Handling Qualities Requirements for Future Personal Aerial Vehicles

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This paper describes research to develop handling qualities guidelines and criteria for a new category of aircraft – the personal aerial vehicle (PAV), which it is envisaged will demand no more skill to fly than that associated with driving a car today. Testing of concept PAV response types has been conducted with inexperienced 'pilots' – ranging from private pilot's license holders through to those with no prior flight experience. The objective was to identify, for varying levels of flying skill, the PAV response type requirements that will ensure safe and precise flight. Conventional rotorcraft response types such as 'rate command', 'attitude command/attitude hold' are unsuitable for likely PAV pilots. However, response types such as 'translational rate command' and 'acceleration command, speed hold' permit 'flight naïve' pilots to perform demanding tasks repeatably and with the required precision.

Nomenclature

δ_{lat}	=	Lateral stick input [-1:1]
δ_{lon}	=	Longitudinal stick input [-1:1]
γ	=	Flight path angle [deg]
A	=	Aptitude Test Score [-]
P	=	Precision Metric [%]
W	=	Workload metric [1/sec]
W_{min}	=	Theoretical minimum workload for an MTE [1/sec]

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I. Introduction

Handling Qualities (HQs) requirements for conventional Vertical Take-Off and Landing (VTOL) vehicles are well understood and are clearly defined in specifications such as ADS-33E-PRF (Ref. 1). Efforts are underway, however, to develop 'revolutionary' VTOL concepts that documents such as ADS-33E-PRF were never intended to cover. Personal Aerial Vehicles (PAVs), such as NASA's Puffin (Ref. 2), the Moller Skycar (Ref. 3) and the Terrafugia TF-X (Ref. 4) are envisaged to be small VTOL aircraft that could be used for commuting (Refs. 2 – 4). Such PAVs might replace a proportion of road traffic and hence reduce major congestion problems in many cities around the world. Taking advantage of its VTOL capabilities, a PAV would be able to operate to and from small landing sites. Between these vertical flight phases, the PAV would spend its time in cruising flight at altitudes of less than 1000ft and airspeeds of up to 100kts (Ref. 5). Whilst various regulatory standards exist for General Aviation (GA) aircraft, these aircraft are operated by a very small fraction of the general population and at much lower air traffic densities than envisioned for a PAV (Ref. 6). To achieve the desired reduction in road traffic congestion, PAVs would need to operable by a significantly broader user group. As such, this paper reports on the results of a study to ascertain the HQ requirements for the envisioned PAV commuting mission that would be suitable for users with a wide range of flying abilities.

To fulfill the commuting role, the PAV would have to be operated at significantly lower cost than is typically expected for private rotorcraft aviation today. Training costs form part of this cost and are typically £20,000-£30000 (Ref. 6), which is significantly higher than those costs associated with learning to drive a car (approximately £1200 (Ref. 7)). For PAVs to capture a proportion of the current commuting market, therefore, it would be necessary to reduce the cost of training to obtain a PAV license towards that associated with the acquisition of a driving license.

There are a number of ways in which this could be done. Firstly, the PAV could be equipped with technologies that permit autonomous operation (Refs. 7, 8). Whilst this might be considered to be the ultimate vision for PAV operation, the required technologies are not yet sufficiently mature to be widely deployed and significant regulatory challenges related to the operation of autonomous vehicles in non-segregated airspace still exist (e.g. Ref. 9). An alternative approach would be to equip the PAV with a flight control system that confers HQs that are intuitive and straightforward for a novice PAV pilot to learn to use safely. By reducing the complexity of the vehicle response, the number of hours required for a student pilot to develop the necessary skills for the safe operation of the PAV should be significantly reduced.

Conventional HQ assessment procedures, (Ref. 1), assume that the assessed vehicle will be operated by a well-trained and well-motivated pilot. This means that existing HQ requirements and procedures will not necessarily be appropriate for a PAV, and there is therefore a need to develop and validate new criteria for the 'flight-naïve' PAV pilot. The European Union Framework Programme 7-funded project *myCopter* (Ref. 6) is addressing the requirement for autonomous flight technologies and HQ requirements for piloted flight. Previous myCopter research includes the development of a methodology through which HQ requirements for PAVs may be assessed (Refs. 10, 11). This paper examines which PAV response type allows a flight-naïve pilot to perform hover and low speed flight manoeuvers to an acceptable level of precision in a safe and repeatable manner. Handling requirements for both benign and harsh environmental conditions are examined.

The 'response type' (Ref. 1) describes the way in which a vehicle responds when a cockpit control is moved. Most GA helicopters exhibit a 'Rate Command' (RC) response type – following the application of a step control deflection from trim, the vehicle will pitch, roll or yaw at an approximately constant rate. As vehicle complexity increases, helicopters equipped with a Stability and Control Augmentation System (SCAS) may exhibit an 'Attitude Command, Attitude Hold' (ACAH) response type. Here, the pitch or roll rate following the application of a step control deflection will return to zero over a period of a few seconds, with the aircraft held at a constant perturbed attitude from trim. A more sophisticated SCAS may exhibit a 'Translational Rate Command' (TRC) response type – here, the velocity of the aircraft over the ground is proportional to the magnitude of the control deflection.

According to the requirements of Ref. 1, it is only necessary for a helicopter to possess a rate response type for Level 1 HQs (that is, the most desirable level of HQs) to be achieved in a good visual environment (GVE). As visual conditions degrade (e.g., at night or in the presence of fog), an ACAH response type is required. In the most severely degraded visual conditions, a TRC response type is required to maintain Level 1 HQs (Ref. 1). This paper will assess whether this requirement for increasing augmentation with degraded environmental conditions also exists for PAVs. The paper proceeds as follows. Section II briefly describes the experimental setup and test methodology that have been employed for this research. Sections III and IV present results and analysis from simulation testing of a reconfigurable PAV model (offering RC, ACAH and TRC response types) in both benign and harsh environmental conditions. Finally, Section V brings the paper to a close with conclusions.

II. Experimental Set-Up

The following provides a brief overview of the experimental set-up used for the research reported in this paper. A more detailed description can be found in Ref. 11.

A. Flight Dynamics Simulation

The PAV flight dynamics model simulation was created in MATLAB/Simulink using the method described in Ref. 12. The on-axis response to a control input is computed using transfer function representations of the required vehicle dynamics. Using this modelling structure, three 'candidate' vehicle configurations were created to assess their suitability for use in PAVs. In each case, an individual axis response was configured to offer predicted Level 1 HQs according to Ref. 1. The pitch and roll response characteristics of the three configurations are summarized in Table 1. The Acceleration Command, Speed Hold (ACSH) response type was introduced for forward flight for the Hybrid configuration. This response type will hold a constant airspeed with the longitudinal control at the zero force position, and allows the pilot to command a constant rate of change of airspeed with a fixed longitudinal control deflection.

Table 1 PAV Configuration Response Types

Configuration	Speed Range	Pitch	Roll	Yaw	Heave
RC	< 15kts	RC	RC	RC	RC
	blend	RC	RC	Smoothed transition between 15-25kts	Smoothed transition between 15-25kts
	> 25kts	RC	RC	γ command + turn coordination	γ command
ACAH		ACAH	ACAH	As per RC config.	As per RC config.
Hybrid	< 15kts	TRC	TRC	As per RC config.	As per RC config.
	blend	Instantaneous at 15kts (accel) and 0kts (decel); internal logic to eliminate transients	Smoothed transition between 15-25kts	As per RC config.	As per RC config.
	> 25kts	ACSH	ACAH	As per RC config.	As per RC config.

Finally, the Hybrid configuration was equipped with pilot-selectable height-hold and direction-hold functions.

The PAV configurations were assessed using the HELIFLIGHT-R full motion flight simulator at the University of Liverpool (Ref. 13). The crew station features reconfigurable glass-cockpit style instrument panels. These displayed a representation of the Garmin G1000 GA glass cockpit Primary Flight Display (PFD, Ref. 14). In addition to the PFD, a set of basic flight data (airspeed, heading, altitude, attitude and flight path) were overlaid on the outside world scene as a Head-Up Display (HUD). Each pilot seat is equipped with four axis dynamic control loading (lateral and longitudinal cyclic, pedals and collective lever).

B. Mission Task Elements

Five hover and low-speed Mission Task Elements (MTEs) were created for use in the investigations reported in this paper, based on an outline description of how a typical PAV commute would operate. The 5 MTEs were the Hover, Vertical Reposition, Landing, Decelerating Descent and Aborted Departure. Where possible, the outline of the task has been drawn from ADS-33E-PRF; some of the task performance requirements were relaxed to reflect the nature of the PAV role. They are described in more detail in Ref. 11.

C. Analysis Methods

Conventional HQ analysis, based around the use of test pilots awarding subjective Handling Qualities Ratings (HQRs), is well-suited to the determination of the suitability of a vehicle for its intended operational role(s) by well-trained professional pilots. It has been shown however that the conventional HQs evaluation process is not sufficient to identify requirements for PAVs in [11]. A new method, based around the performance of flight-naïve pilots in PAV-relevant tasks, has therefore been developed. In this process, each flight-naïve pilot has flown all of the MTEs using all of the configurations. By recording their subjective opinions and taking suitable objective measurements, it has been possible to assess the suitability of each configuration for each Test Subject (TS).

As the flight-naïve pilots have not received the appropriate training, it was not possible for them to use complex rating processes such as the HQR scale. As such, they were asked to use the NASA Task Load Index (TLX) scale (Ref.15). This subjective assessment method was augmented with objective assessments. Two interim metrics were defined: Workload (*W*) and Precision (*P*). Workload is measured as the rate of application of discrete control inputs, measured in [1/sec] (Ref. 11), while precision is measured as the proportion of task time spent within the desired performance boundaries, measured in percent (Ref. 11). *P* and *W* are combined to create the Task Performance Index (TPX, Ref. 11), as shown in Equation 1.

$$TPX = \frac{P^2\sqrt{W_{min}}}{100^2\sqrt{W}} \tag{1}$$

The TPX is a normalized metric, that is, it is divided by the theoretical best achievable score (based on 100% of time spent in the desired performance region, and applying the smallest possible number of control inputs) for any given task, creating values in the range $0 \leq TPX \leq 1$. Higher TPX scores correspond to better performance in the task.

To place the TLX ratings and TPX scores into the context of a TS's natural ability, a computer-based aptitude test battery has been used based upon Refs. 16, 17. The TS aptitude resulting from this test battery was only measured once, prior to their involvement in the experimental testing. It was intended to be a measure only of the TS's 'raw input' at the commencement of the study. Skills development was measured in a different way as a separate exercise. It is beyond the scope of this paper and will be reported in a subsequent publication. The higher the score (A) achieved in these tests, the greater was the expected ability of the TS to perform the required flight tasks. It was shown that a strong correlation existed between TS aptitude score and TLX ratings awarded (Ref. 11). As lower workload would be expected from the more able TSs, this showed that the TLX rating process could be successfully employed to evaluate workload for PAV pilots. A good correlation was also demonstrated between the subjective TLX ratings and the objective TPX scores (Ref. 11), validating the use of the TPX as a quantitative measure of task performance and workload.

D. Harsh Environmental Conditions

Two types of harsh environmental conditions were created, a degraded visual environment (DVE) and a turbulent atmosphere. For the DVE tests, the visibility in the simulation was set to 800ft by introducing a fog effect. Visual Cue Ratings (VCRs) awarded by a test pilot increased for both attitude cueing and translational rate cueing, resulting in the Useable Cue Environment (UCE) degrading from UCE=1 conditions for all tasks to UCE=2 conditions (Ref. 11).

The atmospheric disturbances were introduced into the simulation using the Control Equivalent Turbulence Input (CETI) method (Ref. 18). With the RC configuration, the intensity of the resulting disturbances was assessed by a test pilot using the Turbulent Air Scale (Ref. 19) as 5 (continuous medium bumps), occasionally increasing to 6 (medium bumps with an occasional heavy one, Ref. 11). It was assumed that, for a real-world implementation of the ACAH and Hybrid configurations, closed-loop feedback of the vehicle attitudes would be required. This would have the effect of suppressing the disturbances as they are generated. These two configurations were therefore equipped with a disturbance rejection feedback loop to emulate the expected behavior of a real-world implementation.

III. Handling Qualities Requirements in a Benign Environment

A. Results

Nine TSs took part in the handling assessments in the benign environment. The lowest aptitude score was 7.4, while the highest was 11.9 (out of a theoretical best aptitude score of 15 points). Each TS was exposed to the three different configurations in the same order and flew the MTEs in the same order. Not all TSs flew all MTEs in configurations where they were clearly having difficulty controlling the aircraft (e.g. RC) and not all TSs flew all three configurations (generally due to time constraints). For each configuration, the TS was given approximately 5 minutes of familiarization flight to allow them to develop an understanding of how the vehicle responded to the controls. The evaluation testing was conducted immediately following this familiarization period. Three or four test runs (three if each test point was flown consistently from the start of testing) were flown. The final three test runs were then used to perform the analysis reported in this Section. If a TS struggled to successfully complete the MTE within 4 runs, then up to 4 more test runs were permitted such that the MTE could then be performed in a repeatable manner three times. The results from the testing in the benign environment are reported in two stages. Firstly, TLX workload ratings are shown. These are followed by objective analyses in the form of the TPX. It should be noted that, where relevant, the data associated with the results has been tabulated in the Appendix to this paper.

1. *Analysis of Task Load Index in the Benign Environment*

Fig. 1 shows the TLX ratings, averaged across the five MTES, awarded by each TS for each of the three PAV configurations under assessment.

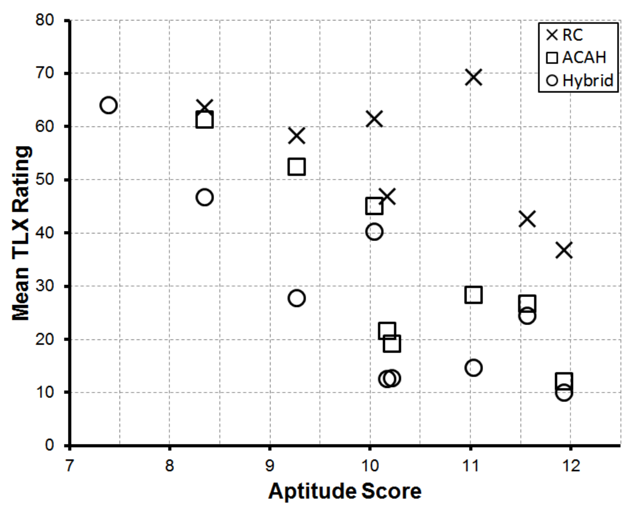
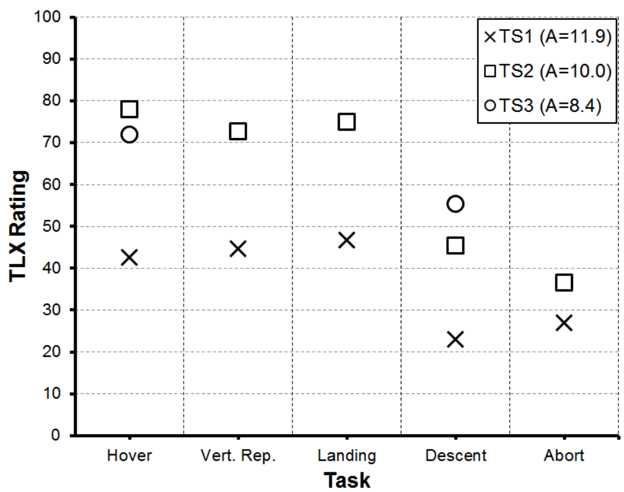


Fig. 1 Average TLX Ratings for Three PAV Configurations

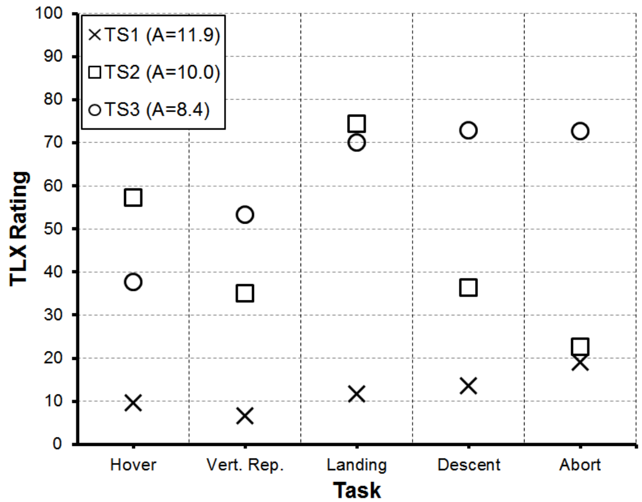
For each configuration, there is an observable reduction in perceived workload as the pilot's aptitude increases. It is also clear that as the configuration changes from RC to ACAH to Hybrid, there is a significant reduction in the reported workload. The exception here was some of the TSs with high aptitude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

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

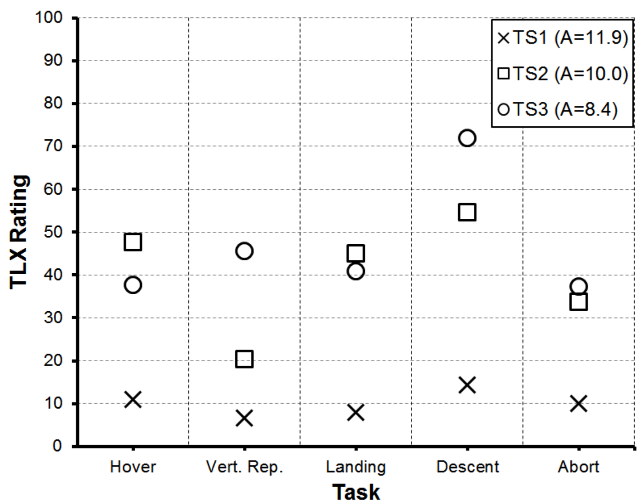
For the individual MTEs, Fig. 2(a) shows a sample of typical results (for the same high, medium and low aptitude TSs) for the RC configuration, Fig. 2(b) for the ACAH configuration, and Fig. 2(c) for the Hybrid configuration.



a) RC Configuration



b) ACAH Configuration



c) Hybrid Configuration

Fig. 2 Sample of TLX Ratings - Individual Tasks

In Fig. 2(a), a clear difference can be seen between the pilots' reported workload for the hover, vertical reposition and landing tasks, and their reported workload for the decelerating descent and aborted departure tasks. For the former group of MTEs, there is a requirement for a continuous, precise flying. For the latter tasks, a somewhat more 'open loop' control strategy for large periods of the task is required. The relatively low level of stability offered by the RC response type means that, for the precision tasks, there will always be a higher workload demand than would be the case for a more 'open loop' task.

For the ACAH configuration, Fig. 2(b) shows a smaller variation in TLX rating between the tasks for each TS. There is no clear pattern connecting all of the TSs – with this configuration, some TSs found the precision tasks more demanding, other TS's found the more 'open loop' tasks more demanding.

For the Hybrid configuration of Fig. 2(c), there are no clear differentiators between tasks. The TSs found all five tasks to be equally demanding with the Hybrid configuration. There are exceptions to this rule, for example, the decelerating descent task. For the Hybrid configuration, the decelerating descent task requires the pilot to coordinate the application of control inputs on two separate inceptors simultaneously (longitudinal cyclic and collective). In every other task, when the HH and DH functions are employed, the pilot is only ever required to apply inputs on a single inceptor at a time. While the higher aptitude pilots did not find this to be a significant challenge, the lower aptitude pilots reported that their workload increased significantly. This result highlights the importance of minimizing or eliminating unnecessary secondary or off-axis control activity in a future PAV.

2. Analysis of Task Performance in the Benign Environment

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

Fig. 3 shows the precision achieved by each TS in each of the PAV configurations, averaged across the final three attempts by a TS for 5 MTEs. A value of 100% precision indicates that the TS was consistently able to achieve 100% of the maneuver time within desired performance in every task.

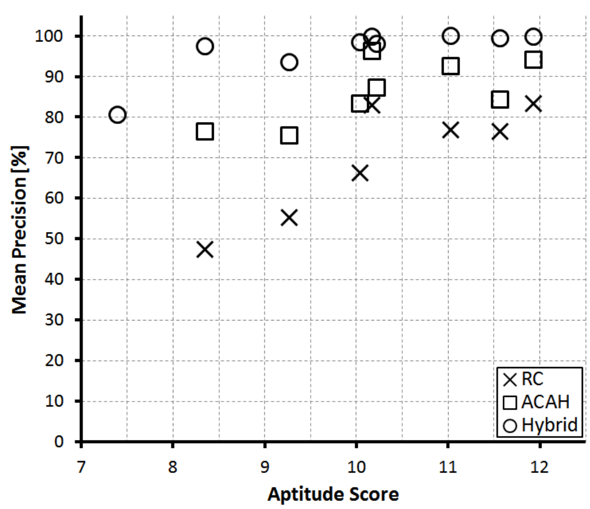


Fig. 3 Precision for PAV Configurations

While the highest aptitude TS was able to perform well (> 90% time spent within desired performance) in the ACAH and Hybrid configurations, and only slightly less well (> 80% time spent within desired performance) in the RC configuration, the same cannot be said of the lower aptitude TSs. It can be seen in Fig. 3 that precision was generally lower (<70% time spent within desired) for the lower aptitude TSs flying the RC configuration. Precision improved progressively as the aptitude score increased. A similar pattern is evident in the data for the ACAH configuration. However, the rate of decay of precision with reducing aptitude was significantly lower. Finally, with the Hybrid configuration, the majority of the TSs were able to achieve an excellent level of precision (>98% time spent within desired performance). Only the TS with the lowest aptitude was not able to consistently achieve the desired task performance requirements.

Fig. 4 shows the TPX score achieved by each of the TSs for each PAV configuration. As above, the scores represent an average of the final three attempts at an MTE, and have been averaged across the five MTEs.

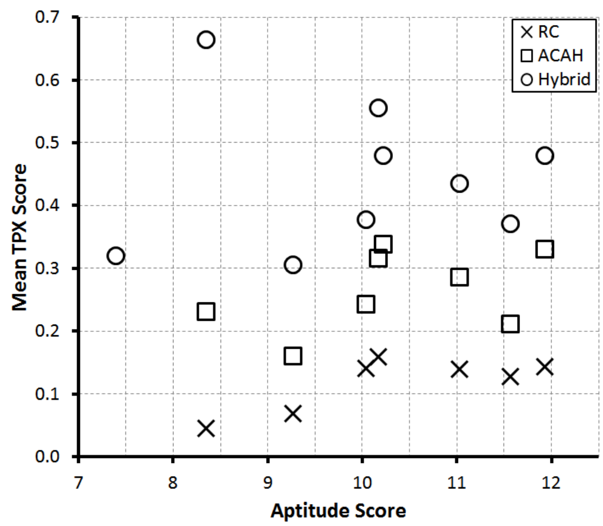


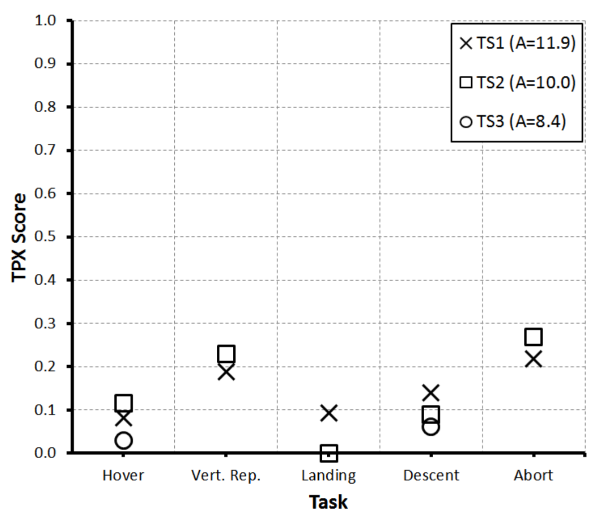
Fig. 4 TPX Scores for PAV Configurations

A similar trend can be seen in the quantitative analysis. There is a steady improvement in achievable TPX moving from the RC configuration, through the ACAH to the Hybrid configuration. It is noteworthy that nearly every TS achieved a better TPX score with the Hybrid configuration than the best-performing TSs did with the ACAH configuration. The same can be seen in the ACAH-RC comparison. Also of note is the low aptitude TS (A=8.4) who achieved an extremely high mean TPX score. As was seen in Fig. 3, this TS achieved comparable precision to the other TSs. The high TPX score is a result of the development of a low frequency control strategy – actually closer to the theoretical ideal than any of the other TSs managed. Although this TS generally flew the MTEs with slightly lower aggression (lower accelerations, lower peak translational velocities) than the higher aptitude TSs, this shows that it was possible for TSs across the aptitude range to develop effective strategies to successfully fly the Hybrid configuration.

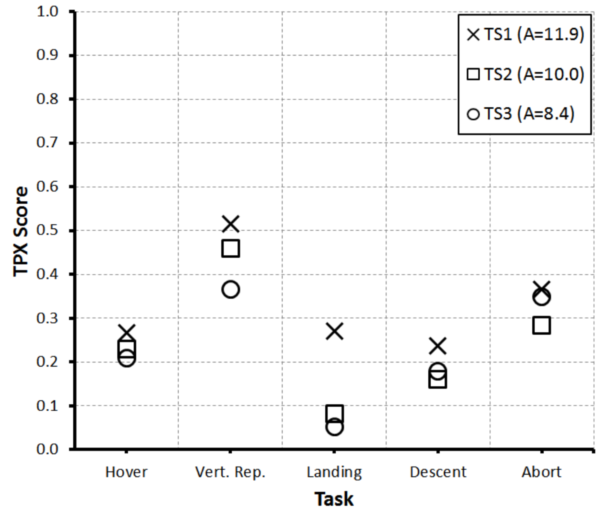
Despite some scatter in the results, the trends in Fig. 4 indicate how pilots of differing aptitude performed with the three PAV configurations. All TSs performed to a much lower standard with RC than with the other configurations. There was an improvement in performance from low aptitude to moderate aptitude, but increasing the aptitude beyond this point did not significantly affect the results achieved. With the ACAH configuration, a slight improvement in task performance with increasing aptitude is visible. Finally, with the Hybrid configuration, all TSs, regardless of aptitude, were able to achieve a good TPX score for each task. Increased scatter is evident in the results for the Hybrid configuration. This is a result of differing levels of 'acceptance' of the positional stability offered by the TRC response type. This allowed some TSs to minimize their control activity, allowing the system to do most of the 'work' for them. In contrast, other TSs felt the need to apply continuous closed-loop control inputs i.e. to continuously 'fly' the vehicle, even when trying to maintain a constant position; hence reducing their TPX scores.

The contrast between the performance scores shown in Fig. 4 and the subjective workload ratings shown in Fig. 1 should be noted. While all pilots were able to achieve a good TPX score with the Hybrid configuration, there was a trend of increasing subjective workload as the aptitude score reduced. This difference reflects the inherent limitation of the TPX calculation method – it can only consider the control movements for the workload component of the score. The mental processing required to determine what those control movements need to be is also an important element in the overall workload for a task, and this appears to be an increasingly important element as the pilot's aptitude reduces.

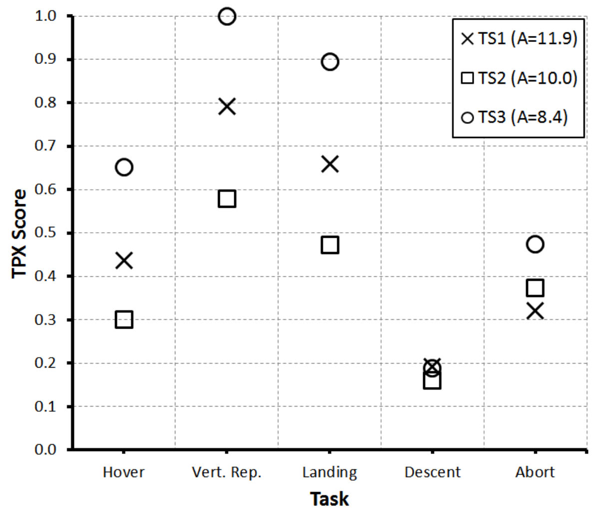
Fig. 5(a) shows the individual TPX scores for each MTE for the same sample of TSs. Fig. 5(b) provides the same analysis for the ACAH configuration, with Fig. 5(c) for the Hybrid configuration.



a) RC Configuration



6b) ACAH Configuration



c) Hybrid Configuration

Fig. 5 Sample of TPX Scores - Individual Tasks

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

Using the data in Fig. 5, it can be seen that for the majority of TS/task combinations, a move from the RC configuration to the ACAH configuration resulted in an improvement in performance, and likewise, a move from the ACAH configuration to the Hybrid configuration again resulted in an improvement in performance. The only exception to this is the decelerating descent MTE, where the results for the ACAH and Hybrid configurations are similar. This is due to the relatively ‘open loop’ nature of this task – at least until the final stage where the pilot is required to capture a hover. The demands of controlling deceleration using an ACAH response type are similar in nature to those when using an ACSH response type. Given that it is difficult for the pilot to take full advantage of the ACSH response type’s advantages for a task such as this one, it is perhaps unsurprising that the final performance is similar.

B. Discussion of Results

1. Effect of Test Subject Aptitude

The results presented above show a considerable difference between the performance achievable by high and low aptitude subjects with the RC configuration. This difference is illustrated in Fig. 6. The high aptitude TS (TS1) was able to maintain the precise hover position for the majority of the task but the low aptitude TS (TS3) was unable to engage with the hovering activity in this configuration. As soon as the vehicle had been moved away from its starting trimmed hover, TS3 was unable to apply appropriate control inputs to decelerate the vehicle back to the hover. Divergent longitudinal and lateral positional oscillations resulted. This level of performance was also reflected in the TLX rating of 72 for this task, the rating being dominated by the mental demand involved in the determination of the desired control inputs, and the frustration of being unable to achieve the task’s goals. In contrast, TS1 awarded a TLX rating of 43 for the hover MTE, with a relatively even distribution of workload across the six components of the rating. Fig. 7 shows the control activity in the lateral (δ_{lat}) and longitudinal (δ_{lon}) axes. It can be seen that TS3 applied corrective inputs at a lower rate and smaller magnitude than TS1, particularly during the first 20 seconds of the maneuver (the translation and deceleration to hover). The variations in height and heading seen in the data for TS1 are a result of the greater confidence with which this subject approached the Hover MTE in the RC configuration, with attempts being made to actively engage with all axes of control. Although not shown in Fig. 7, inspection of the equivalent simulated flight data for the rudder pedals and collective shows that TS3, in contrast to TS1, focused purely on longitudinal and lateral control, and was content to allow height and heading to drift during the task.

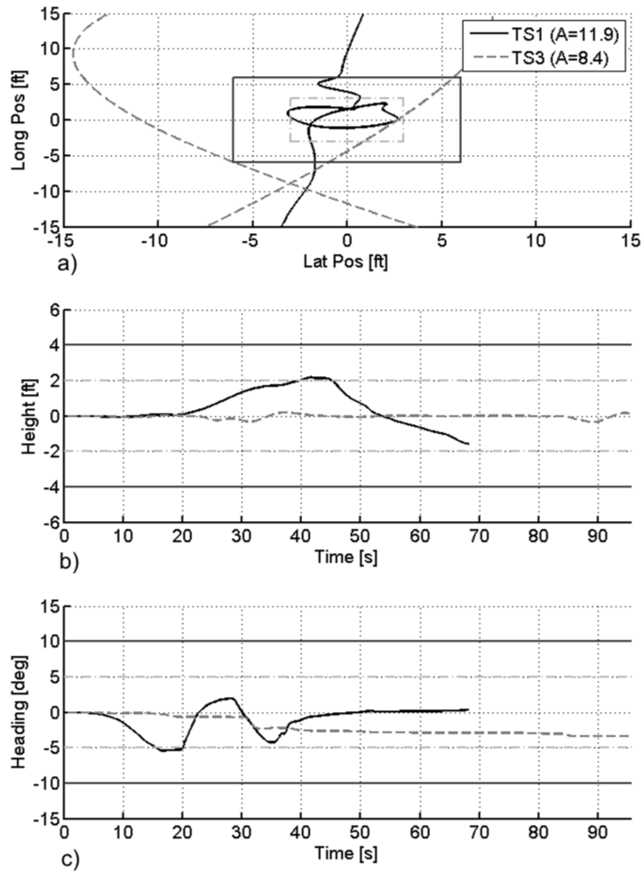


Fig. 6 Comparison of High and Low Aptitude Test Subjects in Hover MTE with RC Configuration

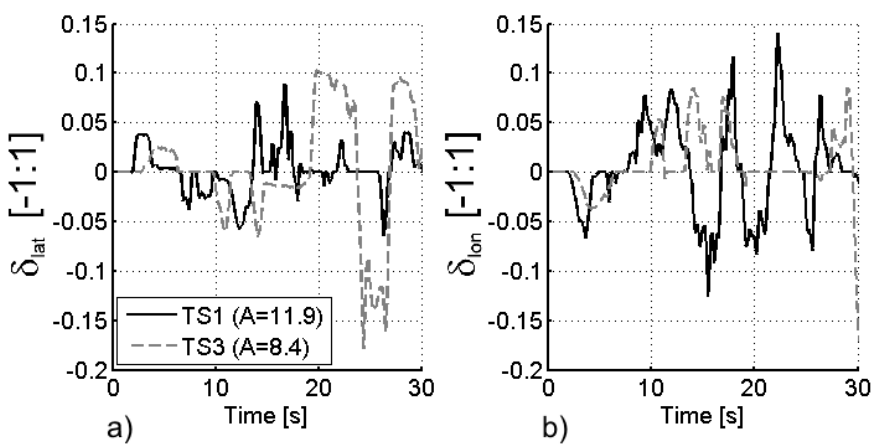


Fig. 7 Control Activity in Hover MTE with RC Configuration

Fig. 8 shows performance in the Hover MTE, for the same two TSs flying the Hybrid configuration. The difference between the two subjects here is much less noticeable. Again TS1 brought a greater level of confidence to the task, decelerating the vehicle to a hover from a higher initial velocity (this can be seen in the larger initial control inputs applied by TS1 in Fig. 9). Both TSs were, however, able to bring the vehicle to a hover within the

MTE's desired performance requirements. The HH and DH functionality of this configuration was employed, allowing both subjects to focus purely on the longitudinal and lateral position control elements of the task. Once the vehicle had been decelerated to a hover, neither TS found it necessary to apply further corrective inputs to maintain position – the TRC response type functioned effectively to command zero velocity with the cyclic stick centered.

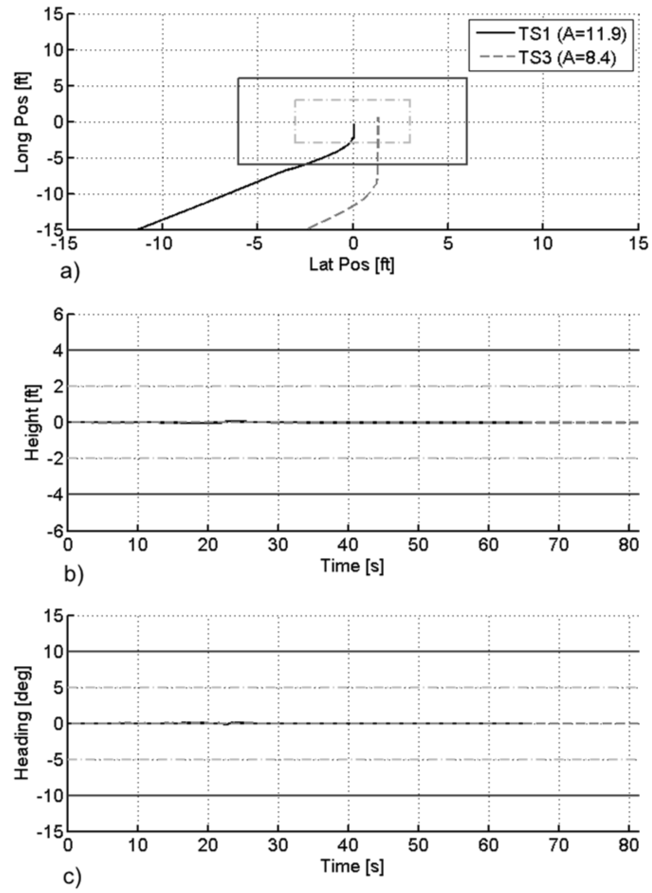


Fig. 8 Comparison of High and Low Aptitude Test Subjects in Hover MTE with Hybrid Configuration

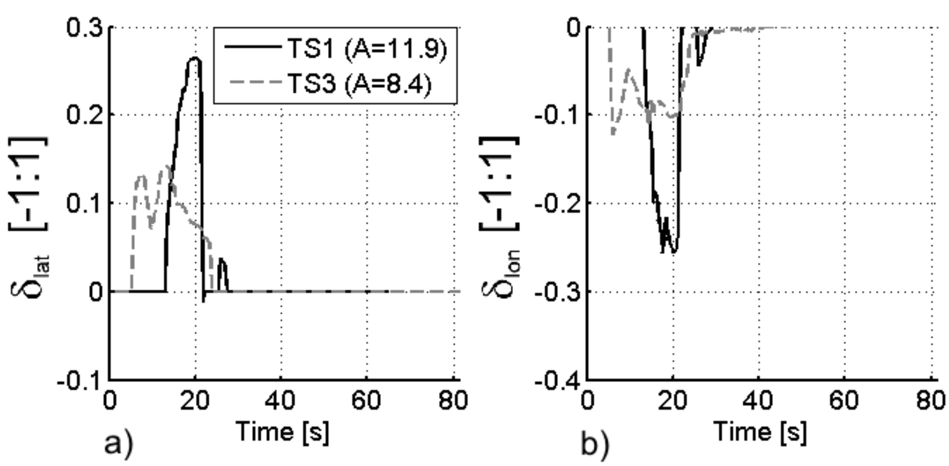


Fig. 9 Control Activity in Hover MTE with Hybrid Configuration

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

2. PAV response type requirements in the Benign Environment

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

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

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

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

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

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

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

IV. Handling Qualities Requirements in a Harsh Environment

A. Results

A total of 7 test subjects have taken part in the PAV HQ evaluations for the harsh environment. Their aptitude scores ranged from A=9.3 to A=11.9. Some of these TSs also took part in the evaluations for the benign environment, while others were newly recruited for the harsh environment assessments. The evaluations can be broken down into three phases. The first phase examined the impact of degrading the Usable Cue Environment (UCE) or introducing atmospheric disturbances individually on all of the PAV configurations in the Hover MTE.

Three TSs took part in this phase of testing (TS1 – A=11.9; TS4 – A=10.33 and TS5 – A=10.39). In the second phase, all of the TSs flew the Hover MTE in both a 'benign' environment – one with good visual conditions and no turbulence, and in the harsh environment – with degraded visual conditions coupled with atmospheric disturbances. All configurations were again used in this phase of testing. The third phase involved all of the TSs flying the Hybrid configuration in all of the MTEs (apart from the Decelerating Descent MTE, where the reliance on far-field visual cues to perform the task precluded its use in the Degraded Visual Environment (DVE) evaluations).

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

Fig. 10 shows TLX ratings awarded by the three TSs for the three PAV configurations in the Hover MTE. Four datasets are presented, showing subjective workload evaluations for a benign environment with neither DVE nor disturbances (GVE, no turb), the two cases which introduce the DVE or atmospheric disturbances individually (GVE, turb and DVE, no turb) and finally, the full harsh environment which combines both the DVE and the atmospheric disturbances together (DVE, turb). Fig. 11 shows TPX scores for the same set of test points.

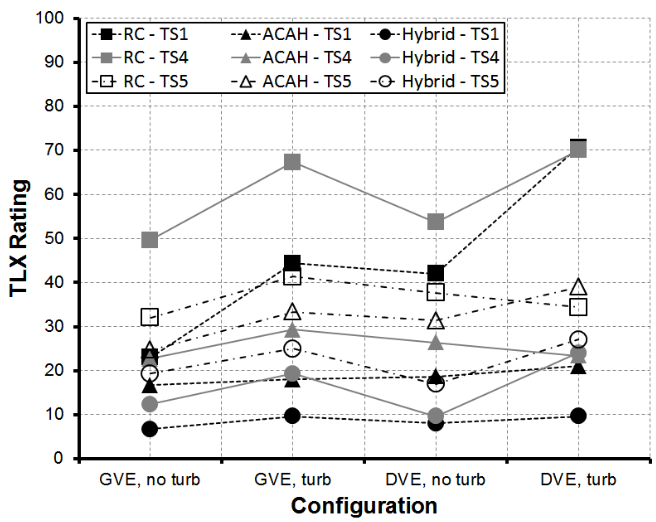


Fig. 10 TLX Ratings for effect of DVE and turbulence in Hover MTE

Although there is considerable variation in the subjective workload interpretation between the three TSs, it can be seen in Fig. 10 that each TS reported a reduced workload transitioning from RC to ACAH and from ACAH to Hybrid. This confirms the findings reported above for the benign environment. Further, Fig. 10 shows that the TSs reported greater increases in workload due to the introduction of turbulence than they did due to degradation of the UCE. Subjectively rated workload in the DVE was only slightly higher than workload in the GVE, whether or not turbulence was present. The exception was the RC configuration, where two of the TSs found similar workload was required in the DVE without turbulence to that in the GVE with turbulence. This finding is in agreement with the statement in [1] that ACAH and TRC response types are suitable for operations in degraded visual conditions.

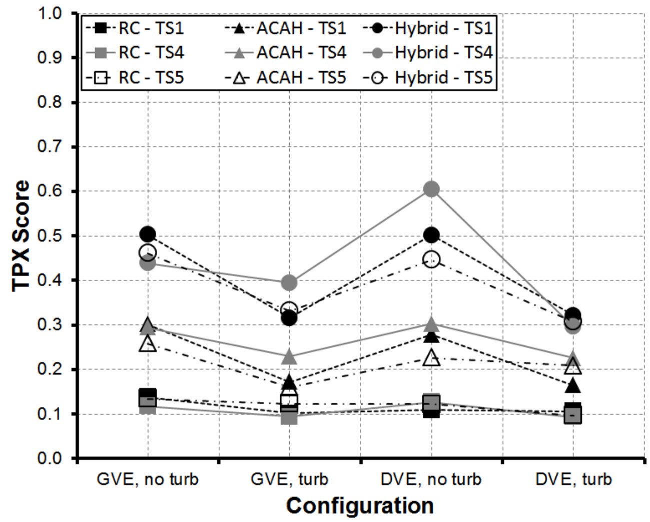


Fig. 11 TPX Scores for effect of DVE and turbulence in Hover MTE

For the quantitative analysis of these tests, Fig. 11 shows a more consistent picture of the behavior of the three configurations in the various environmental conditions. The Hybrid configuration clearly allowed the best performance to be achieved, followed by ACAH, with the RC configuration resulting in the poorest performance. This was the case in all conditions. Indeed, the TSs were able to achieve better performance in the harsh conditions with the Hybrid configuration than they were able to achieve in the most benign conditions with the ACAH configuration. Similar patterns can be seen in the data for the Hybrid and ACAH configurations – similar levels of performance were achieved in GVE and DVE conditions, whilst introducing turbulence caused a reduction in the TPX score. For the Hybrid configuration, this was primarily a result of an increased level of control activity rather than a reduction in the precision with which the TSs were flying the task (see below). For the ACAH configuration, the reduction in TPX was due to a simultaneous reduction in precision and an increase in control activity. With the RC configuration, the picture is somewhat different. Here, the TPX score is lower in the DVE than is the case in the GVE, being similar to the TPX scores achieved when turbulence was introduced in the GVE. Together, these results confirm the UCE measurements for the test database, as the degraded visual conditions adversely affected the RC configuration, but not the ACAH or Hybrid configurations.

One interesting result that can be seen in Fig. 11 is that one of the TSs achieved a higher level of performance in the DVE (without turbulence) than they did in the GVE. In both cases the TS achieved 100% precision in the Hover

MTE; the improvement in the TPX resulted from a reduction in the applied control activity. While this is likely to be in part due to the effect of learning (the DVE case was flown shortly after the GVE case), the degraded UCE may have also had the effect of limiting the cueing of small translational rate errors, and therefore slowed the rate at which the TS applied corrections (Fig. 12).

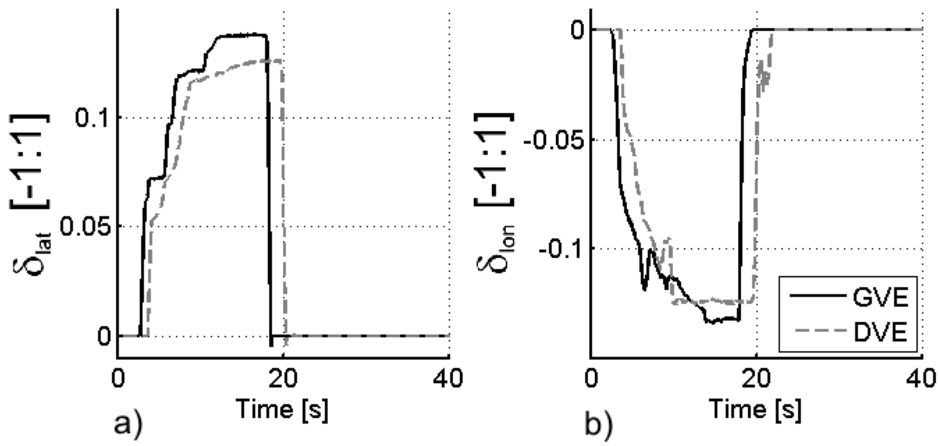
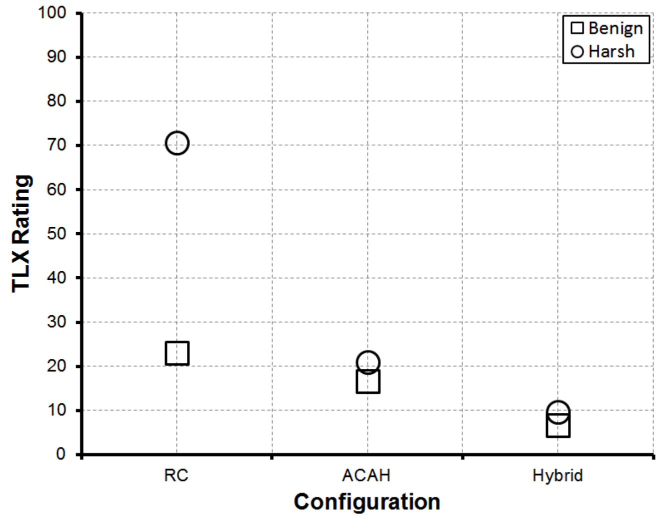


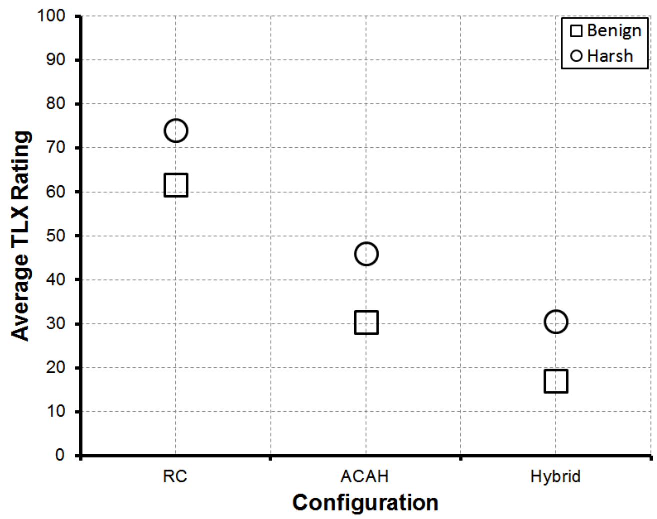
Fig. 12 TS4 control activity in good and poor visual conditions

The key question to be answered by these tests relates to the level of degradation experienced by the pilot in moving from the fully benign condition (GVE, no turbulence) to the harsh environment (DVE, turbulence). Fig. 13(a) shows the TLX ratings awarded by TS1 for these two conditions. This TS achieved the highest aptitude score and holds a PPL(Helicopter). Nevertheless, the results shown provide a clear picture. A slow increase in workload can be observed in the benign environment moving from Hybrid to ACAH to RC. In the harsh environment, the rate of change is faster, especially transitioning between the ACAH and RC configurations. These results show that the closed-loop disturbance rejection features of the ACAH and Hybrid configurations can be effective at minimizing the additional workload required to perform the Hover MTE in the harsh conditions, and that the DVE does not necessarily adversely affect workload, given the correct response characteristics.

Not all of the TSs, however, achieved the same results as TS1. Fig. 13(b) shows the average TLX rating for each configuration given by the 7 TSs who took part in the harsh environment testing. It can be seen that the difference in average TLX ratings between the benign and harsh environments is fairly similar for all three configurations.



a) TS1



b) All TSs

Fig. 13 Average TLX ratings for Hover MTE

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

A picture that is more consistent with that seen in Fig. 13(a) can be observed if the task precision achieved by all of the TSs is considered. Fig. 14 shows the average percentage of time spent within the Hover MTE's desired performance boundaries for each of the PAV configurations in the benign and harsh environments. Across all of the TSs, there was a small reduction in the precision achieved with the Hybrid configuration (3%) in the harsh environment, compared to a larger reduction with the ACAH configuration (7%), and a larger still reduction with the RC configuration (12%). The small reduction in precision with the Hybrid configuration provides confidence that this remains a suitable option for implementation in future PAVs, even in the presence of atmospheric disturbances and a DVE. The analysis of the tests in the benign environment indicated that the ACAH and RC configurations were unsuitable for use in PAVs due to the relatively low levels of precision achievable, and the results seen in Fig. 14 confirm this conclusion, with even lower levels of precision achieved in the harsh environment.

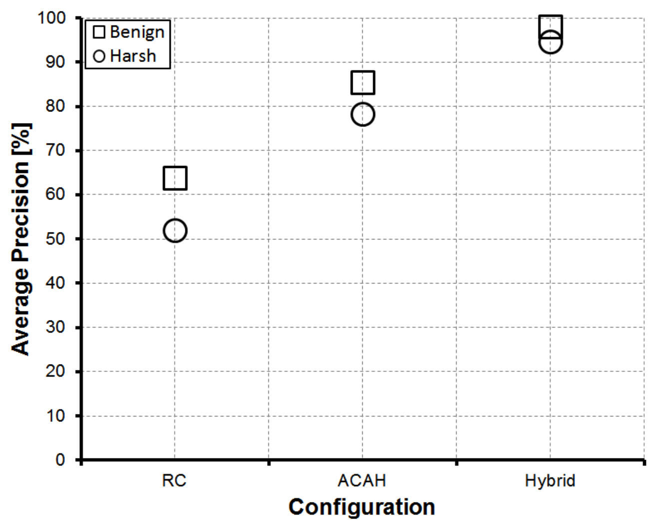


Fig. 14 Average precision from all TSs for the Hover MTE

2. Suitability of Hybrid Configuration for Operations in Harsh Environment

The results presented above suggest that the Hybrid configuration remains suitable for use on a PAV operating in a harsh environment, albeit with an increased workload. However, this is based on just one of the four MTEs used for the assessments. Fig. 15 shows the average TPX score achieved by each TS across all four MTEs.

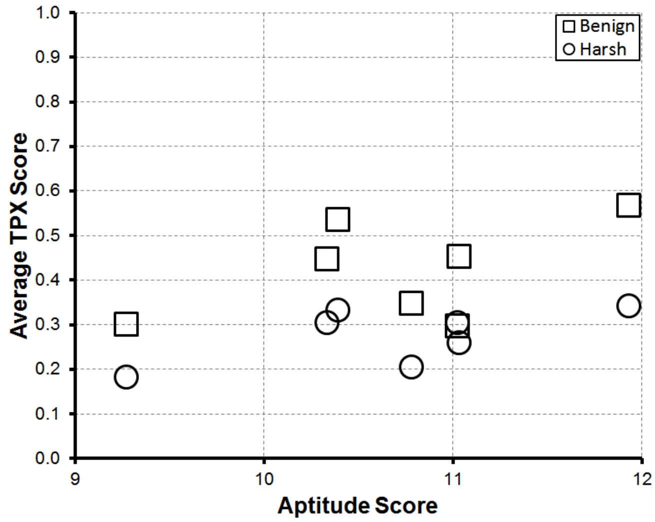


Fig. 15 TPX scores from all TSs averaged across all MTEs

It can be seen that, when all MTEs are considered, there is a considerable drop in the TPX score when moving from the benign to the harsh environment – somewhat more so than was seen in Fig. 11 for the Hover MTE alone. The reason for this reduction in performance is the same as for the Hover MTE – an increased level of control activity, rather than a reduction in the level of precision achieved in the tasks. An example is shown in Fig. 16. It can be seen that there was an increased number of corrective control inputs required to establish and maintain the 45° translation in the first 20 seconds of the task when flown in the harsh environment. However, in both cases, the TS was able to judge the deceleration phase of the MTE correctly, bringing the PAV to a hover inside the task's desired performance boundaries. Thereafter, the PAV maintained its position inside the desired performance boundaries without requiring additional corrective inputs from the pilot.

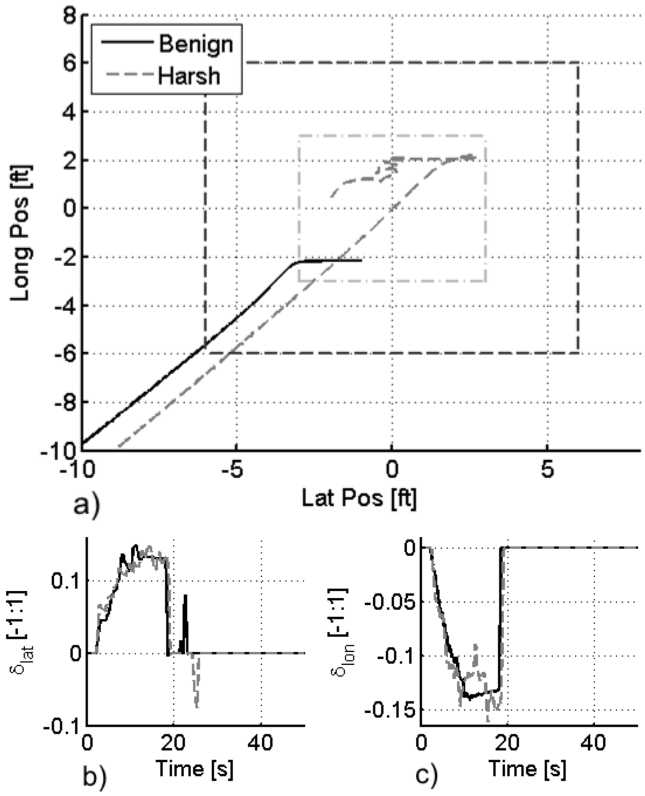
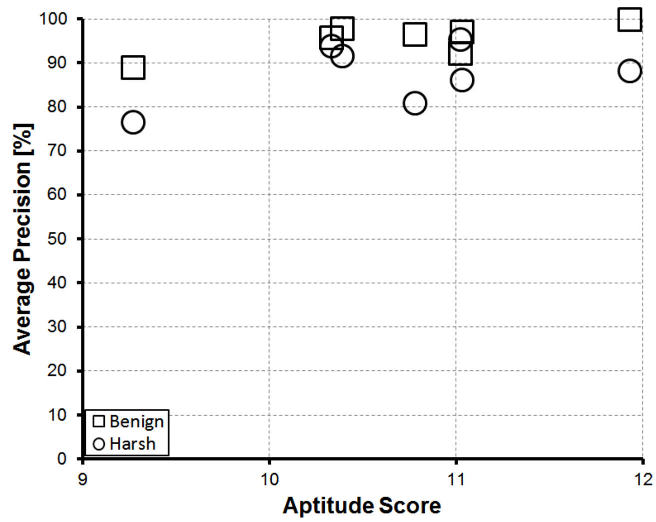
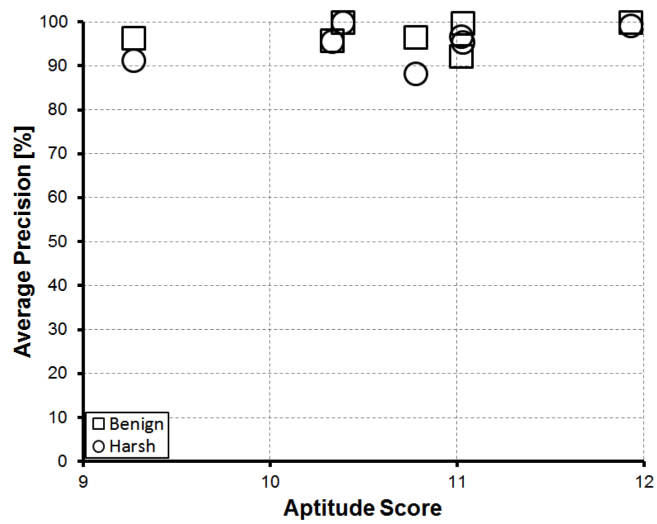


Fig. 16 Plan position and control activity in Hover MTE

There was, however, one notable exception to the trend described above, and that was the Landing MTE. To achieve desired performance, the PAV pilot must touch down inside a target box measuring 2ft longitudinally by 1ft laterally. It proved difficult for the flight-naïve TSs to achieve this high level of accuracy consistently in the presence of atmospheric disturbances.



a) All MTEs



b) All MTEs bar Landing

Fig. 17 Precision achieved by all TSs

When comparing precision in the benign and harsh environments across all four MTEs (Fig. 17(a)), there is typically a 10-15% reduction for each TS in the harsh environment. If the Landing MTE is excluded, however (Fig. 17(b)), the reduction in precision is much smaller (<5%), with several of the TSs able to achieve the same, or better, level of precision as they could achieve in the benign environment. When excluding the Landing MTE, in only one case did the level of precision achieved in the harsh environment fall below the 90% threshold used to measure success in the benign environment analysis.

B. Discussion of Results

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

Despite the demonstrated capability of the Hybrid configuration to maintain precision in the harsh environment in most of the investigated tasks, the workload experienced by the TSs did increase (both qualitatively and quantitatively). This was, in part, due to occasional corrections being required (or perceived as being required) to maintain plan position within the desired tolerances. Again, incorporation of position-hold functionality would be of benefit here. However, workload also increased due to additional effort being required to establish and maintain translational rates in the desired direction (e.g. in the Hover and Aborted Departure MTEs), and in interpreting the more restricted visual cues. In these scenarios, the elevated level of workload may have to be accepted as a consequence of operating manually in the harsh environment. A question would therefore exist regarding the duration of time that a PAV would be expected to operate in such conditions, and hence the expected level of pilot fatigue that would occur. In terms of high precision tasks, such as those employed in this paper, it would be expected that these would form only a small part of a complete PAV mission. The majority of the flight would take place at higher altitudes and away from ground obstacles (Ref.[5]). However, assuming that all phases of the flight would be controlled manually, an elevated level of workload would still be likely in the cruise phase. This is a beyond the scope of the current study.

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

V. Conclusions

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

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

- In contrast to ADS-33E-PRF guidance, with the exception of high precision tasks, the Hybrid configuration – the minimum acceptable level of augmentation in the benign environment – is equally as suitable for operations in a harsh environment as it is in a benign environment.

This paper describes the experimental work conducted and the results achieved to establish the likely handling qualities requirements for a Personal Aerial Vehicle. Of those tested, the Hybrid configuration proved to be a good one to allow representative tasks to be performed by a number of flight-naïve test subjects with a wide range if aptitudes prior to the testing. However, the question remains as to how members of the general public might be trained to a sufficiently high standard that they would be able to pilot the vehicles in a real commuting situation. This topic forms the next phase of the research activity.

As a corollary to PAV pilot training, there is an open question regarding how much, or how little higher level automation would need to be present on board a PAV (beyond the control augmentation described in this work) for commuting journeys to be carried out at traffic densities that are high enough to make a worthwhile reduction in road-based traffic to meet the stated aim of easing congestion. Functions that a trained pilot would normally carry out, such as the maintenance of separation from other vehicles might also have to be automated in such a scenario. Whilst the answer to this question is beyond the scope of the present work and project, it is one that will need to be answered if the mass adoption of PAVs as a form of transport is to become a reality.

Appendix

Table 2 provides the mean, maximum, minimum and standard deviations for the TLX ratings presented in Fig. 1.

Table 2 TLX statistical data for three vehicle configurations

	Mean TLX Rating			Maximum TLX Rating			Minimum TLX Rating			Standard Deviation		
Aptitude	RC	ACAH	Hybrid	RC	ACAH	Hybrid	RC	ACAH	Hybrid	RC	ACAH	Hybrid
11.9	36.8	12.1	10.0	46.7	19.0	14.3	23.0	6.7	6.7	11.0	4.6	3.0
10.0	61.5	45.1	40.3	78.0	74.3	54.7	36.7	22.7	20.3	19.1	20.5	13.5
10.2	46.9	21.5	12.5	73.0	26.0	24.0	24.0	15.7	7.0	21.5	3.9	6.8
11.0	69.3	28.4	14.6	93.3	41.0	16.0	32.0	18.7	12.3	31.1	9.8	1.4
8.4	63.7	61.3	46.7	72.0	73.0	72.0	55.3	37.7	37.3	11.8	15.5	14.5
7.4			64.1			79.0			45.0			15.0
10.2		19.2	12.7		23.7	16.0		15.7	7.7		3.2	3.3
9.3	58.3	52.4	27.8	81.0	68.3	33.3	39.3	34.3	19.3	21.1	12.3	5.6
11.6	42.7	26.7	24.4	70.0	35.7	34.7	22.3	18.3	15.7	20.0	7.7	8.3

Table 3 provides the mean, maximum, minimum and standard deviations for the precision data presented in Fig. 3.

Table 3 Precision statistical data for three vehicle configurations

	Mean Precision Rating (%)			Maximum Precision Rating (%)			Minimum Precision Rating (%)			Standard Deviation (%)		
Aptitude	RC	ACAH	Hybrid	RC	ACAH	Hybrid	RC	ACAH	Hybrid	RC	ACAH	Hybrid
11.9	83	94	100	100	100	100	66	78	100	15	9	0
10.0	66	83	98	99	100	100	0	44	95	38	23	2
10.2	77	93	100	100	100	100	50	78	100	20	9	0
11.0	83	96	100	99	100	100	44	89	99	22	5	0
8.4	48	77	97	61	100	100	34	33	88	19	26	5
7.4			81			96			67			13
10.2		87	98		100	100		78	94		10	3
9.3	55	75	94	86	98	100	24	42	89	31	22	4
11.6	76	84	100	97	100	100	33	56	98	26	18	1

Table 4 provides the mean, maximum, minimum and standard deviations for the TPX data presented in Fig. 4.

Table 4 TPX statistical data for three vehicle configurations

	Mean TPX Rating			Maximum TPX Rating			Minimum TPX Rating			Standard Deviation		
Aptitude	RC	ACAH	Hybrid	RC	ACAH	Hybrid	RC	ACAH	Hybrid	RC	ACAH	Hybrid
11.9	0.14	0.33	0.48	0.22	0.51	0.79	0.08	0.24	0.19	0.06	0.11	0.25
10.0	0.14	0.24	0.38	0.27	0.46	0.58	0.00	0.08	0.16	0.11	0.14	0.16
10.2	0.14	0.29	0.44	0.27	0.42	0.58	0.05	0.22	0.26	0.08	0.09	0.13
11.0	0.16	0.32	0.56	0.27	0.51	1.02	0.06	0.22	0.17	0.08	0.12	0.34
8.4	0.05	0.23	0.64	0.06	0.37	1.00	0.03	0.05	0.19	0.02	0.13	0.33
7.4			0.32			0.66			0.09			0.21
10.2		0.34	0.48		0.46	0.73		0.22	0.19		0.11	0.23
9.3	0.07	0.16	0.31	0.16	0.30	0.42	0.01	0.05	0.13	0.08	0.09	0.10
11.6	0.13	0.21	0.37	0.23	0.36	0.60	0.03	0.10	0.18	0.08	0.10	0.16

Table 5 provides the mean, maximum, minimum and standard deviations for the TLX data presented in Fig. 13b.

Table 5 TLX statistical data for three vehicle configurations and the Hover MTE

	Mean TLX Rating			Maximum TLX Rating			Minimum TLX Rating			Standard Deviation		
Condition	RC	ACAH	Hybrid	RC	ACAH	Hybrid	RC	ACAH	Hybrid	RC	ACAH	Hybrid
Benign	61.7	30.4	17.0	93.3	53.0	29.3	32.0	9.7	7.7	21.7	14.0	8.0
Harsh	74.1	46.1	30.5	89.0	69.0	44.0	34.3	23.3	11.3	18.9	18.1	11.3

Table 6 provides the mean, maximum, minimum and standard deviations for the precision data presented in Fig. 14.

Table 6 Precision statistical data for three vehicle configurations and the Hover MTE

	Mean Precision Rating (%)			Maximum Precision Rating (%)			Minimum Precision Rating (%)			Standard Deviation (%)		
Condition	RC	ACAH	Hybrid	RC	ACAH	Hybrid	RC	ACAH	Hybrid	RC	ACAH	Hybrid
Benign	64	85	98	95	96	100	18	64	92	30	11	3
Harsh	52	78	95	89	97	100	15	62	84	31	14	6

Table 7 provides the mean, maximum, minimum and standard deviations for the TPX data presented in Fig. 15.

Table 7 TPX statistical data for all TS averaged across all MTEs

	Mean TPX		Maximum TPX		Minimum TPX		Standard Deviation	
Aptitude	Benign	Harsh	Benign	Harsh	Benign	Harsh	Benign	Harsh
11.93	0.57	0.34	0.79	0.65	0.32	0.12	0.20	0.22
10.33	0.45	0.31	0.46	0.37	0.44	0.27	0.01	0.05
10.39	0.54	0.33	0.90	0.58	0.29	0.15	0.26	0.18
9.27	0.30	0.18	0.42	0.26	0.19	0.03	0.10	0.11
11.03	0.45	0.26	0.57	0.48	0.34	0.10	0.09	0.16
11.02	0.30	0.31	0.30	0.46	0.30	0.19	0.00*	0.12
10.78	0.35	0.21	0.35	0.35	0.35	0.11	0.00*	0.10

* standard deviation is zero for these points as data relates to one test point for these pilots in the benign environment.

Table 8 provides the mean, maximum, minimum and standard deviations for the precision data presented in Fig. 17a.

Table 8 Precision statistical data for all TS for all MTEs

	Mean Precision (%)		Maximum Precision (%)		Minimum Precision (%)		Standard Deviation (%)	
Aptitude	Benign	Harsh	Benign	Harsh	Benign	Harsh	Benign	Harsh
11.93	100	88	100	100	100	55	0*	22
10.33	96	94	100	100	92	89	6	5
10.39	98	92	100	100	92	67	4	17
9.27	89	77	100	95	67	33	15	29
11.03	97	86	100	100	89	59	5	19
11.02	92	95	92	98	92	92	0*	3
10.78	97	81	97	94	97	59	0*	15

* standard deviation is zero for these points as data relates to one test point for these pilots in the benign environment.

Table 9 provides the mean, maximum, minimum and standard deviations for the precision data presented in Fig. 17b.

Table 9 Precision statistical data for all TS for all MTEs except Landing

	Mean Precision (%)		Maximum Precision (%)		Minimum Precision (%)		Standard Deviation (%)	
Aptitude	Benign	Harsh	Benign	Harsh	Benign	Harsh	Benign	Harsh
11.93	100	99	100	100	100	98	0*	1
10.33	96	96	100	100	92	91	6	4
10.39	100	100	100	100	100	100	0*	0
9.27	96	91	100	95	91	85	5	5
11.03	100	95	100	100	99	91	0*	5
11.02	92	97	92	98	92	95	0*	2
10.78	97	88	97	94	97	84	0*	5

* standard deviation is zero for these points as data relates to one test point for these pilots in the benign environment.

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