Investigation of Personal Aerial Vehicle Handling Qualities Requirements for Harsh Environmental Conditions

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ABSTRACT

This paper describes the continuing research at the University of Liverpool in the *myCopter* project to develop handling qualities guidelines and criteria for a new category of aircraft – the personal aerial vehicle (PAV), which, it is envisaged, should demand no more skill to fly than that associated with driving a car today. Previously published research showed that a translational rate command (TRC) response type allowed a majority of 'flight-naïve' pilots to operate within desired performance limits in a series of hover and low speed tasks in good environmental conditions. This paper extends the research by exploring the impact of degrading the usable cue environment and introducing atmospheric disturbances on performance in these tasks. Results from simulation trials involving test subjects with little or no flight experience are reported, showing that, in general, task performance can be maintained with the TRC response type, although workload increases. The paper concludes that the TRC response type remains suitable for use by 'flight-naïve' pilots in PAVs, even in degraded environmental conditions.

NOTATION

βC	Sideslip Angle Command
δ_{lat}	Lateral stick input [-1:1]
δ_{lon}	Longitudinal stick input [-1:1]
γC	Flight Path Angle Command
A	Aptitude Test Score
ACAH	Attitude Command, Attitude Hold
ACSH	Acceleration Command, Speed Hold
AFCS	Automatic Flight Control System
CETI	Control Equivalent Turbulence Input
DH	Direction Hold
DVE	Degraded Visual Environment
EC	European Commission
FP7	7th Framework Programme
GA	General Aviation
GPDM	Generic PAV Dynamics Model
HH	Height Hold
HMI	Human-Machine Interaction
HQs	Handling Qualities
HQR	Handling Qualities Rating
HUD	Head-Up Display
MTE	Mission Task Element
P	Precision Metric
PATS	Personal Aerial Transportation System
PAV	Personal Aerial Vehicle
PFD	Primary Flight Display
PPL(A)	Private Pilot's License (Aeroplanes)
PPL(H)	Private Pilot's License (Helicopter)
PSD	Power Spectral Density
RC	Rate Command
RCAH	Rate Command, Attitude Hold
TLX	Task Load Index
TPX	Task Performance Index
TP	Test Pilot
TRC	Translational Rate Command
TS	Test Subject
UCE	Usable Cue Environment
UoL	University of Liverpool
VCR	Visual Cue Rating
VTOL	Vertical Take-Off and Landing
W	Workload metric
W_{min}	Theoretical minimum workload for an MTE

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INTRODUCTION

This paper reports on the research being undertaken in the European Union Framework Programme 7-funded project *myCopter – Enabling Technologies for Personal Aerial Transportation Systems* (Ref. 1). The *myCopter* project's aim is to contribute to the development of technologies that would ultimately permit the Personal Aerial Vehicle (PAV) to be realised, and for its mass adoption to be possible. The research activities of the myCopter project can be categorised into three main themes:

1) Human-Machine Interaction (HMI), including cockpit technologies for inceptors and displays, and vehicle handling characteristics;
2) Autonomous flight capabilities, including vision-based localisation and landing point detection, swarming and collision detection and avoidance;
3) Socio-economic aspects of a Personal Aerial Transportation System (PATS) – the requirements for such a system to become accepted and widely adopted by the general public.

Two approaches to the operation of PAVs are being considered. The first approach would be for the human occupant to simply act as a passenger, with the PAV operation being fully automated or even autonomous. The second, contrasting approach would be for the human occupant to be able to manually control some, or all of the piloting functions of the vehicle. For mass adoption of PAVs to be feasible however, it is anticipated that the costs associated with becoming sufficiently qualified to operate a PAV in this mode would have to be significantly lower than those currently associated with general aviation (either fixed- or rotary-wing). Therefore, the manually-operated PAV would still need to feature a significant level of automatic control, with the 'pilot' providing steering commands to the Automatic Flight Control System (AFCS), rather than being required to perform all of the stabilisation functions as well. The question of which response types should be presented to the PAV pilot by the AFCS is the topic of research being undertaken by the University of Liverpool (UoL) within the first of the *myCopter* project themes identified above.

Previously reported research has described the assessment of a range of 'conventional' response types applied to a generic PAV simulation (Refs. 2-4). Models were differentiated by their response type in the pitch and roll axes – the yaw and heave responses of all of the models were identical. Rate Command (RC), Attitude Command, Attitude Hold (ACAH) and Translational Rate Command (TRC) response types were evaluated for their suitability for PAV hover and low speed Mission Task Elements (MTEs). The evaluations were conducted by a group of 'flight-naïve' Test Subjects (TSs) – subjects with little or no flight experience and training – with a range of aptitudes for flight tasks (Ref. 4). The results of these tests showed that only the highest aptitude flight-naïve pilots were able to successfully fly the RC-configured model, whilst the half of the TSs with the highest aptitude scores could successfully fly the ACAH-configured model. In contrast to these results, all but the very lowest aptitude test subject was able to successfully fly the TRC-configured model and complete the MTEs to the desired standard (Ref. 4).

The tests described in the above paragraph were all completed in 'ideal' i.e. benign environmental conditions, with 'infinite' visibility and no atmospheric disturbances. In the real world, of course, conditions are usually somewhat more difficult. For example, the three main airports in the North West of England, at Liverpool, Manchester and Blackpool, have recorded an average of 21.7 days with fog (visibility less than 1000m) per year over the period 1993-2013 (Ref. 5). 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. 5). If a PAV was unable to operate in these conditions (or in other degraded visibility conditions such as rain, sleet or snow), it would be a significant impediment to the utility of the vehicle for one of its anticipated primary roles: commuting to and from a place of work. The purpose of this paper is, therefore, to explore the impact on the conclusions reached in the previously cited research of reducing the Usable Cue Environment (UCE) and introducing atmospheric disturbances.

The US military performance specification for the Handling Qualities (HQs) of helicopters, ADS-33E-PRF (Ref. 6) defines minimum acceptable response types for various stages of degradation in the 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 stabilised 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 a PAV, however, the previous research (Ref. 4) has shown that the TRC response type is the minimum that is acceptable for the majority of the flight-naïve TSs, even in UCE=1 conditions. Given that ADS-33E-PRF requires an increased level of augmentation for each stage of degradation in the UCE to maintain an equivalent level of workload, the question for this paper is whether this trend also holds true for the flight-naïve PAV pilot.

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. 7). 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.

The paper will begin with a description of the methods used to simulate the PAV, and the degraded UCE and atmospheric disturbances. The methodology used to analyse results from the flight-naïve TSs will also be described. A selection of results from the piloted simulation trials will be shown to highlight the key outcomes of these investigations.

GENERIC PAV SIMULATION

To facilitate the myCopter research, a generic Vertical Take-Off and Landing (VTOL) vehicle was simulated using Matlab/Simulink and was designed to be rapidly reconfigurable (Ref. 3). Vehicle responses to cockpit control inputs are modelled using either 1st order or 2nd order transfer functions. The model features two fundamental response types – a rate response, which uses a 1st order transfer function to represent the angular/vertical rate response to a control input, and an attitude response, which uses a 2nd order transfer function to represent the attitude response to a control input. The four control axes of the model (pitch, roll, yaw and heave) are, at the basic level, uncoupled. Various augmentations can be inserted into the model to modify the responses. For example, a turn coordination system can be activated, which couples the yaw and pitch responses into the roll response. An outer velocity feedback loop can be placed around the attitude response to create a translational velocity response type.

These basic model principles have been used to create a number of different 'configurations'. Three of those configurations have been used in the research reported in this paper.

Configuration 1: 'Rate Command'

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. Additionally, 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 completely omitted from the model, on the basis that its presence would complicate the analysis of individual response types and would be likely to compromise the ability of flight-naïve pilots to complete the specified tasks. The dynamics of this configuration have been tuned to offer predicted Level 1 HQs for the 'All Other MTEs' category of tasks according to the US Army rotorcraft handling qualities specification, ADS-33E-PRF (Ref. 6). 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.

Configuration 2: 'Attitude Command, Attitude Hold'

The second configuration may be considered as being approximately similar to a modern, augmented helicopter. It is generally the same as the first configuration described above. 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 specified to offer predicted Level 1 HQs according to ADS-33E-PRF (Ref. 3).

Configuration 3: 'Hybrid'

The 'hybrid' configuration has been designed so that the response type offered to the pilot in each axis changes with flight condition, allowing the dynamics to be more closely matched to the demands of the task than is the case with configurations 1 and 2. For the tests described in this paper, there are sets of response types for hover and low speed manoeuvring (at speeds up to 15kts), and for forward flight manoeuvring (at speeds above 25kts). 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.

In the hover and low speed segment of the flight envelope, the response type for the pitch and roll axes is Translational Rate Command (TRC). Yaw and heave are RC as with configurations 1 and 2. In forward flight, yaw behaves in the same way as with configurations 1 and 2, but in the heave axis the response type changes to γC. In roll, the response type changes to ACAH. In pitch, 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 stop. At this point, the response type is switched back to TRC, ready for the next pilot input.

In addition, the hybrid configuration is equipped with pilot selectable Height Hold (HH) and Direction Hold (DH) functions.

The philosophy behind the selection of response types for the hybrid configuration has been, where possible, to minimise the number of control inputs required to perform a manoeuvre. This extends both to control of a single axis, and also to eliminating the need to apply inputs in secondary axes for a single axis task (e.g. lateral control activity during acceleration).

The dynamics of the hybrid configuration have also, where possible, been specified to offer predicted Level 1 HQs for 'All Other MTEs' according to the specifications in ADS-33E-PRF. 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 on the basis of feedback from test pilots and flight-naïve TSs who have flown the hybrid configuration during its development (Ref. 8). Validation of the suitability of the dynamics of these response types is taking place as part of the *myCopter* project.

Mission Task Elements

Four Mission Task Elements (MTEs) were used to investigate the effect of the harsh environment. These MTEs generally assessed hover and low speed handling characteristics, although one of the MTEs also assessed moderate forward flight speeds (and hence, transition between the low speed and forward flight modes of the Hybrid configuration). The MTEs, derived from those contained in ADS-33E-PRF (Ref. 6) but with the performance requirements modified to reflect the PAV mission, were defined as follows:

Hover MTE

The hover manoeuvre is initiated in a hover at an altitude of 20ft, and the aircraft is accelerated towards the target hover position. The target hover point is oriented approximately 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 1, and the test course used in the piloted simulations is shown in Figure 1.

Table 1. Hover performance requirements

Parameter	Desired	Adequate
Attain a stabilised hover within X seconds of reaching the target hover point	5	8
Maintain the longitudinal and 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

Figure 1. Hover test course

Vertical Reposition MTE

The vertical reposition manoeuvre starts in a stabilised 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 the specified time. Overshooting the end point is not permitted. The manoeuvre is complete when a stabilised hover is achieved. The performance requirements for the vertical reposition manoeuvre are shown in Table 2, and the test course used in the piloted simulations is shown in Figure 2.

Table 2. Vertical reposition performance requirements

Parameter	Desired	Adequate
Maintain the longitudinal and 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

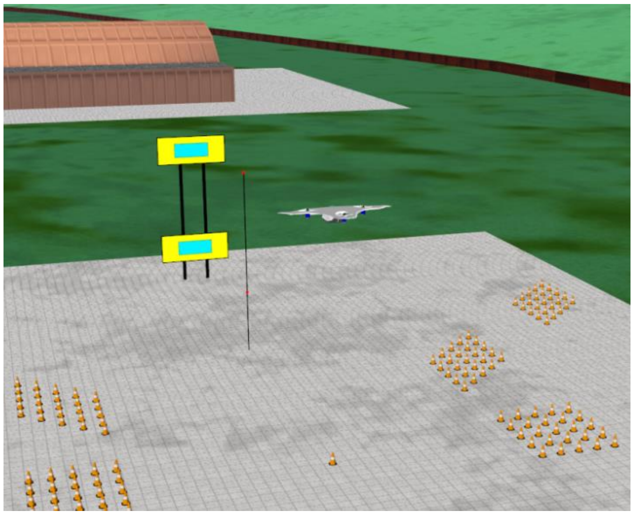

Figure 2. Vertical reposition test course

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, a constant rate 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 3, and the test course used in the piloted simulations is shown in Figure 3.

Table 3. Landing 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

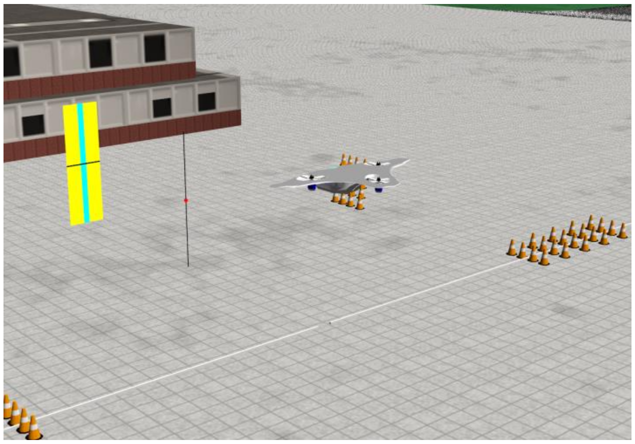

Figure 3. Landing test course

Aborted Departure MTE

The aborted departure begins in a stabilised 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 4, and the test course used in the piloted simulations is shown in Figure 4.

Table 4. Aborted departure 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

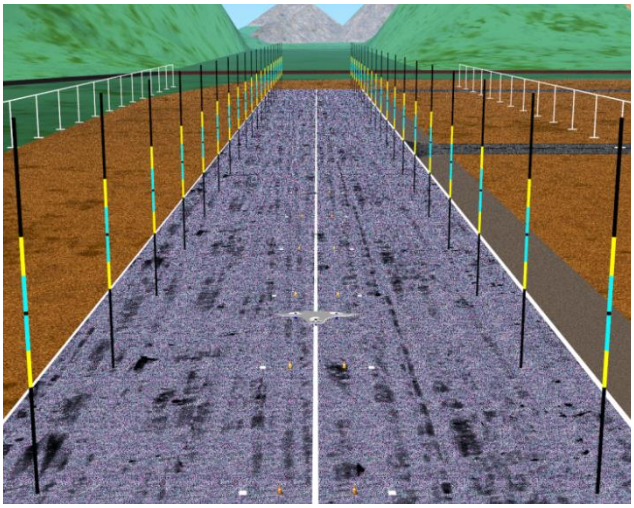

Figure 4. Aborted departure test course

SIMULATING THE HARSH ENVIRONMENT

Degraded Visual Conditions

Degradation in the Usable Cue Environment (UCE, Ref. 6) was achieved by restricting the visibility range of the UoL HELIFLIGHT-R (Ref. 9) simulator's Vega Prime (Ref. 10) 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 practice, the effect of reductions in the scene contrast and partial obscuration of features at ranges less than the visibility range makes the apparent visibility somewhat less than that stated.

In the previously reported simulation trials, the visibility range was set to a sufficiently large value that there were no apparent reductions in scene contrast and no obscured features within the regions scanned by the pilot (Figure 5).

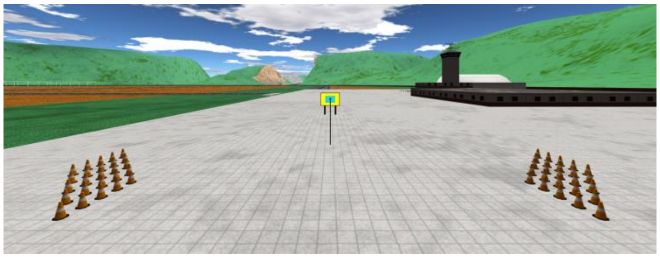

Figure 5. Hover test course in good visual conditions

For the investigation into the effect of degraded UCE, the visibility range was reduced to 800ft (Figure 6). 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 reduced significantly.

Figure 6. Hover test course in poor visual conditions

The effect of the introduction of the fog model was assessed by a test pilot using Visual Cue Ratings (VCRs, Ref. 6). With reduced visibility and micro-contrast, the VCRs were increased, creating a Degraded Visual Environment (DVE). Taking the hover test course as an example, for attitude control, the VCR awarded by the assessing test pilot increased from 1.5 to 4.5, whilst the translational rate VCR increased from 3 to 5. Together, the effect of these changes is to degrade the UCE from UCE=1 to UCE=3.

The flight-naïve TSs were not, however, asked to fly the MTEs in UCE=3 conditions. To augment the outside visual scene, the PAV simulation is equipped with a Head-Up Display (HUD). Two features of the HUD in particular provide enhancements to the UCE. The first is a wide field of coverage artificial horizon (a Malcolm Horizon, Ref. 11), seen as the orange-brown line in Figure 7. This, together with the green 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, the white circle in Figure 7. This marker shows the pilot the current direction of travel (in three dimensions) of the PAV, and hence can be used to augment cueing of the ratio of longitudinal to lateral translational movement.

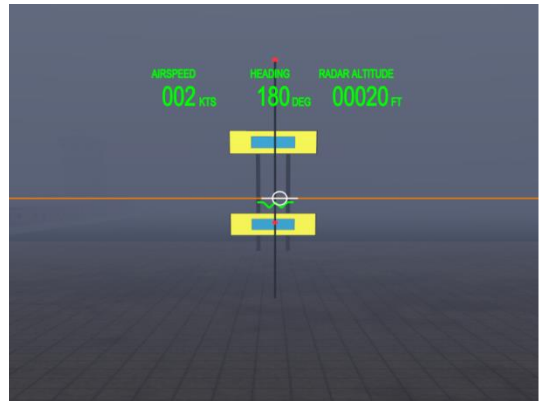

Figure 7. Head-up display symbology

The effect of these HUD features was to improve the cueing from UCE=3 to UCE=2 for the hover MTE. The VCRs awarded by the test pilot for the four MTEs used in the evaluations being reported in this paper are shown in Figure 8, where the MTE identifications are as follows:

MTE 1 = Hover
MTE 2 = Vertical Reposition
MTE 3 = Landing
MTE 4 = Aborted Departure

In general, the harsh environment evaluations were conducted in UCE=2 conditions. The exception was the Aborted Departure 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.

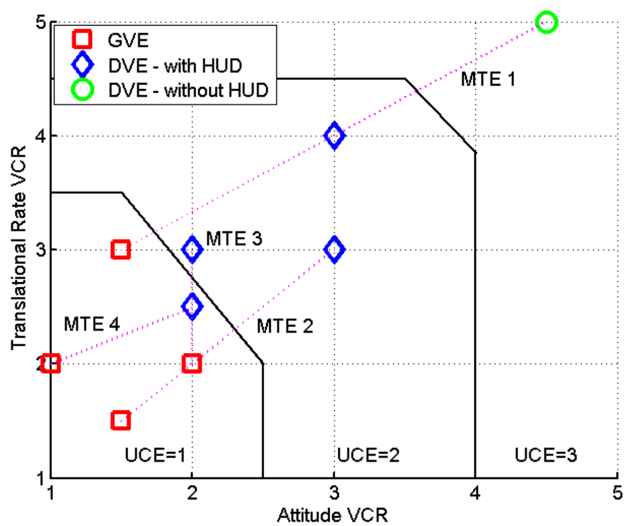

Figure 8. Determination of UCE for hover and low speed MTEs

Atmospheric Disturbances

Many different models of atmospheric disturbances have been created and applied to the simulation of helicopters (Ref. 12). Among the most popular of these is the von Karman method (Ref. 13). This method models continuous gusts with specified Power Spectral Density (PSD) characteristics for gust magnitudes in surge, sway and heave. Angular gust components are also modelled. Wind speed variations are generated for insertion into the simulation by passing white noise signals through filters that are designed to approximate the von Karman PSD characteristics.

Due to the generic nature of the PAV simulation model, it was not feasible to generate disturbances using the von Karman method. Instead, the method of the Control Equivalent Turbulence Input (CETI, Ref. 14) 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. With the CETI method, 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 be 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 realised 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. 14. For example, the structure of the CETI model for the longitudinal cyclic is shown in Eq. 1 below:

$$\frac{\delta_{lon,gust}}{W_{noise}} = A_{lon}\frac{1}{\left(s+\frac{U_0}{L_W}\right)} \qquad \text{Eq. 1}$$

where the symbols are defined as:

- $\delta_{lon,gust}$ - Longitudinal cyclic gust input
- W_{noise} - White noise input
- A_{lon} - Turbulence amplitude
- U_0 - Mean wind speed [m/s]
- L_w - Scale length parameter [m]

Initial parameter settings for the turbulence filters were also drawn from Ref. 14. 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 a light helicopter pilot to create a turbulence response that was considered appropriate for a vehicle of the size of the PAV. Frequency spectra for the transfer functions used in the harsh environment study are shown in Figure 9 below.

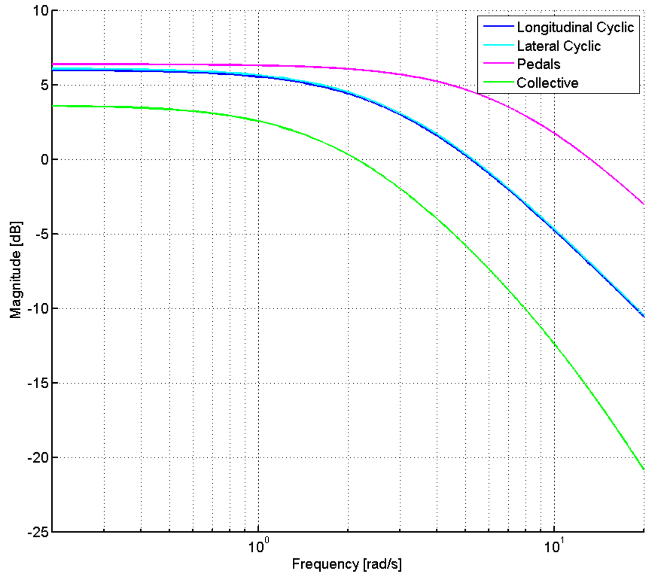

Figure 9. Comparison of CETI filters for PAV simulation

When driven by white noise generators, these transfer functions produce control input signals (such as those shown in Figure 10) which command angular rate (or vertical rate in the case of the heave axis) perturbations.

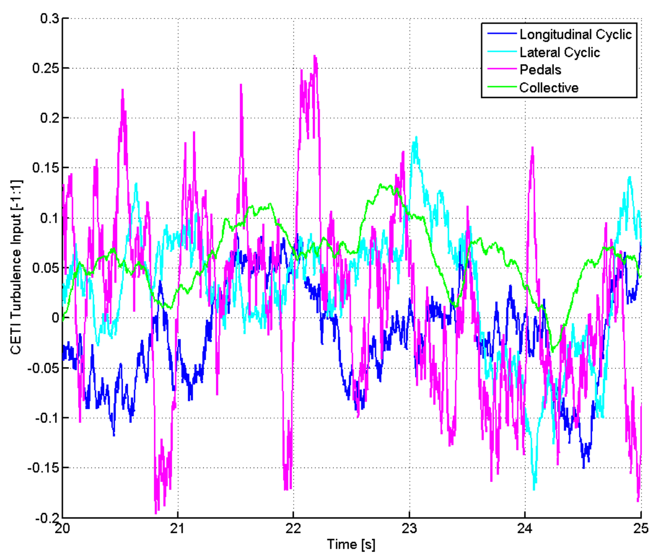

Figure 10. Sample of typical turbulence inputs to PAV simulation

For the RCAH configuration, the CETI signal is fed directly into each channel of the model, as shown in Eq. 2 for the pitch axis:

$$\delta_{lon,total} = \delta_{lon,pilot} + \delta_{lon,gust} \qquad \text{Eq. 2}$$

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. 3:

$$\delta_{lon,total} = \delta_{lon,pilot} + \left(\int \delta_{lon,gust}.\,dt\right) - \left(e^{-\tau s} \int \delta_{lon,gust}.\,dt\right) \quad \text{Eq. 3}$$

The time delay of the 'sensor' (τ in Eq. 3) was modelled as being 100ms. The turbulence implementations for the yaw and heave axes are also subject to the closed-loop feedback, meaning that, although the underlying vehicle response to a control input is identical in these axes, the turbulence response is different.

The effect of the turbulence on the RCAH and ACAH configurations is shown in Figure 11. The attitude response of the Hybrid configuration is similar to that of the ACAH configuration seen in Figure 11, but the translational response is more stable due to the additional closed-loop feedback of velocity present in the TRC control loop.

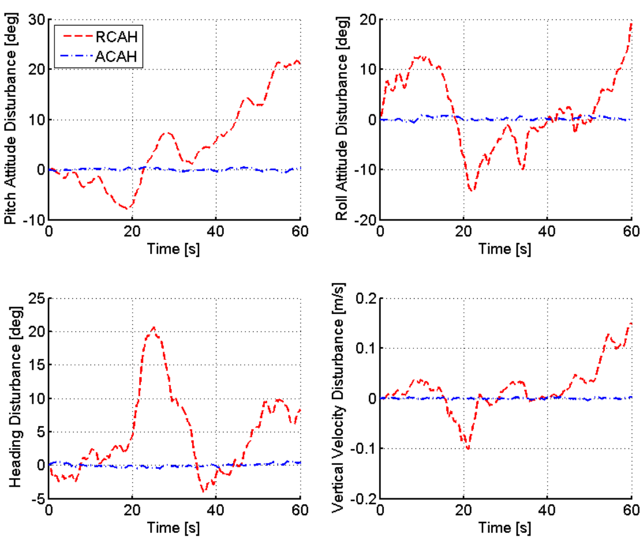

Figure 11. Turbulence response of RCAH and ACAH configurations

The strength of the turbulence was assessed subjectively by a test pilot using the Turbulent Air Scale (Ref. 15, repeated in Table 5). For the 'unaugmented' RCAH configuration, a rating of 5, occasionally increasing to 6, was awarded, indicating moderate turbulence intensity. Ratings were not taken for the ACAH and Hybrid configurations; the effectiveness of their closed-loop disturbance rejection functions was assessed by the flight-naïve TSs.

Table 5. Turbulent Air Scale

Rating	Definition	Air Conditions
1	-	Flat calm
2	Light	Fairly smooth, occasional gentle motion
3		Small movements requiring correction
4	Moderate	Continuous small bumps
5		Continuous medium bumps
6		Medium bumps with occasional heavy one
7	Severe	Continuous heavy bumps
8		Occasional negative 'g'
9	Extreme	Rotorcraft difficult to control
10		Rotorcraft lifting several hundred feet

ASSESSMENT METHODOLOGY

Rather than using test pilots to award Handling Qualities Ratings (HQRs, Ref. 16), the Handling Qualities (HQs) of the PAV configurations have been evaluated using flight-naïve Test Subjects (TSs). These are 'pilots' who have little or no prior flight experience. For the tests reported in this paper, experience ranged from one holder of a helicopter Private Pilot's Licence (PPL(H)) through to a number of people with no experience of flight at all. The advantage of this method is that it directly assesses the ability of people with different aptitudes for flight to control the various PAV configurations, rather than relying on the ability of test pilots to transfer their experiences with each configuration to the level of beginner pilots. The intent of the tests was to determine the minimum level of aptitude required to successfully control each PAV configuration in the hover and low speed MTEs in a harsh environment. This subsequently allowed conclusions to be reached regarding the suitability of each configuration for the expected level of piloting skill that will be shown by qualified PAV pilots.

As the pilots performing the PAV HQ assessments are not test pilots, the HQR scale (Ref. 16) is not appropriate as a method of gathering feedback on the handling qualities of each configuration. A number of alternative methods have been adopted and developed to allow both qualitative and quantitative analysis of the three PAV configurations.

The primary qualitative assessment method is the NASA Task Load Index (TLX) subjective workload assessment scale (Ref. 17). The TLX rating involves the assessment of six aspects of workload – mental demand; physical demand; temporal demand; performance; effort and frustration. The ratings for each of these aspects are then combined using a weighting system, in which the TS compares each workload element to all of the other elements and decides in each case which represented the greater contribution to the overall workload of the task. This process allows a single workload score for each task to be produced. The TLX rating process was designed to be straightforward for new users to understand the concepts involved in its use; hence making it suitable for use by the flight-naïve TSs who have not previously been involved in the use of such rating scales.

A TLX rating of 100 indicates an exceptionally high workload, while a rating less than 10 indicates minimal workload.

Workload and task performance have been assessed quantitatively using a combined metric, developed during the project, which has been given the name Task Performance Index (TPX). A complete description of the derivation of the TPX metric is provided in Ref. 4. It is calculated using the method shown in Eq. 4:

$$TPX = \frac{P^2\sqrt{W_{min}}}{100^2\sqrt{W}} \qquad \text{Eq. 4}$$

where the symbols are defined as:

- P - precision achieved in the task – measured as the percentage of task time spent within the MTE's desired performance boundaries
- W - workload required to complete the task – measured as the average number of control inputs applied per second
- W_{min} - theoretically-derived minimum W required to complete the MTE

A TPX score of 1.0 indicates that the TS was able to achieve desired performance in an MTE with the theoretical minimum number of control inputs. Scores of less than 1.0 indicate either a failure to achieve desired performance for the complete MTE, or an elevated level of control activity.

Finally, to allow the performance of each TS to be compared equitably, the aptitude of the TSs for flight tasks was measured prior to the commencement of the assessments in the flight simulator. Aptitude was measured using a suite of computed-based tests that assessed different aspects of hand-eye coordination, visual recognition and other mental abilities. The aptitude test battery is described in Ref. 4. A higher aptitude test score (A) indicates a TS who should be more capable of performing the MTEs than a TS with a lower test score. At the time of writing, the range of aptitude scores achieved by the 26 TSs who have taken the full battery of tests is $7.4 \leq A \leq 11.9$, while the theoretical maximum score for the complete assessment is A=15.

RESULTS

A total of 7 test subjects have taken part in the PAV HQ evaluations for the harsh environment. Their aptitude scores ranged from A=9.3 to A=11.9. The TSs flew in the HELIFLIGHT-R simulator at UoL (Ref. 9). HELIFLIGHT-R is a full motion simulator featuring a generic, reconfigurable crew station mounted inside a projection dome which offers a wide field-of-view outside world scene rendition.

The evaluations can be broken down into a number of phases. The first phase examined the individual impacts of degrading the UCE and introducing atmospheric disturbances on all three of the PAV configurations in the Hover MTE. Three of the TSs took part in this phase of testing (aptitude scores for these TSs were TS1 – A=11.9; TS2 – A=10.33 and TS3 – 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. The RC, ACAH and Hybrid configurations were again all used in this phase of testing. Finally, the third phase of testing saw all of the TSs fly the Hybrid configuration in all of the MTEs.

Effect of Degraded UCE and Atmospheric Disturbances on Hover MTE

Results from tests designed to investigate the individual impacts of introducing a Degraded Visual Environment (DVE) and introducing atmospheric disturbances are shown below. Figure 12 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). Figure 13 shows TPX scores for the same set of test points.

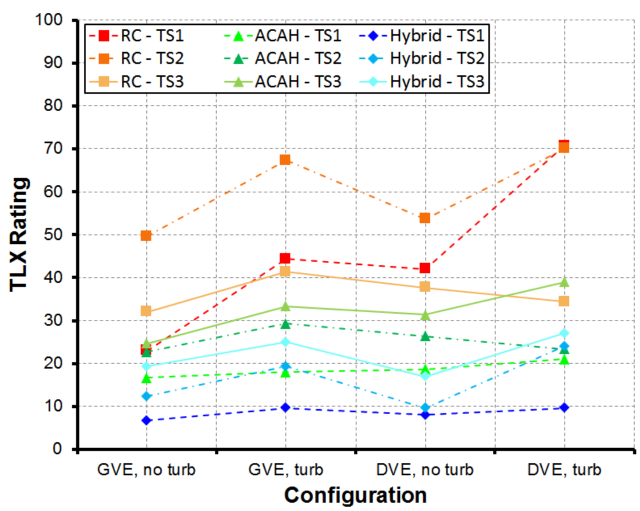

Figure 12. TLX Ratings for effect of DVE and turbulence in Hover MTE

Although there is considerable variation in the subjective workload interpretation between the three TSs, it can be seen in Figure 12 that each TS found the transition from RC to ACAH and from ACAH to Hybrid allowed a reduction in workload. This confirms the findings of Ref. 4. Further, however, Figure 12 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. 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. These findings are in agreement with the ADS-33E-PRF (Ref. 6) statement that ACAH and TRC response types are suitable for operations in degraded visual conditions – these response types provide a sufficient degree of stabilisation that the loss of some visual cueing information does not adversely affect a pilot's ability to attain the desired level of performance.

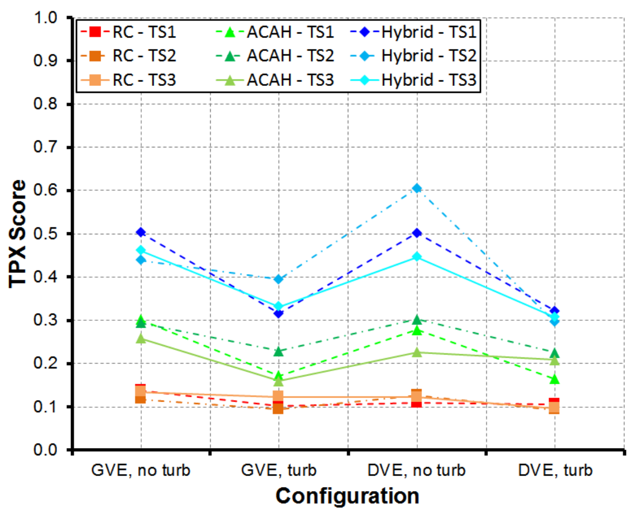

Figure 13. TPX Scores for effect of DVE and turbulence in Hover MTE

Turning to the quantitative analysis of these tests, Figure 13 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 the ACAH configuration, with the RC configuration offering the poorest performance. This was the case in all conditions, and 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 measured 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. For the ACAH configuration, in contrast, 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 Figure 13 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 (Figure 14).

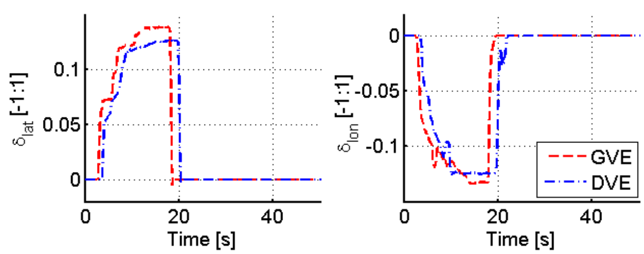

Figure 14. TS2 control activity in good and poor visual conditions

The key question related to 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). Figure 15 shows the TLX ratings awarded by one of the TSs for these two extreme conditions. This TS achieved the highest aptitude score, and holds a PPL(H). Nevertheless, the results shown paint a very clear picture. While a slow increase in workload can be seen in the benign environment as the response configuration of the model is changed from Hybrid to ACAH to RC, in the harsh environment the rate of change is faster, especially in the transition 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 minimising 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.

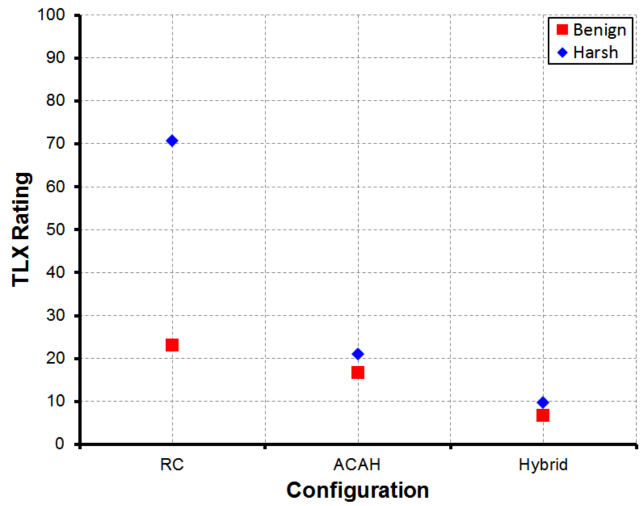

Figure 15. TLX ratings from TS1 for Hover MTE

Not all of the TSs, however, achieved the same results as TS1. Figure 16 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.

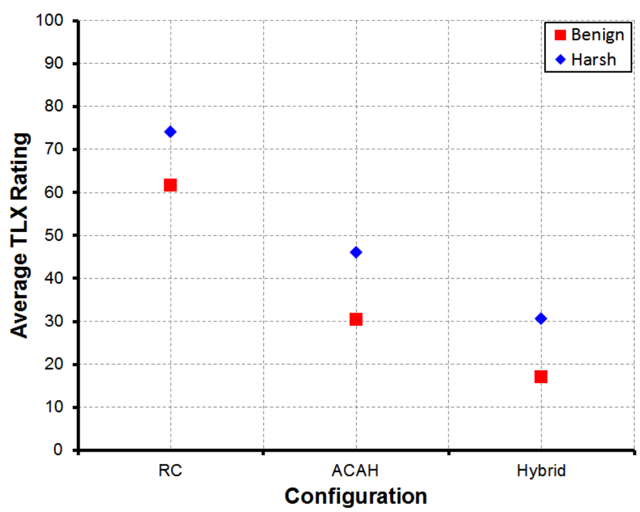

Figure 16. Average TLX ratings from all TSs for Hover MTE

In the case of the Hybrid configuration, some of the TSs found that they were drawn to apply corrective control inputs when they felt the PAV being displaced by the atmospheric disturbances, even if the disturbance would not be so severe as to cause the aircraft to move outside the MTE's desired performance boundaries (on average, over the thirty second period of hovering performed in this task, the Hybrid PAV would be disturbed beyond the desired position boundaries no more than once, given no corrective control inputs). 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 Figure 15 can be observed if the task precision achieved by all of the TSs is considered. Figure 17 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. Here, it can be seen that, 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. Ref. 4 concluded 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 Figure 17 confirm this conclusion, with even lower levels of precision achieved in the harsh environment.

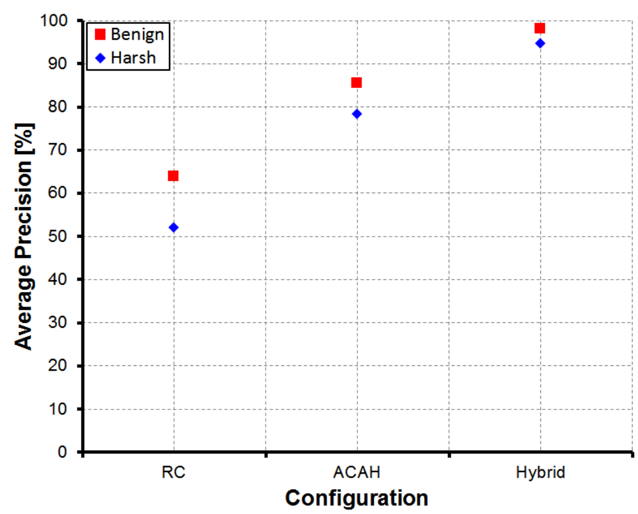

Figure 17. Average precision from all TSs for Hover MTE

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. Figure 18 shows the average TPX score achieved by each TS across all four MTEs.

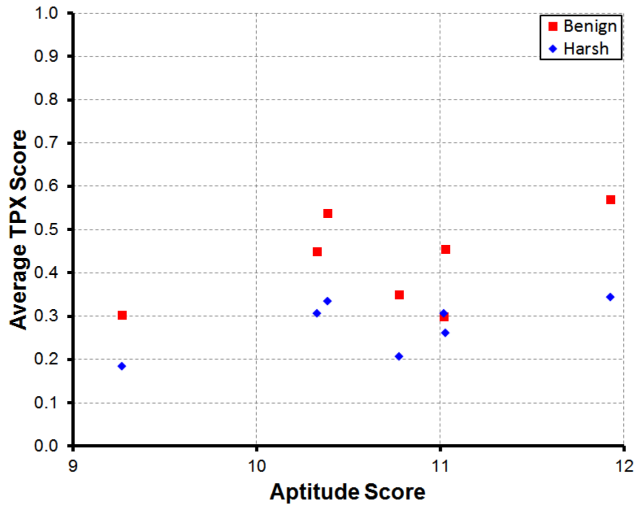

Figure 18. TPX scores from all TSs averaged across all MTEs

It can be seen in this figure that, when all MTEs are considered, there is a considerable drop in the TPX score – somewhat more so than was seen in Figure 13 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 of this is shown in Figure 19. 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 desired performance boundaries of the task. Thereafter, the PAV maintained its position inside the desired performance boundaries without requiring additional corrective inputs from the pilot.

There was, however, one notable exception to the trend described above, and that was the Landing MTE. Table 3 shows that, for desired performance to be achieved, it is necessary for the PAV pilot to make touchdown inside a box on the ground measuring 2ft longitudinally by 1ft laterally. Given the characteristics of the TRC response type and the control feel settings used for these tests, it proved difficult for the flight-naïve TSs to achieve this very high level of accuracy consistently. The impact of poor precision in the Landing MTE is shown in Figure 20 (showing average precision across all four MTEs) and Figure 21 (showing average precision across the Hover, Vertical Reposition and Aborted Departure MTEs).

When comparing precision in the benign and harsh environments across all four MTEs (Figure 20), there is typically a 10-15% reduction for each TS in the harsh environment. If the Landing MTE is excluded, however (Figure 21), 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 Ref. 4.

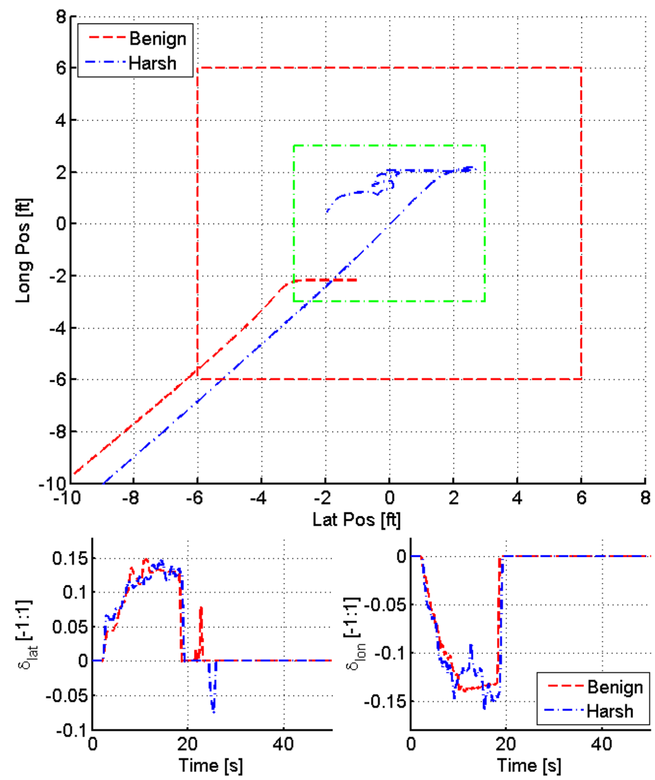

Figure 19. Plan position and control activity in Hover MTE

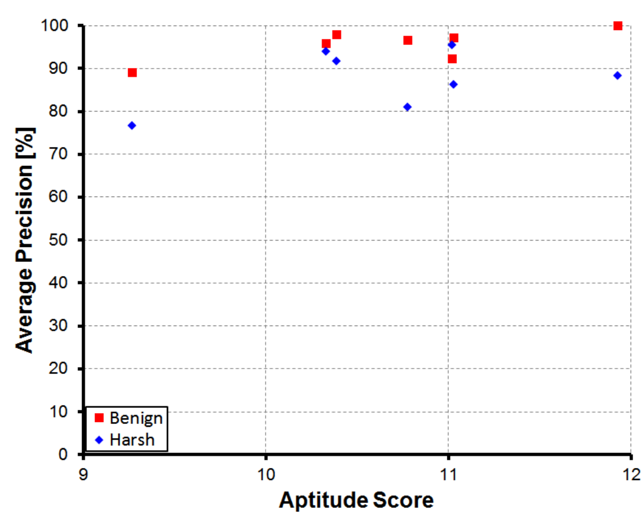

Figure 20. Precision achieved by all TSs averaged across all MTEs

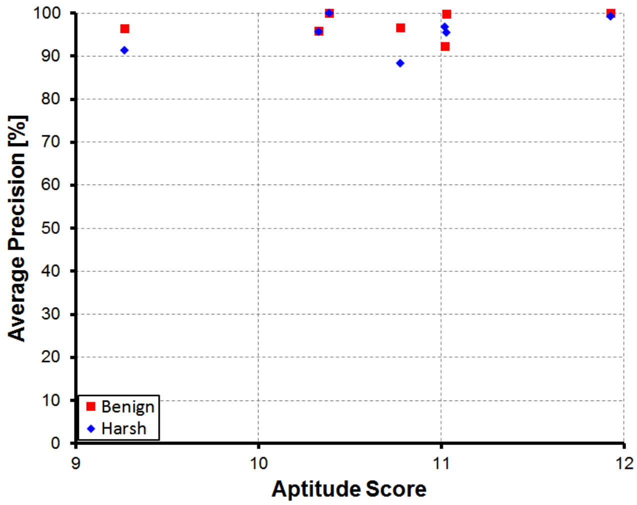

Figure 21. Precision achieved by all TSs in tasks excluding the Landing MTE

DISCUSSION

The results presented above show that, with the Hybrid configuration, the TSs were largely able to maintain their level of precision when confronted with 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 provide an improved level of precision 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 as reported subjectively and as measured 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 paper, 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. 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 is a subject for further study beyond the current scope of the *myCopter* project.

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 suitable for operations in the harsh environment as it is in the benign environment. This is an interesting contrast to the ADS-33E-PRF specifications for military rotorcraft, which determine that response types offering greater levels of augmentation and stability are required as the visual environment degrades. For the flight-naïve PAV pilot, it appears that the same (highly augmented) response type may be acceptable in all visual conditions.

CONCLUSIONS

This paper has described research into the handling requirements for a new category of flying vehicle – the PAV. In particular, the focus has been on requirements for operations in 'harsh' environmental conditions – in the presence of atmospheric disturbances and with degradation in the available visual cueing.

The following conclusions can be drawn from this work:

- 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.
- Flight-naïve pilots with a wide range of aptitudes can perform a range of hover and low speed MTEs at the desired level of precision with the Hybrid configuration.

- Tasks demanding very precise station-keeping will require an additional level of vehicle stabilisation, such as a position-hold function, for a consistently acceptable level of performance to be achieved.
- With the exception of very high precision tasks, the Hybrid configuration is equally as suitable for operations in a harsh environment as it is for the benign environment. This finding is in contrast to the ADS-33E-PRF guidance that requires improved levels of vehicle augmentation for degradation in the UCE.
- Measured performance is lower in the harsh environment than in the benign environment due to the elevated level of workload. This may lead to pilot fatigue issues if the PAV is required to operate in these conditions for extended periods of time.

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