Development of Handling Qualities Requirements for a Personal Aerial Vehicle

Dr Philip Perfect, p.perfect@liv.ac.uk
Dr Michael Jump, mjump1@liv.ac.uk
Dr Mark D. White, mdw@liv.ac.uk
The University of Liverpool (UK)

ABSTRACT

This paper describes progress that has been made in the European Commission funded project *myCopter* on the development of handling qualities requirements for future Personal Aerial Vehicles (PAVs). A generic PAV dynamics model has been developed to permit the simulation of a range of tasks that are representative of a typical PAV commuting role. The model has been configured to provide a number of different response types – with a constant control deflection commanding a constant angular rate, a constant attitude or a constant translational rate. Results from simulation trials with test pilots have shown that, of the response types investigated, the translational rate response is most suited for PAV pilots flying low speed tasks. Ongoing work will identify whether the response types selected with the test pilots remain valid for pilots with reduced levels of training – more akin to those expected for future PAV operations.

NOTATION

ACAH	Attitude Command, Attitude Hold
AGL	Above Ground Level
ARC	Acceleration Rate Command
DH	Direction Hold
EC	European Commission
FCMC	Flight Control Mechanical Characteristics
FP	Framework Programme
GPDM	Generic PAV Dynamics Model
HH	Height Hold
HQs	Handling Qualities
HQR	Handling Qualities Rating
HUD	Head Up Display
MTE	Mission Task Element
PATS	Personal Aerial Transportation System
PAV	Personal Aerial Vehicle
PPL	Private Pilot's License
RCAH	Rate Command, Attitude Hold
TC	Turn Coordination
TP	Test Pilot
TRC	Translational Rate Command
UoL	University of Liverpool
VRC	Inertial Vertical Rate Command
βC	Sideslip Angle Command
γC	Flight Path Angle Command

K_{lat}	Lateral control to roll attitude gearing
XA	Lateral control input
XB	Longitudinal control input
XC	Collective control input
XP	Pedal control input
ϕ_{cmd}	Commanded bank angle
ω_{lat}	Natural frequency of the lateral response
ζ_{lat}	Damping ratio of the lateral response

1. INTRODUCTION

Road networks in and around urban areas are becoming increasingly congested[1,2], leading to greater environmental and financial costs[3]. The 'Out of the Box' project[4] was funded by the European Commission (EC) to identify new concepts for the future of air transport in the second half of the 21st Century. Amongst the proposed new concepts was the development of a Personal Aerial Transportation System (PATS), which would take commuting traffic into the third dimension and hence help to alleviate many of the road traffic congestion problems faced by today's cities.

The EC Framework Programme (FP) 7 funded project *myCopter* aims to develop enabling technologies to support the future implementation of a PATS. Within the PATS concept of operations being used by the *myCopter* project, commuters will travel by air over relatively short distances of between 20 and 60 miles in a Personal Aerial Vehicle (PAV). For further details on the background to the project, the reader is referred to previous project publications[5],[6],[7].

While the form and function of any future PAV is undecided, a reference outline specification for such a vehicle has been generated to inform the *myCopter* research. This specification states that the vehicle will be small and light, with seating capacity for one or two (including the pilot) plus a small amount of baggage; will require vertical takeoff and landing capability; and would cruise at relatively low speeds (60-100kts) and altitudes (500ft AGL). A typical scenario in which the PAV might operate would be a commute from a home in a low population density environment (rural or suburban), to a place of work in a city centre, and *vice versa*. Particularly during peak times in the centre of the major cities, it is envisaged that the density of PAVs would exceed that found in current civil aviation by several orders of magnitude, creating challenges related to detection and avoidance of other PAV traffic.

1.1. The myCopter Project

The *myCopter* project is seeking to address a number of the technical and socio-economic challenges related to the PATS concept[6]. These challenges include:

- How much, and what type of, training should the PAV pilot receive?
- What should the handling characteristics of the PAV be when it is being flown manually?
- What are the requirements for the interface between the PAV pilot and the PAV?
- What level of computer assistance is required for the PAV to operate safely in regions of very high traffic density? Particular topics include:
    - Autonomous flight
    - Landing point detection/PAV localisation
    - Collision detection and avoidance
- How would a PATS come to be accepted by potential end-users?

For a PATS to become widely accepted, it is imperative that the cost-of-entry is reduced significantly in comparison to existing private aviation. In addition to the costs of running the aircraft itself, the cost of undertaking the necessary training required to acquire and maintain the PPL is very significant. Hence, it is seen as being highly desirable to be able to reduce the amount of training required by a PAV pilot (to a level that might be termed ‘minimal training’). One method of achieving this is to allow the PAV to operate autonomously, while an alternative is to confer on the PAV Handling Qualities (HQs) such that the necessary level of skill required to operate the vehicle safely is significantly reduced when compared to a traditional fixed- or rotary-wing vehicle.

Handling Qualities requirements for conventional air vehicles have been under continuous development for many years, particularly in the US military. The results of this research have been formalised in a number of publically-available standards[8,9,10]. For a PAV, however, these HQ requirements are not necessarily appropriate. Not only do the standards pertain principally to military aircraft while the PAV fulfils a civilian role, but the standards assume that the pilots who will be operating the aircraft are fully trained in the conventional sense. For a PAV, where the emphasis is on reducing the training burden, it is envisaged that the vehicle must be significantly “easier” to fly than a conventional aircraft.

As part of the *myCopter* project, the University of Liverpool (UoL) is seeking to establish HQ requirements for future PAVs flown by minimally-trained pilots. The requirements contained in the existing standards[8],[9],[10] are being taken as a starting point, and their validity to the PAV role examined. Where necessary, new criteria will be developed that are specific to the PAV. In addition to the HQ requirements, the types and level of training required for the operation of PAVs are also being examined.

In the first instance, this process involves the determination of the vehicle response types that are required to allow pilots of differing levels of training to successfully complete tasks that would form part of the PAV’s ‘mission’. Subsequently, the research will be extended to determine the qualities that are required of each of the identified response types.

1.2. Paper Overview

This paper reports on the progress to date with the development of PAV HQ criteria. This includes the assessment of a wide range of vehicle response types with test pilots, and the extension of testing to pilots with lower levels of training. The paper begins with a discussion of the methodology that has been adopted for this process, followed by descriptions of the generic PAV simulation that is being used in the research and the tasks that are being flown. Results from the simulation trials with test pilots are then presented, and the paper is drawn to a close with a discussion of the results, a description of the upcoming work and some concluding remarks.

2. HANDLING QUALITIES ASSESSMENT METHODOLOGY FOR PAVS

Traditional HQ evaluations involve test pilots (TPs), and it is common practice to employ the Cooper-Harper Handling Qualities Rating (HQR) Scale[11] to allow the TP to make subjective judgements regarding the ease and precision with which a prescribed task can be flown. However, effective use of the HQR scale is limited to those practitioners who have been trained specifically in its use. For the purposes of the research being described in this paper, evaluations exclusively using TPs cannot comprehensively identify those characteristics that are suitable for a minimally-trained PAV pilot. It is instead a requirement that pilots of this low level of training are used to verify the quality of a given response type through demonstrating their ability to complete tasks.

In addition, the HQR scale was constructed on the basis that the outcome of a handling investigation would be an aircraft that would be flown by a well trained pilot. These factors mean that the HQR scale cannot be the sole tool used to determine the HQs suitable for a PAV. However, in much the same way that better HQRs indicate a conventional rotorcraft that will be easier for a pilot to fly, it may still be anticipated that better HQRs would be indicative of a vehicle that is more suitable for a PAV pilot. Other rating systems exist, such as the NASA Task Load Index (TLX)[12] or Bedford Workload Rating Scale[13], which allow an evaluator to make judgements on some aspects of the handling characteristics of a vehicle without the extensive training necessary to award HQRs. They do not, however, provide direct measurement of the HQs of a vehicle.

An alternative methodology is under development in the *myCopter* project to facilitate the determination of the HQ requirements for a future PAV. In this methodology, traditional assessments of the vehicle's HQs by TPs will play a part, but the performance of pilots with reduced levels of flight training will also form a key component of the assessment.

The stages of the HQ assessment process for PAVs may be summarised as follows:

i. Test pilots award HQRs in the conventional sense to quantify the basic handling characteristics of the vehicle
ii. Pilots with varying levels of training repeat the tasks and comment on their difficulty, through use of scales such as the NASA TLX
iii. The control activity used during each task and the precision of task performance achieved are compared across the different pilots. Indications of inadequate HQs are provided by large differences between the results for the pilots with reduced levels of training and the test pilots

This process makes it possible to assess the level to which pilots with differing training backgrounds can adapt to and fly each task successfully and accurately. It is expected that for HQs which are suitable for a PAV, the difference in precision and workload will be minimal across all pilots – no matter the level of training and experience, a trainee will be able to fly the vehicle with the same level of performance and repeatability as the test pilots. In contrast, assessment of those HQ characteristics that are unsuitable for a minimally trained operator will result in much larger differences between the pilots.

Within a cohort of pilot test subjects, even those with similar training backgrounds, there will exist a significant variation in their levels of skill and aptitude towards flying PAV tasks. This is even more so the case when we examine those 'pilots' with little or no formal aviation training. In this category will fall test subjects who show excellent coordination and considerable experience of 'flying', for example in video games. At the same time, this category also includes test subjects with no experience of video games, or indeed other hand-eye coordination tasks such as driving a car.

It is therefore necessary to look beyond simple categorisation of test subjects via their training backgrounds. Instead, a process of measuring the natural aptitude of each test subject towards flying has been adopted. Here, the ability of each test subject to perform fundamental exercises, such as spatial recognition, memory recall, decision making and coordination are assessed and the subject is awarded a 'score'. The higher the score, the more naturally suited to the flying tasks that test subject should be. This is a similar process to that used by many airlines and Air Forces across the world to select their pilots[14].

The resultant output from the HQ assessment process will be charts of change in performance and workload against aptitude (measured relative to the TPs) for each response type/handling characteristic under investigation. Using these charts, decisions may be made regarding permissible performance differences between the TPs and other subjects, and hence the level of aptitude required to accomplish the tasks with each handling characteristic.

The final stage in the process is therefore to study the amount of training required to bring an acceptable proportion of the test subject cohort to the target skill level, the results from which will allow a correlation between required training and allowable HQs to be made.

This paper reports on progress made to date in the first stage of the HQ assessment process – that of assessing HQ characteristics with TPs. In a traditional HQ evaluation, a vehicle response is considered to be acceptable if Level 1 HQs are demonstrated (i.e. the HQRs awarded fall in the range 1-3). This of course assumes that the pilots who will fly the vehicle in service are well trained. For the PAV, with the requirement that its pilots must have a minimal amount of training, it is expected that the vehicle must exhibit much better handling qualities than may be expected of a traditional rotorcraft. The target has been set for the PAV to ideally reach HQR=1 ("*Excellent handling characteristics; Pilot compensation not a factor for desired performance*"[8]) for all tasks prior to performing assessments with the other categories of pilot. An important component of the ongoing research will be to evaluate whether this is an acceptable standard for the PAV, or whether a new, more stringent, requirement must be introduced. Additionally, the research will seek to validate the methodology described in this section as a suitable method for the assessment of PAV HQs.

3. GENERIC PAV SIMULATION

As noted above, the *myCopter* PAV is a concept for the future. This means that flight simulation must play a key role in developing an understanding of the required HQs for it. As no actual vehicle exists, it is not possible to construct a traditional physics-based flight dynamics model. Instead, a 'Generic PAV Dynamics Model' (GPDM) has been developed at UoL within the *myCopter* project. Rather than modelling the aerodynamic forces and moments produced by each component of the vehicle, the GPDM directly computes the angular response (pitch, roll, yaw) to the pilot's control input using low-order transfer functions (see Eq. 1 for roll dynamics)[17]

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

The rotational dynamics provide the pilot with control over the model in three axes. Changing the structure of the transfer function model allows either a rate or an attitude response type to be configured (see below). Additional response types can be provided by implementing outer loop controllers around these basic inner loop responses. A fourth axis of control is provided by a controllable 'lift' force acting in the body vertical axis. The rotation of this force generates the horizontal accelerations used to manoeuvre the vehicle. The lift force is combined with the output from the angular dynamics modelling (i.e. the Euler angles) and is used as input to a set of standard rigid body equations of motion[15,16] which calculate the translational (surge, sway and heave) dynamics of the model.

This structure provides a number of key advantages for the PAV HQ work:

- Easy to configure the model to confer different HQs & response types

- Possible to configure the model by specifying the desired HQs[17]
- Outer control loops for highly-augmented flight can be implemented quickly

The GPDM has been implemented in two different software environments; MATLAB/Simulink and FLIGHTLAB[18]. The first allows the model to be easily shared amongst the *myCopter* project partners, while the latter enables the model to be fully integrated into the UoL flight simulators, HELIFLIGHT[19] and HELIFLIGHT-R[20], for pilot-in-the-loop simulation.

To date, the GPDM has been configured to offer a wide range of response types. These include:

- Pitch:
    - Rate Command, Attitude Hold (RCAH) – a constant deflection of the pilot's control creates a constant pitch rate;
    - Attitude Command, Attitude Hold (ACAH) – a constant deflection of the pilot's control creates a constant pitch attitude;
    - Translational Rate Command (TRC) – a constant deflection of the pilot's control creates a constant vehicle velocity;
    - Acceleration Rate Command (ARC) – a constant deflection of the pilot's control creates a constant rate of change of the vehicle's velocity;
- Roll:
    - RCAH – as above;
    - ACAH – as above;
    - TRC – as above;
- Yaw:
    - Rate Command (RC) – a constant deflection of the pilot's control creates a constant yaw rate;
    - Sideslip Command (βC) – a constant deflection of the pilot's control creates a constant sideslip angle;
    - Turn Coordination (TC) – the vehicle will automatically maintain zero sideslip during turning manoeuvres unless the pilot applies a pedal control input;
    - Direction Hold (DH) – a pilot-selectable function to maintain a constant heading through any vehicle manoeuvring;
- Heave:
    - Body Vertical Rate Command (RC) – a constant deflection of the pilot's control creates a constant rate in the vehicle's body heave axis;
    - Inertial Vertical Rate Command (VRC) – a constant deflection of the pilot's control creates a constant rate in the inertial vertical axis;
    - Flight Path Angle Command (γC) – a constant deflection of the pilot's control creates a constant vertical flight path angle change;
    - Height Hold (HH) – a pilot-selectable function to maintain a constant height through any vehicle manoeuvring;

The US Military Rotorcraft Handling Qualities design specification, ADS33-E-PRF[8] requires a rotorcraft to exhibit certain response types under different visual conditions. For a good visual environment, a rate response type in each axis is acceptable for Level 1 handling, while only in a very poor visual environment is a TRC response type required for Level 1 HQs. It is anticipated that, for a PAV, the required basic level of augmentation will be significantly higher than this under all visual conditions due to the limited nature of the training received by future PAV pilots. The work being described in this paper is seeking to determine which of the existing HQ criteria, such as those of ADS-33E-PRF, remain applicable to PAV operations. Where the existing criteria are found not to apply to the PAV, the research will examine what the new response type requirements should be.

Each of the response types is best suited to certain types of task in certain parts of the flight envelope, depending on the relative levels of agility and precision required in a task. This has lead to the development of a version of the GPDM where the expected 'optimum' response type is automatically provided to the pilot depending on the flight condition. For example, in hover and low speed flight (<15kts), the model will provide TRC for pitch and roll, RC+DH in yaw and VRC+HH in heave. In cruising flight, this transitions to ARC in pitch, ACAH in roll, βC+TC in yaw and γC+HH in heave. This system will be referred to as the 'Hybrid' response type in the remainder of the paper.

For pilot-in-the-loop simulations, the GPDM has been implemented on simulators at a number of the *myCopter* project partners: HELIFLIGHT-R[20] at UoL, the Cybermotion simulator[21] at the Max Planck Institute for Biological Cybernetics (MPI-BC), and at the German Aerospace Research Centre (DLR).

HELIFLIGHT-R (Figure 1) is being used as the primary research tool for the HQs components of the *myCopter* project. It was commissioned in the School of Engineering at UoL during the summer of

2008. The key features of the simulator are as follows:

- 12ft visual dome with 3 LCoS HD projectors on gimballed mounts to provide up to 210x70 deg field of view (FoV);
- Interchangeable crew stations with front pilot and co-pilot seats and a rear engineer seat;
- Moog FCS ECoL 8000 Q&C-Line electric control loading system four-axis control loading;
- Moog MB/E/6dof/24/1800kg electric motion system
- Instructor-Operator Station in separate control room
- Reconfigurable instrument panel displays (left and right primary flight displays, backup analogue displays and Head Up Display (HUD));
- FLIGHTLAB multi-body dynamics modelling is the primary software tool, but HELIFLIGHT-R is flexible and any simulation package can be interfaced with the simulator hardware;

Figure 1: HELIFLIGHT-R Simulator at UoL

In addition to the vehicle flight dynamics, other factors that can influence the perceived HQs of a vehicle are also being investigated, including display symbology (Head Up/Head Down displays) and inceptor type and feel characteristics. A set of basic head-up symbology used during the TP trials is shown in Figure 2. The symbology was developed to be more akin to that found in current automotive, rather than aerospace, applications[22], with simplicity of the information displayed at the centre of the concept – the driver/pilot is not required to interpret large amounts of data to extract the one parameter that is relevant at that particular point.

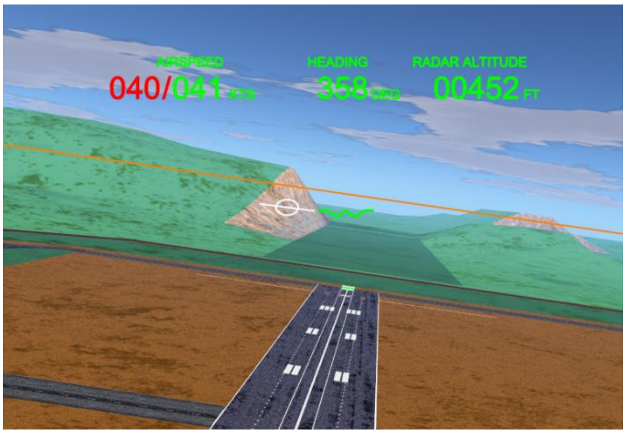

Figure 2: Basic HUD, showing commanded velocity (in red) and actual velocity, heading and altitude values, horizon reference and markings for boresight and flight path vector

4. PAV TASKS

The handling qualities of the PAV model are being investigated using a series of tasks that have been developed from a reference PAV commuting scenario. The PAV begins its flight in a rural or suburban region (small number of ground obstacles; low traffic density) and flies to the centre of a city business district (large number of ground obstacles; high traffic density)[6]. From this basic scenario, a series of Mission Task Elements (MTEs) have been developed, with a subset of these being selected for the purposes of the current investigation. The focus in the present work is on hover and low speed tasks, and the transition between hover and forward flight. Operations close to ground obstacles are typically critical for the determination of a vehicle's HQs. A future phase of work will investigate HQ requirements for forward flight tasks. Where possible, the MTEs have been developed from those contained within ADS-33E-PRF[8], with suitable adaptations to the performance requirements to reflect the civilian nature of the PAV role. The MTEs are described in more detail in the following Sections.

4.1. Steady Hover

The Steady Hover MTE investigates the ability of the PAV to capture and maintain a fixed ground-referenced position with precision. It examines the stability and controllability of the vehicle when operating in confined areas. The manoeuvre consists of the vehicle approaching the target hover point at an angle of approximately 45°, capturing the target position smoothly, and then maintaining that position for a further 30 seconds. The test course used to assess Steady Hover performance is shown in Figure 3. The performance standards used for the award of HQRs are shown in Table 1.

Figure 3: Steady Hover Test Course

Table 1: Steady Hover Performance Requirements

Parameter	**Desired**	**Adequate**
Attain stable hover within X seconds of reaching the target position	5	8
Maintain position within ±X feet of the target position	3	6
Maintain heading within ±X°	5	10
Maintain height within ±X ft	2	4

4.2. Vertical Reposition

The Vertical Reposition MTE allows the heave axis HQs of the PAV to be assessed, and identifies any inter-axis coupling between heave and the other axes of control. The task requires the PAV to climb or descend through a height change of 30ft within a fixed period of time whilst maintaining a fixed position relative to the ground. The test course used for this MTE is shown in *Figure 4*, and the performance standards in Table 2.

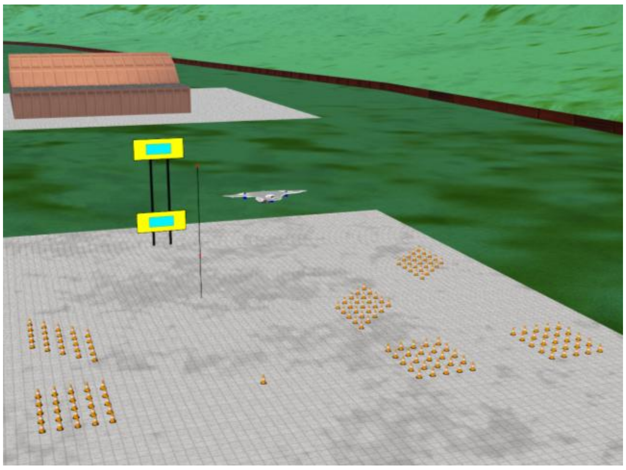

Figure 4: Vertical Reposition Test Course

Table 2: Vertical Reposition Performance Requirements

Parameter	**Desired**	**Adequate**
Maintain position within ±X feet of the target position	5	10
Maintain heading within ±X°	5	10
Capture height within ±X ft	2	4
Complete the task within X seconds	10	15

4.3. Landing

The Landing MTE assesses the HQs of the PAV when the pilot is forced into a tight compensatory tracking task – achieving the precise touchdown point. The manoeuvre consists of the PAV being positioned above a target landing point, before a vertical descent to the touchdown. The test course used for the Landing MTE is shown in Figure 5, and the performance requirements associated with the task are shown in Table 3.

Figure 5: Landing MTE Test Course

Table 3: Landing Performance Requirements

Parameter	**Desired**	**Adequate**
Accomplish a smooth touchdown with no objectionable oscillations	✓	N/A
Complete landing from 10ft within X seconds	10	N/A
Touch down within ±X ft longitudinally of target point	1	3
Touch down within ±X ft laterally of target point	0.5	3
Touch down with heading within ±X° of target heading	5	10

4.4. Decelerating Descent

The Decelerating Descent MTE represents the transition from cruising flight to hover at a landing point. The task investigates flight path control, coordination of the pitch and heave axes, and, in the case of the 'Hybrid' response type, the "smoothness" of the transition between the forward flight modes and the hover modes. The task begins with the PAV in forward flight at 60kts, at a height of 500ft. At the correct position (indicated by passing over a line marked on the ground), the pilot initiates a descent along a 6° glideslope to a marked hover point. Simultaneously, the pilot should begin to decelerate the PAV in such a way that both the height change and speed change are completed together, at the marked hover point. The course used for the Decelerating Descent MTE is illustrated in Figure 6, and the performance requirements are listed in Table 4.

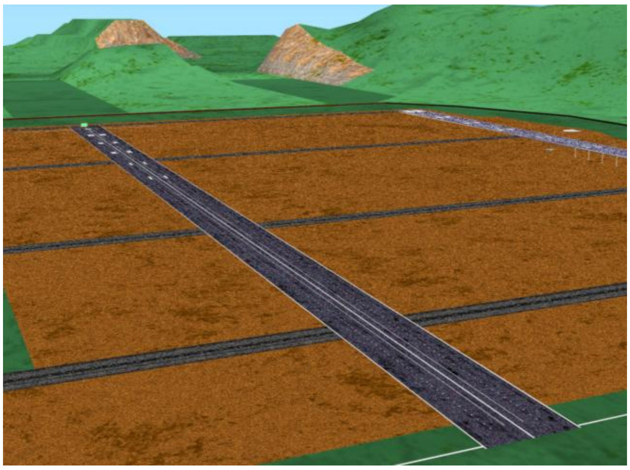

Figure 6: Decelerating Descent Test Course

Table 4: Decelerating Descent Performance Requirements

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

4.5. Aborted Departure

The Aborted Departure MTE represents an emergency scenario where an obstacle appears ahead of the PAV during a normal departure. Due to the emergency nature of this task, the requirement is for the PAV to manoeuvre aggressively. The vehicle is initially accelerated to a speed of 40kts, at which point the pilot is requested to abort and return the vehicle to a hover as rapidly as possible. The test course used to fly the Aborted Departure MTE is shown in Figure 7, and the performance requirements are listed in Table 5.

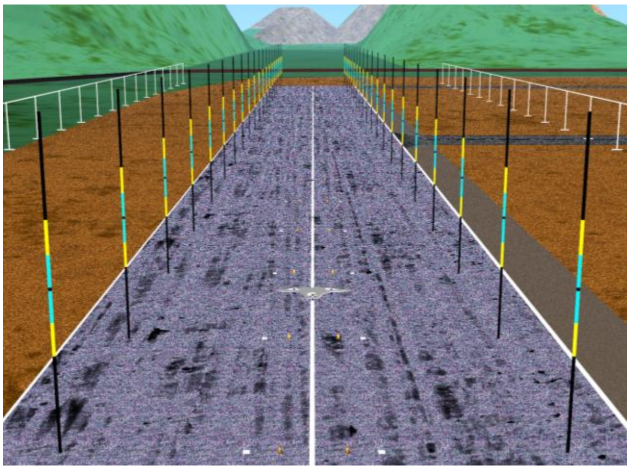

Figure 7: Aborted Departure MTE Test Course

Table 5: Aborted Departure Performance Requirements

Parameter	**Desired**	**Adequate**
Maintain lateral position within ±X ft	10	20
Maintain heading within ±X°	10	15
Maintain height within ±X ft	10	20
Complete task within X sec	25	30

5. RESULTS

A total of four simulation trials involving five test pilots have been conducted to date, examining a range of PAV response types. The configurations assessed are shown in Table 6, which lists the response type in each axis together with the vehicle speed range (in knots) over which those response types are active.

Table 6: GPDM Configurations

Config.	**V**	**Pitch**	**Roll**	**Yaw**	**Heave**
RCAH	All	RCAH	RCAH	RC	RC
ACAH v1	All	ACAH	ACAH	RC	RC
ACAH v2	≤15	ACAH	ACAH	RC+DH	RC+HH
	>15	ACAH	ACAH	βC+TC	RC+HH
Hybrid	≤15	TRC	TRC	RC+DH	VRC+HH
	>15	ARC	ACAH	βC+TC	γC+HH

For the first phase of the PAV HQs work, the objective has been to identify the response types that are required to permit minimally-trained PAV pilots to successful fly the vehicle. For this reason, the HQs were configured to offer an optimum response to the pilot's controls. In the cases of the RCAH and ACAH pitch and roll response types, together with the RC responses in yaw and heave, this was achieved by exceeding the 'Level 1' predictive requirements contained in ADS-33E-PRF[8]. For the remaining response types, the HQs were tuned during the initial piloted simulation trials. For each case where a response type is noted as being of the same type in Table 6 above, the HQs of that response were configured to be the same.

5.1. Example Responses

A selection of the responses that were used during the TP simulation campaign are shown below in Figure 8, Figure 9, Figure 10 and Figure 11. The figures show that, in each case, the response types defined in Section 3 above are delivered for the GPDM.

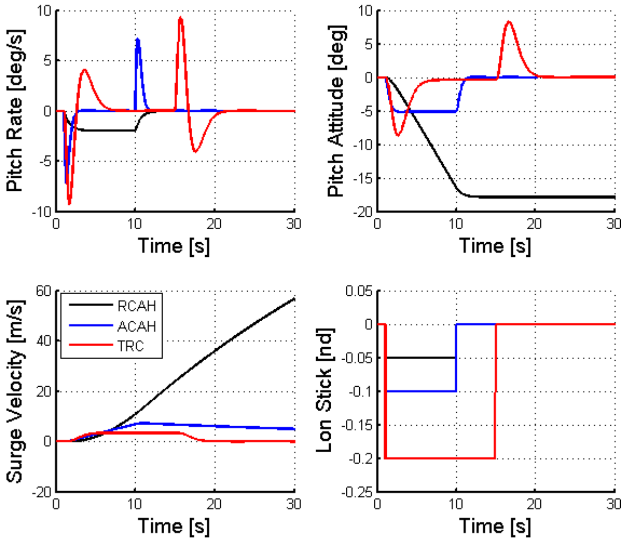

Figure 8: Pitch Axis Responses – RCAH, ACAH and TRC

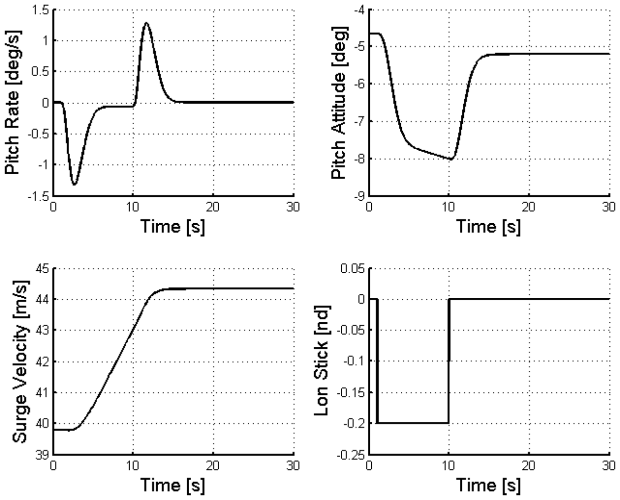

Figure 9: Pitch Axis Response – ARC

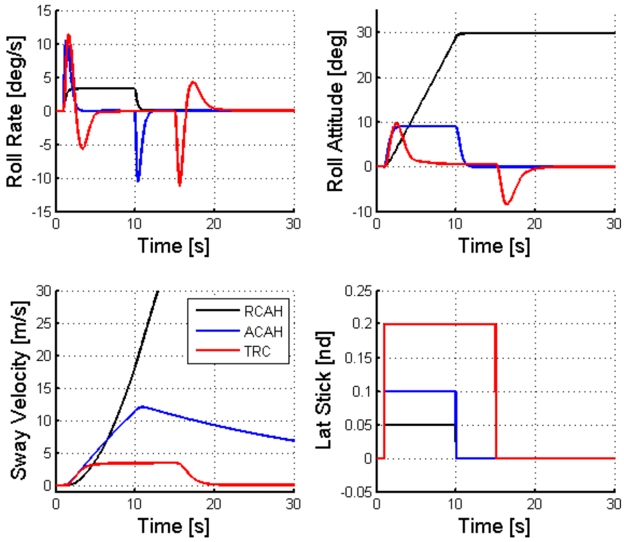

Figure 10: Roll Axis Responses – RCAH, ACAH and TRC

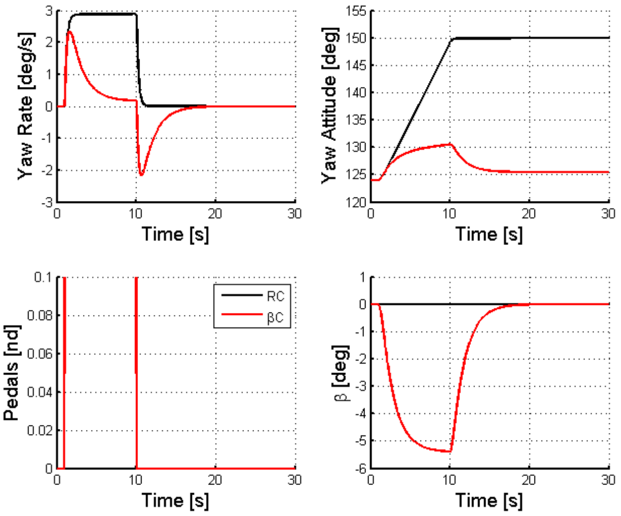

Figure 11: Yaw Axis Responses – RC and βC

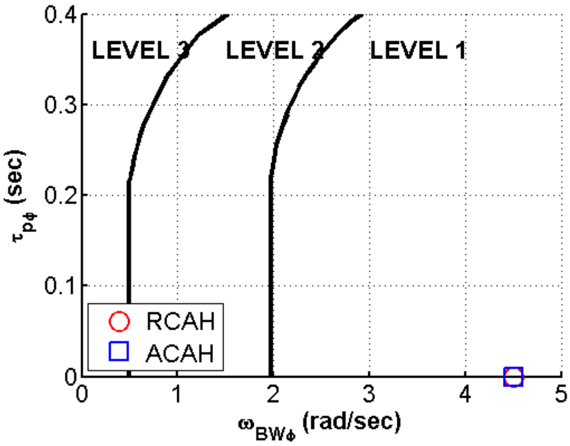

Figure 12: Roll Bandwidth of RCAH and ACAH Response Types

The figures above demonstrate that the 'shape' of each response matches the definition of the response type in Section 3, but do not quantify the 'quality' of the response. The next Section details predictions of the HQs for each of the traditional responses (RCAH, ACAH, RC). This has been performed using ADS-33E-PRF metrics.

5.2. Predicted Handling Qualities

As noted above, the GPDM was configured to confer Level 1 HQs according to the ADS-33E-PRF specification. Although ADS-33E-PRF is not directly applicable to the PAV role, the metrics contained in the document provide a useful method of quantifying responses, and permit comparisons between different responses to be made. The ongoing *myCopter* research will seek to evaluate the applicability of the Level boundaries placed on these metrics (originally developed for conventional rotorcraft) to the PAV mission.

Figure 12 and Figure 13 show the predicted HQs for the roll axis of the RCAH and ACAH systems, while Figure 14 and Figure 15 do the same for the pitch axis. Figure 16 and Figure 17 detail the predicted HQs in the yaw axis. Note how the HQs were configured, to the greatest extent possible, to be the same across both inner loop response types. Some differences are observed in the Attitude Quickness parameter (particularly in roll) due to differences in the structure of the inner loop response types.

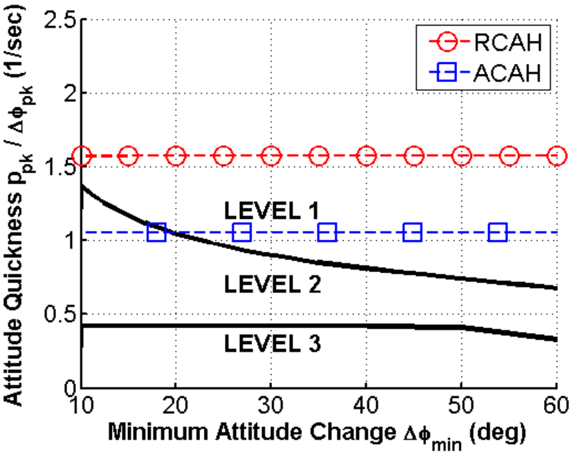

Figure 13: Roll Quickness of RCAH and ACAH Response Types

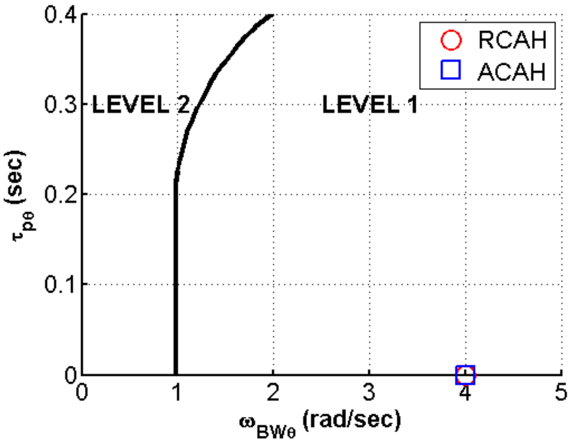

Figure 14: Pitch Bandwidth of RCAH and ACAH Response Types

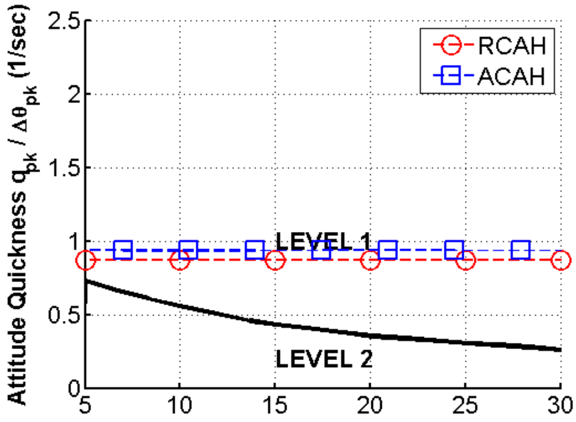

Figure 15: Pitch Quickness of RCAH and ACAH Response Types

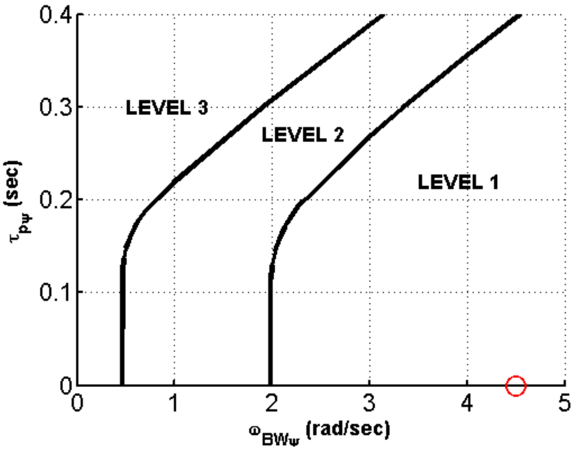

Figure 16: Yaw Bandwidth of RC Response Type

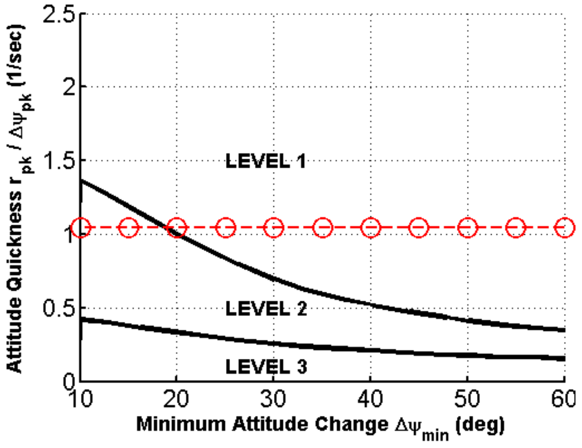

Figure 17: Yaw Quickness of RC Response Type

For the TRC response type, the underlying ACAH dynamics were identical to those described above. The pitch and roll axes were both configured to give a rise time (the time to reach 63.2% of the final steady state velocity) of 2.5 seconds. This is the smallest value in the range specified by ADS-33E-PRF for Level 1 handling. However, ADS-33E-PRF further specifies that the attitude changes during transition from one velocity to a second with a TRC response type shall not be 'objectionable'. The evaluating TPs felt that, at a 2.5s rise time, the pitch and roll attitude changes were acceptable (Figure 8 and Figure 10), but additionally, that the vehicle may be easier to control if the attitude changes were smaller. This topic will be returned to in the Discussion Section later in the paper.

5.3. Piloted Simulation Results

A summary of the Handling Qualities Ratings (HQRs) awarded by the evaluating Test Pilots (TPs) for the five PAV manoeuvres is shown in Table 7. Here, the HQRs from each of the evaluating pilots have been averaged to give a single rating for each task. Not all tasks were flown by all pilots – the ACAH v2 configuration for example being assessed by just two pilots in the most recent of the simulation trials.

Table 7: Mean Handling Qualities Ratings for PAV MTEs

	Mean HQR			
Task	**RCAH**	**ACAH v1**	**ACAH v2**	**Hybrid**
Steady Hover	4.67	3.7	3.5	2.25
Vertical Reposition	Not Flown	3.5	4	2.25
Landing	Not Flown	5	5	2.5
Decelerating Descent	Not Flown	3	3	2.25
Aborted Departure	3	3	2	1.75

The mean HQRs in the results table provide a strong indication that the RCAH and ACAH response types are unsuitable for PAVs, as the averaged HQRs are well below the HQR=1 target. In both cases, the HQRs were typically in the borderline region between Level 1 and Level 2 handling (HQRs 3-5). Only the Hybrid configuration reached Level 1 across all five tasks. Indeed, none of the pilots was drawn to award a Level 2 HQR (HQR>3) to the Hybrid configuration for any of the tasks. Despite the preference of the TPs for the Hybrid configuration over the other options, this result does not meet the objective defined previously of HQR=1 for all tasks. Analysis of the simulation recordings, however, provides strong evidence that the response types of the Hybrid configuration are those most suited for the PAV. Example results will be presented in this Section.

The results table also shows that some tasks are inherently more demanding than others, with poorer HQRs awarded across all GPDM configurations. This is especially the case with the Landing MTE, where a very high level of precision is required at the touchdown point. One consideration in the determination of HQ requirements for PAVs is whether certain tasks place too great a demand on the minimally trained pilot no matter what level of HQs the vehicle exhibits. In these cases, it may be necessary for the PAV to be completely automated to achieve the required level of safety. It should, however, be noted that the degradation in HQRs for the Landing MTE was significantly lower with the Hybrid configuration than with the other model options. This may suggest that achievement of the correct response type could allow the minimally trained pilot to successfully fly all tasks. This topic is an active area of research within the *myCopter* project.

A selection of results from the piloted simulation trials will now be presented to demonstrate the differences between the response types and to show the reasons for the award of specific HQRs.

5.3.1. Steady Hover

The Steady Hover MTE is a good example of a task that requires a vehicle capable of being flown with a high level of precision. Figure 18 shows the plan position of one of the TPs flying the Steady Hover in the ACAH v1 configuration and in the Hybrid configuration. To allow a fair comparison to be made between the two sets of responses, in this case, the pilot was instructed not to make use of the height hold and direction hold functionality that would otherwise have assisted in the Hybrid configuration.

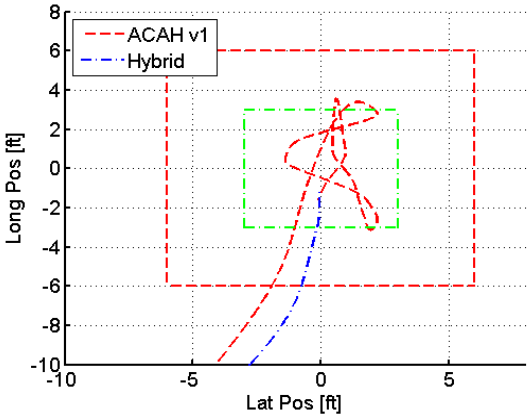

Figure 18: Position Keeping During Steady Hover Task

It is evident in Figure 18 that the ACAH response type required the pilot to apply continuous corrections to the vehicle's position to remain within the desired performance tolerances (Figure 19) for the task (shown in green on Figure 18). Although the precision of the hover improved during the thirty seconds of the task, at no point did the pilot reach the point where the vehicle was maintaining its position without further corrective control inputs. Considering the Hybrid configuration, the pilot was able, through progressive deceleration across the five second period permitted by the task, to bring the vehicle directly to a hover within the desired performance tolerances. With the TRC response type, at the point that the pilot releases the controls with the vehicle stationary, the system will automatically maintain position with respect to ground objects. The benefit of this response can be seen in Figure 19 – once the vehicle has been brought to rest, the pilot applies no further control inputs in either the lateral axis (XA) or the longitudinal axis (XB).

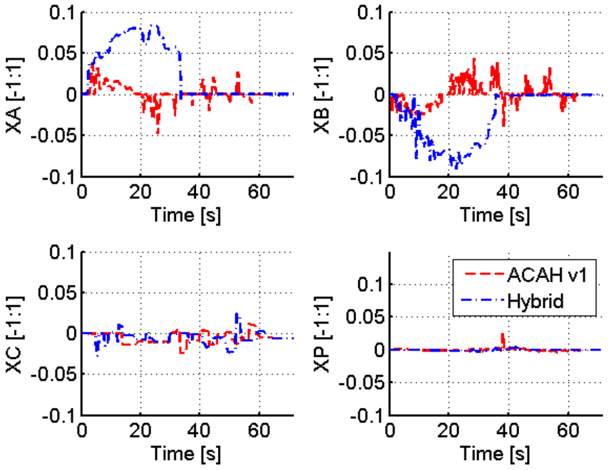

Figure 19: Pilot Control Activity During Steady Hover Task

With the Hybrid configuration, the peak physical workload (measured through quantitative analysis of the pilot's control activity[23],[24]) can actually be seen to occur during the initial phase of the task (first 10seconds), where the pilot is accelerating the vehicle away from a starting hover along the desired 45° trajectory. Once this has been established, the workload reduces for the remainder of the manoeuvre. In contrast, with the ACAH v1 configuration, the workload is relatively continuous throughout the task. This can be seen more clearly in Figure 20, which shows the rate at which the pilot applied control inputs during the task with both configurations. At no point during the task was the pilot applying more control inputs in the Hybrid configuration than he was in the ACAH v1 configuration.

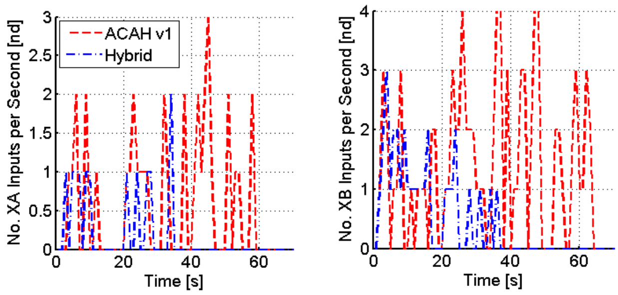

Figure 20: Number of Control Inputs per Second in Steady Hover Task

Discussion with the pilots following assessment of the Steady Hover MTE indicated that, in general, the Hybrid configuration's responses were highly suited to the hovering task. The primary reasons why this configuration did not receive better HQRs were felt by the pilots to be due to factors beyond the pure HQs of the vehicle. In particular, the way in which the pilot was being cued as to his position and trajectory, and the feel characteristics of the cockpit inceptors were highlighted. For the first of these deficiencies, Head-Up symbology (such as that illustrated in Figure 2) may be used to improve the cueing environment. However, this introduces a further consideration in terms of the dynamics of the flight path vector display. In the simulations to date, the HUD has directly displayed the current flight path of the vehicle. However, the symbology may be of greater use to the pilot if the HUD could indicate the position that the vehicle will be in at some point in the future, possibly employing guidance laws inspired by the natural principle of *tau*, the time-to-contact[25]. For the inceptor force-feel characteristics, the ongoing *myCopter* research will consider the effect on the PAV response types of both varying the control dynamics, and the effect of different types of inceptors – to date, traditional rotary-wing centre-stick and collective lever controls have been adopted, but this may not necessarily be the optimum cockpit layout for the PAV.

5.3.2. Aborted Departure

Table 7 shows that, for the Aborted Departure MTE, the mean HQR awarded to the Hybrid configuration was less than 2, signifying that one of the evaluating pilots awarded a HQR=1 for this task. Figure 21 shows the level of performance attained, and Figure 22 shows the control activity during this particular run. In this case, the pilot was instructed to make use of the height hold and direction hold functionality of the Hybrid configuration.

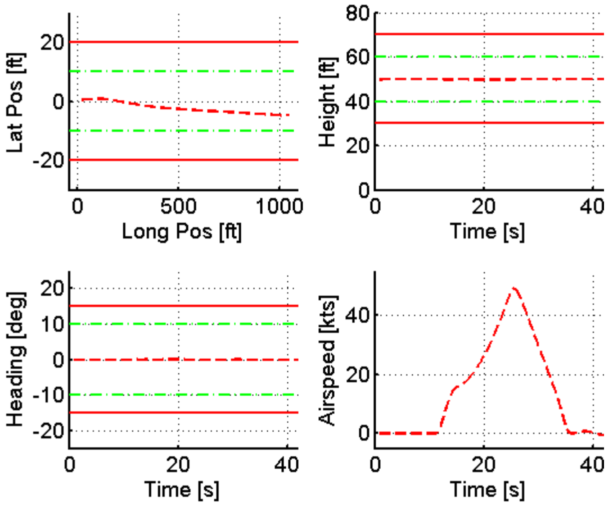

Figure 21: Hybrid Configuration Performance in Aborted Departure MTE

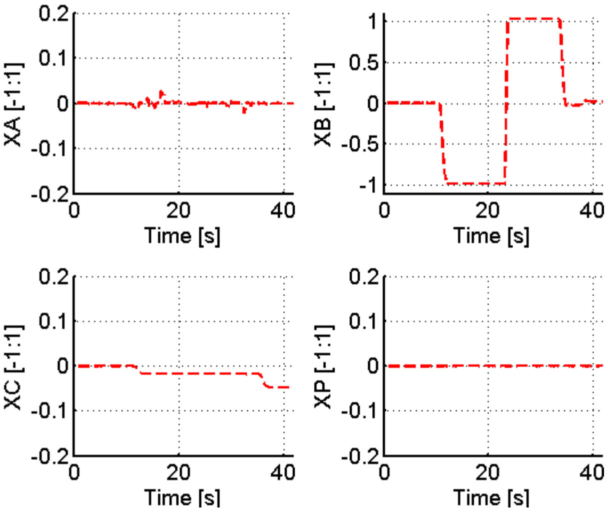

Figure 22: Pilot Control Activity with Hybrid Configuration in Aborted Departure MTE

The control activity (Figure 22) shows that the pilot was making minimal corrective inputs for the duration of the manoeuvre. This was especially the case in the longitudinal axis – the primary axis for this task. Here, the pilot found that it was possible to simply hold the stick fully forward until the desired velocity had been reached, at which point the stick was pulled fully back until the vehicle returned to the hover. Returning the stick to the neutral position at this point maintained the hover until the run was complete. The only source of compensatory control activity for this run was in the lateral axis. As the GPDM exhibits no coupling between any pair of axes, the disturbances in vehicle trajectory that required the pilot to correct with lateral control inputs would have been created by the pilot himself. With the existing inceptor configuration in the HELIFLIGHT-R cockpit, it is possible for the pilot to inadvertently apply small lateral control inputs whilst making large longitudinal inputs. Tuning of the Flight Control Mechanical Characteristics (FCMC; breakout forces, spring gradients etc.) helps to mitigate against this, but it has been found that FCMC that are optimum for the Aborted Departure MTE cause difficulties in other tasks, and *vice versa*. In the Aborted Departure MTE, for example, high cyclic breakout forces are desirable to limit the tendency for the pilot to inadvertently apply off-axis lateral control inputs. These high breakout forces, however, prevent the pilot from making small positional corrections in the Steady Hover and Landing MTEs. Identification of these optimum FCMC is another area of ongoing research within the *myCopter* project, and improvements here should lead to further reductions in the workload in the Aborted Departure MTE.

5.3.3. Decelerating Descent

The Decelerating Descent MTE is generally a low aggression and relatively low precision task, with the primary objective of assessing pitch and heave axis coordination. However, when the Hybrid configuration is under investigation, the Decelerating Descent additionally provides an opportunity to assess the GPDM during the transition between the forward flight modes and the hover and low speed modes.

During the development of the GPDM, a number of different methods of transitioning between the modes have been investigated. Two of these were felt to be worthy of formal evaluation with the TPs. These modes are as follows:

- Transition 1:
    - On acceleration from hover, the response type is switched from TRC to ARC at 15kts. The longitudinal control position for zero acceleration under ARC is configured to be the same as the longitudinal control position for 15kts under TRC. This requires the pilot to hold a constant force to maintain a constant speed. Under further acceleration to 25kts, the control position for zero acceleration is moved progressively to the neutral control position, so that zero applied force corresponds to zero commanded acceleration.
    - On deceleration from forward flight, the response type is switched from ARC to TRC at 15kts. The longitudinal control position corresponding to 15kts under TRC is configured to be the neutral control position. On further deceleration towards the hover, this is moved forwards so that the neutral control position corresponds to the command of 0kts, allowing the pilot to maintain position with no applied force on the controls.
- Transition 2:
    - On acceleration, transition 2 behaves identically to transition 1 described above.
    - On deceleration, the GPDM remains in ARC mode until the velocity has been reduced to almost zero (0.5kts). At this point, the response type switches to TRC. At all times during this decelerating transition, the neutral control position corresponds to either zero commanded acceleration (ARC mode) or zero commanded velocity (TRC mode).

Transition 1 was found to reasonably effective for general flight. However, when a requirement for either highly aggressive deceleration, or deceleration to stop at a specific point was made (such as during the Decelerating Descent MTE), the pilots found this transition to be somewhat uncomfortable, with some unexpected vehicle attitude changes due to decelerating more rapidly than the system design limit (see Figure 23 for an example of this). Transition 2 was found to be the more predictable of the two options in these scenarios.

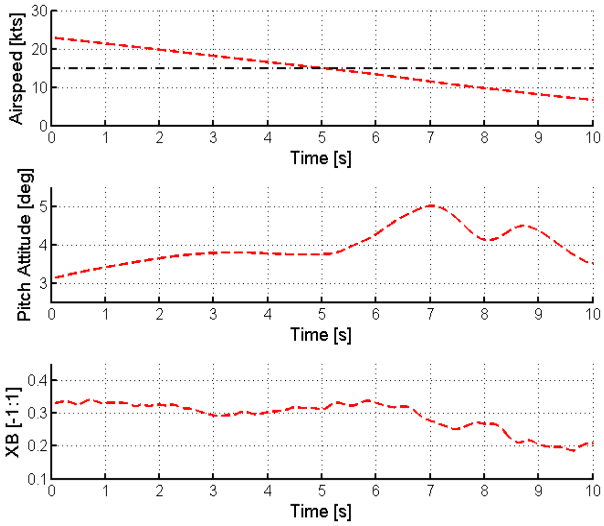

Figure 23: PAV decelerating through Transition 1, showing uncommanded pitch attitude change

Figure 24 and Figure 25 show that the achieved level of precision and workload during the Decelerating Descent MTE with these two transition methods is relatively similar. All other aspects of the vehicle configuration were held constant across the two runs.

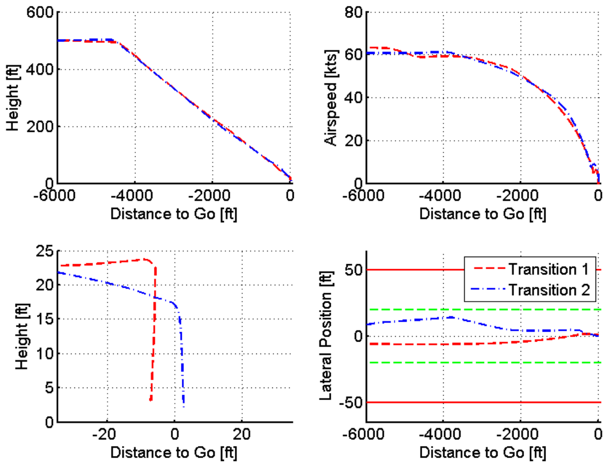

Figure 24: Performance Achieved During Decelerating Descent MTE

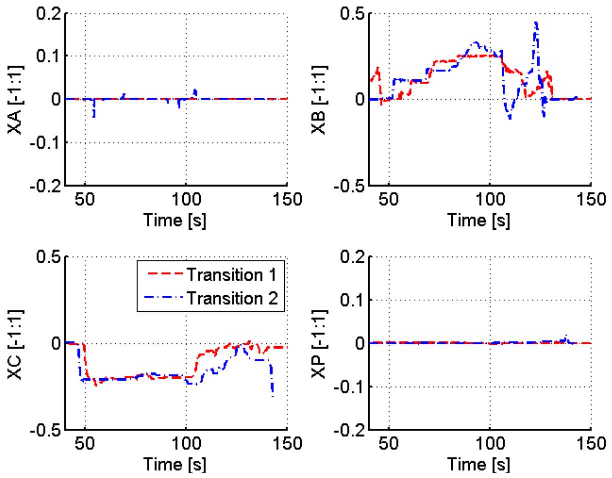

Figure 25: Control Activity During Decelerating Descent MTE

In both cases, the pilot was able to decelerate the vehicle smoothly to a stop at the target position. The workload required to achieve this was primarily focussed on the longitudinal axis – the flight path angle command response type proved to be effective at assisting the pilot with maintaining the target glideslope during the deceleration.

While the time histories (Figure 25) indicate that the level of control activity was similar for the two transitions, the improved predictability of Transition 2 was considered to be highly beneficial for this type of task, leading to the HQR improving from HQR=4 with Transition 1 to HQR=2.5 for Transition 2.

In the case of this MTE, the remaining sources of compensation were found to lie in judging the required profiles for the deceleration and descent. Beyond the flight path vector indicator on the HUD, the pilot is not currently provided with any additional cueing regarding distance remaining or the optimum airspeed at any point on the approach. Provision of a target speed value may be useful for the pilot in relieving this aspect of the task.

5.3.4. Landing

The Landing MTE was generally found to pose the greatest difficulty with all of the GPDM configurations (Table 7). This was due to the very high level of precision in lateral and longitudinal positioning required at the touchdown point. This led the pilots to apply excessively large control inputs in an attempt to track the target position. While the standard Hybrid configuration offered a significant improvement over the other systems in this task, the mean HQR was still poorer than for the other four MTEs.

One possible reason why this task proved to be more difficult than the other MTEs in the Hybrid configuration is that the attitude changes that occur when the pilot commands a new velocity give the pilot the impression that the vehicle is being destabilised. This provides the pilot with a reason to apply additional control inputs in an attempt to recover stability, when in actual fact these inputs are not necessary as the vehicle possesses sufficient stability to adjust itself automatically.

One of the pilots assessed a modified version of the Hybrid configuration in which the apparent vehicle pitch and roll attitudes were frozen, meaning the vehicle remained level throughout the task. All other vehicle dynamics (rise time of translational rate responses etc.) remained the same as in the basic Hybrid configuration. The effect on positional accuracy and control activity are shown in Figure 26 and Figure 27 below.

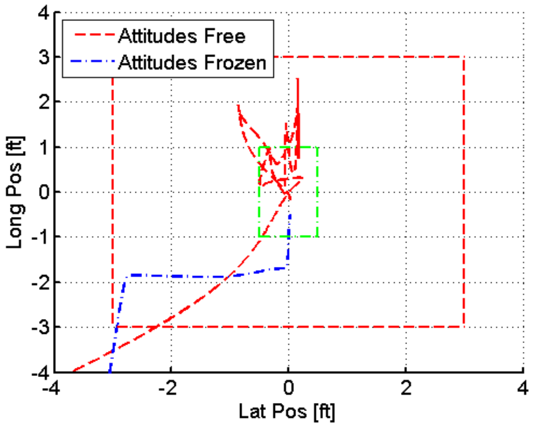

Figure 26: Positional Accuracy During Landing MTE

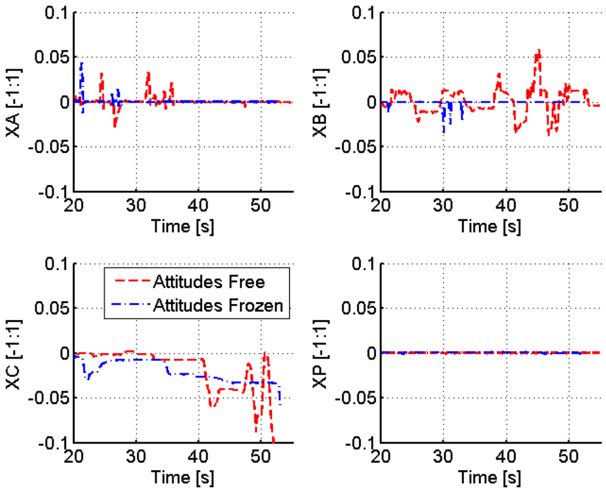

Figure 27: Control Activity During Landing MTE

It is evident that the pilot was able to acquire the target landing point much more readily when the vehicle attitudes were frozen. In contrast, there were a number of positional overshoots, particularly in the less well cued longitudinal axis (lateral task cues are located ahead of the pilot; longitudinal task cues in the pilot's peripheral vision) when the vehicle attitudes were free. This can also be seen in the control activity, with the pilot being required to correct continually in the longitudinal axis all the way to the touchdown point with the basic Hybrid configuration. With the modified configuration, after initially bringing the vehicle to a hover, the pilot found it was possible to immediately lower the collective lever and settle the vehicle onto the marked touchdown point.

The accuracy of the final touchdown point was similar for both configurations, but the higher level of workload lead this pilot to the award of a HQR=3 with the attitudes free to vary. With the attitudes frozen, this rating improved to HQR=2.

As it is no longer necessary to restrict the rise time of the translational rate response in order to minimise the attitude disturbances (as required by ADS-33E-PRF for example), an interesting possibility with the vehicle attitudes frozen is that it becomes possible to significantly increase the rate at which the vehicle's velocity responds to the pilot's control inputs. Making improvements to the response rise time would be expected to have the effect of improving the apparent predictability of the vehicle, as the velocity will more rapidly follow the pilot's commands. Of course, a different method of generating the translational forces becomes necessary. The ability to vector the thrust used to lift the PAV would be required.

6. DISCUSSION

As a general trend, the handling results shown in Table 7 indicate that the Hybrid configuration will be significantly more suitable for minimally trained PAV pilots than either of the ACAH configurations or the RCAH configuration. At the same time, however, the results also show that the Hybrid configuration does not fully meet the target goal of HQR=1 for all tasks.

As the results presented in the previous Section show, in the majority of cases the primary reason for failing to achieve HQR=1 is not the responses of the vehicle itself, but rather, due to inceptor or cueing characteristics (HUD symbology) that did not fully assist the pilot with the task. Therefore, it is anticipated that the response types encapsulated within the Hybrid configuration are those required for PAV pilots. Further tuning of the simulation setup is expected to elicit improvements in HQRs for the majority of the tasks.

With the required response types identified, attention is now turning to the next phase of the research; that of repeating the tests with other categories of pilot. It is anticipated that, with the Hybrid configuration, the majority of pilots across all of the assessed levels of ability will be capable of completing the PAV MTEs successfully. In contrast, with the ACAH and RCAH configurations, it is anticipated that the majority of the test subjects will struggle to complete the tasks. Once this task has been completed, boundaries to permit the prediction of the HQs of each of the response types (through charts such as those shown in Section 5.2) will be determined for the PAV. This will be accomplished by progressively degrading the rapidity and magnitude of the responses to the pilot's controls until the point is reached that the pilots are no longer able to satisfactorily complete the tasks. Results from these phases of work will be reported in the near future.

7. CONCLUDING REMARKS

This paper has presented results from the early stages of the development of handling qualities requirements for future Personal Aerial Vehicles (PAVs), whose pilots will receive a reduced level of training prior to taking to the air.

A range of vehicle response types have been assessed, and it has been shown that, for hover and low speed tasks, a Translational Rate response type is highly beneficial in both the pitch and roll axes. In forward flight, other response types become more suited to the tasks that form the PAV mission. A 'Hybrid' configuration has been developed that confers the optimum response type in all areas of the flight envelope onto a PAV simulation.

The results presented in this paper show that, while the target of a Handling Qualities Rating of 1 for all tasks has not been met, the sources of additional compensation driving the pilots to the award of poorer HQRs were typically not the responses of the vehicle itself. Instead, the drivers lay in other aspects of the wider simulation, such as the inceptors used by the pilots to control the vehicle and the lack of additional cueing provided to the pilot through Head-Up symbology.

The ongoing *myCopter* PAV HQs research will employ pilots of varying levels of basic training to determine whether the response types identified in the work to date are indeed suitable for future PAV pilots, and hence, will validate the proposed methodology for this process.

8. ACHKNOWLEDGEMENTS

The work reported in this paper is funded by the EC FP-7 research funding mechanism under grant agreement no. 266470.

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