Towards Handling Qualities Requirements for Future Personal Aerial Vehicles

Dr Philip Perfect

p.perfect@liv.ac.uk Research Associate University of Liverpool Liverpool, UK Dr Mark D. White <u>mdw@liv.ac.uk</u> Flight Simulation Laboratory Manager University of Liverpool Liverpool, UK Dr Michael Jump

<u>mjump1@liv.ac.uk</u> Lecturer University of Liverpool Liverpool, UK

ABSTRACT

This paper describes research under way 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, which it is envisaged will demand no more skill than that associated with driving a car today. Testing has been conducted both with test pilots and pilots with less experience – ranging from private pilot's license holders through to those with no prior flight experience. 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 repeatedly perform demanding tasks with the required precision.

NOTATION

βC	Sideslip Angle Command
γC	Flight Path Angle Command
A	Aptitude Test Score
ACAH	Attitude Command, Attitude Hold
ACSH	Acceleration Command, Speed Hold
DH	Direction Hold
EC	European Commission
FP7	7 th 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
Р	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)
RC	Rate Command
RCAH	Rate Command, Attitude Hold
TLX	Task Load Index
TPX	Task Performance Index

Presented at the AHS 69th Annual Forum, Phoenix, Arizona, May 21-23, 2013. Copyright © 2013 by the American Helicopter Society International, Inc. All rights reserved.

TP	Test Pilot
TRC	Translational Rate Command
TS	Test Subject
UoL	University of Liverpool
VTOL	Vertical Take-Off and Landing
W	Workload metric
W_{min}	Theoretical minimum workload for an MTE
XA	Lateral stick input [%]
XB	Longitudinal stick input [%]

INTRODUCTION

The development of aviation technology in the last half century has followed an evolutionary, rather than revolutionary trend. While this has led to significant gains in performance, efficiency and safety at a component level, aviation today functions in essentially the same way as it did 50 years ago. To counter this perceived lack of revolutionary innovation in the air transport industry, the European Commission (EC) funded the 'Out of the Box' study (Ref. 1) to identify new concepts for air transport in the second half of the 21st century.

One of the concepts proposed by the 'Out of the Box' study was that of the Personal Aerial Transportation System (PATS). The rationale behind the need for a PATS is the continued increase in the volume of road traffic in and around the world's cities (Refs. 2 & 3), and the congestion that results during peak times. In major European cities such as London, Cologne or Amsterdam, a road-bound commuter might expect to spend over 50 hours a year in traffic jams. Across Europe, delays due to road congestion have been estimated to cost approximately $\notin 100bn$ per year (Ref. 4). A radical solution to these problems, which will only become worse if road traffic continues to grow as predicted, is to move commuting traffic from the ground into the air with a PATS.

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, relatively 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 heavy traffic flow whilst mitigating any environmental impact, and would have to ensure safety through the application of pilot-vehicle interaction and collision avoidance technologies, to name but a few of the challenges with such a system. At the same time, the PATS must be designed with consideration for the general population's needs and wants, including cost effectiveness and affordability.

The Personal Aerial Vehicle

Since the 1950s, a number of vehicle designs combining the benefits of the car and the aircraft have been produced. These have included the Taylor 'Aerocar' (Ref. 5), the Carplane (Ref. 6) and the Terrafugia Transition (Ref. 7) in the category of 'roadable aircraft' – vehicles which can be driven on the road and are also capable of conventional fixed-wing flight. Similarly, a number of rotary-wing designs, such as the PAL-V (Ref. 8), Carter PAV (Ref. 9), Moller Skycar (Ref. 10) and Urban Aeronautics X-Hawk (Ref. 11) have been proposed or have reached the prototype stage.

Each of these designs may be considered as meeting some or all of the criteria for a Personal Aerial Vehicle (PAV) – the aircraft that would operate within a PATS. However, while some are in the process of being developed for the market, to date none has achieved mass-production success. It is believed that the reason for this is the starting consideration of the vehicle design, rather than addressing the method in which it would be operated and how it would integrate with existing road and air transportation methods.

The myCopter Project

The results from the 'Out of the Box' study were used to inform the direction of some of the 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. 12). The aim of the four year *myCopter* project, launched in 2011, is to develop the technologies that will ultimately enable a PATS to be realised. In this, the *myCopter* project is tackling the challenge of personal aviation from the opposite direction to PAV designers – to first identify how the system would work and how vehicles would operate within the system. The actual design of the PAV could then follow using the outputs of the *myCopter* project as a basis.

The *myCopter* consortium consists of six partner institutions in Germany, Switzerland and the UK, and the project's research activities cover three main themes:

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

In order to inform the direction of the research, a broad specification for a potential PAV configuration was drawn up in the early stages of the *myCopter* project (Ref. 13). It is envisaged that the PAV will 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.

To meet the requirement for general access to the PATS for all, it is envisaged that it will be necessary to make significant reductions in the costs associated with traditional General Aviation (GA) - including training, ownership and on-going operation. In order to reduce the training burden, two approaches are being considered in *myCopter*. The first of these is to implement autonomous capabilities on the PAV so that the occupant is not required to fly manually. The second, alternative option is to improve the Handling Oualities (HOs) of the PAV in such a way that the degree of 'skill' associated with PAV flight is significantly reduced in comparison to that required for a traditional GA rotorcraft, for example. The University of Liverpool (UoL) is working within the first of the themes described above to develop HQ requirements for PAVs that will operate within the PATS. The objective of this research is to identify required response types and boundaries for predictive metrics for the PAV in much the same way as ADS-33E-PRF (Ref. 14), the US Army HQ performance standard, does for military rotorcraft. This paper reports on the progress made to date in the development of these requirements.

Paper overview

While standard methods for HQ assessment of conventional rotorcraft have become widely accepted, the broad spectrum of potential PAV occupants (as with car driving, from naïve through to highly skilled) means that it is not necessarily the case that these methods will be directly applicable to PAV HQs. The paper will therefore begin with a description of the methodology that has been developed to support the analysis of PAV HQ requirements.

Following descriptions of the test environment and scenarios, the analysis methods that have been adopted to interpret the data will be presented. Results from piloted simulation trials at UoL, including traditional HQ evaluation methods with Test Pilots (TPs), and tests with progressively more 'flight naïve' pilots, will be reported. Results for a range of candidate configurations will be discussed in the context of pilot skill level and hence the training requirements associated with each configuration. The paper will be brought to a close with conclusions regarding the work and comments on the planned future activities within the *myCopter* project.

PAV HANDLING QUALITIES ASSESSMENT PROCEDURE

In a Handling Qualities (HQs) evaluation for a conventional rotorcraft, quantitative metrics describing the vehicle response to control inputs and disturbances are assessed and used to compute the predicted HQs of the vehicle. Test Pilots (TPs) then fly a series of Mission Task Elements (MTEs), awarding Handling Qualities Ratings (HQRs, Ref. 15) and hence allowing the assigned HQs of the vehicle to be computed.

For a PAV HQ assessment, these procedures are still being followed. However, it is not necessarily the case that existing boundaries on predictive metrics will apply to the PAV, as they have been developed to assess HQs for specific roles, such as the military rotorcraft in ADS-33E-PRF. Further, while the TP experience of a conventional test vehicle can be transposed to the experience of a line pilot, the potentially much greater experience gap between the TP and the 'flight naïve' PAV pilot makes this process more difficult.

In order to determine HQ requirements for this new category of aircraft, 'pilots' with a broad spectrum of previous experience – ranging from professional rotary-wing pilots, through JAR PPL(H) or UK PPL(A) holders and those learning to fly, to those with no previous flight experience – are being used to directly assess their ability to fly candidate vehicle configurations through a range of MTEs that are representative of the PAV commuting scenario.

While it is possible to broadly categorise 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 sits a series of psychometric tests (see 'Assessment Methods' later for details) to determine their underlying aptitude towards flying before attempting the PAV tasks.

As the majority of the 'pilots' taking part in the assessments do not possess training in HQ evaluations, alternative approaches to those described above for the assessment of conventional rotorcraft with TPs must be employed. Workload in each task is assessed subjectively through the NASA Task Load Index (TLX) rating (Ref. 16). Performance in the completion of each task is then evaluated through quantitative analysis of precision with which the task was completed and the amount of control activity required to perform the task. The methods used to analyse this data are described in the 'Assessment Methods' section later in the paper.

With this data in place, suitability of candidate vehicle configurations can be assessed in terms of the aptitude required to meet various levels of performance, and hence also the amount of training required to be capable of operating the PAV safely and precisely.

TESTING ENVIRONMENT

The HQ evaluations have taken place in the HELIFLIGHT-R flight simulation facility at UoL (Ref. 17), using a MATLAB/Simulink model of a generic VTOL aircraft - the Generic PAV Dynamics Model (GPDM, Ref. 18). Each test subject (TS - those who are not test pilots) flew each of the configurations described below in a series of MTEs. Prior to each sortie, the TS was briefed on the nature of the tasks that they would be flying, along with the associated performance requirements, but were not informed of the nature of the vehicle's HQs (the intention here being to assess the 'intuitiveness' of a given response type). The TSs were allowed to 'self-train' for approximately 5 minutes prior to the beginning of the MTE evaluations with each new vehicle configuration. In cases where it was obvious that the TS was struggling to control the vehicle, general guidance was provided (such as which task cues to look at, or the order in which to tackle task elements), but no specific training regarding VTOL flight was given. If a TS was still unable to perform a manoeuvre after a number of repeats, subsequent MTEs with similar demands (e.g. precision hover control) were omitted from the test plan.

PAV Model Configurations

The underlying response types offered by the GPDM are either Rate Command, Attitude Hold (RCAH) or Attitude Command, Attitude Hold (ACAH) in the pitch and roll axes, and Rate Command (RC) in the yaw and heave axes. These responses are created through 1st order (RC/RCAH) or 2nd order (ACAH) transfer functions (Ref. 19). The use of transfer functions for the rotational motion permits the vehicle dynamics to be tuned rapidly and to obtain precise HQs (e.g. a specified bandwidth value can be set directly), facilitating evaluation of multiple configurations. 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 (γ C) in the heave axis.

Three baseline vehicle configurations have been developed for the first stage in the HQ requirements definition process – that of identifying the response types that are required for PAVs. A second stage, currently on-going, will examine the issue of HQ boundaries for predictive metrics. The three configurations are as follows:

Configuration 1: 'Rate Command, Attitude Hold'

RCAH 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 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. 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.

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 RCAH response type of configuration 1. Again, the dynamics of this configuration have been tuned to offer predicted Level 1 HQs according to ADS-33E-PRF.

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 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 γ C. 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).

As with the other configurations, the dynamics of the hybrid configuration have, where possible, been tuned to offer predicted Level 1 HQs for 'All Other MTEs' according to 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 the first group of TPs to fly the GPDM in the hybrid configuration. Validation of the suitability of the dynamics of these response types is taking place as part of the *myCopter* project.

Mission Task Elements

A *myCopter* 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 slow to come to a 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 selected for use in the investigations reported in this paper. The 5 MTEs are the Hover, Vertical Reposition, Landing, Decelerating Descent and Aborted Departure. Where possible, the outline of the task has been drawn from ADS-33E-PRF; the task performance requirements have, however, been modified (generally relaxed) to reflect the nature of the PAV role.

Hover MTE

The hover manoeuvre is initiated at a ground speed of between 6 and 10kts, at an altitude of 20ft. 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. Upon arrival at the hover point, a stable hover should be captured and held for 30 seconds. The transition to hover is 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	-	0
seconds of reaching the target	5	8
hover point		
Maintain the longitudinal and		
lateral position within $\pm X$ ft of the	3	6
target hover point		
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	5	10
target hover point	C	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, 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 3, and the test course used in the piloted simulations is shown in Figure 3.

Table 3. Landing Performance Requirements

Fable 4. Decelerating Descent 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 $\pm X$ ft laterally of the reference point	0.5	3
Attain rotorcraft heading at touchdown that is within $\pm X^{\circ}$ of the reference heading	5	10
Final position shall be the position that existed at touchdown	\checkmark	N/A



Figure 3. Landing Test Course

Decelerating Descent MTE

The decelerating descent manoeuvre begins with the aircraft in a stable cruise at 60kts at a height of 500ft. Once a specified ground marking has been overflown, the aircraft descends and is decelerated towards a target hover point and an altitude of 20ft. The approach is configured to give a mean glideslope angle of 6 degrees. The manoeuvre is complete when the aircraft has been stabilised 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 4, and the test course used in the piloted simulations is shown in Figure 4.

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 $\pm X$ ft longitudinally of marked position	10	20



Figure 4. Decelerating Descent Test Course (inset: final hover position)

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 5, and the test course used in the piloted simulations is shown in Figure 5.

Table 5. Aborted D	Departure Peri	formance Re	quirements
--------------------	----------------	-------------	------------

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 5. Aborted Departure Test Course

HELIFLIGHT-R simulator

The HELIFLIGHT-R simulator (Figure 6, Ref. 17) has been the main research tool for HQ criteria development in the *myCopter* project. HELIFLIGHT-R features a two-seat crew station inside a 12ft diameter dome, and a simulation engineer's station at the rear. The outside world scene is rendered using the Vega Prime image generator, and projected onto the dome by three HD projectors. The output from each Vega Prime display channel is warped and blended to create a seamless image on the surface of the dome covering a field of view of approximately 210° by 70°. This is extended in the region ahead of, and below, the pilot by a pair of 'chin' windows.



Figure 6. The HELIFLIGHT-R Simulator at the University of Liverpool

Four axis (lateral and longitudinal cyclic, collective and pedals) dynamic control loading permits the inceptor forcefeel characteristics to be tuned to represent specific configurations or adjusted to investigate impact on vehicle handling. While these standard rotorcraft inceptors have been used in the HQ evaluations to date, one of the areas of study as the *myCopter* project progresses will be to identify whether these are the most suitable inceptors for a PAV, or whether an alternative configuration, such as a yoke, or even a steering wheel as would be found in a car, would be more suitable.

The crew station's instrument panel features a pair of reconfigurable 'glass cockpit' style Primary Flight Displays (PFDs) together with two smaller displays on a centre console. For the *myCopter* HQ evaluations, the instrument panel displays were configured to show a slightly modified (through the addition of a radar altimeter and HH and DH engaged indicators) representation of the Garmin G1000 GA glass cockpit suite (Figure 7, Ref. 20).



Figure 7. Garmin G1000 PFD

In addition to the head-down display symbology offered by the G1000 panel, a set of Head-Up Display (HUD) symbology has been developed, which is overlaid onto the outside world scene (Figure 8). The HUD symbology includes:

- 1) A Malcolm horizon line (Ref. 21) spanning the full field of view of the simulator;
- 2) A flight path vector indictor showing the current direction of flight (white circle);
- A pitch attitude indicator showing attitude relative to the horizon (green gull's wings);
- Numerical readouts of current airspeed (and, for the hybrid mode, commanded airspeed – shown in red), heading and height above the terrain;
- 5) During decelerating flight, a display of the point on the ground above which the vehicle will come to a stop assuming the deceleration rate remains constant (not shown in Figure 8).



Figure 8. Head-Up Display Symbology

The HUD symbology has been kept deliberately simple and sparse so as to facilitate assimilation and interpretation by flight-naïve pilots. The exact requirements for such a display are one of the areas of study for the myCopter project (Ref. 22). The intention is that the symbology complements the response types of the vehicle – particularly the hybrid configuration. For example, in the hover task, the target hover point can be reached by placing the flight path indicator on the horizon line above the target hover point using a single 45° input on the cyclic control. For the decelerating descent task, once the descent point has been reached, the flight path indicator can be placed over the hover board positioned at the finish point using a single downwards movement on the collective lever, and the deceleration indicator can be overlaid on the marked hover point using a single aft input on the longitudinal cyclic. As flight path angle and deceleration rate stay constant for fixed control deflections in the hybrid configuration, no additional control activity should be required to bring the aircraft to a hover at the desired position.

The crew station and projection dome are mounted on top of a hexapod platform offering six degrees-of-freedom motion cueing.

ASSESSMENT METHODS

In this Section, the methods used to determine pilot aptitude and to assess task performance and workload are described.

Aptitude

The suite of psychometric tests used to determine aptitude for piloting a PAV consists of 9 separate computer-based tests examining different aspects of the piloting task. The tests were developed from elements of the US Air Force Basic Attributes Test (Ref. 23) and a kit of standard psychometric tests (Ref. 24). The 9 components of the *myCopter* aptitude test are 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 (Figure 9) 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.



Figure 9. Complex Coordination Task

- 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 (Figure 10) 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.



Figure 10. Dot Estimation Task

- 5) Identical Pictures the TS is shown a series of reference images together with a group of candidate images. The subject must identify within a very constrained amount of time 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.
- 6) Line Orientation (Figure 11) 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.



Figure 11. Line Orientation Task

7) Locations (Figure 12) – the TS is shown four lines each with a pattern of dashes and spaces. On each line is a single cross. 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.



Figure 12. Locations Task

- 8) Picture-Number Test the TS is shown a set of pictures, and must memorise 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 picturenumber test is a measure of a participant's memory capacity.
- 9) Shortest Roads (Figure 13) 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.



Figure 13. Shortest Roads Task

The 9 psychometric tests can be grouped into a number of categories, which are expected to affect the piloted simulation test results as follows:

- Hand-eye coordination tasks Ability to apply appropriate control inputs relative to visual stimuli (e.g. positional errors)
- Visual tasks Ability to develop spatial awareness
- Decisiveness task Ability to make rapid decisions regarding the correct course of action
- Memory task Ability to remember task instructions
- Problem solving task Ability to work out the correct control inputs for a given response type

Scoring for each of the psychometric tests is performed as follows:

- Hand-eye coordination tasks: the task score is based on the ability of the TS to keep the targets aligned in their correct positions. The greater the distance away from the ideal position at any time, the greater the reduction in the score.
- Dot estimation task: the number of correct decisions is divided by the average time required to make a decision to arrive at the score.
- Other tasks: scoring is based on the guidelines provided in Ref. 24. Typically, the score for that task is based on the number of correct answers given. In some of the tasks, half a point (or even a whole point) is subtracted from the score for incorrect answers to penalise guessing.

For each task apart from the two coordination exercises, the task score is then normalised against the maximum available score for that task so that each score is evenly weighted. For the coordination exercises, the scores are normalised as above and then multiplied by four to increase their relative weighting in the overall aptitude score. This step signifies the greater importance placed on hand-eye coordination skills for flying a PAV. The normalised and weighted scores are finally added together to produce a TS's overall aptitude score (the symbol *A* will be used to symbolise the overall

aptitude test score). From the nine tests, the theoretical maximum achievable score is therefore fifteen.

The tests described in this section have all been previously employed in the process of measuring aptitude, either generally or for specific requirements. However, their applicability to aptitude assessment for flying a PAV remains to be validated. This topic will be returned to later in the paper.

Task Load Index

The Task Load Index (TLX, Ref. 16) 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 for it to be straightforward for new users to understand the concepts and processes involved in its use.

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 together using a weighting system, in which the TS compares each of the workload elements to 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.

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 for an MTE (which shall be called P for the purposes of this paper). Higher P values correspond to better task performance.

The second parameter is a quantitative measurement of the task workload, captured 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. 25), attack analysis (Ref. 26) etc.), the technique used to assess workload for the trials reported in this paper was to count the number of discrete movements of the controls (above a threshold of 0.5% of full stick deflection - this is implemented to prevent measurement noise from affecting the analysis), and average against the time required to complete the task - giving a number of control inputs made per second in each axis. Again, this is averaged across the four control axes to produce a single value for each MTE (denoted W in this paper). With the control activity evaluation, the ability to perform a task with fewer control inputs has been judged to be preferable. It is acknowledged that a metric such as this does not capture all

aspects of a pilot's workload, and that there can in fact be cases where a low amount of control activity correlates with a high workload (a good example of this would be a situation where a large time delay is present in a system – the pilot then has to apply considerable mental effort to reduce their natural amount of control activity in order to prevent the excitation of pilot induced oscillations). However, it is considered that the benefits of having a single metric to capture a basic representation of the workload outweigh these disadvantages, provided that the subjective workload assessments are also considered to ensure that the correlation between low workload and low control activity holds.

Taking the quantitative analysis a stage further, it is possible to combine the metrics used to assess precision and workload into a single metric to represent the overall performance achieved in a given MTE. At a basic level, the precision and control activity metrics can be combined directly:

performance
$$=\frac{p}{W}$$
 (Eq. 1)

However, if it is considered that ability to achieve an MTE's desired performance requirements is of greater importance than achieving a minimal workload for a given task, the relative weighting of precision and workload metrics can be adjusted so that the overall metric becomes:

performance
$$=\frac{P^2}{\sqrt{W}}$$
 (Eq. 2)

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 can be computed by determining the fewest control inputs required to complete a given MTE. To give an example for the hover MTE, assuming that the HH and DH functions are engaged, one movement of the cyclic at 45° is required to initiate the translation to the hover point, and a second movement is required to decelerate to the hover. As each of these inputs occurs in both the longitudinal and lateral cyclic axes, there is a minimum of four discrete inputs required to complete the hover task (assuming that no control activity is required during the stable hover phase). By estimating a duration of 40 seconds (10 seconds of translation followed by 30 seconds of stable hovering), the average number of control inputs per second can be computed (called W_{min}).

These theoretical maximum performance values for each MTE are used to normalise the values of achieved performance. We call this the Task Performance Index (TPX):

$$TPX = \frac{P^2 \sqrt{W_{min}}}{100^2 \sqrt{W}}$$
(Eq. 3)

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 minimal 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.

RESULTS

In this Section, two sets of results will be presented. The first will be a traditional HQ analysis using ADS-33E-PRF predictive metrics and assigned HQRs. The second will present results using the proposed new assessment methods for pilots from across the aptitude spectrum.

Firstly, however, it is useful to consider the way in which the various response types behave when a pulse control input is applied. Inputs such as these form the basis for many of the ADS-33E-PRF predictive analyses, and so examination of the time histories can help to understand the HQ results. Figure 14 shows the responses in the pitch axis, Figure 15 the responses in the roll axis and Figure 16 the responses in the yaw axis. The progressively increasing stability of the responses as we progress from RCAH through ACAH to TRC is evident in the velocity traces for each axis.

In each case, it can be seen that the responses of the three PAV configurations under test have been tuned, where possible, to offer similar characteristics. For example, it can be seen in the upper left plot of Figure 15 that the initial roll acceleration is similar for all three configurations, providing the same bandwidth.



Figure 14. Pitch Axis Responses



Figure 16. Yaw Axis Responses

Conventional handling qualities evaluation

The three configurations have been assessed against the ADS-33E-PRF hover and low speed criteria for 'All Other MTEs'. 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 actually remain constant across the flight envelope.

In the pitch axis, the bandwidth of the RCAH and ACAH configurations is as shown in Figure 17, while the attitude quickness is as shown in Figure 18. The bandwidths of the two configurations were set to be the same, so the result in Figure 17 is confirmation that this goal was achieved. Due to the different structures used to implement the RCAH and

ACAH response types in the GPDM, it was not possible to match the attitude quickness values exactly. However, the responses have been tuned to achieve as close a match as possible. For both criteria, the handling qualities are predicted to lie well within the Level 1 region.

It should be noted that, for all of the bandwidth results shown below, the phase delay has been calculated as 0 seconds. This is because the GPDM simulation does not incorporate any delay elements – the inherent stick-tovisuals transport delay of the HELIFLIGHT-R simulator (approximately 80ms) provides an appropriate phase delay modification when the GPDM is used in piloted simulations.





In the roll axis, the bandwidth is shown in Figure 19, and the attitude quickness is shown in Figure 20. Again the bandwidth values are perfectly matched between the two responses. However, there is a considerably larger difference in the attitude quickness results than was evident in the pitch axis. This is due to different requirements in meeting the maximum response amplitude criteria in pitch and roll meaning that the structures of the RCAH and

ACAH transfer function models could be less well matched in roll than was the case in pitch.





In yaw, all configurations employ the same RC response type in the hover. The bandwidth for this response is shown in Figure 21, and the attitude quickness is shown in Figure 22.



Figure 21. Yaw Axis Bandwidth



Figure 22. Yaw Axis Attitude Quickness

The TRC response type of the hybrid configuration is created through 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 to increase the predictability of the vehicle response to a change in control position for flight naïve pilots. The trade-off between improving predictability and improving hover sensitivity for PAV pilots will be examined in the continuing myCopter research.

Turning to piloted assessment of the three PAV configurations, Figure 23 shows the HQRs awarded in each of the five MTEs. To date, five TPs have been involved in the assessment process, although not all pilots have flown all configurations. Figure 23 shows the mean HQR awarded by the pilots, and also the spread between the best and worst ratings for each configuration.

It can be seen in Figure 23 that, despite offering predicted Level 1 handling, it was not always possible for the TPs to achieve the desired level of performance in each task with the RCAH and ACAH configurations, leading to a number of Level 2 HQRs. This was most evident in the 'precision/stabilisation' tasks – the hover, vertical reposition and landing. Generally fewer deficiencies were identified in the decelerating descent and aborted departure tasks, although one pilot did find the workload required to achieve the desired performance in the aborted departure to be greater than would be acceptable for Level 1 handling.

It is only with the hybrid configuration that every TP awarded a Level 1 HQR for every task; further, it can also be seen in Figure 23 that the mean HQR is better, and the spread between best and worst HQRs is smallest for the hybrid configuration.



Figure 23. PAV Handling Qualities Ratings

These results provide a strong indication that the hybrid configuration offers the best handling characteristics of the three configurations under test. The results suggest that the hybrid configuration would be highly suited for use by a typical helicopter pilot of today. Further, these 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. The improvement in HQRs as the response type is changed from RCAH 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.

While the results in Figure 23 indicate that the hybrid configuration is highly suited to current helicopter pilots, there is insufficient evidence upon which to draw conclusions regarding its suitability for the less experienced, flight naïve pilots who might be expected to be flying PAVs, hence requiring the extension of the HQ analysis process to incorporate this group of pilots.

Aptitude test results

Figure 24 shows the test scores achieved by each of the 21 subjects (18 male, 3 female, age range 19-43 with mean age of 25) who have taken the aptitude test to date. The test subjects (TSs) have been broadly categorised 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 the desktop level through packages such as "Microsoft Flight Simulator", or in a

full flight simulator such as HELIFLIGHT-R. It is to be expected that these TSs will begin their experience of the PAV simulation with an understanding of the primary effects of the controls;

- Flight Experience these TSs have undergone some elementary flying training, and have generally achieved solo flight;
- Flight Qualified these TSs have completed their elementary flying training (either military or civilian), and are qualified pilots. The most experienced pilot in this group has just over 200 hours of flight time.

It will be noted in the categorisations above that no distinction is made between those with fixed-wing experience and those with rotary-wing experience. This is because 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 highest and second highest aptitude scores amongst those TSs in the 'Flight Qualified' category.



Figure 24. Aptitude Test Scores

The test scores presented in Figure 24 show a reasonable trend of improving aptitude score with greater levels of experience (and hence training). This is especially the case if the subjects with no experience are compared to those who have flown (i.e. fall in either of the 'flight experience' or 'flight qualified' categories). These results provides confidence that the aptitude testing process provides a viable means of differentiating between pilots of differing skill levels, and hence validates its use in the PAV HQ assessment process. One significant outlier is to be found in the set of results for the 'flight qualified' group - with an aptitude score of just 8.1. This TS scored very poorly in the Complex Coordination and Card Rotations tasks; in the case of Complex Coordination, this TS was apparently unable to control all three movements simultaneously - accuracy was reasonable for the central crosshair, but very low for the rudder bar.

Analysis of Task Load Index

The analysis of the performance of the non-TP TSs will begin with an examination of the TLX ratings awarded for each configuration. Figure 25 shows the TLX ratings awarded by each TS for each of the three PAV configurations under assessment. The ratings for the individual tasks have been averaged to produce the data shown in the figure.



Figure 25. TLX Ratings for PAV Configurations

In each case, there is a trend of a subjective reduction in workload as the pilot's aptitude increases. It is also clear that as the configuration changes from RCAH to ACAH, and then to hybrid, there is a significant reduction in the workload involved in flying the vehicle at each stage. The only exception to this rule was some of the TSs with high aptitude scores, who rated the ACAH and hybrid configurations as having similar, low levels of workload to fly.

While workload reduces as aptitude increases with all three configurations, the way in which this reduction occurs is different in each case. With the RCAH configuration, there is considerable scatter in the results, with some TSs finding this configuration extremely difficult, and other merely difficult. With 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.

Considering the ratings for the individual tasks, Figure 26 a sample of the results for the RCAH configuration, Figure 27 the results for the ACAH configuration, and Figure 28 the results for the hybrid configuration. The same pilots have been used to construct all three figures.



Figure 26. Sample of TLX Ratings for RCAH Configuration - Individual Tasks



Figure 27. Sample of TLX Ratings for ACAH Configuration - Individual Tasks



Figure 28. Sample of TLX Ratings for Hybrid Configuration - Individual Tasks

In Figure 26, a clear difference can be seen between the pilots' perceptions of the hover, vertical reposition and landing tasks, and their perceptions of the decelerating descent and aborted departure tasks. The key differentiating factor between these two groups of MTEs is that with the first, there is a demand for a continuous high level of precision, whereas with the second the tasks require a somewhat more 'open loop' control strategy for large periods of the task. The relatively low level of stability offered by the RCAH 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, Figure 27 shows a smaller variation 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.

Turning to the data for the hybrid configuration shown in Figure 28, it can be seen that there are no clear differentiators between tasks. In general, each TS found all five tasks to be equally demanding with the hybrid configuration. There are exceptions to this rule, however for example the decelerating descent task. Unlike the other tasks with the hybrid configuration, the decelerating descent task requires the pilot to coordinate the application of control on two separate inceptors simultaneously inputs (longitudinal cyclic and collective). In every other task, assuming that the HH and DH functions are being employed, the pilot is only ever required to apply inputs on a single inceptor at a time (in the hover MTE, the input to position the vehicle over the target hover point is made using both longitudinal and lateral cyclic, but these are both made using one inceptor – the cyclic handle). While the higher aptitude pilots did not find this to be a significant challenge, the lower aptitude pilots saw their workload increase significantly. This result highlights the importance of minimising or eliminating unnecessary secondary or off-axis control activity in a future PAV.

Analysis of Task Performance

The TLX results have shown that the hybrid configuration offers subjectively the lowest workload of the three configurations under test. In this Section, the quantitative assessment of each manoeuvre will be presented.

Figure 29 shows the precision (percentage of task time spent within the desired performance boundaries) achieved by each TS in each of the PAV configurations. The results for the individual MTEs have been averaged to produce the data shown in the Figure, meaning that a plotted value of 100% precision indicates that the TS was able to achieve 100% time spent within desired performance in every task.



Figure 29. Precision for PAV Configurations

While the highest aptitude TS was able to perform roughly equivalently (> 90% time spent within desired performance) in all three configurations, the same could not be said of the lower aptitude TSs. It can be seen in Figure 29 that precision was very poor (<70% time spent within desired) for the lower aptitude TSs flying the RCAH 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.

Bringing the numerical assessment of workload into consideration, Figure 30 shows the TPX score achieved by each of the TSs for each PAV configuration. As with the TLX ratings shown in Figure 25, the scores have been averaged across the five MTEs.



A very similar trend to that discussed for the subjective evaluation can also be seen in the quantitative analysis. As we move from the RCAH configuration, through the ACAH configuration to the hybrid configuration, there is a steady improvement in achievable TPX. 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 (and it can be said that these results, for A=10.2, are significant outliers relative to the other ACAH results). The same can be seen in the ACAH-RCAH comparison.

Although there is some scatter in the results, the trends evident in Figure 30 provide an indication of how pilots of differing aptitude performed with the three PAV configurations. Starting with the RCAH configuration, all TSs performed poorly. There was an improvement in performance from low aptitude to moderate aptitude, but increasing the aptitude beyond this point did not affect the With the ACAH configuration, a slight result greatly. improvement in task performance with increasing aptitude is visible. Finally, with the hybrid configuration, all TSs, regardless of aptitude, were able to achieve a reasonably good TPX score for each task. Increased scatter is evident in the results for the hybrid configuration. This is believed to be a result of some TSs accepting the positional stability offered to them by the TRC response type. This allowed these TSs to minimise their level of control activity and allowed the system to do most of the 'work' for them. In contrast, other TSs felt a requirement 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 Figure 30 and the subjective workload ratings shown in Figure 25 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 on 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.

Figure 31 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 Figure 26 to Figure 28. Figure 32 provides the same analysis of the ACAH configuration, with Figure 33 for the hybrid configuration.

Figure 30. TPX Scores for PAV Configurations



Figure 31. Sample of TPX Scores for RCAH Configuration - Individual Tasks



Figure 32. Sample of TPX Scores for ACAH Configuration - Individual Tasks



Figure 33. Sample of TPX Scores for Hybrid Configuration - Individual Tasks

Generally, there is a considerable spread between the scores for each task for any one TS and the TSs performed relatively better or more poorly in different tasks; this is true for all configurations. The differing comparative levels of performance across the five MTEs are believed 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 spread across tasks is believed to be a result of the different natures 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 (Figure 33) - the vertical reposition and the decelerating descent - will be used. In the vertical reposition task, the pilot is required to align 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, meaning that the only remaining control activity for the task is for the pilot to raise the collective lever to initiate the climb, and then to lower it again to capture the new height. In total therefore, an absolute minimum of six control inputs is 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 provision 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.

This can be contrasted with the decelerating descent task. This is a relatively long manoeuvre (several minutes to complete the descent), but requires only 6 theoretical control inputs to accomplish. However, as the initial descending flight path angle and deceleration rate must be set up when still a long way from the final hover point, it is difficult for the pilot to position the controls at exactly the correct points, even with the enhanced visual cueing provided by the HUD. As the approach continues, the pilot is able to refine his control positions so as to improve the accuracy of the final hover – but 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 will be required to 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 perceived position. Again, this reduces the TPX score for the task.

Using the data in Figure 31 to Figure 33, it can be seen that for the vast majority of TS/task combinations, a move from the RCAH 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 can be seen in the data for the decelerating descent MTE, where the results for the ACAH and hybrid configurations are very similar. It is believed that 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, as discussed above, 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.

DISCUSSION

Comparison of High and Low Aptitude Test Subjects

The results presented above show a considerable difference between the performance achievable by a high aptitude subject and that achievable by a low aptitude subject with the RCAH configuration. This difference is illustrated in Figure 34 below.

Whereas the high aptitude TS (TS1) was able to maintain the precise hover position for the majority of the task, the low aptitude TS (TS4) 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, TS4 was unable to apply appropriate control inputs to decelerate the vehicle back to the hover. Divergent longitudinal and lateral positional oscillations resulted. This poor 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. Figure 35 shows the control activity in the lateral (XA) and longitudinal (XB) Particularly during the first 20 seconds of the axes.

manoeuvre (the translation and deceleration to hover), it can be seen that TS4 applied corrective inputs at a lower rate and smaller magnitude than TS1, reflecting their inability to process positional and velocity errors and apply appropriate corrective inputs in a timely manner. 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 RCAH configuration, with attempts being made to actively engage with all axes of control. TS4, in contrast, was focussed purely on longitudinal and lateral control, and was content to allow height and heading to drift during the task.



Figure 34. Comparison of High and Low Aptitude Test Subjects in Hover MTE with RCAH Configuration



Figure 35. Control Activity in Hover MTE with RCAH Configuration

Turning to the hybrid configuration, Figure 36 shows performance in the hover MTE, for the same two TSs as in Figure 34. The difference between the two subjects here is much less noticeable, although 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 Figure 37). 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 centred.



Figure 36. Comparison of High and Low Aptitude Test Subjects in Hover MTE with Hybrid Configuration



Figure 37. 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 RCAH 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 TS4, the TLX rating for the hybrid configuration was 38. Again, the mental demand of the task was the most significant component of the workload. While the workload for this task is obviously significantly higher than was the case for TS1, it is important to note that this type of manoeuvre would constitute a small proportion of an overall PAV flight, and TS4 was still able to complete the manoeuvre successfully and with a high level of precision.

PAV response type requirements

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 RCAH configuration is clearly inappropriate for use in a future PAV. Test pilots (TPs) were not able to consistently award Level 1 HQRs in this configuration, and there was a very rapid reduction in achievable task precision and TPX as a pilot's aptitude reduced, leading to scenarios where the TSs were completely unable to control the vehicle when attempting precision tasks. This means that the range of pilots that would be able to safely fly the RCAH 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, making this configuration difficult to fly for prolonged periods of time.

Turning to the ACAH configuration, the TPs were able to award Level 1 HORs in the majority of cases. Precision and TPX were increased compared to the RCAH 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 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 RCAH configuration, this would prevent a large proportion of the pool of potential PAV users from doing so, although it is possible that with a moderate amount of training, TSs with a greater range of aptitude would be capable of performing well with this configuration.

Finally, the hybrid configuration is the only one tested where all TPs awarded Level 1 HQRs in all tasks. To date, only one TS (who recorded the lowest aptitude score of all) has been unable to achieve at least 98% 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), the minimum aptitude level for a PAV pilot would reduce from 10 for the ACAH configuration to 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 and skills development training. 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; a larger number of low aptitude TSs would need to be assessed to refine the figure.

The concept of making PAV flight the third-dimensional equivalent of driving a car was introduced at the start of this paper. While the results that have been presented do not permit a direct comparison to be made, one of the TSs (A=10.2, four hours of fixed-wing piloting time) anecdotally compared the challenge of the ACAH configuration to reversing a car into a parking space, and the challenge of the hybrid configuration to driving forwards into a parking space. A more detailed study of the workload comparison between road driving and PAV flight will be conducted in the continuing *myCopter* research.

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.

CONCLUSIONS

This paper has described an assessment of a range of potential 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 (RCAH configuration), attitude (ACAH configuration) and translational rate (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 which can be drawn from the work reported in this paper are as follows:

- From a handling evaluation with a pool of test pilots, the hybrid configuration was shown to be the most suitable, with Level 1 HQRs awarded by all test pilots for all tasks.
- Only the test subject with the highest aptitude score (A=11.9) was able to safely fly the RCAH configuration at the required level of precision; this configuration is therefore unsuitable for PAV use.
- A moderate aptitude score (A>10) was required for the ACAH configuration, limiting the proportion of the pool of potential PAV users who would be able to operate a PAV in this configuration.
- A relatively low aptitude score (A>8) was required for the hybrid configuration; this encompasses a majority of the test subjects assessed to date.
- The results for the hybrid configuration (from both the test pilots and the other test subjects) suggest that this is the configuration, of those developed so far, that is most suited to the requirements of a PAV.
- The psychometric testing process has been shown to be effective for quantitative assessment of piloting skill; good agreement has been found between the aptitude test scores and the subsequent piloted simulation results.

FUTURE WORK

As the *myCopter* project continues, the focus of the research will shift to examine the sensitivity of TSs to variations within the hybrid configuration – for example, to identify the optimum velocity rise time for the translational rate response type, or the set of inceptors required to achieve the best possible level of performance. The paper was introduced using the analogy that the PAV could become the car of the third dimension, in the sense of its potential widespread adoption and everyday use for commuting and similar roles. The relationship between the difficulty and workload associated with driving a car, and piloting a PAV, will be examined.

ACKNOWLEDGEMENTS

The work reported in this paper is funded by the EC FP7 research funding mechanism under grant agreement no. 266470. The authors would like to thank all those who have participated in the simulation trials reported in this paper for their contributions to the research.

REFERENCES

- Anon., Out of the Box: Ideas about the Future of Air Transport. Part 2, European Commission, Brussels, November 2007
- 2. Anon., *Transport Trends: 2009 Edition*, Department for Transport, London, 2009
- 3. Anon., *Energy, Transport and Environment Indicators, Eurostat Pocketbook*, EUROSTAT, Publications Office of the European Union, Luxembourg, 2009
- Anon., Green Paper Towards a new culture of urban mobility, COM(2007) 551 final, Commission of the European Countries, Brussels, September 2007
- 5. Anon., *Aerocar 2000*, 2002 [cited 2013 10th April]; Available from: <u>http://www.aerocar.com/</u>.
- Anon., Carplane Road/Air Vehicle, 2013 [cited 2013 10th April]; Available from: <u>http://www.carplane.com/</u>.
- Anon., *Terrafugia*, 2012 [cited 2013 10th April]; Available from: <u>http://www.terrafugia.com/</u>.
- Anon., PAL-V. Personal Air and Land Vehicle. 2013 [cited 2013 10th April]; Available from: http://www.pal-v.com/.
- 9. Carter, J., *CarterCopter -- A High Technology Gyroplane* in *American Helicopter Society Vertical Lift Aircraft Design Conference*. 2000, AHS: San Francisco, CA.
- 10. Anon., *Moller International*, 2013 [cited 2013 10th April]; Available from: <u>http://www.moller.com/</u>.
- 11. Anon., Urban Aeronautics X-Hawk Aerial Vehicle, 2013 [cited 2013 10th April]; Available from: http://www.urbanaero.com/category/x-hawk.
- Jump, M. et al, myCopter: Enabling Technologies for Personal Air Transport Systems, Royal Aeronautical Society conference "The Future Rotorcraft – Enabling Capability through the application of technology", London, UK, June 2011
- Jump, M. et al, myCopter: Enabling Technologies for Personal Air Transport Systems – An Early Progress Report, Proceedings of the 37th European Rotorcraft Forum, Gallarate, Italy, September 2011
- 14. Anon., Handling Qualities Requirements for Military Rotorcraft, ADS-33E-PRF, USAAMC, March 2000
- 15. Cooper, G.E. and Harper, Jr. R.P., *The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities*, NASA TN-D-5153, April 1969
- Hart, S.G. and Staveland, L.E., Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research, In P.A. Hancock and N. Meshkati (Eds.) Human Mental Workload. Amsterdam: North Holland Press, 1988
- 17. White, M.D., Perfect, P., Padfield, G.D., Gubbels, A.W. and Berryman, A.C., "Acceptance testing and commissioning of a flight simulator for rotorcraft simulation fidelity research", *Proceedings of the*

Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, Volume 227 Issue 4 April 2013 pp. 655 – 678, 2013

- Perfect, P., Jump, M. and White, M.D., Development of Handling Qualities Requirements for a Personal Aerial Vehicle, Proceedings of the 38th European Rotorcraft Forum, Amsterdam, Netherlands, September 2012
- Schönenberg, T., Design of a Conceptual Rotorcraft Model Preparing Investigations of Sidestick Handling Qualities, Proceedings of the 67th Annual Forum of the American Helicopter Society, Virginia Beach, VA, USA, May 2011
- Anon., *Garmin G1000*, 2013 [cited 2013 10th April]; Available from: http://www8.garmin.com/products/g1000/
- 21. Anon., *Peripheral Vision Horizon Display*, NASA Conference Publication 2306, November 1984
- 22. Chuang L.L., Nieuwenhuizen F.M. and Bülthoff H.H., Investigating Gaze Behavior of Novice Pilots during Basic Flight Maneuvers, International Conference on Human-Computer Interaction in Aerospace, Brussels, Belgium, 2012
- Carretta, T.R., Basic Attributes Tests System: Development of an Automated Test Battery for Pilot Selection, AFHRL-TR-87-9, US Air Force Human Resources Laboratory, September 1987
- 24. French, J.W., Ekstrom, R.B. and Price, L.A., *Manual* and *Kit of Reference Tests for Cognitive Factors*, Educational Testing Service, 1963
- 25. Blanken, C.L. and Pausder H.-J. "Investigation of the effects of bandwidth and time delay on helicopter rollaxis handling qualities", *Journal of the American Helicopter Society*, July 1994, 39, (3), pp. 24-33
- Perfect, P., White, M.D., Padfield, G.D. and Gubbels, A.W., "Rotorcraft Simulator Fidelity: New Methods for Quantification and Assessment", *The Aeronautical Journal*, Vol. 117, Number 1189, pp. 235-282, March 2013