX was found to increase with greater experience. Furthermore, the subject with the lowest experience was found to have the highest variation in TPX for the last four cases, although the remaining five subjects showed little variation across these runs. For Case II, the Automobile configuration, TPX appeared to show less, or indeed no direct dependency on pilot experience. An interesting result was that the pilot with least experience achieved very similar performance to the pilot with highest experience level. Both of these TPX scores were higher than had been achieved in Case I, the Hybrid configuration. This suggests that the Automobile configuration provides a system that allows the test subject pilots to more rapidly learn how to complete low speed flying tasks than when using traditional rotorcraft control methods. Additionally, comparing the results of the more experienced subjects, the Automobile configuration also appears to allow a greater absolute level of performance to be attained than does the Hybrid configuration.

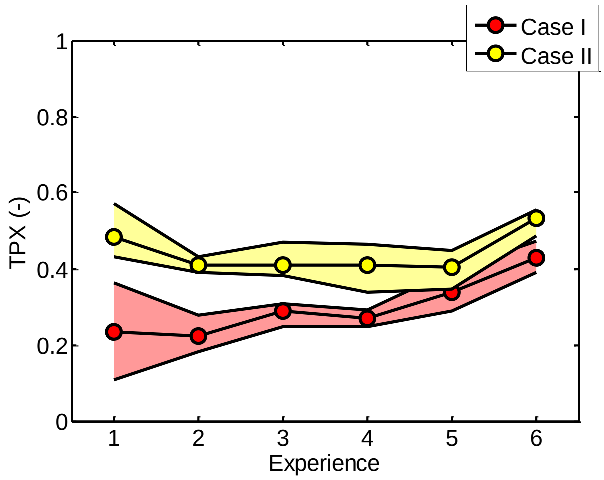


Fig. 83: TPX with respect to pilot experience

6.4.3. Decelerating Approach MTE with non-Professional Pilot Test Subjects

Three subjects completed tests on the Decelerating Approach MTE. All of these pilots had relatively low experience levels (*Exp. = 2-3*). These tests were only performed with the 'standard' variants – insufficient time was available to repeat the tests with the TV variant of each configuration. Each test subject completed 6 runs of the manoeuvre, awarding TLX ratings following the 4th and 6th runs. The ratings are shown in Table 14 and Table 15. As observed with the Hover Reposition results, TLX ratings were found to vary significantly between the pilots. However, unlike with the Hover Reposition, no significant difference was found between results obtained for the Hybrid and Automobile configurations. The characteristics of the Automobile configuration did not appear to be beneficial for this task, and pilots found it difficult to decide whether it was easier or more challenging in comparison to the Hybrid system. The average TLX rating for the two configurations differed by less than 0.1%. Despite the low change in average result, variability for the Automobile control was larger than for the Hybrid control. Two of the pilots awarded higher TLX ratings in the Automobile configuration than they did in the Hybrid configuration. Normalized TLX results, highlighting the increased variation in TLX ratings with the Automobile configuration, are shown in Fig. **84**.

Table 14: TLX Ratings for Decelerating Approach Manoeuvre – Case I

Aptitude	Exp. Code.	1st	2nd	Average
9.27	**3**	47.66	48.99	48.33
10.78	**2**	74.66	79.66	77.16
11.02	**2**	32.66	34.00	33.33
		51.66	54.22	52.94

Table 15: TLX Ratings for Decelerating Approach Manoeuvre – Case II

Aptitude	Exp. Code.	1st	2nd	Average
9.27	**3**	57.33	46.66	51.00
10.78	**2**	54.66	76.99	65.83
11.02	**2**	42.00	39.33	40.67
		51.33	54.33	52.83

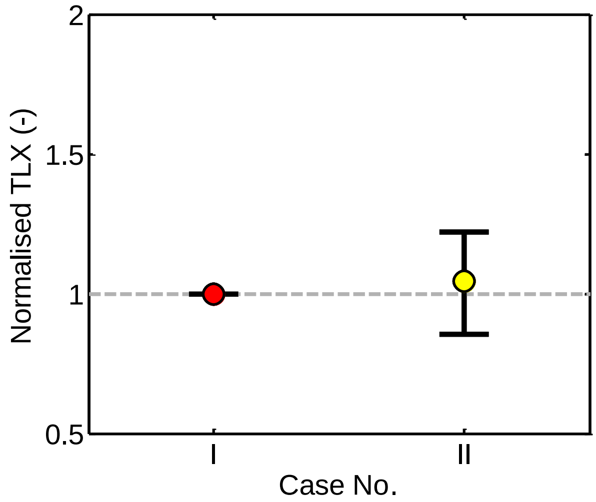


Fig. 84: Comparison between normalized TLX ratings – Decelerating Approach

Unlike for the Hover Reposition task, no significant difference was found in the TPX scores attained with the different configurations. TPX scores are shown in Fig. **85** and Fig. **86** for each individual run.

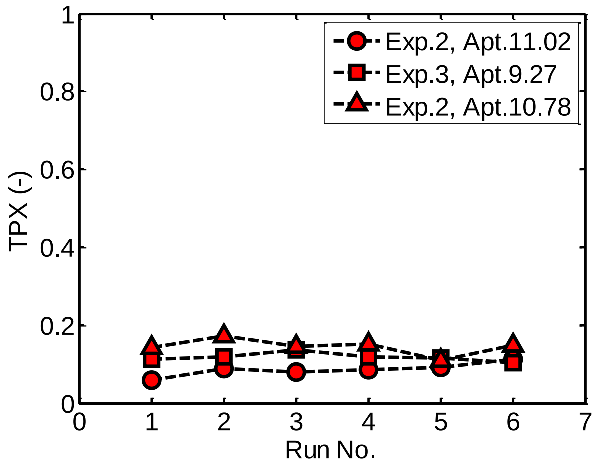


Fig. 85: TPX from Decelerating Approach manoeuver – Case I

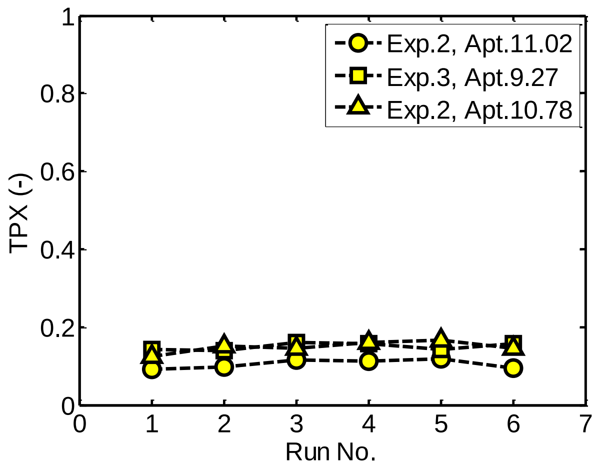


Fig. 86: TPX from Decelerating Approach manoeuver – Case II

In addition to the similar TPX scores for the two configurations, it can be seen that all of the TPX scores achieved in the Decelerating Approach task were lower than those or the Hover Reposition. The Decelerating Approach is a long manoeuvre, during which the pilots are required to continually monitor the progress of the vehicle's deceleration and descent towards the final hover point. As a result, pilots apply minor corrections throughout the task to maintain the desired trajectory. However, the TPX metric is normalized using the minimum required number of inputs (W_{min}). Using both control methods, W_{min} = 6, spread over approximately 180 seconds. This level of workload is significantly lower than that actually recorded during this task. For both configurations, the TPX metric showed minimal improvement in task performance as the pilots repeated the task. Furthermore, no strong links were discernible between performance and either pilot Aptitude or Experience. All pilots were able to perform the task to the desired performance tolerances, and had no clear difficulties with either of the vehicle response types.

Due to the limited size of the sample group for the Decelerating Approach task, it is difficult to provide an overall conclusion regarding the relative suitability of the Hybrid and Automobile configurations here. However, from the limited results obtained it appears that the two systems allow similar levels of performance to be attained and lead to similar levels of subjective workload. Results from the test subjects reflect the comments and ratings of the test pilot. For this task, it appears that the two methods are `different', but neither appears to offer a significant advantage over the other.

7. Conclusions

The main conclusions are given below for each Section, respectively.

In Section 2, this report has briefly described the activities of the *myCopter* research project and the development of a simulation environment to allow the assessment of PAV handling qualities requirements and training needs. The report has also described the development of an aptitude assessment process designed to determine the flying abilities of 'flight-naïve' test subjects, and quantitative metrics for the assessment of performance and workload in mission task elements that these subjects have been asked to fly in simulated flight vehicles with response types configured to behave as though they are equipped with different levels of augmentation.
The main conclusions that can be drawn from this Section are:

- The conventional handling qualities assessment process is not suitable for the analysis of PAV handling requirements. Despite good handling qualities ratings being awarded by a test pilot for all configurations, in many cases flight-naïve test subjects were unable to perform to a comparable level of precision and their corresponding level of workload was higher than desirable.
- A computer based aptitude test battery has been created, and has been shown to be a good predictor of the ability of flight-naïve test subjects to achieve precise vehicle control in various flight tasks.
- There is a strong correlation between increasing aptitude score and perceived reduction in workload, indicating that the TLX rating can be effectively utilized by flight-naive test subjects.
- A TPX metric has been created. A coherent relationship has been shown to exist between the recorded TPX and subjective TLX values, showing that TPX provides a useful method for the objective assessment of workload and task performance of flight-naïve test subjects.

Section 3 has described an assessment of a range of candidate Personal Aerial Vehicle (PAV) configurations, with the aim to identify response type requirements for this new category of vehicle and its (potentially) flight-naïve pilots. Three configurations were assessed, with rate (RC configuration), attitude command, attitude hold (ACAH configuration) and translational rate command (TRC, Hybrid configuration) response types respectively in the pitch and roll axes for hover and low speed flight. The Hybrid configuration additionally offered a change in response type for forward flight – an attitude response in roll and an acceleration command, speed hold response in pitch. The conclusions that can be drawn from the work reported in this report are as follows:

- Only the most able test subjects with the highest aptitude scores can safely fly the RC configuration at the required level of precision; this configuration is therefore unsuitable for PAV use.
- Roughly half of the test subjects could fly the ACAH configuration, limiting the proportion of the pool of potential PAV users who would be able to operate a PAV in this configuration without extensive training.
- A significant majority of the test subjects could fly the Hybrid configuration (TRC in hover); of the assessed configurations, this is most suited to the requirements of a PAV.
- The ACSH response type was found to be equally as suitable for the Decelerating Descent MTE as the ACAH response type. Additional benefits in terms of automatic trim and any airspeed mean that the ACSH response type is preferable for use on a PAV.
- Obscuring task cues to create UCE=2 conditions does not significantly affect performance or workload for ACAH and Hybrid configurations flown by flight-naïve pilots. Performance degrades to a much greater extent with the RC configuration. This finding agrees with the ADS-33E-PRF guidance for military rotorcraft.
- Introducing atmospheric disturbances results in an increase in workload with all three assessed configurations. The increase is smallest with the most heavily augmented Hybrid configuration.
- Tasks demanding very precise station-keeping will require an additional level of vehicle stabilization, such as a position-hold function, for a consistently acceptable level of performance to be achieved in the presence of atmospheric disturbances.
- With the exception of very high precision tasks, the Hybrid configuration – the minimum acceptable level of augmentation in the benign environment – is equally as suitable for operations in a harsh environment. This finding is in contrast to the ADS-33E-PRF guidance that requires improved levels of vehicle augmentation for degradation in the useable cue environment.

Section 4 has described the creation and evaluation of a training syllabus for PAV pilots. The work has assumed that the PAV is to be flown manually, and that it responds according to the best characteristics identified during earlier work in the *myCopter* project. The following conclusions can be drawn from this work:

- A PAV training syllabus should cover the key skills associated with being able to establish and hold airspeed, heading and height in low speed and cruising flight modes. It should also cover the methods required to transition between the two modes.
- The syllabus would also need to cover use of ancillary functions and display symbology.
- A typical training duration of less than five hours was required in a simulation environment to develop the skills necessary for PAV flight in benign environmental conditions.
- Less able students require longer periods of training. One test subject – who typically struggles to learn new manual skills – completed approximately 60% of the training in 4 hours 45 minutes.

- Short periods of effective training can improve performance, even when the 'operator' is controlling a highly intuitive system.

This work described in this Section does not present a complete picture of the training that would be required by a prospective PAV pilot. In particular, further training would be required for handling of emergency situations, and any other aspects of conventional private aviation that would not be eliminated by the incorporation of automatic or autonomous functions within the PAV. This is the subject of the ongoing research in the myCopter project at UoL.

Section 5 has reported upon the work made in the development of a "natural feeling" landing profile from a set of piloted simulation test results. The following conclusions have been drawn from the work presented. First, NASA's computed longitudinal approach profile has been shown to be consistent with the results illustrated in this report, even though it was a different vehicle model and the experience of the test subjects was very different. Second, Tau theory has been applied to both model and then design the landing profile in the vertical axis. The simulation results showed that τ coupling was applicable to the final stages of the approach. The resulting design profile is in good agreement with the visual-landing results. Third, the separate guidance designed individually for the cyclic and collective control channels work effectively even though the landing profiles and the experience of the test subjects are very different. Finally, for the automatic landing situation, the TSs prefer the CD profile. For the manual landing situation, the "natural-feeling" profiles were the most favoured by the TS. The OF profile was the least favoured for both situations.

Section 6 has reported an investigation into the design and use of novel methods for the control of a PAV, based around the recreation of a 'driving' experience in flight. The main conclusions that can be drawn from this work are as follows:

- Both the previously developed Hybrid and novel Automobile configurations can be successfully controlled by the test subject pilots, during both hover and forward flight tasks in benign flight conditions.
- The Automobile configuration, employing pedals for speed control, shows promise as an alternative method of control for future PAVs, compared to tradition rotorcraft control mechanisms. This finding was supported through successful completion of both of the assessed manoeuvres using this novel control method. During the Hover Reposition task, pilots with lower experience were found to achieve greater levels of 'Precision' and lower 'Workload' than for the same conditions using the Hybrid configuration.
- The TPX scores awarded during the completion of the Hover Reposition manoeuvre showed a dependency upon experience for the Hybrid system but no dependency for the Automobile system. Higher TPX scores, indicating better performance, were attained with the Automobile configurations following completion of the task. Together, these results highlight the benefits of the car-like responses.
- Ratings from a professional test pilot and from the group of non-professional pilots indicated that the Hybrid control system without pitch and roll motion was not suitable for flying low speed Hover Reposition tasks. However, very little difference was found between Automobile configurations with and without pitch and roll motion.
- Significant variations in the TLX ratings awarded by the test subjects introduced additional complexity to the analysis process. Normalizing the results against the first rating awarded by each subject allowed a clearer picture to be discerned.

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Appendix 1 - Methods to Assess the Handling Qualities Requirements for Personal Aerial Vehicles – Supplementary Material 1

This Supplementary Material provides further details about the Mission Task Elements used in the study reported in the above-named report.

A. Mission Task Elements

As part of the wider *myCopter* project, a commuting scenario was developed, whereby the PAV flight would begin with a vertical take-off from a rural or suburban region. The PAV would accelerate and climb into a cruise towards its final destination, typically the central business district of a major city. Upon arrival at the destination, the PAV would descend and decelerate to hover at a designated PAV landing point, before executing a vertical landing. From this general commuting scenario, a series of Mission Task Elements (MTEs) appropriate to the PAV role have been identified and a subset of 5 hover and low speed MTEs were selected for use in the investigations reported in this paper. The 5 MTEs used were the Hover, Vertical Reposition, Landing, Decelerating Descent and Aborted Departure. Where possible, the outline of the task has been drawn from ADS-33E-PRF; some of the task performance requirements have, however, been modified (generally relaxed) to reflect the nature of the PAV role.

1. Hover MTE

The hover manoeuvre is initiated from a stabilized hover at a height above ground level of 20ft and the aircraft is accelerated towards the target hover position. The target hover point is oriented at 45° relative to the heading of the aircraft. The ground track is such that the aircraft will arrive over the hover point, and the aircraft should translate at a ground speed between 6 and 10kts. Upon arrival at the hover point, a stable hover should be captured and held for 30 seconds. The transition to hover should be accomplished in one smooth movement; it is not acceptable to accomplish most of the deceleration well before the hover point and then to creep up to the final position. The performance requirements for this task are shown in Table S1, and the test course used in the piloted simulations is shown in Fig. S1.1 – the board and pole together provide the pilot with cueing for desired and adequate vertical and lateral positioning, whilst the cones on the ground around the target hover point indicate the desired and adequate longitudinal position tolerances.

Table S1 Hover MTE Performance Requirements

Parameter	Desired	Adequate
Maintain longitudinal position within ±X ft of the target hover point	3	6
Maintain lateral position within ±X ft of the target hover point	3	6
Maintain heading within ±X°	5	10
Maintain height within ±X ft	2	4

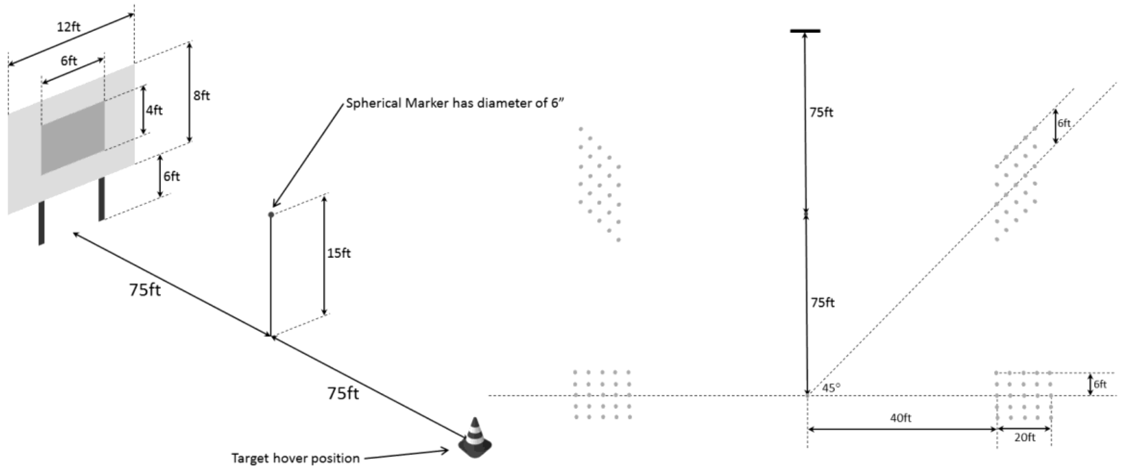

Fig. S1.1 Hover MTE Test Course

2. Vertical Reposition MTE

The vertical reposition manoeuvre starts in a stabilized hover at an altitude of 20ft with the aircraft positioned over a ground-based reference point. A vertical climb is initiated to reposition the aircraft to a hover at a new altitude of 50ft within a specified time. Overshooting the end point is not permitted. The manoeuvre is complete when a stabilized hover is achieved. The performance requirements for the vertical reposition manoeuvre are shown in Table S2, and the test course used in the piloted simulations is shown in Fig. S1.2.

Table S2 Vertical Reposition MTE Performance Requirements

Parameter	Desired	Adequate
Maintain longitudinal position within ±X ft of the target hover point	5	10
Maintain lateral position within ±X ft of the target hover point	5	10
Maintain heading within ±X°	5	10
Capture new height within ±X ft	2	4
Complete the manoeuvre within X seconds	10	15

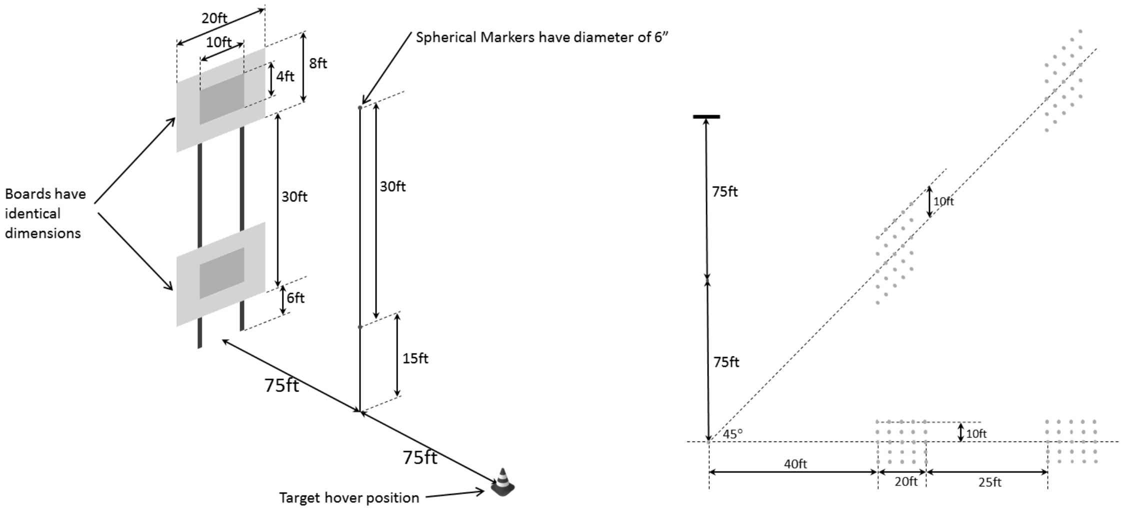

Fig. S1.2 Vertical Reposition MTE Test Course
(note: ground markings are repeated to the left of the hover point)

3. Landing MTE

The landing manoeuvre starts with the vehicle in a stable hover at a height of 20ft, offset laterally and longitudinally from the prescribed landing point. Following a repositioning phase to place the vehicle in a hover directly above the landing point, an essentially steady descent to the landing point is conducted. It is acceptable to arrest sink rate momentarily to make last-minute corrections prior to touchdown. The performance requirements for the landing manoeuvre are shown in Table S3, and the test course used in the piloted simulations is shown in Fig. S1.3.

Table S3 Landing MTE Performance Requirements

Parameter	Desired	Adequate
Accomplish a gentle landing with a smooth continuous descent, with no objectionable oscillations	✓	N/A
Once height is below 10ft, complete the landing within X seconds	10	N/A
Touch down within ±X ft longitudinally of the reference point	1	3
Touch down within ±X ft laterally of the reference point	0.5	3
Attain rotorcraft heading at touchdown that is within ±X° of the reference heading	5	10
Final position shall be the position that existed at touchdown	✓	N/A

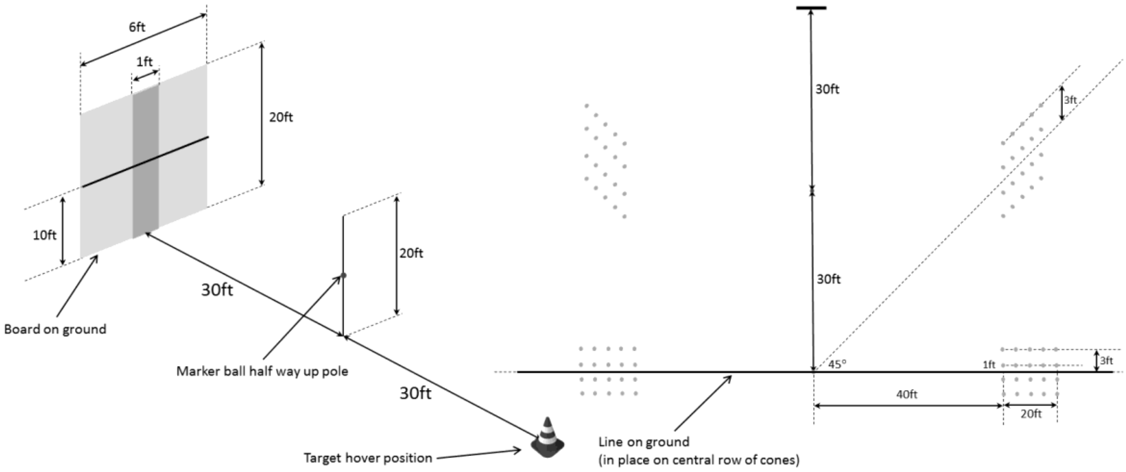

Fig. S1.3 Landing MTE Test Course

4. Decelerating Descent MTE

The decelerating descent manoeuvre begins with the aircraft in a stable cruise at 60kts at a height of 500ft above the ground. Once a specified ground marking has been reached, the pilot initiates a descent and decelerates towards a target hover point and a height of 20ft. The approach is configured to give a mean glideslope angle of 6 degrees. The manoeuvre is complete when the aircraft has been stabilized over the marked manoeuvre end point. Overshooting the approach beyond the front longitudinal adequate tolerance, or the lower vertical adequate tolerance is not permitted. The performance requirements for the decelerating descent manoeuvre are shown in Table S4, and the test course used in the piloted simulations is shown in Fig. S4.

Table S4 Decelerating Descent MTE Performance Requirements

Parameter	Desired	Adequate
Maintain the lateral position within ±X ft	20	50
Maintain heading within ±X°	10	15
Stabilise target height within ±X ft	5	10
Stabilise hover point within ±X ft longitudinally of marked position	10	20

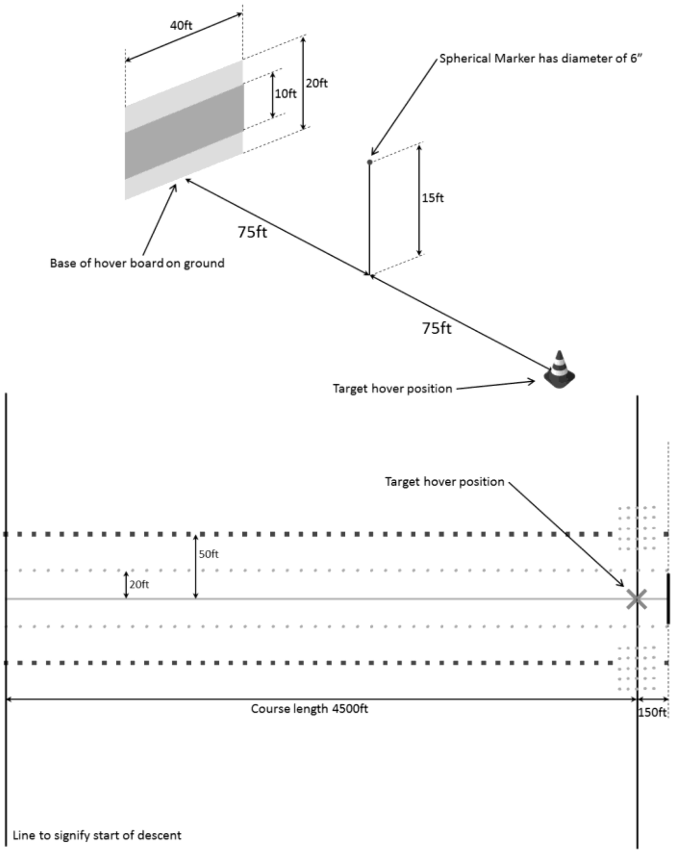

Fig. S1.4 Decelerating Descent MTE Test Course
(note: upper figure shows final 150ft of test course only for clarity)

5. Aborted Departure MTE

The aborted departure begins in a stabilized hover at an altitude of 50ft. A normal departure is initiated by accelerating the aircraft longitudinally along a target trajectory (using a nose down pitch attitude of approximately 15°). When the groundspeed has increased to 40kts, the departure is aborted and the vehicle is decelerated to a hover as rapidly and as practicably as possible. The acceleration and deceleration phases should each be accomplished in single, smooth manoeuvres. The manoeuvre is complete when control motions have subsided to those necessary to maintain a stable hover. The performance requirements for the aborted departure manoeuvre are shown in Table S5, and the test course used in the piloted simulations is shown in Fig. S1.5.

Table S5 Aborted Departure MTE Performance Requirements

Parameter	Desired	Adequate
Maintain the lateral position within ±X ft	10	20
Maintain heading within ±X°	10	15
Maintain height within ±X ft	10	20
Complete the manoeuvre within X seconds	25	30

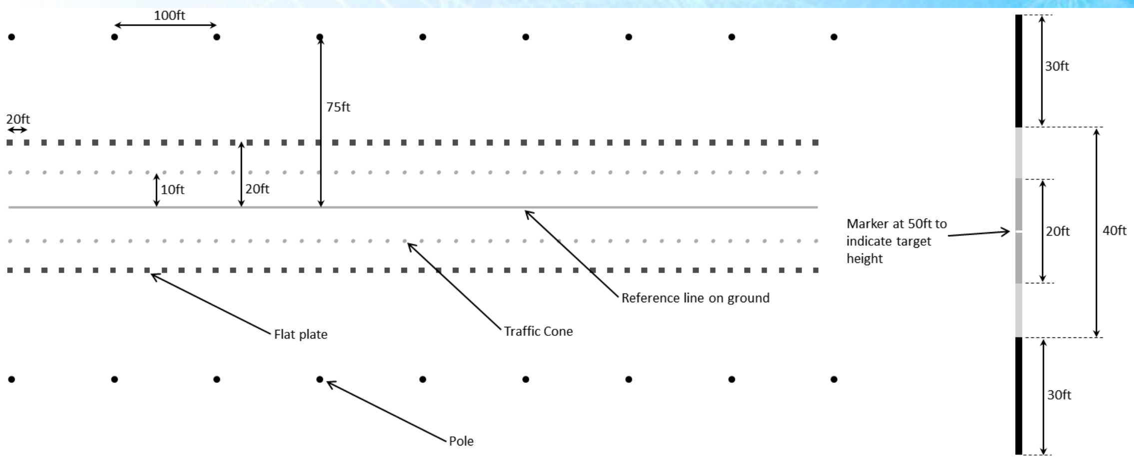

Fig. S1.5 Aborted Departure MTE Test Course

Appendix 2 - Methods to Assess the Handling Qualities Requirements for Personal Aerial Vehicles – Supplementary Material 2

This supplementary material details the settings used for the PAV CETI turbulence model described in the above-named paper. Frequency spectra for the turbulence transfer functions used to simulate disturbances in the harsh environment are shown in Fig. S2.1.

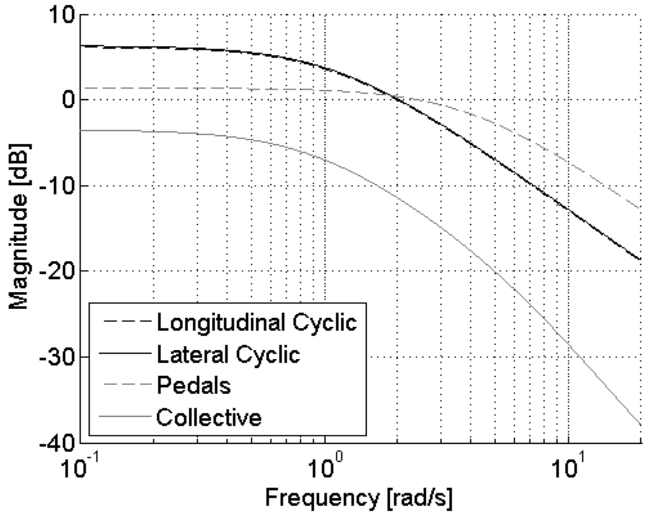

Fig. S2.1 Comparison of CETI Filters for PAV Simulation

When driven by white noise generators, these transfer functions produce control input signals (such as those shown in Fig. S2.2) which command angular rate (or vertical rate in the case of the heave axis) perturbations.

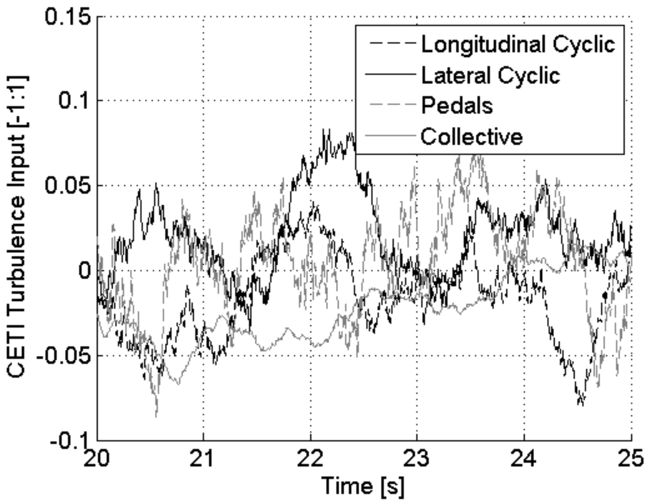

Fig. S2.2 Samples of Typical Turbulence Inputs to PAV Simulation

For longitudinal, lateral and pedal inputs, the structure of the turbulence filter is:

$$\frac{\delta_{gust}}{W_{noise}} = A\frac{1}{\left(s+\frac{U_0}{L}\right)} \quad \text{(S2.1)}$$

For the longitudinal filter, the settings were:

A = 2.29

U0/L = 1.13

For the lateral filter, the settings were:

A = 2.33

U0/L = 1.13

For the pedal filter, the settings were:

A = 4.68

U0/L = 4.00

For collective inputs, the structure of the turbulence filter is:

$$\frac{\delta_{gust}}{W_{noise}} = A\frac{\left(s+20\frac{U_0}{L}\right)}{\left(s+0.63\frac{U_0}{L}\right)\left(s+5\frac{U_0}{L}\right)} \quad 2.2)$$

The settings used were:

A = 0.153

U0/L = 3.85

Appendix 3 - Methods to Assess the Handling Qualities Requirements for Personal Aerial Vehicles – Supplementary Material 3

The following supplementary material provides more detail on the Aptitude tests that were created for the flight-naïve pilot assessment in terms of the nine individual components of the aptitude test battery. The 9 components of the *myCopter* aptitude test were as follows:

1) Two Handed Coordination – the test subject (TS) is required to track a circling target using separate controllers for horizontal and vertical position. This is a test of hand-eye coordination.

2) Complex Coordination – the TS is required to align a crosshair (vertical and horizontal motion) and a 'rudder bar' (horizontal motion only) in the face of continuous disturbances. One hand controls the crosshair, the other controls the rudder bar. As with the two handed coordination task, this is a test of hand-eye coordination.

3) Card Rotations – the TS is presented with a series of reference images together with derivations of that reference image. The subject must identify which of the derivations have just been rotated relative to the reference image, and which have been mirrored in addition to being rotated. This is a test of visual pattern recognition.

4) Dot Estimation – the TS is shown pairs of windows containing randomly dispersed dots. The subject must determine as rapidly as possible which of the pair of windows contains the greater number of dots. The dot estimation task is a test of a participant's decisiveness.

5) Identical Pictures – the TS is shown a series of reference images together with a group of candidate images. The subject must identify which one of the candidate images is identical to the reference image. This test examines a participant's visual pattern recognition and speed of mental processing capabilities – there are ninety six questions to be answered in three minutes.

6) Line Orientation – the TS is shown pairs of lines radiating from a central point. Using a reference array of lines, the subject must identify which of the reference lines correspond to the pair of lines. The line orientation task again examines pattern recognition abilities.

7) Locations – the TS is shown four lines each with a pattern of dashes and spaces. There is a single cross on each line. The subject must identify the pattern connecting the location of the cross on each of the lines, and apply that pattern to a fifth line to determine the location in which the cross would be found. This task examines a participant's problem solving ability.

Picture-Number Test – the TS is shown a set of pictures, and must memorize the numbers associated with each picture. The positions of the pictures on the screen are then shuffled, and the subject must recall the numbers that correspond to each picture. The picture-number test is a measure of a participant's memory capacity.

Shortest Roads – the TS is shown a series of images of three routes connecting two points on the screen. For each image, the subject must identify which of the three routes represents the shortest distance between the two points. The shortest roads test is a measure of a participant's spatial reasoning capabilities.

Each of these is now described in more detail.

A. Two-Handed Coordination

The two-handed coordination test, illustrated in Fig. S3.1, requires the TS to align the crosshair with the target (the aircraft symbol), using a pair of controllers – one determines the vertical position of the crosshair, the other the lateral position. The test subject is given an unscored practice period of 3 minutes, following which the assessment takes place over a period of 5 minutes.

Scoring for the two-handed coordination test is based on the proximity of the crosshair to the target. A proximity score at each time step is calculated as follows:

1) The distance (measured in number of pixels on the screen) between the crosshair and the target is computed
2) This distance is normalized using the vertical screen resolution (in pixels)
3) The score is computed as *proximity_score = 1 – normalized_distance*

The overall score for the task is computed as the numerical mean of the individual scores at each time step.

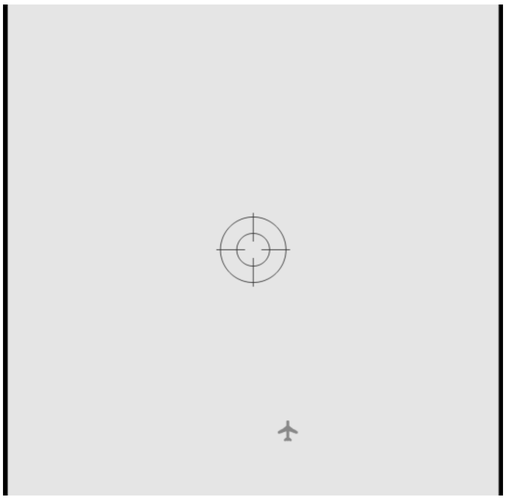

Fig. S3.1 Two-Handed Coordination Test

B. Complex Coordination

The complex coordination test, illustrated in Fig. S3.2, requires the TS to align a crosshair and a rudder bar with a pair of reference markers. A pair of controllers is used – one determines the position of the crosshair (both vertical and lateral), the other the lateral position of the rudder bar. The crosshair and rudder bar are disturbed from their reference positions by pseudo-random signals created as a sums of sine waves. The test subject is given an unscored practice period of 3 minutes, following which the assessment takes place over a period of 5 minutes.

Scoring for the complex coordination test is based on the proximity of the crosshair and rudder bar to their targets. A proximity score at each time step is calculated as follows:

1) The separation (in pixels) between each controlled parameter (i.e. crosshair vertical; crosshair horizontal and rudder bar horizontal) and the reference position is calculated
2) The root-mean-square of the three separations is calculated, giving an 'average' position error
3) This error is normalized using the vertical screen resolution (in pixels)
4) The score is computed as *proximity_score = 1 – normalized_error*

The overall score for the task is computed as the numerical mean of the individual scores at each time step.

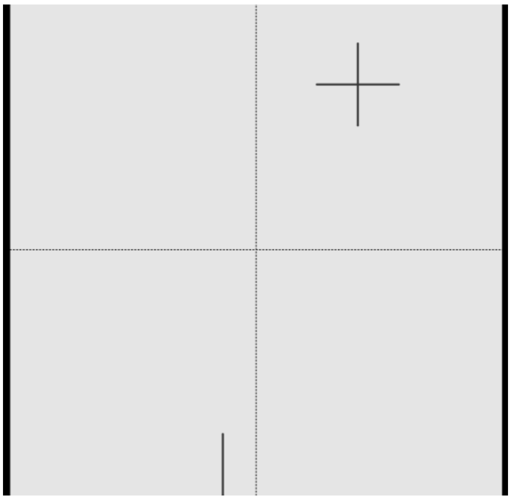

Fig. S3.2 Complex Coordination Test

C. Card Rotations

The card rotations test, illustrated in Fig. S3.3, presents the test subject with one reference shape and eight candidate shapes. The candidate shapes are rotated and/or mirrored relative to the reference shape. The test subject is required to identify all of the candidate shapes that are only rotated (i.e. are not mirrored). A total of 28 questions are attempted, and the test subject has 8 minutes to complete the test (a one minute break is provided after 14 questions). One point is gained for finding all of the correct answers to a question, while one point is lost for failing to find all of the correct answers.

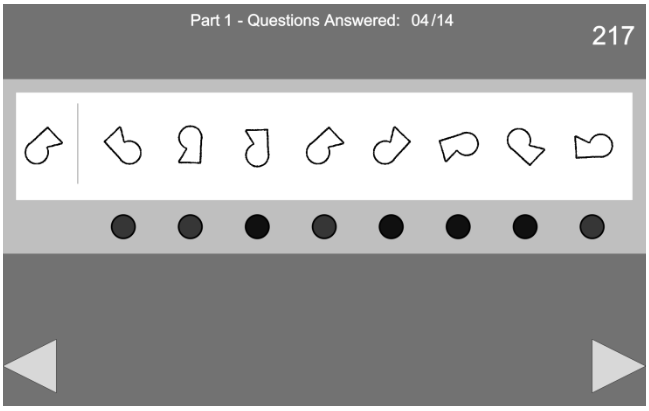

Fig. S2.3 Card Rotations Test

D. Dot Estimation

The dot estimation task, illustrated in Fig. S3.4, requires the test subject to make a judgement regarding which of a pair of boxes contains a greater number of 'dots'. As the test progresses (with 55 pairs of boxes to assess in total), greater numbers of dots populate each of the boxes. For each pair, one of the boxes contains one additional dot compared to the other box. At the start, one box contains 10 dots and the other 11. By the end of the test, each box will contain either 50 or 51 dots.

The score for the dot estimation task considers both the accuracy of the judgements made and also the time taken to make the judgements. The total number of correct answers is summed, and this is divided by the average time required by the test subject to decide on their answer for each pair of boxes. Hence, slow decision-making (such as counting all fifty dots in each box at the end of the test) is penalized.

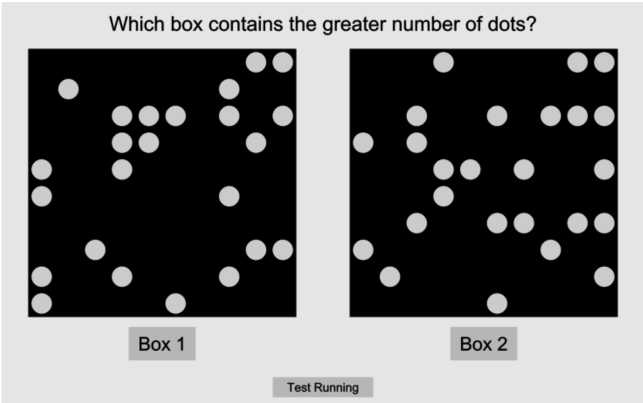

Fig. S3.4 Dot Estimation Test

E. Identical Pictures

The identical pictures test, illustrated in Fig. S3.5, requires the test subject to determine which of five candidate shapes is identical to a reference shape. The correct shape is not rotated or mirrored. The test consists of 96 questions, and the test subject has three minutes to answer them all. A thirty second break is provided after the first 48 questions.

For each correct answer, a test subject's score is increased by one point. An incorrect answer results in a penalty of 0.5 points.

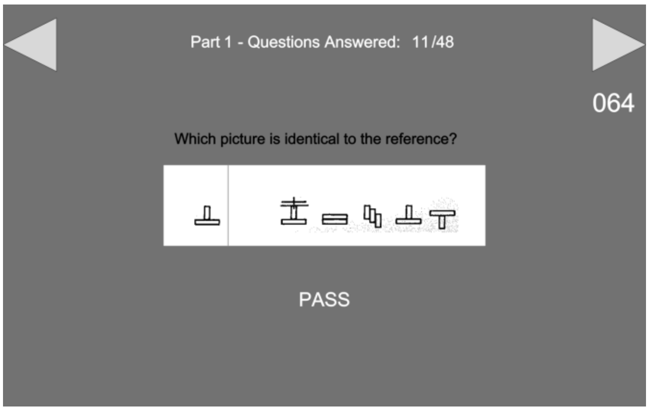

Fig. S3.5 Identical Pictures Test

F. Line Orientation

The line orientation test, illustrated in Fig. S3.6, requires a test subject to match the orientations of two candidate lines with a grid of reference lines. The test consists of thirty questions, and the test subject has two minutes to complete the test. For each correct answer (i.e. both candidate lines correctly matched), one point is scored. An incorrect answer results in a penalty of 0.5 points.

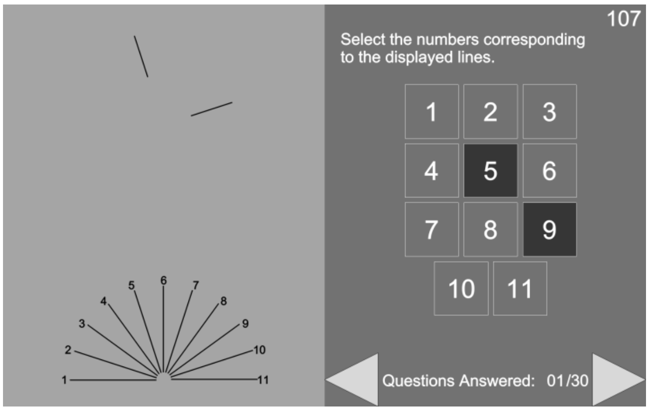

Fig. S3.6 Line Orientation Test

G. Locations

The locations test, illustrated in Fig. S3.7, presents the test subject with four patterns, consisting of dashes and spaces. In each pattern, one X is placed instead of a dash according to a certain rule. The test subject must identify the rule and then apply it to a fifth pattern in order to determine which of five potential positions is correct for the X. The test consists of 28 questions, and the test subject has 12 minutes to complete the test (with a one minute break after the first 14 questions). One point is scored for each correct answer in this test, with a 0.5 point penalty applied for an incorrect guess.

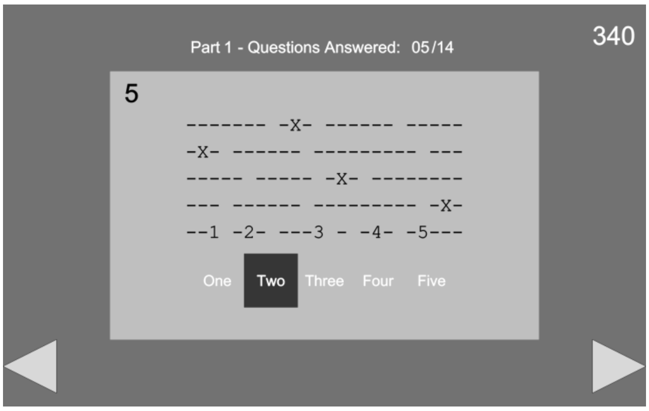

Fig. S3.7 Locations Test

H. Picture-Number Test

The picture-number test, illustrated in Fig. S3.8, assesses a test subject's memory. A screen of drawings of everyday objects is presented to the test subject; each drawing has a number associated with it. This screen is displayed for four minutes, during which time the test subject attempts to memorize as many of the combinations of object and number as possible. At this point, the numbers are removed and the order of the pictures rearranged. The test subject then has three minutes to enter the numbers that correspond to each object. For each correctly memorized and recalled combination of object and number, one point is scored. This test does not penalize incorrect guesses.

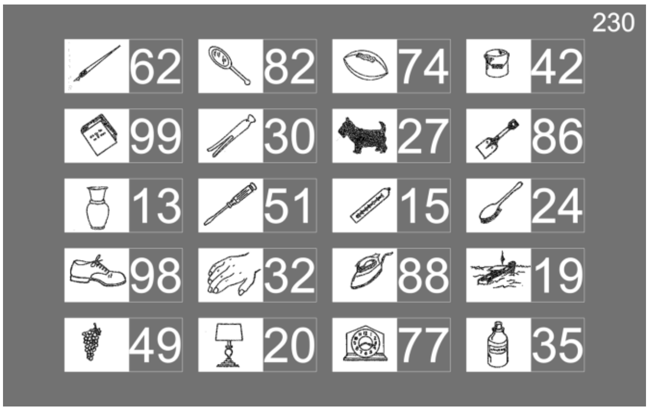

Fig. S3.8 Picture-Number Test

I. Shortest Roads

In the shortest roads test, illustrated in Fig. S3.9, three routes between a 'start' point and an 'end' point are shown. The test subject is required to identify which of the three routes represents the shortest distance between the two points. This test consists of 56 questions, and the test subject has four minutes to answer all of the questions. A one minute break is provided after the first 28 questions. One point is scored for each correct answer in this test. An incorrect answer is penalized by a 0.5 point deduction.

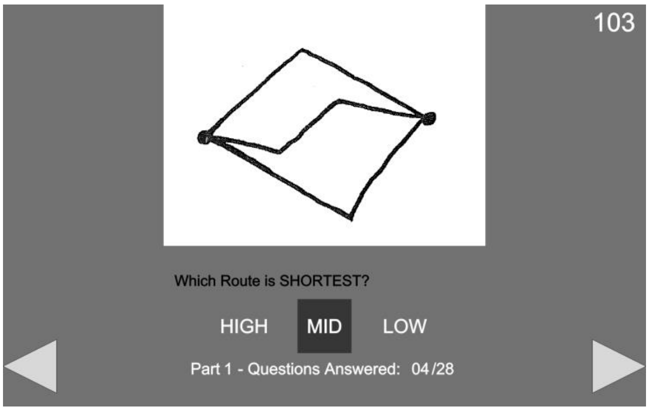

Fig. S3.9 Shortest Roads Test

J. Determination of Overall Aptitude Score

The first stage in the determination of the overall aptitude score is normalization of the scores for each of the individual tests. This is performed by dividing the test score by the theoretical best score for each test. Following this step, all nine test scores are measured as a fraction, with 1 being the best score. The scores for the two-handed coordination and complex coordination tests are weighted by multiplying by 4. The final aptitude score is then found as a sum of the weighted, normalized scores for each individual test. The maximum achievable score in the overall test is 15 points.

Appendix 4

A. Training Exercises

This appendix lists each of the skills identified earlier in the report. For each skill, the exercises used to develop that skill are listed.

1) Use of longitudinal inputs in hover to control forward speed (TRC response type)
   a. Use longitudinal stick input to set a desired forward speed
   b. Accelerate/decelerate from one forward speed to another forward speed
   c. Decelerate to hover
   d. Control deceleration to hover at a specific point above the ground
2) Use of lateral inputs in hover to control lateral speed (TRC response type)
   a. Use lateral stick input to set a desired forward speed
   b. Accelerate/decelerate from one lateral speed to another lateral speed
   c. Decelerate to hover
   d. Control deceleration to hover at a specific point above the ground
3) Combined use of longitudinal and lateral inputs to control horizontal flight path angle
   a. Use of simultaneous longitudinal and lateral stick inputs to generate 45° trajectory
   b. Use of longitudinal and lateral stick inputs to modify trajectory
   c. Slalom using lateral stick inputs
   d. Decelerate to hover
   e. Control deceleration to hover at a specific point above the ground
4) Use of pedals in hover to control heading and yaw rate (Rate Command (RC) response type)
   a. Use of pedal input to set desired yaw rate
   b. Use of pedals to modify yaw rate
   c. Decelerate yaw to stop at specific heading
   d. Slalom using pedal inputs
5) Use of the collective lever in hover to control height and vertical rate (Vertical Rate Command (VRC) response type)
   a. Use of collective input to set desired vertical rate
   b. Use of collective input to modify vertical rate
   c. Decelerate to stop at specific height
6) Combined use of pedals and lateral inputs at low speed (<25kts) to improve turn coordination
   a. Demonstration exercise of effect of flight path lead/lag when using either pedals or lateral stick individually
7) Use of longitudinal inputs in forward flight to control speed (Acceleration Command, Speed Hold (ACSH) response type)
   a. Use of longitudinal stick input to set acceleration/deceleration rate
   b. Capture of new forward speed
8) Use of lateral inputs in forward flight to control heading (Attitude Command, Attitude Hold (ACAH) response type)
   a. Use of lateral stick input to set bank angle
   b. Changing from one bank angle to another
   c. Capture of a new heading
   d. Capture of defined track over ground (e.g. along runway centreline)

e. Effect of speed on turning dynamics

9) Use of the collective lever in forward flight to control vertical flight path angle (flight path angle command (⍰C) response type)

a. Use of collective lever to set climb or descent angle
b. Capture of new height
c. Effect of speed on climbing dynamics

10) Function of the pedals in forward flight (sideslip angle command (⍰C) response type)

a. Demonstration of sideslip angle response type

11) Combined use of lateral inputs and collective in forward flight to perform climbing and descending turns

a. Commencing lateral and collective inputs simultaneously
b. Turning to new heading while climbing or descending to new height
c. Capture of defined ground track while climbing or descending to new height
d. Pacing turn and climb/descent to complete both simultaneously

12) Combined use of lateral and longitudinal inputs in forward flight to perform accelerative and decelerative turns

a. Commencing lateral and longitudinal inputs simultaneously
b. Turning to new heading while accelerating or decelerating to new speed
c. Capture of defined ground track while accelerating or decelerating to new speed
d. Pacing turn and acceleration/deceleration to complete both simultaneously

13) Combined use of longitudinal inputs and collective in forward flight to perform accelerative and decelerative climbs and descents

a. Commencing longitudinal and collective inputs simultaneously
b. Accelerating/decelerating to new speed while climbing/descending to new height
c. Pacing acceleration/deceleration and climb/descent to complete both simultaneously

14) Combined use of longitudinal and lateral inputs and collective in forward flight to perform accelerative or decelerative climbing or descending turns

a. Commencing inputs on all three controls simultaneously
b. Turning, climbing/descending and accelerating/decelerating to new heading, height and speed
c. Capture of defined ground track while climbing/descending and accelerating/decelerating
d. Pacing manoeuvres to complete all three simultaneously

15) Longitudinal transition from TRC to ACSH

a. Discuss theory of mode change
b. Accelerate from hover to forward flight – slowly
c. Accelerate from hover to forward flight - rapidly

16) Lateral transition from TRC to ACAH

a. Discuss theory of mode change
b. Demonstration of why lateral inputs during transition should be avoided where possible

17) Collective transition from VRC to ⍰C

a. Discuss theory of mode change
b. Use collective control to perform height change while accelerating from hover to forward flight

18) Pedals transition from RC to ⍰C

a. Discuss theory of mode change
b. Demonstration of why pedal inputs during transition should be avoided where possible

19) Longitudinal transition from ACSH to TRC
   a. Discuss theory of mode change
   b. Decelerate from forward flight to hover
20) Lateral transition from ACAH to TRC
   a. Discuss theory of mode change
   b. Demonstration of why lateral inputs during transition should be avoided where possible
21) Collective transition from ⍰C to VRC
   a. Discuss theory of mode change
   b. Use collective control to perform height change while decelerating from forward flight to hover
   c. Use collective control to track ground object while decelerating from forward flight to hover
22) Pedals transition from ⍰C to RC
   a. Discuss theory of mode change
   b. Demonstration of why pedal inputs during transition should be avoided where possible
23) Use of secondary ‘automation’ functions (such as height hold, direction hold etc.)
   a. Use of height hold function – when to use, how to engage
   b. Use of direction hold function – when to use, how to engage
   c. Use of speed beep function – when to use, how to operate
24) Use of instrumentation
   a. General use of head down and head up symbology
   b. Use of HUD flight path marker
   c. Use of HUD deceleration rate indicator
   d. Use of HUD highway-in-the-sky display

B. Progress Record Sheets

PAV Student Record

Name:

Session	Start	Finish	Duration	Topics Covered	Progress	Areas for Development
1						
2						
3						
4						
5						
6						
7						
8						

Figure B1: Training Session Record

PAV Student Record

Name:

		Topic Introduced	Skill Developing	Acceptable	Good	Excellent	Notes
Hovering Flight	Longitudinal Velocity Control						
	Longitudinal Hover Capture						
	Lateral Velocity Control						
	Lateral Hover Capture						
	Combined Longitudinal and Lateral Control						
	Pedal Control						
	Collective Control						
	Landing						
	Combined Pedal and Lateral Control						

		Topic Introduced	Skill Developing	Acceptable	Good	Excellent	Notes
Cruise Flight	Longitudinal Velocity Control						
	Lateral Control						
	Collective Control						
	Use of Pedals						
	Combined Lateral and Collective Control						
	Combined Lateral and Longitudinal Control						
	Combined Longitudinal and Collective Control						
	Combined Longitudinal, Lateral and Collective Control						

		Topic Introduced	Skill Developing	Acceptable	Good	Excellent	Notes
Transition	Longitudinal Acceleration Transition						
	Longitudinal Deceleration Transition						
	Collective Acceleration Transition						
	Collective Deceleration Transition						
	Transition of lateral and pedal control						

		Topic Introduced	Skill Developing	Acceptable	Good	Excellent	Notes
Advanced	Use of Height Hold						
	Use of Heading Hold						
	Use of Hat						
	Use of Flight Path Indicator						
	Use of Deceleration Rate Indicator						
	Use of Highway in the Sky						

		Topic Introduced	Skill Developing	Acceptable	Good	Excellent	Notes
Manoeuvres	Hover						
	Vertical Reposition						
	Landing						
	Decelerating Descent						
	Aborted Departure						

Commute Scenario						

Figure B2: Training Progress Record

Appendix 5

A. Comfort Rating Scale for Automatic Landing

The highlighted terms in green have a positive meaning for the higher scores. For the other items, a high score has a negative connotation.

1	I felt general discomfort during the manoeuvre. 0__________100 Strongly Disagree Strongly Agree
2	The movement in the procedure was uncomfortable 0__________100 Strongly Disagree Strongly Agree
3	The sense of moving around outside cockpit was compelling. 0__________100 Strongly Disagree Strongly Agree
4	The movement in the virtual environment seemed unnatural. 0__________100 Strongly Disagree Strongly Agree
5	The manoeuvre negatively impacted my ability to concentrate. 0__________100 Strongly Disagree Strongly Agree

B. Comfort Rating Scale for Manual Landing

The highlighted terms in green have the positive meaning.

1	I felt general discomfort during the manoeuvre. 0__________100 Strongly Disagree Strongly Agree
2	I felt I was in the control of the events. 0__________100 Strongly Disagree Strongly Agree
3	The movement in the procedure was uncomfortable 0__________100 Strongly Disagree Strongly Agree
4	The sense of moving around outside cockpit was compelling. 0__________100 Strongly Disagree Strongly Agree
5	I experienced annoyance with the task. 0__________100 Strongly Disagree Strongly Agree
6	The movement in the virtual environment seemed unnatural. 0__________100 Strongly Disagree Strongly Agree
7	I felt involved in the virtual reality environment. 0__________100 Strongly Disagree Strongly Agree
8	The manoeuvre negatively impacted my ability to concentrate. 0__________100 Strongly Disagree Strongly Agree
9	The interation with the environment seems natural. 0__________100 Strongly Disagree Strongly Agree