DEVELOPMENT OF OCCUPANT-PREFERRED LANDING PROFILES FOR PERSONAL AERIAL VEHICLE APPLICATIONS

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ABSTRACT

Previous studies using both rotorcraft and fixed-wing aircraft have indicated that providing the pilot with more intuitive physiological information can enhance task performance because of the increased level of pilot's awareness of aircraft orientation and workload required to control the aircraft. This will also be true for Personal Aerial Vehicles (PAV) operating in a Personal Aerial Transportation System (PATS) because of its anticipated large user base and envisaged concept of operations. A new landing profile, which is motivated from the point of view that "natural-feeling" cues are related to the physiological cues presented during a visual landing, has been developed in the first stage of research under way at the University of Liverpool to develop technologies that will enable the everyday use of a Vertical Take-Off and Landing (VTOL)-capable (PAV). The paper reports the continued progress made in the design and assessment of a number of different methods and trajectories to guide PAV occupants from cruising flight, down an approach path, to bring the vehicle to a successful hover. Four profiles: constant deceleration, constant optical flow, and two versions of the "natural-feeling" profiles, have been flown by the test subjects using an automatic landing and a manual flight method using different guidance aids. Subjective and objective assessments were gathered to evaluate the impact in the airspeed profiles and associated control strategies of these four different approach profiles. The results indicate that the test subjects prefer the constant deceleration profile with the automatic landing and the "natural-feeling" profiles for the manual landing. Moreover, it is found that the different tau guide control strategies at the later part of the profile have profound effects on the pilot preference.

NOMENCLATURE

a_x	= acceleration in the x axis, ft/s^2
a_{xc}	= longitudinal commanded acceleration, ft/s^2
C	= constant parameters
h	= instantaneous height above the ground, ft
K	= coupling constant
m	= number of test subjects
n	= number of rating times for each assessment item of a test subject
p	= relating to the current profile
t	= time, s
V_x, V_z	= ground speed and vertical speed, ft/s
V_{xc}	= longitudinal commanded velocity, ft/s
x, z	= pilot's viewpoint distance ahead of the aircraft and instantaneous height above the ground, ft
x_i	= subjective rating value
δ_{col},δ_{lon}	= collective and longitudinal control input, inch
γ	= flight patch angle, deg
η	= pilot's control deflection, inch
$\dot{\eta}_{pk}$	= peak of the rate of control input, inch/s
ω	= eye height velocity, 1/s
τ_d	= time delay between the cyclic input and acceleration response, s

1. INTRODUCTION

The four-year myCopter project, funded by the European Commission (EC) 7th Framework Programme (FP7), was launched in 2011 to investigate a possible future mode of air transportation – the Personal Aerial Vehicle (PAV) [1-3]. This project aims to investigate the technologies that would be required for PAVs to operate safely within a Personal Aerial Transportation System (PATS), perhaps with a higher traffic density than current General Aviation (GA). The myCopter consortium consists of six partner institutions located in Germany, Switzerland and the UK. The main focus of the University of Liverpool's (UoL) activities is the investigation of the Handling Qualities (HQs) requirements for a piloted flight PAV concept and the concomitant PAV pilot training requirements.

This paper focuses on a description of the research underway at the UoL to develop nature-inspired guidance trajectories for the visual landing of a PAV in a good visual environment (GVE)[1-3]. The motivation for the study is as follows. If PAVs, within a wider PATS, were to become a widely-used transportation method, the expectation is that the 'piloting' of them should demand no more skill than that associated with driving a car today. In addition, it would also be expected that the number of hours of training received by a novice PAV 'pilot' would be lower than that currently required to gain and maintain a Private Pilot's License (PPL) – a level that might be termed 'flight naïve' (this is based upon the assumption that training costs need to be reduced compared to those of today's general aviation aircraft). It is not expected that the general public will all become private pilots, rather, that different 'modes' of PAV operation might be employed, ranging from 'highly augmented' to fully 'autonomous', leading to a new licensing category specifically for PAV pilots. For the former case, what might be termed partial authority manual flight modes could be made available. For the manoeuvres where such a mode were available, it is of interest to design a flight trajectory, perhaps indicated to the pilot by some kind of flight director, that provides the required "natural" physiological cues, as well as meeting the requirement to ensure that the PAV and its occupants follow the trajectory in a safe manner[4]. For the fully autonomous flight case, the occupant would be relieved of the need to manually fly the aircraft. In this case, if the manoeuvre profiles were not appropriately designed, the cues (e.g. visual and proprioceptive motion cues) sensed by the driver/pilot might be inconsistent with the PAV occupant's natural expectations. This inconsistency may impair the ability of the PAV occupant to satisfactorily monitor the manoeuvre if needed[5;6]. For example, approaches to land at a constant deceleration rate conducted in the University of Liverpool's HELIFLIGHT-R simulation facility[7] appear to provide visual cues in the latter parts of the constant-deceleration manoeuvre that imply accelerative flight[8]. This leads to an increased level of discomfort for the cockpit occupants in terms of their confidence that the on-board guidance system will actually achieve the task that it is designed to do.

Therefore, it is important to design trajectories that provide the PAV occupant with intuitive guidance cueing that is consistent with their expectations. It is anticipated that the more intuitive and salient the perceptual information provided to the pilot is, the greater will be their ability to make rational and correct decisions to control the aircraft. Numerous previous studies have been undertaken to understand pilot control behaviour during a visual landing task[5;6;9-12]. Some initial research was conducted by NASA to design a desired approach with "natural physiological" cues for the design of a flight director system by studying the characteristic shapes of various visual approach profiles[5]. 236 visual approaches using four helicopter types and nine sets of initial conditions were conducted for that study. The characteristic shapes of the altitude, ground-speed, and deceleration profiles of visual approaches were then mathematically determined. The results have been replicated during flight simulation trials at the University of Liverpool[5] and by Heffley's mathematical model based on the crossover model of the human operator[9].

The NASA Advanced General Aviation and Transportation Experiments (AGATE) to design Small Aviation Transportation System (SATS) also aimed to make aircraft avionics more intuitive so pilots require less training to stay safe[13].

More recently, the research in Ref. [11] proposed an improved deceleration guidance cueing system (a hybrid profile consisting of constant deceleration and constant optical flow phases) within the Brown-Out Symbology Simulation (BOSS) display to provide the pilot with intuitive guidance cues to enable the safe landing of a rotorcraft in brownout, zero-visibility conditions.

The research reported in this paper consisted of two stages. The first stage in Ref. [8] focused on the development of the new landing profile, motivated from the point of view that 'natural-feeling' cues are related to the physiological cues presented during a visual landing. As such, test subjects with little or no prior flight experience flew simulated approaches to a hover following limited instruction in the use of a vehicle model. The first stage of the research found that the approaches were broadly similar and could be grouped into four distinct phases. Previous work in this field and Lee's optical tau theory[14;15] were used to design an idealized approach profile based upon the simulation results. The key results from the first stage of the work has been reported in Ref. [8].

The second stage of the work evaluated the "natural-landing" profiles designed in the first stage and compared it to other possible guidance profiles, such as a constant deceleration approach (CD)[11] and a constant optical-flow approach (OF)[16]. The results of this evaluation are the subject of this paper. For the initial stage of the research, the approach was flown purely with reference to the outside world visual cues. However, for the second stage, the profiles were evaluated in two modes of operation; either using manual flight or automatic flight. For the manual case, the Test Subjects (TSs) flew the approach task using flight-path and speed guidance head-up symbology. For the automatic case, the TS was a passive passenger. As such, no guidance symbology was required and only outside-world visual cues were provided. The results from this research will help to determine an optimal profile for a future PAV landing approach descent profile.

The paper proceeds as follows. First, the algorithms for the different landing profiles are briefly presented. Second, the PAV model and the decelerating descent manoeuvre used for this paper are reviewed. The guidance symbology used for the manually-flown landing cases will also be introduced. Third, the key features of the adopted landing profiles in this paper are summarized. The fourth part of this paper then focuses on the analysis of the subjective and objective assessment results obtained from a test campaign conducted at the University of Liverpool. A discussion is provided on some of the key issues that emerged during the investigation. Finally conclusions from the work are drawn and the planned future work outlined at the end of the paper.

2. REVIEW OF LANDING PROFILES

In this Section, the profiles investigated in this paper are first briefly reviewed.

2.1 Constant deceleration (CD) profile with constant flight path angle

The CD profile algorithm adopts a constant deceleration value (a_x) that can be determined from Eq. (1) in the longitudinal axis during the whole manoeuvre,

(1) $$a_x = \frac{V_{x0}^2}{2x_0}$$

in which x_0 is the initial distance to the end and V_{x0} is the initial ground speed. Therefore, the longitudinal position (x) is given by,

(2) $$x = V_{x0}t - 0.5a_x t^2$$

Moreover, the forward velocity (V_x) and the total manoeuvre period (T) can also be determined. The vertical velocity (V_z) is defined by maintaining the flight path angle (γ),

(3) $$V_z = V_x \tan\gamma$$

2.2 Constant optical flow (OF) profile with constant flight path

The optical flow (ω, the velocity in eye heights per second) perceived by a subject during the flight is given by[12],

(4) $$\omega = \frac{V_x}{h}$$

where V_x is the ground speed and h is the instantaneous height above the ground. The reason for investigating the constant optical flow profile in this paper is that professional helicopter pilots are trained to use this strategy at the level flight and landing stages[16]. With an assumed constant flight path, the position information in the x-axis can be derived as follows,

(5) $$x = x_0 e^{-\omega \tan\gamma \cdot t}$$

The V_x information as well as the speed and position information in the vertical axis can then be derived from Eq. (5) for a fixed flight path angle. As shown in Eq.(5), a PAV being flown with the constant OF profile approaches the target at an exponentially decreasing rate with respect to time.

2.3 "Natural-feeling" profiles

The development of the 'natural-feeling' profile has been reported in detail in Ref. [8]. This profile was developed by simply observing how flight-naïve test subjects undertook the landing manoeuvre using only the outside-world visual cues available to them. The reader is directed to Ref. [8] for more detailed information.

Two versions of the natural-feeling profile have been investigated in this paper. These are denoted 'VL6' and 'VL67'. Both versions are designed to follow the proposed algorithm in Ref. [8]. The main differences between these two versions are the landing flight path angle (Υ) and the final tau coupling value (K) used between the x- and z- axis. VL6 and VL67 use Υ = 6.0 deg and Υ = 6.7 deg respectively. The former flight path angle value is consistent with those used for the CD and OF profiles. The latter is chosen based on the findings of the first stage of the research[8]. The V_x profiles for both versions were constructed using the profile derived in Ref. [5]. The required PAV velocity and acceleration in the z-axis can then be derived as follows:

(6) $$\dot{z} = C(1/K)(-x)^{1/K-1}(-\dot{x})$$

(7) $$\ddot{z} = C(1/K)(-x)^{1/K-2}[(1/K-1)\,\dot{x}^2 - x\ddot{x}]$$

where C is the constant depending on the initial conditions and K is the tau coupling term. The K values were selected to be 1.2 and 0.9 for the VL6 and VL67 profiles respectively. These were chosen to take into consideration the manoeuvre final phase initial conditions and to avoid discontinuities in the defined trajectory, as mentioned in Ref. [8]. The use of these two different values means that the trajectories flown by a test subject will be slightly different in the final phase of the approach[14].

3. EXPERIMENTAL SETUP

3.1 Outline of the PAV model

The PAV flight dynamics model used in this paper was reported in Ref. [15]and is a decoupled system i.e. there are no couplings present between the collective, longitudinal and lateral control channels. It is not anticipated that PAVs will exhibit any significant helicopter-like control cross-couplings by design. This will allow the PAV pilot to operate using a more instinctive piloting strategy than is possible in a conventional, strongly coupled helicopter[2]. Within the model, the PAV pilot commands flight path angle using the collective control and forward speed using the longitudinal cyclic.

3.2 Simulation Facility

The test campaign was conducted in the HELIFLIGHT-R simulator shown in Fig. 1.

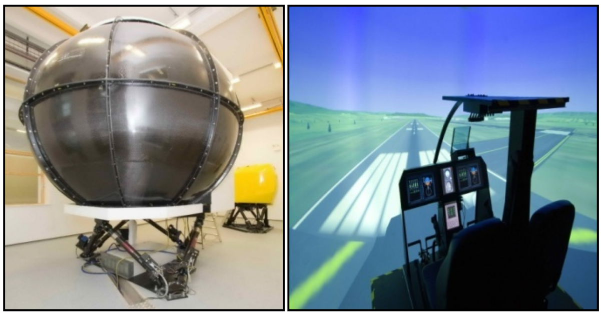

Fig. 1 External and interior views of HELIFLIGHT-R simulator[17]

This simulator features a two seat crew station inside a projection dome, offering a high resolution, wide field of view outside world image. The dome is mounted on a six degree of freedom motion platform. Moreover, the cockpit layout of the HELIFLIGHT-R simulator is configured to be a conventional helicopter type.

3.3 Decelerating descent manoeuvre description

The mission task element (MTE) used for the work documented in this paper is the decelerating descent (landing) manoeuvre taken from ADS-33E-PRF, shown in Fig. 2[2;4], and is implemented in the simulation visual database as shown in Fig. 3.

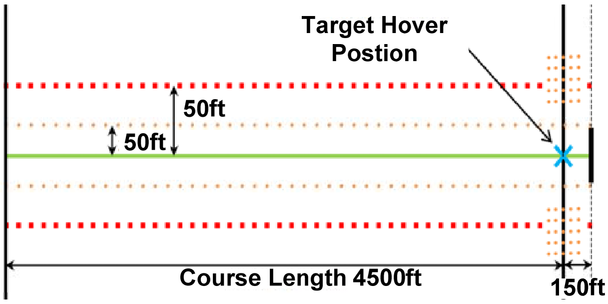

Fig. 2 General plan-view arrangement for decelerating descent manoeuvre

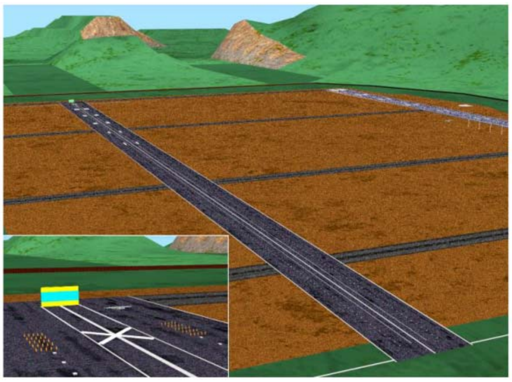

Fig. 3 Decelerating descent test course (inset: final hover position)

The manoeuvre begins with the aircraft in a stable straight and level cruise at 60kts at a height of 500ft above ground level (AGL). At a pre-defined point, the aircraft is placed into a descent and is decelerated towards a hover condition. This ideal descending approach is configured to give a mean glide slope angle of 6 degrees. The original lateral track and heading should be maintained during this process. The manoeuvre is completed once a stabilized hover is achieved at a height of 20ft AGL within pre-defined lateral and longitudinal ground positions (see inset on Fig. 3).

3.4 Test Subjects

The test campaign involved 6 male, what have been termed, “flight naïve” subjects, i.e. not professional pilots. The TSs were broadly categorized by their prior flight experience: Flight Experience (No 1 and 2), Simulator (Sim) Experience (No 3 and 4), and No Experience (No 5 and 6).

3.5 Test campaign methodology

This paper explores the impact of the four approach profiles discussed in the previous Section on the airspeed profiles and associated control strategies of the four approach profiles discussed in the previous

Section. As previously mentioned, each profile was flown in two modes, either manual or automatic. For the automatic flight mode, each subject was required to repeat each test manoeuvre at least three times. After each run, the TSs were asked to provide objective assessments using the Comfort and Presence questionnaire shown in Appendix A1.

For the manually flown MTE test points, test runs were only conducted following a number of familiarization runs conducted by each test subject. The number of familiarization runs used was subjectively varied based upon both the participant's previous flight experience and observed aptitude/competence on the day. For those test subjects with limited experience, limited instruction was made available to them e.g. effects of controls etc.

3.6 Guidance display for manual flight

The TSs were provided with head-up guidance symbols as illustrated in Fig. 4 for the assessment of the flight profiles conducted manually.

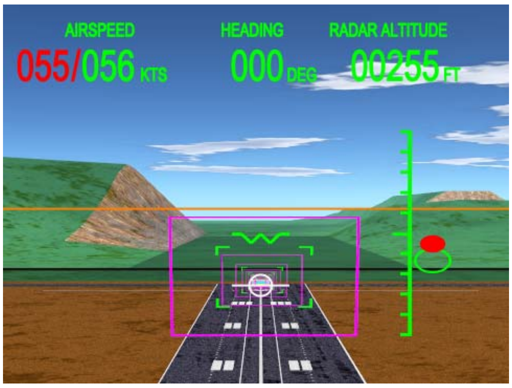

Fig. 4 Head up display used for PAV manual landing

The Head Up display shown in Fig. 4 provides the following information. First, the airspeed, heading, and radar altitude can be readily observed. The velocity indicated in red is the current commanded velocity. The velocity indicated in green shows the current actual velocity. Second, there are two new symbols also implemented specifically for the research reported in this paper in Fig. 4. The red ball and green circle symbols, to the right of the display, are used to indicate the correct position for the longitudinal cyclic stick to the PAV pilot. The green circle shows the required position of the cyclic for the current descent profile, whilst the red ball indicates the current actual position. The TSs were required to place the red ball within the green circle which moved up and down the vertical green bar. The information (a_{xd}) used to drive this symbology is given by,

$$a_{xd} = a_{xc} e^{\tau_d s} + k(V_x - V_{xc}) \quad (8)$$

in which a_{xc} and V_{xc} are the longitudinal commanded acceleration and velocity respectively. V_x is the current PAV forward velocity. The first term on the right-hand side of Eq. (8) provided the acceleration information to drive the green circle symbol. The term τ_d was introduced to account for the time delay between the cyclic input and acceleration response to increase the symbol tracking accuracy. The second term on the right-hand side of Eq. (8) contains the difference between the actual and commanded velocities. This term removed the observed velocity drift that simply following the acceleration command alone induced. This configuration worked effectively with the human-in-the-loop being part of a PI feedback control loop.

The second symbol-set adopted in this paper is the graphical highway-in-the-sky (HITS) flight path display system[18]. This intuitive cockpit display shows the virtual path that the aircraft must follow to maintain the desired Earth-referenced lateral and vertical positions. The inner green brackets define the desired performance and the outer pink brackets define the adequate performance tolerances for the manoeuvre. The TSs were only required to use the collective lever to alter their vertical position within this virtual tunnel. After three attempts at each profile, the TSs were again asked to provide subjective assessments by following the Comfort and Presence questionnaire in Appendix A2.

As well as the subjective assessments obtained by using the rating scales, heart-rate information was used as an objective assessment of the differences among the four profiles in both sets of experiments. The equipment used was the Pulse Oximeter CMS50E and is illustrated in Fig. 5.

Fig. 5 Pulse Oximeter used to record heart rate

Two signals measured through the finger can be read from Fig. 5: the pulse oxygen saturation (98) and the pulse rate (069) at a sampling rate of 10Hz. The latter is of interest in this paper. Previous research has shown that test subject heart-rates can be highly sensitive to intrinsic and extraneous influences[19;20]. Therefore, the following measures were taken during the test campaign to try to ensure that reliable heart-rate data were obtained:

- subjects were asked to 'rest' before the experiment began to stabilise their at-rest heart rate
- only the minimum necessary stimuli were provided to the TS during the test runs

4. SUMMARY OF FEATURES OF LANDING PROFILES

Based on the information provided in the previous Section, the forward velocity and the vertical position of the four profiles used in this paper are illustrated in Fig. 6. Moreover, a simple pilot model, modelled as a pure gain, was implemented to "fly" the four profiles adopted here to derive the required inputs that are shown in Fig. 7.

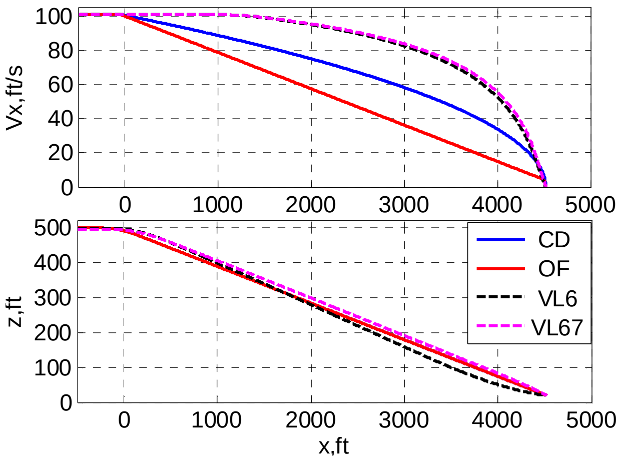

Fig. 6 Comparison of profiles used for investigation

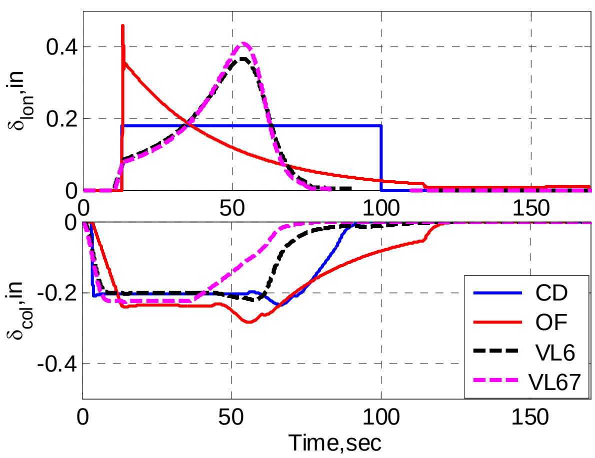

Fig. 7 Pilot model inputs for each of the designed profiles

The altitude profiles in Fig. 6 that are used to drive the HITS flight path display system all appear to be reasonably similar for all of the profiles with the exception of VL6 as the landing point is approached. This profile has a smaller flight path angle due to the particular tau control strategy being used. It is noticeable that the forward speeds in Fig. 6 (note, these are plotted against along-track distance) are quite different for the CD, OF, and VL profiles. It is also evident that the VL6 and VL67 profiles have almost the same V_X rate of change. The acceleration features of these four profiles are reflected in the longitudinal control input shown in Fig. 7 (note that these are plotted with respect to time). The control inputs effectively show the vehicle acceleration command as this response type has been used for this channel. A review of these in Fig. 7 indicates that the VL6 and VL67 profiles have the majority of the deceleration in the later stages of the task. In contrast, the CD profile has a constant deceleration profile (as expected) and the OF profile has an exponentially reducing deceleration throughout the whole manoeuvre. It should be noted that, by inspection of Fig. 7, the lower average speed of the OF case results in a significantly extended manoeuvre time when compared to the other cases used (170 sec, whereas VL6 and VL67 are around 80 sec, and CD is around 100 sec).

The forward speed difference is reflected in the required control effort in Fig. 7. As shown, the CD profile requires a constant longitudinal cyclic input for the acceleration command response type of the vehicle model. Conceptually, this might be the easiest to achieve for a flight naïve pilot, with the assistance of some form of guidance. This potentially represents a lowest workload configuration since no additional control inputs are required to accomplish this profile. The constant optical flow profile requires an exponentially decreasing stick deflection, as expected from rest, which might be harder to achieve for a TS. However, the small control deflection changes following the initial large input and the low speed at the final approach may make this profile the 'safest' approach for a flight-naive pilot. Moreover, it is acknowledged that the initial spike associated with the OF's longitudinal input is due to the numerical issue relating to the model inversion process. However, the OF profile may suffer from the long-time spent at low speeds when approaching the stop point. For the designed profiles (VL6 and VL67), they require the highest peak control deflections and the most rapid control movements during the manoeuvre, but may be intuitive for flight naïve subjects in mimicking their natural operational mode discussed in Ref. [8].

5. EXPERIMENTAL RESULTS

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

5.1 Ranking of subjective rating scale values

The subjective rating scale values from the 6 TSs are presented in Fig. 8 and Fig. 9 for each assessment point based on the scales of Appendix A1 and A2, respectively. It should be noted that, for those questions where a high score indicates a positive outcome, the score has been modified to reflect the opposite i.e. a negative outcome. For example, the score awarded for Question 3 in Appendix A1 would be subtracted from 100 before being included in the results of the Figures. Therefore, the final results presented that have a high value indicate a more negative outcome.

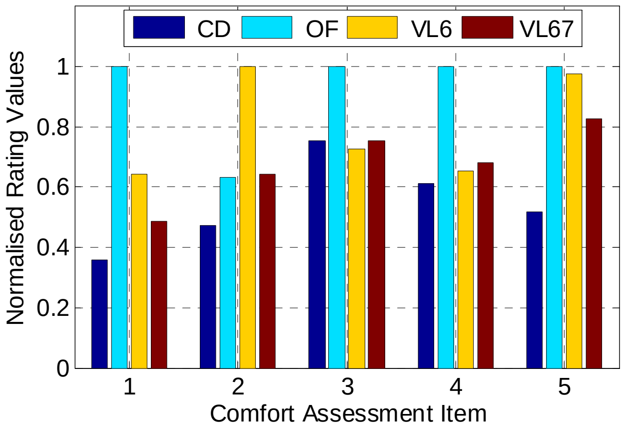

Fig. 8 Illustration of normalized summed rating values for all test subjects (automatic landing)

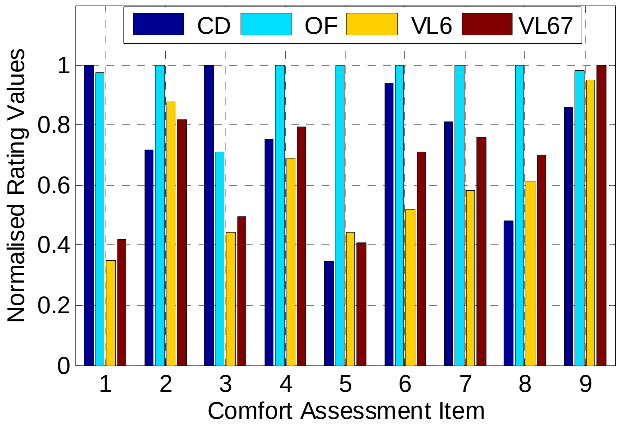

Fig. 9 Illustration of normalized summed rating values for all test subjects (manual landing)

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

$$\overline{x}_p = \frac{\sum_{j=1}^{m}\sum_{i=1}^{n} x_{i,j}}{\max\left\{\sum_{j=1}^{m}\sum_{i=1}^{n} x_{i,j}\right\}_{p=1,\cdots,4}} \qquad (9)$$

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

For the subjective rating values for the automatic landing cases, the first thing to notice is that the OF profile is ranked worst 4 times from the 5 assessment points (question 2 being the exception). This is interpreted to mean that the TSs felt the most uncomfortable and unnatural when being flown along the OF profile. On the contrary, the CD profile has been awarded the lowest comfort rating 4 times out of the 5 possible. This suggests that the TSs felt at their most comfortable during this manoeuvre. The rankings for the VL6 and VL67 profiles exist in between these two extremes.

The distribution of the ratings for the manual landing cases, shown in Fig. 9, departs somewhat from the results of the automatic landing. First, although the OF profile is still rated most negatively for 6 out of the 9 assessment items, the CD profile has been indicated as the most uncomfortable manoeuvre overall by a small margin (Question 1 in Appendix A2). Second, the VL6 profile has been rated most favourably, having the least negative rating 5 times out of the 9 possible assessment items. This is interpreted to mean that the TSs generally felt at their most comfortable for this profile during this form of the experiment. On this basis, the VL67 profile is ranked the 2nd most favourable profile of the 4 tested.

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

5.2 Analysis of control inputs efforts

The root-mean-square (RMS) control inputs of the longitudinal and collective channels from the 6 TSs are presented in Fig. 10. Moreover, a case conducted by TS 1 has been plotted in Fig. 11 for illustrative purposes.

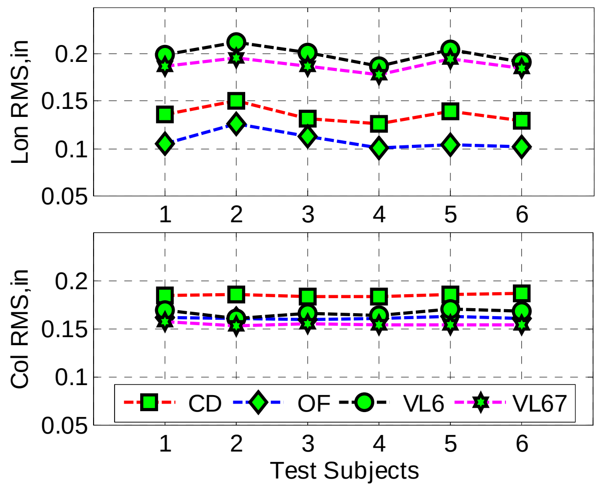

Fig. 10 RMS values of control inputs (manual landing)

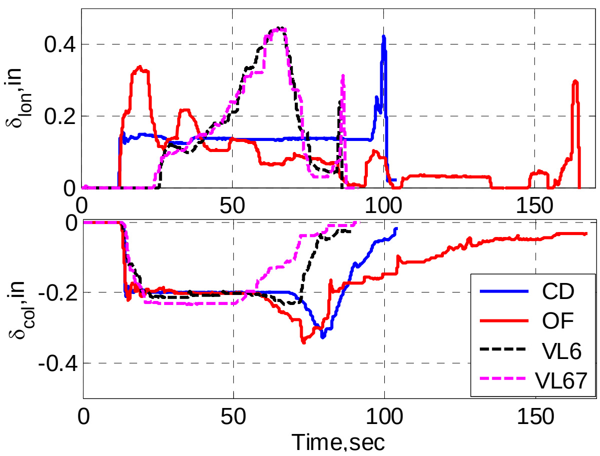

Fig. 11 Illustration of control inputs of four profiles (TS 1)

The difference between the four landing profiles in Fig. 10 is quite evident and consistent. For the longitudinal input, the designed profiles (VL6 and VL 67) have input amplitudes that are almost double the other two profiles. This may be due to the requirement to decelerate the PAV at the later part of these two profiles, as depicted in Fig. 7 and Fig. 11. For the CD profile, the TSs only needs to move the stick to a fixed position and hold it there. For the OF profile, the exponentially decreasing profile as well as the longest manoeuver period (170 sec) result in the smallest RMS value. As for the collective input, the four profiles have achieved generally similar levels of average control input.

However, the control input information shown in Fig. 10 cannot give the TS's level of compensation that is associated with the workload experienced during the manoeuver. This can be effectively addressed by calculating the control attack which measures the size and rapidity of a pilot's control inputs[21], defined as,

$$attack = \left| \frac{\dot{\eta}_{pk}}{\Delta \eta} \right| \quad (10)$$

where η is the pilot's control deflection and $\dot{\eta}_{pk}$ is the peak of the rate of control input. The number of times that a TS moves a particular control can be used to describe the TS's control activities (the attack number). In this paper, one 'attack' is defined as being when a TS makes a control input of more than 2% of full travel. The attack number per second (ANPS) can then be used to describe the average number of control movements per second. The summed values of the ANPS, normalised by the whole manoeuver period, are illustrated in Fig. 12.

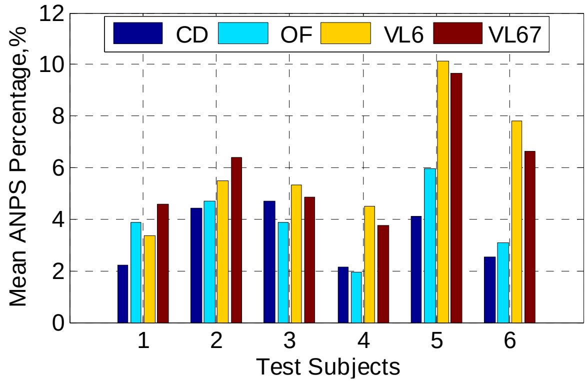

Fig. 12 Mean attack number per second of longitudinal control input (manual landing)

The results in Fig. 12 emphasize the lowest control activities associated with the CD profile. Four of the 6 TSs achieve the lowest ANPS for the CD approach from the four manual profiles flown. This is consistent with the theoretical prediction in Fig. 6 and Fig. 7 i.e. that the TS only need to hold the stick due to the acceleration command response type of the PAV system. The VL6 and VL67 profiles show the largest attack number with the VL6 having a slightly higher value. This may be due to the less aggressive deceleration required (due to a smaller flight path angle when approaching the terminal phase of the manoeuvre, as reflected in Fig. 6 and Fig. 7).

5.3 Guidance-following precision

As shown in Fig. 4, all four landing profiles for the manual flight were conducted by following the same form of guidance symbology. Therefore, it might be expected that the profile for which the TSs achieved the smallest deviations from the desired inputs might be considered to be the profile that is, in some way, 'easiest' to follow. The deviation errors for the forward speed and vertical position, normalised by the manoeuvre period, are plotted in Fig. 13 and Fig. 14, respectively.

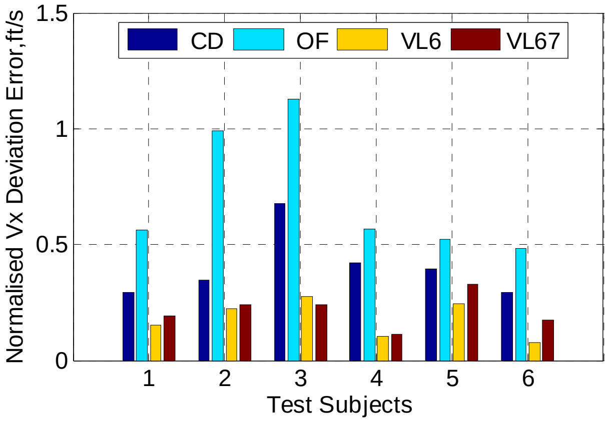

Fig. 13 Illustration of the normalised *Vx* deviation

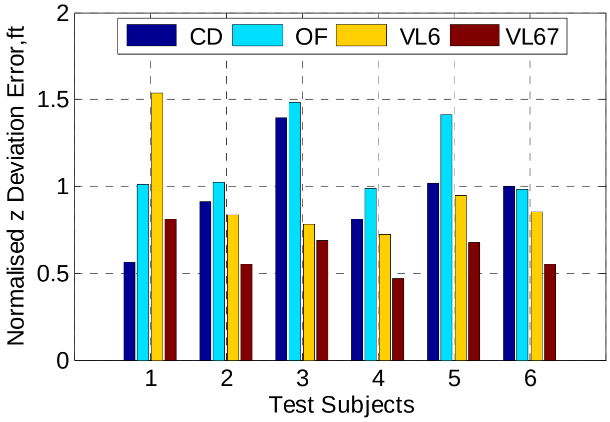

Fig. 14 Illustration of the normalised *z-position* deviation

The results in Fig. 13 and Fig. 14 show that the TS's achieved the best task performance with the designed profiles (VL6 and VL67) than for the other two tested profiles. For the V_x channel, Fig. 13 shows that all of the TSs exhibited the worst adherence to the desired profile for OF case, followed by the CD profile. However, 5 of the 6 TSs showed the best performance for the VL6 profile and the remaining TS (no. 3) showed the best performance for the VL67 profile. For the vertical channel, the main difference from the V_x channel is that the VL67 profile was the one that was better adhered-to.

5.4 Heart rate variation

The intention behind the measurement of TS heart-rate data, using the device in Fig. 5, was to try to extract meaningful information from the measurements to show the possible psychological effects of the different profiles on the TSs. In the field of psychophysiology, the information associated with heart rate is widely used to study emotional arousal. Heart activity has been found to increase under pressure, strain, anxiety, and focused attention and motor inhibition conditions[22;23]. Therefore, it was reasonably hypothesized that the preferred landing profile(s) would lead to less variation of the subject's heart rate from their respective rest values. The standard deviation (Std) values of the TSs' heart rates are shown in Fig. 15.

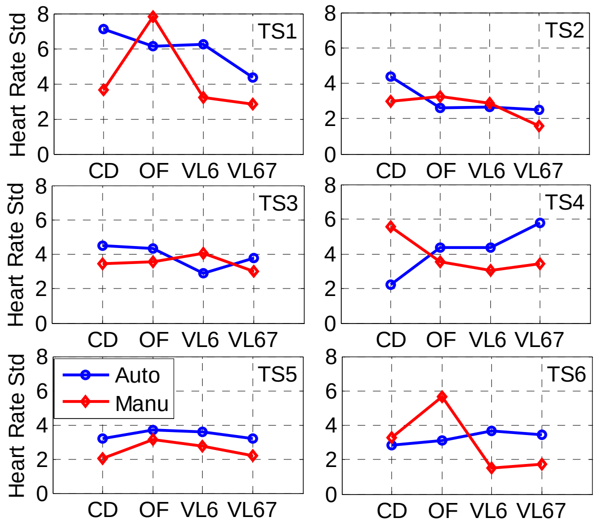

Fig. 15 Standard deviation values for the heart rates of 6 TSs

The Std distribution patterns of the 6 TSs heart-rate data in Fig. 15 show that the Std values of the designed profiles (VL6 and VL67) are generally smaller than the other two profiles. This is more evident for the manual landing situation, where 5 of the 6 TSs demonstrated the least variation of their heart rate when conducting the VL67 profile (TS4 being the exception). The heart rate Std results here may indicate that the "natural-feeling" profiles have less of a physiological effect on the participants.

6. DISCUSSION

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

Table 1 Comparisons of key features associated with four profiles (auto landing)

Profiles	Discomfort	Natural Feeling	Whole Subjective Ratings
CD	1	1	1
OF	4	4	4
VL6	3	2	3
VL67	2	3	2

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

Profiles	Discomfort	Natural Feeling	Whole Subjective Ratings	Attack Number	Tracking Precision V_x	Tracking Precision z	Heart Rate Std
CD	4	3	3	1	3	3	3
OF	3	4	4	2	4	4	4
VL6	1	1	1	4	1	2	2
VL67	2	2	2	3	2	1	1

The results shown in the above two tables indicate that the answer to the research question is dependent on the point of interest. For example, the VL6 profile is ranked highest based upon the subjective ratings for the manual landing manoeuvre, but appears to require the highest workload based upon the attack number. However, there are still a few conclusions that can be drawn from these two Tables. First, based on the values in the Tables, the OF profile was the least favoured by the TSs. This profile is consistently ranked worst in Table 1 for the automated landing cases and worst for 5 of the 7 factors in Table 2 for the manual landing. Second, the preference for a profile is dependent upon the mode of operation i.e. automated or manual. For the automatic landing, the CD profile is the most preferred. It is ranked as being lowest in terms of discomfort and feeling the most natural. However, for the manual landing, the VL6 profile was preferred. It was rated as providing the most general subjective satisfaction and having most natural-feel by the TS. If the requirement is to achieve the highest tracking performance and the lowest physiological variation, then the VL67 profile would be the profile of choice for a manual descent. Overall, for the manual landing situation, taking into account all of the 7 factors listed in Table 2, the "natural-feeling" profiles (VL6 and VL67) were generally preferred over the other two profiles.

7. CONCLUSIONS

This paper has reported upon the continued progress made in the development of a "natural feeling" landing profile from a set of piloted simulation test results. The motivation for this work has been based upon the future envisaged use of PAVs. The following conclusions have been drawn from the work presented. First, the separate guidance designed individually for the cyclic and collective control channels work effectively even though the landing profiles and the experience of the test subjects are very different. Second, for the automatic landing situation, the TSs prefer the CD profile. For the manual landing situation, the “natural-feeling” profiles were the most favoured by the TS. The OF profile was the least favoured for both situations.

8. FUTURE WORK

The next step in the research will be to investigate the pilot training requirements for the four different landing profiles reported in this paper for the PAVs. The research will also focus on studying the difference results achievable by using different tau-guided final approach strategies.

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APPENDIX

A1. Comfort Rating Scale for Automatic Landing

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

1	I felt general discomfort during the manoeuvre. 0________________________100 Strongly Disagree Strongly Agree
2	The movement in the procedure was uncomfortable 0________________________100 Strongly Disagree Strongly Agree
3	The sense of moving around outside cockpit was compelling. 0________________________100 Strongly Disagree Strongly Agree
4	The movement in the virtual environment seemed unnatural. 0________________________100 Strongly Disagree Strongly Agree
5	The manoeuvre negatively impacted my ability to concentrate. 0________________________100 Strongly Disagree Strongly Agree

A2. Comfort Rating Scale for Manual Landing

The highlighted terms in green have the positive meaning.

1	I felt general discomfort during the manoeuvre. 0________________________100 Strongly Disagree Strongly Agree
2	I felt I was in the control of the events. 0________________________100 Strongly Disagree Strongly Agree
3	The movement in the procedure was uncomfortable 0________________________100 Strongly Disagree Strongly Agree
4	The sense of moving around outside cockpit was compelling. 0________________________100 Strongly Disagree Strongly Agree
5	I experienced annoyance with the task. 0________________________100 Strongly Disagree Strongly Agree
6	The movement in the virtual environment seemed unnatural. 0________________________100 Strongly Disagree Strongly Agree
7	I felt involved in the virtual reality environment. 0________________________100 Strongly Disagree Strongly Agree
8	The manoeuvre negatively impacted my ability to concentrate. 0________________________100 Strongly Disagree Strongly Agree
9	The interation with the environment seems natural. 0________________________100 Strongly Disagree Strongly Agree

REFERENCES

[1] Jump, M., Padfield, P.; White, M., Floreano, Dario, Fua, Pascal, Zufferey, Jean-Christophe, Schill, Felix Stephan, Siegwart, Roland, Bouabdallah, Samir, Decker, M., "MyCopter: Enabling Technologies for Personal Air Transport Systems," in RAeS Rotorcraft Conference: The Future Rotorcraft - Enabling Capability Through the Application of Technology, London, UK, 15th -16th June 2011.

[2] Perfect, P., White, M.D., and Jump, M., "Pilot Sensitivity to Handling Qualities-Related Design Parameters for A Future Personal Aerial Vehicle Concept," Proceedings of the 39th European Rotorcraft Forum. ERF, Moscow, pp 1-12, 3rd-6th Sep2013.

[3] Perfect, P., White, M. D., and Jump, M., “Towards Handling Qualities Requirements for Future Personal Aerial Vehicles," in the AHS 69th Annual Forum, Phoenix, Arizona, May 21-23, 2013.

[4] Anon., *Handling Qualities Requirements for Military Rotorcraft US Army Aviation and Missile Command*, ADS-33E-PRF, 2000.

[5] Moen, G. C., DiCarlo, D. J., Yenni, K. R., “A Parametric Analysis of Visual Approaches for Helicopters,” United States. National Aeronautics and Space Administration, National Aeronautics and Space Administration, 1976.

[6] Heffley, R.K., “*A Model for Manual Decelerating Approaches to Hover*", Proceedings of the Fifteenth Annual Conference on Manual Control, AFFDL-TR-79-3134, pp. 545-554, Dayton, Ohio, March 20 - 22, 1979.

[7] White, M.D., Perfect, P., Padfield, G. D., and Gubbels, A. W., "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*, Vol. 227, (4), Apr.2013,pp. 655-678,.

[8] Lu, L., Jump, M., Perfect, P., A., and White, M.D., "Development of a Visual Landing Profile with Natural-Feeling Cues," Proc. American Helicopter Society 70th Annual Forum, Montreal, Quebec, Canada, 20th-21st, May 2014.

[9] Lockett, H. A., "The Role of Tau-Guidance during Declarative Helicopter Approaches," PhD Thesis, Faculty of Engineering, University of Liverpool, Liverpool, 2010.

[10] Perrone, J. A.,"The Perception of Surface Layout during Low Level Flight," NASA CP 3118, 1991.

[11] Neiswander, G. M., "Improving Deceleration Guidance for Rotorcraft Brownout Landing," Master Thesis, University of Iowa, 2010, 2010.

[12] Phatak, A. V., Jr. Peach, L. L., Hess, R. A., Ross, V. L., Hall, G. W., and Gerdes, R. M., "A Piloted Simulator Investigation of Helicopter Precision Decelerating Approaches to Hover to Determine Single-Pilot IFR /SPIFR/ Requirements," AIAA PAPER 79-1886， Guidance and Control Conference，Boulder, CO，August 6-8, 1979.

[13] AGATE Consortium, "Affordable Alternative Transportation," NASA Langley Research Center, Hampton, VA, FS-1996-07-02-LaRC, July1996.

[14] Lee, D. N., “Guiding Movement by Coupling Taus,” *Ecological Psychology*, Vol. 10, (3), 1998, pp. 221-250. doi:10.1207/s15326969eco103&4_4

[15] Padfield, G. D., “The Tau of Flight Control,” *Aeronautical Journal*, published online Sept. 2011, Vol. 115, (1171), pp. 521-555.

[16] Padfield, G. D., *Helicopter Flight Dynamics,* 2nd ed., Blackwell Science, Oxford, 2007.

[17] Szoboszlay, Z., Albery, W. B., Turpin, T., and Neiswander, G. M., " Brown-Out Symbology Simulation (BOSS) on the NASA Ames Vertical Motion Simulator," American Helicopter Society 64th Annual Forum, Montreal, Quebec, Canada, 29th April - 1st May 2008

[18] Nolan-Proxmire D., and Henry, D., *Highway in the Sky" Ready for Atlanta Olympics*, NO. 96-071, NASA Langley Research Center, Hampton, VA, July 1996.

[19] Winsley, R. J., Armstrong, N., Bywater, K., and Fawkner, S. G., "Reliability of Heart Rate Variability Measures at Rest and during Light Exercise in Children," *Br J Sports Med*, Vol. 37, (6), pp. 550-552, 2003.

[20] Sandercock, G. R., Bromley, P. D., and Brodie, D. A., "The Reliability of Short-term Measurements of Heart Rate Variability," *Int J Cardiol*, Vol. 103, (3), pp. 238-247, Sept. 2005.

[21] Perfect, P., White, M., Padfield, G. D., and Gubbels, "Rotorcraft Simulation Fidelity: New Methods for Quantification and Assessment," *The Aeronautical Journal*, Vol. 117, (1189), pp. 235-282, Mar.2013.

[22] Nickel, P., and Nachreiner, F., "Sensitivity and Diagnostics of the 0.1-Hz Component of Heart Rate Variability as an Indicator of Mental Workload," *Human Factors*, Vol. 45, (4), pp. 575-590, 2003.

[23] Jönsson, P., "Respiratory Sinus Arrhythmia as a Function of State Anxiety in Healthy Individuals," *International Journal of Psycho-physiology*, Vol. 63, (1), pp. 48-54, 2007.