Evaluation of Heave Disturbance Rejection and Control Response Criteria on the Handling Qualities Evaluation of Urban Air Mobility (UAM) eVTOL Quadrotors Using the Vertical Motion Simulator

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ABSTRACT

The first piloted handling qualities study of an urban air mobility (UAM) vehicle leveraging the Vertical Motion Simulator (VMS) at NASA Ames Research Center was conducted in Spring 2021. The VMS provides a unique capability to reduce risk by assessing and iterating control designs. Minimal sources currently exist to provide performance and handling qualities data for large, rotor speed-controlled vehicles outside of the software environment. The study compares multiple handling qualities performance configurations for rotor speed and blade pitch-controlled variants of a six-passenger quadrotor conceptual design model developed by the NASA Revolutionary Vertical Lift Technology (RVLT) Project. Additionally, both ADS-33 and a tailored set of performance standards (notionally representing the agility required of a UAM mission) are examined under conditions with and without light turbulence. Preliminary results did show significant variation in ratings based on the set of standards utilized, controller tuning to either Level 1 or boundary Level 1/ Level 2 conditions, and presence or lack of turbulence. A custom approach and landing maneuver was also designed to bring these evaluation tasks together in a more comprehensive application.

INTRODUCTION

This paper describes the preparation, set up, procedure, and initial results of a VMS test sponsored by the RVLT Project that was completed in Spring 2021. Future documentation will go further into trend analysis. The test featured a conceptual six-passenger quadrotor sized for a representative UAM mission (in downtown San Francisco) and evaluated using mission task elements (MTEs) that were simulated at Moffett Field (Ref. 1). Four configurations were flown: a single blade pitch-controlled configuration and three rotor speed-controlled configurations. The blade pitch-controlled configuration was designed to achieve "marginal" Level 1 handling qualities requirements (per ADS-33 and others), while the variable rotor speed configurations were configured to "boundary" Level 1 and "degraded" handling qualities requirements, primarily in the heave axis. This approach will allow for future examination of tradeoffs in required motor power and handling-qualities performance.

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The motivation of this study was to investigate the handling qualities of blade pitch-controlled and rotor speed-controlled multirotor electric vertical take-off and landing (eVTOL) concept aircraft in a flight simulation. Primary objectives were twofold: 1) explore the levels of maneuvering aggressiveness and precision in a UAM mission, and (2) investigate the effect of flight control augmentation disturbance rejection and agility on electric motor power usage. Power usage and analysis will be discussed in future publications. Various mission-representative maneuvers were evaluated using both Attitude Command-Attitude Hold (ACAH) and Translational Rate Command (TRC) response types with and without light turbulence. A secondary objective was to collect representative aircraft motion data suitable to a first-order analysis of passenger acceptance in face of mission-based pilot maneuvering requirements in hover and low speed.

BACKGROUND

Previous Work: Vehicle Model

Malpica and Withrow-Maser (Ref. 2) examined the initial trade-offs between a fixed pitch, variable rotor speed-controlled and blade pitch-controlled quadrotor configuration. The variable speed-controlled configuration is prioritized by some UAM designers due to its lower design gross weight as a function of the passenger count (Fig. 1). Ref. 2 showed that UAM quadrotors sized for rotor speed-control are not stabilizable with adequate closed-loop performance, based on the drive system mechanical limits (from the NDARC model) and technology factors programmed into the sizing analysis as described.

Ref. 3 later found a closed-loop solution by unbounding the current available to the motor model. For the VMS study, current was not bounded to allow pilots to make assessments independent of powertrain limitations. Ref. 4 describes the alterations to the motors and vehicle required for the quadrotor to achieve desirable stability margins.

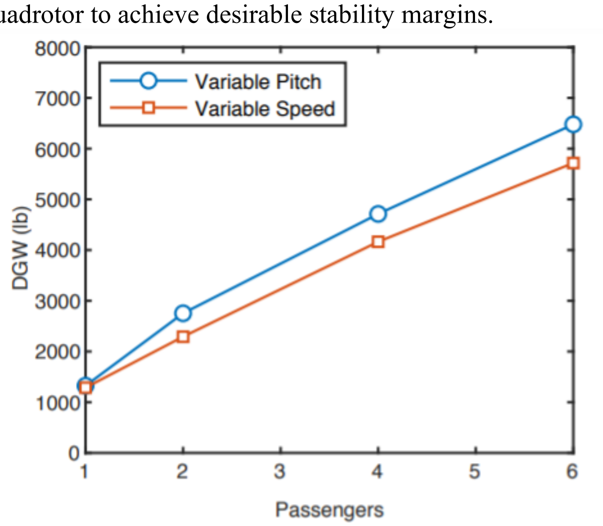


Fig. 1. Design gross weight versus number of passengers for variable pitch and variable speed quadrotor configurations.

Previous Work: Controller

A discrete-time model predictive control (MPC) system was developed for the vehicle. Details of this system and other modeling considerations are described in Ref. 5. One of the more important details is that the control system consisted of two loops: a fast inner-loop ACAH controller and an outer-loop for augmentation of different control modes as well as command filtering. This setup allowed the vehicle's open-loop disturbance rejection characteristics to be driven by the weights of the MPC cost function while the pilot-commanded response metrics were shaped using the outer-loop filters. This independent tuning greatly facilitated the design objective to meet borderline ADS-33 standards.

TEST PREPARATION

Vehicle Model

An electric propulsion six-passenger (1,200-lb payload) NASA reference concept quadcopter described in Ref. 1 and a specifically designed variant using rotor speed for control were studied. The general concept is illustrated in Fig. 2. Both quadrotor variants were designed to the common sizing mission profile detailed in Ref. 2. A summary of design parameters for the two aircraft is given in Table 1. Both aircraft were equipped with electric motors for propulsion, but the vehicle of Ref. 2 used collective control (and constant rotor speed), while the second vehicle used variable rotor speed control (and constant pitch).

Bare-airframe linear stability and control derivative models of these configurations were generated with FlightCODE (formerly SIMPLI-FLYD Ref. 6), based on aircraft designs and performance maps obtained using the rotorcraft design tool NDARC (Ref. 7 and 8) for discrete points within the operating envelope. The discrete-point dynamic models were "stitched" together into a quasi-linear parameter varying (qLPV) full-envelope simulation model. The integration of the qLPV model was done within FlightDeckZ, a NASA Ames vehicle management system, which combined the bare-airframe, motor, actuator, and sensor models with the flight control system and interfaced with the VMS facility.

Flight control system augmentation provides the vehicles with TRC, ACAH, and Rate Command-Attitude Hold (RCAH) response types for attitude control; combinations of Rate Command-Direction Hold (RCDH) or Turn Coordination (TC) for directional control; and Rate Command-Height Hold (RCHH) for heave.

An important note is that the configuration of the TRC control mode varied as the experiment progressed in response to the subpar handling quality comments received from the pilots. The original TRC setup, TRC1a, had its outer-loop, second-order filter set with an undamped natural frequency, ω_n, of 0.290 and damping ratio, ζ, of 1.000. The second version, TRC1b, attempted to reduce oscillations with an ω_n of 0.281 and a ζ of 1.128. Finally, it was found that speed limitations imposed on the TRC were slightly asymmetrical based on the logic used to calculate them. This was corrected to make the responses symmetric and expanded from ±15 to ±23 knots. Additionally, the outer loop was tuned with an ω_n of 0.290 and a ζ of 2.950. This third version will be referred to as TRC2 throughout the paper.

Fig. 2. NASA concept quadrotor.

A representative model of the electric propulsion system was required to accurately characterize power demands resulting from aircraft maneuvering. The motor model was chosen to adequately represent the fundamental electromechanical dynamics that govern the motor torque output generation without being overburdened with the complexities of a real electric propulsion system architecture. The basic equations governing the rotational dynamics of the motor are thus defined by:

Motor armature electrical circuit

$$L_a \frac{di_a}{dt} = -R_a i_a - K_e \omega + V_a \quad (1)$$

Mechanical relationship

$$J \frac{d\omega}{dt} = K_m i_a - \tau \ [-B\omega] \quad (2)$$

such that torque applied at the rotor shaft is

$$Q_s = \tau_r = K_m r i_a - J r^2 \frac{d\Omega}{dt} \quad (3)$$

Here L_a, R_a, and K_e are the motor armature winding inductance, resistance, and back-EMF coefficients, and V_a and i_a are the applied voltage and current flowing through the armature winding. In practice inductance values are small enough to be neglected ($L_a \approx 0$). The motor rotational speed is denoted by ω and J is the moment of inertia of the motor shaft, $K_m i_a$ is the electric torque (where $K_m = cK_e$ and c is a unit conversion constant), τ is the mechanical load (positive opposing the direction of rotation) applied at the output shaft, and, optionally, internal viscous "friction" losses $B\omega$ could be included. For the mechanical equation of the rotor: Ω is its rotational speed and Q_s is the mechanical torque applied at the shaft. Finally, r is the transmission gear ratio between the motor and the rotor.

Table 1. Basic characteristics of NASA quadrotor configurations.

Configuration	Collective	RPM Control
Design Gross Weight (lb)	6,480	5,716
- Payload	1,200	1,200
- Weight Empty	5,269	4,507
- Operating Weight	5,279	4,517
Capacity (passengers + crew)	6	6
Number of rotors	4	4
Disk loading (lb/ft^2)	3.0	3.0
Number of blades	3	3
Rotor radius (ft)	13.1	12.3
Solidity, thrust-weighted	0.055	0.055
Hover tip-speed (ft/s)	550	550
Rotational speed (rad/s)	42.0	44.7
Flapping frequency (/rev)	1.030	1.030
Lock number	5.16	4.95
Moments of inertia (slug ft^2)		
- I_{xx}	15,540	12,094
- I_{yy}	16,963	13,201
- I_{zz}	20,525	15,973
- I_{xy}	0	0
- I_{yz}	0	0
- I_{xz}	0	0
Rotor moment of inertia (slug ft^2)	265.8	202.6
Propulsion group	Centralized	Distributed
Number of motors	4	4
Sea Level Static power available per motor (hp)	168.0	130.5
Specification engine speed (rpm)	8,000	8,000
Engine power limit (hp)	319.9	254.3
Drive system torque limit (lb-ft)	8,389	1,566
Battery energy capacity (MJ)	1,331	1,196

Description of the Facility

The VMS (Fig. 3) features very large-amplitude motion cueing. The cockpit cab (T-cab) has dual pilot seats mounted in the cab and seven-image presentation "windows" to provide outside imagery (Fig. 4). The visual imagery is generated using an 8-channel RSi Image Generator. The visual delay was measured to be ~40 ms. The Moffett Field database was carefully tailored to contain adequate macro-texture (i.e. large objects and lines on the ground) for the determination of the rotorcraft position and heading with reasonable precision. This visual database is modeled after the flight tests of Ref. 9 and 10. Additionally, a visual database modeling a vertiport or heliport terminal building located amongst building structures allusive to a metropolitan urban setting was designed. The appropriate heliport markings were modeled to adequately cue the pilot to the desired landing point and precision (Ref. 11). For the approach and landing, a flight director allows the pilot to fly the planned flight path while providing visual cueing of desired and adequate performance requirements. See Fig. A1 (Appendix, Section A) for a description of the visual guidance system for guided approach and landing.

Aural cueing was provided to the pilot via a WaveTech sound generator and cab-mounted speakers. Rotor noise was emitted to mask external noise from the VMS motion system and enhance the sense of immersion. Each rotor/motor pair was modeling independently with an RPM range between 300-2000 and a selectable volume gain. Airspeed noise was available between 0-100 kts.

Pilot controllers were installed in the cab cockpit for the right-hand seat in a configuration shown in Fig. 4. Note the chin window and the cueing it provides (Fig. 4). The custom TCL grip (Fig. 5-Left) was configured with a proportional controller under the pilot's left thumb. Controller switches were configured to allow the pilot to manually select the flight control mode between Rate Command (RC), for up-and-away flight, and higher augmentation modes (ACAH and TRC) for hover and low speed maneuvering.

Main controller forces, in terms of gradients, breakouts, and friction are provided by a hydraulic McFadden variable force-feel system. A switch was configured to allow the pilot to engage and disengage the trim forces. Starting values for the gradients, breakouts, and friction are provided in Table 2. Force-displacement relationships for the side stick controller and force gradient values for the stick [lbf/in] are reported in Fig. 6. Note the asymmetry of the lateral force gradient (Fig. 6(a)) required to account for neuromuscular differences in the force exerted between left and right input deflections. Final values were set by the project pilot before final testing. Special consideration was given to the dynamic characteristics of the side stick inceptor, ensuring the optimal combination of natural frequency and damping to provide the quickest input response (Ref. 12).

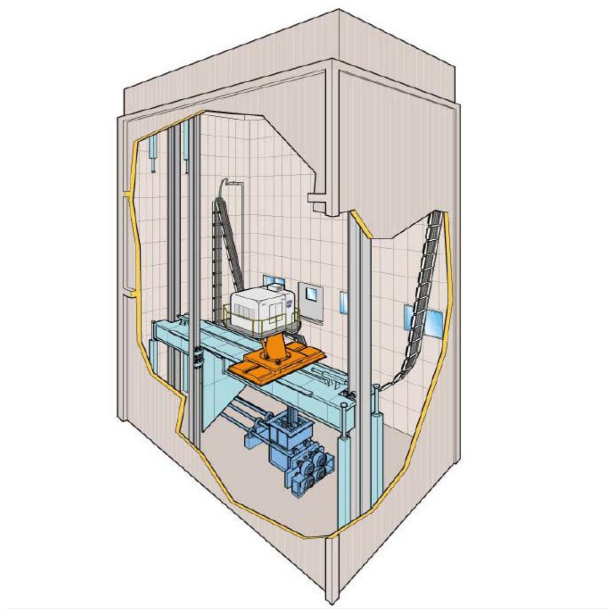


Fig. 3. NASA-Ames Vertical Motion Simulator (VMS).

The primary flight instruments (Primary Flight Display, and Horizontal Situation Indicator,) were electronically drawn on two panel-mounted cathode-ray tube displays. Fig. 7 shows, as an example, an emulation of the Rockwell Collins CAAS primary flight instruments. Instrument Landing System (ILS) localizer and glideslope indicators, augmented with pursuit guidance symbology, were overlaid in order to conduct instrumented precision approaches (See Fig. A1). Additionally, active control mode was shown to the pilot with separate cockpit indicators.

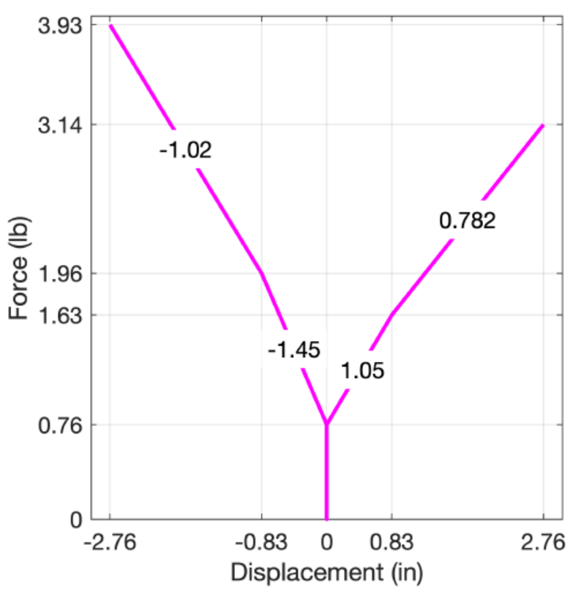
Pilot reference station and eye point positions (Table 3) were defined, according to MIL-STD-1333A, based on cabin geometry of the conceptual vehicle. Appropriate transformations to the VMS motion reference point were applied. These allowed cab occupants to experience ride quality consistent with the seating arrangement of the vehicle.

Fig. 4. NASA-Ames VMS T-cab cockpit.

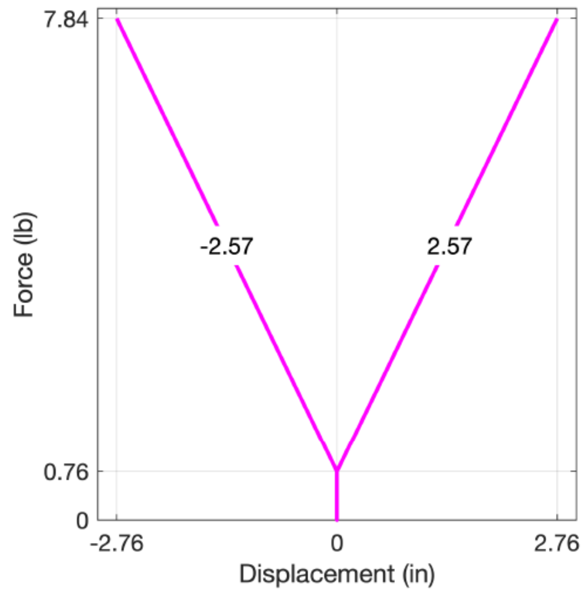
Fig. 5. (Left) Thrust Control Lever (TCL) for vertical control, (Right) Side-stick for pitch and roll control.

Table 2. Inceptor Force-Displacement Characteristics.

	Cockpit control	Gradience (lb/in)	Break-Out (lb)	Friction (lb)	Damping (lb/in/s)
Trim release engaged	Lat	Variable	0.76	0.0	0.5
	Lon	2.57	0.76	0.0	0.88
	Dir	15.0	10.0	0.0	0.5
	TCL	1.5	1.0	3.0*	0.0
Trim release disengaged	Lat	0.0	0.0	0.7	0.0
	Lon	0.0	0.0	0.3	0.0
	Dir	0.0	0.0	0.8	0.0
	TCL	0.0	0.0	3.0*	0.0
*Default values. Pilot selectable.					



(a) Lateral Input

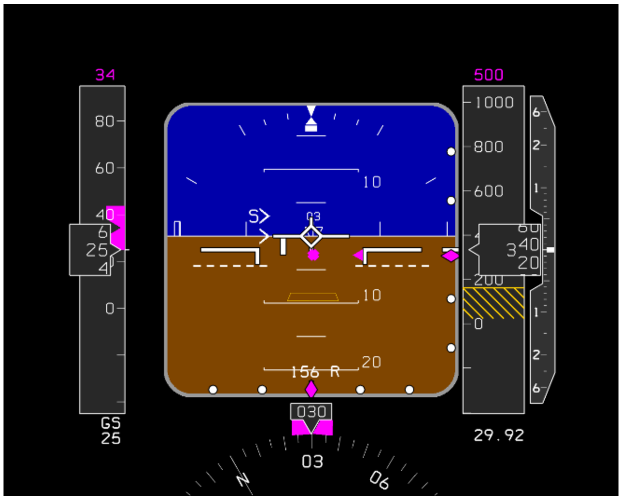


(b) Longitudinal Input

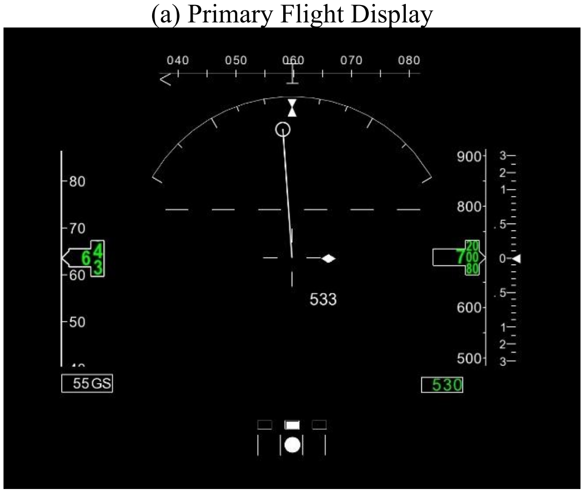
Fig. 6. Side stick force-displacement characteristics as set by project pilot during fixed-base assessment.

Table 3. Pilot station reference points (inches).

Reference Line	Station	Buttock	Water
Seat Reference Point	-41	21.6	-48
Buttock Reference Point	-46.75	21.6	-48
Design Eye Position	-47	21.6	-16.5
Aircraft Center of Mass	-9.6	0	0



(a) Primary Flight Display



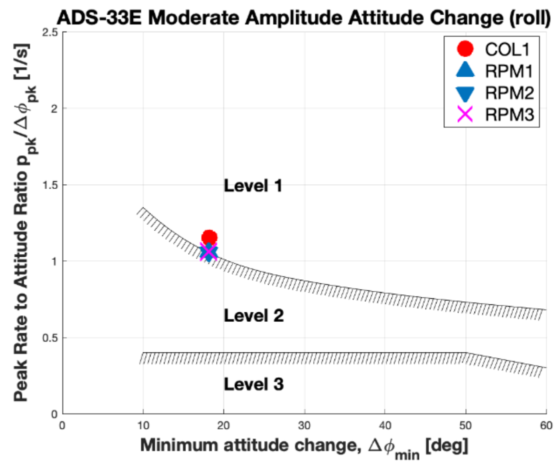
(b) Horizontal Situation Indicator

Fig. 7. Example of Primary Flight Instruments to be drawn in VMS cab heads-down panel displays.

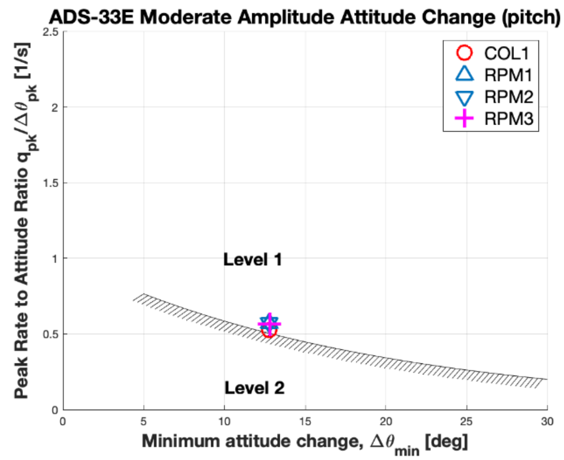
Test Description

The handling qualities of two conceptual quadrotor configurations were evaluated, via pilot-in-the-loop simulation, in the NASA Ames VMS facility as described above. Although civilian rotorcraft are not certified to military specifications, the standards entailed in ADS-33 provide a good set of guidelines to use in flight control design. Therefore, these were the primary evaluation guidelines used throughout the experiment. In addition, a specifically tailored approach and landing was simulated, linking multiple MTEs into one operationally relatable procedure. Hover, Lateral Reposition, and Vertical Maneuver MTEs were explored. The Lateral Reposition and Vertical Maneuvers were chosen to identify vehicle behavior in the primary lateral and vertical axes, while Hover represented a basic, multi-axis maneuver. The Lateral Reposition and Hover MTEs were flown primarily in ACAH while the Vertical Maneuver was flown with varying iterations of TRC to minimize lateral and longitudinal excursions and pilot workload. Pilots were also instructed to disregard the horizontal position errors.

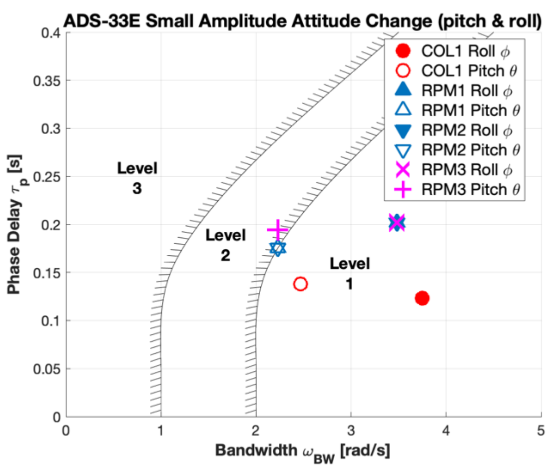
Six experimental test pilots performed evaluations in simulated light wind/turbulence conditions and provided comments and handling qualities ratings (HQRs) using the Cooper-Harper rating scale (Ref. 14) and Bedford Workload Scale (BWS) (Ref. 15).



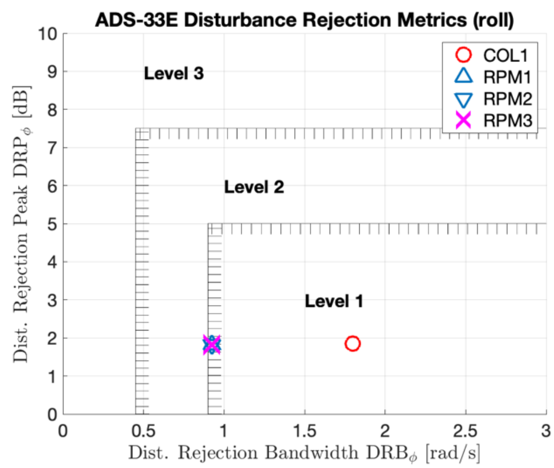
(a) Moderate-Amplitude Roll Performance



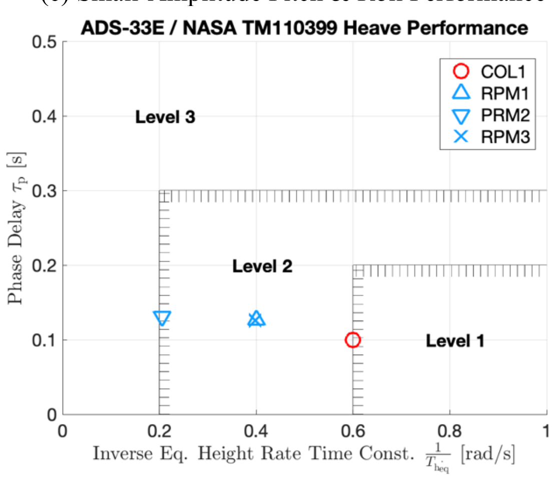
(b) Moderate-Amplitude Pitch Performance



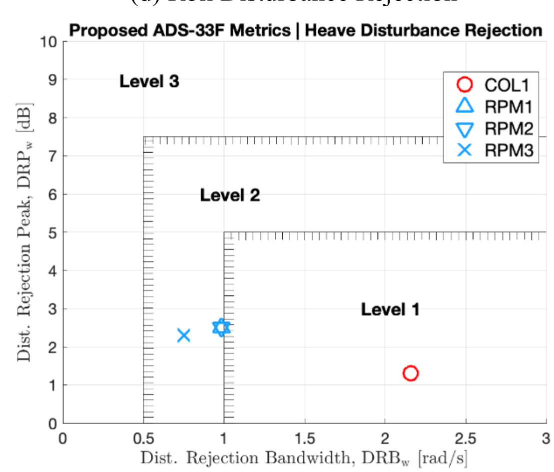
(c) Small-Amplitude Pitch & Roll Performance



(d) Roll Disturbance Rejection



(e) Closed-Loop Heave Performance[1]



(f) Heave Disturbance Rejection

Fig. 8. Notional small & moderate-amplitude control response and disturbance rejection specifications.

The experiment focused on the heave axis where control system tuning was used to establish different ADS-33 based disturbance rejection bandwidths (DRB) as shown in Fig. 8(f). Findings from Franklin and Stortz (Ref. 16) were used to

[1] Figure 8(e) depicts a hybrid plot of phase delay from ADS-33E and the inverse height rate time constant from work by Franklin and Stortz (Ref. 16).

set the time constant response to pilot input for the heave axis (Fig. 8(e)). The variable blade pitch configuration (referred to as "COL1") was used as a baseline model and was designed to meet ADS-33 Level 1 standards for attitude and direction control with margin (approximately 10%) for the moderate and small-amplitude ADS-33 metrics as well as recently proposed Level 1 DRB thresholds in (Ref. 17). The first and second variable rotor speed configurations (referred to here as "RPM1" and "RPM2", respectively) each had borderline Level 1/Level 2 DRB for all axes (roll, pitch, yaw, and heave). Additionally, their direction and attitude performance were tuned for borderline Level 1/Level 2 small and moderate-amplitude metrics. The heave response time constants were tuned to 2.5 seconds (mid-Level 2) for RPM1, and 5 seconds (borderline Level 2/Level 3) for RPM2. A third rotor speed-controlled configuration, RPM3, was designed to have the same metrics as RPM1, but with a reduced, mid-Level 2 DRB (approximately 0.75 rad/s).

One caveat is that COL1 had its moderate-amplitude pitch tuned to a 10% margin based on a hand-estimated version of the ADS-33E plot (the true plot is depicted in Fig. 8(a)). Following the experiment, it was found that the actual Level 1/Level 2 boundary was slightly higher. Since the magnitude of the Level 1/Level 2 peak rate to amplitude ratio is so small (on the order of 10^{-1}[1/s]), the original 10% margin was very susceptible to the slight rise of the corrected boundary line. As such, the actual margin for the COL1 configuration was only about 4%. Future studies will need to use larger margins if deeper, more well-defined Level 1 performance values are desired.

TEST PROCEDURE

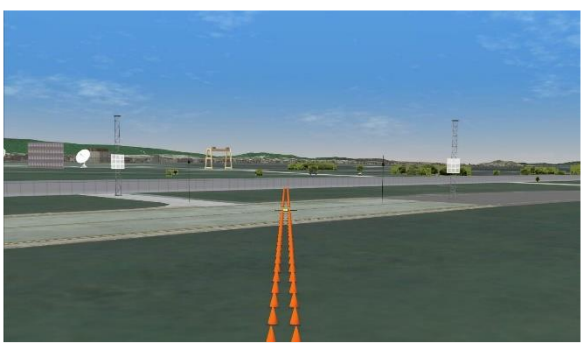


Fig. 9. Visuals for the Hover MTE in the VMS.

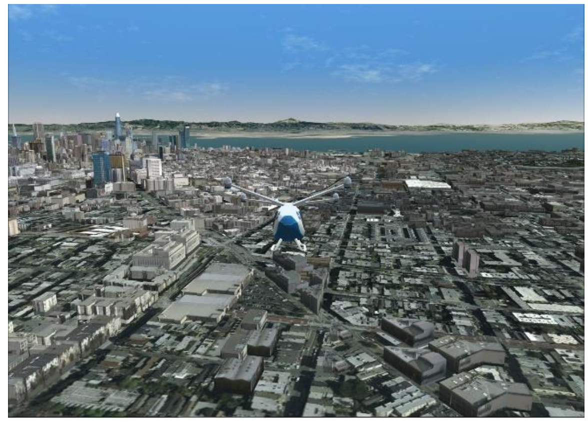


Fig. 10. Visuals for the Approach and Landing MTE in the VMS.

Test configurations were evaluated using flight test maneuvers derived from ADS-33. The hover and low-speed ADS-33 flight test maneuvers, or mission task elements (MTEs) are well established and proven handling qualities test evaluation standards. Additionally, a "custom" precision approach to landing task, linking multiple elements into one operationally relatable mission scenario, was employed to evaluate the handling qualities in forward flight and during the transition from forward flight to low-speed flight and hover. The visuals for the approach to landing task are shown in Fig. 10. The test matrix can be found in Table 4.

Pilots performed one or more general training sessions followed by evaluation sessions. Evaluation sessions allowed for a limited number of practice runs per aircraft-task configuration, followed by at least three evaluations for record. These latter three evaluations formed the basis for the pilots' comments and a single handling quality rating (HQR) using the Cooper-Harper rating scale (Ref. 14). A pilot questionnaire to help solicit comments leading up to the HQR is provided in the appendix (Appendix, Section C). Pilot comments were recorded and transcribed for inclusion in a report documenting the VMS results. The Bedford workload scale and the pilot induced oscillation rating (PIOR) scale were also utilized for some of the data runs. Maneuver descriptions can also be found in the appendix (Appendix, Section B).

Table 4. Test Matrix.

Task/MTE	Mode*	Comments
Hover		
- Moderate winds	ACAH	
- Calm winds	ACAH	
- Moderate winds	TRC	
Vertical Maneuver		
- Moderate winds	TRC	Executed in TRC to reduce lateral and longitudinal
- Calm winds	TRC	control workload, and emphasize heave control.
Hovering Turn		
- Moderate winds	TRC	Executed in TRC to reduce lateral and longitudinal control workload, and emphasize yaw control.
Lateral Reposition		
- Calm winds	ACAH	
UAM Approach and Landing		
- Moderate winds	ACAH	RC for up and away flight. Pilot manually selects higher
- Calm winds	ACAH	augmentation mode (ACAH or TRC) within pre-determined
- Moderate winds	TRC	airspeed.

*Refers to the basic lateral-longitudinal response type. Directional and heave response types are RCDH and RCHH, respectively. Four (4) experimental variants, spanning the disturbance rejection and control response design space, are defined for evaluation at each Task/MTE mode pairing.

INITIAL RESULTS

Preliminary analyses of the seven pilot feedback metrics (Cooper Harper handling quality, ride quality, aggressiveness, precision, predictability, pilot-induced oscillation, and Bedford workload ratings) and pilot comments are detailed below. All rating scales have been reproduced in Section C of the Appendix. Note that, while the predictability and ride quality scales range linearly from 1-9, the rest of the metrics assign, specific definitions for each number and the differences between ratings are not necessarily proportional. Scores for these seven categories were collected and averaged from all the applicable pilots to populate the respective tables and bar plots throughout the paper.

Handling Qualities Ratings (HQRs)

Table 5 shows the average HQR for each vehicle configuration in the Hover, Lateral Reposition, and Vertical Maneuver. Two sets of standards were used with the first being the traditional ADS-33 standards (Ref. 13). The second, tailored specifically for hypothetical UAM application, demanded higher precision, but required less aggressiveness. It is noteworthy that all vehicle configurations, including the COL1 configuration, were rated, on average, in Level 2 handling qualities range. This was unexpected for the COL1 variation which was designed to meet Level 1 with margin.

Table 5. Average Cooper-Harper Handling Quality Ratings.

<table>
<tr><th>Vehicle</th><th colspan="5">COL1</th><th colspan="3">RPM1</th><th colspan="3">RPM2</th><th colspan="3">RPM3</th></tr>
<tr><td>Standard</td><td>ADS-33</td><td>UAM</td><td colspan="3">UAM</td><td>ADS-33</td><td>UAM</td><td>UAM</td><td>ADS-33</td><td>UAM</td><td>UAM</td><td>ADS-33</td><td>UAM</td><td>UAM</td></tr>
<tr><td>Turbulence</td><td>None</td><td>None</td><td colspan="3">Light</td><td>None</td><td>None</td><td>Light</td><td>None</td><td>None</td><td>Light</td><td>None</td><td>None</td><td>Light</td></tr>
<tr><td>Hover</td><td>4.1</td><td>4.5</td><td>5.1</td><td>5.1</td><td>3.8</td><td>4.5</td><td>4.7</td><td>6.8</td><td>4.3</td><td>4.8</td><td>6.8</td><td>4.3</td><td>4.8</td><td>6.8</td></tr>
<tr><td rowspan="2">Vertical Maneuver</td><td>3.5</td><td>3.0</td><td colspan="3">3.6</td><td rowspan="2">3.8</td><td rowspan="2">3.4</td><td rowspan="2">5.0</td><td rowspan="2">5.0</td><td rowspan="2">3.9</td><td rowspan="2">4.6</td><td rowspan="2">4.3</td><td rowspan="2">4.0</td><td rowspan="2">6.5</td></tr>
<tr><td>3.0</td><td>3.5</td><td colspan="3">3.5</td></tr>
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<tr><td colspan="3">Control Mode Color Legend</td><td colspan="3">ACAH</td><td colspan="3">TRC1a</td><td colspan="3">TRC1b</td><td colspan="3">TRC2</td></tr>
</table>

While results are not comprehensive, some noteworthy observations have been made. Individual pilot ratings do not invariably follow average trends. Therefore, more data points through testing or simulation may be required to confirm some of the trends discussed below. First, for the Hover and Lateral Reposition with ACAH control, the UAM standards received similar or higher handling qualities ratings (and, thus, vehicles were less likely to satisfy the desired requirements) than the ADS-33 standard runs for the same configuration. This emphasizes the importance of determining if the assumptions used traditionally for rotorcraft design (heavily derived from military needs) are the same standards that should be applied to UAM. The UAM standards used here did identify potential undesirable motion that was not identified by the ADS-33 maneuvers, but it was not determined if this level of precision will be required for UAM vehicles. Another general observation was that the addition of turbulence during the maneuver did affect vehicle performance, producing degraded ratings. It was also noted that the HQRs for COL1 were, on average, lower than the RPM-controlled cases for nearly all maneuvers, reflecting the difference in control design.

The UAM and ADS-33 standards affected the HQR ratings of the RPM variations. As seen in the table above for the Vertical Maneuver, there is a stark drop from RPM1 to RPM2 for the ADS-33 standard while the difference from RPM1 to RPM2 for the UAM standard is less substantial. The shorter time restrictions imposed by the ADS-33 standards demand quicker control response for the heave axis compared to the UAM standard. As such, pilots had less control margin available to be more aggressive in the maneuver. This is corroborated by the pilot aggressiveness ratings (see Fig. E14). The effect of these standards on pilot ratings for the fixed-pitch vehicles is not as clear for the Hover Task and Lateral Reposition MTEs since the DRB and control response were only varied along the vertical axis. While there was no significant difference in HQR ratings for the Hover Task, there are variations to the other rating categories (aggressiveness, precision, etc.). Likewise, there is an incongruity between the two standards during the Lateral Reposition. There is a slight dip in the HQR rating for RPM2 compared to RPM3 under ADS-33 standards that does not exist for the UAM standard (see Fig. E7), suggesting that the ADS-33 standards are advantageous for the RPM2 configuration. This is also supported by pilot ratings for precision and aggressiveness where the UAM standard ratings for the RPM3 vehicle are about the same as the RPM2, but substantially worse than RPM2 under the ADS-33 standards. These trends warrant further investigation to address how the standards may have pronounced and/or suppressed the effects of varying heave DRB and control response in the RPM vehicles.

It should also be noted that the difference in control parameters between the RPM configurations did not have a significant impact on the average HQRs for the Hover maneuvers, and to a lesser extent, the Lateral Reposition maneuvers. It is hypothesized that this is because the Hover maneuver is primarily a lateral and longitudinal control task, so the degradation in both the DRB and the response time in the heave axis may not be reflected in this maneuver. This is also partially corroborated in the similar values between the Lateral Reposition cases, which is also a primarily lateral maneuver. However, there is also a possibility that the similar ratings for the Hover MTE in turbulence may stem from the turbulence's ability to significantly interfere with the pilots' ability to differentiate the control design. Further analysis into the off-axis impact of the varying control parameters would be necessary to fully justify this claim.

Ride Quality

Similarly to the average Cooper-Harper ratings, the average ride quality ratings shown in Table D1 (Appendix, Section D), reflect differences between the configuration tuned marginally into Level 1 handling qualities (COL1) and the borderline Level 1/Level 2 handling qualities (RPM1, RPM2, and RPM3). Lower ratings correspond to more desirable ride quality. In most cases, COL1 produced better ride quality ratings than the RPM cases. Little variation exists between the ADS-33 standards and the UAM standards; however, it appears that the presence of turbulence resulted in a considerable increase in ride quality rating.

During the Hover Task MTE, pilots, on average, rated the ride quality for RPM2 configuration slightly better than the RPM1 and RPM3 configurations for the ADS-33 and UAM (without turbulence) standards. This gave RPM2 average ratings that were similar to the COL1 vehicle for the same standards. However, when examining the individual pilot ratings (see Fig. E5), this improvement is less substantial, especially for the ADS-33 standards. While it could be argued that RPM2 slightly improved ride quality over RPM1 and RPM3 based on the averages, the variation in individual pilot ratings appears to be too close to make this claim with certainty.

Similarly, the RPM2 vehicle appeared to improve ride quality over RPM1 and RPM3 for the Vertical Maneuver under UAM standards with turbulence, but when looking at individual pilot ratings, only 4 of the 6 pilots rated the RPM2 configuration. After taking this into account, only pilot F gave RPM2 a lower rating compared to RPM1 while pilots E and F gave RPM2 a lower rating compared to RPM3 (see Fig. E17). Again, the values may be too close to conclusively distinguish the RPM2 configuration from the others.

Finally, while the TRC adjustments were not an intended focal point of the study, there was no variation in ride quality for the RPM configurations in the Lateral Reposition and TRC2 was rated better than TRC1a in the Hover Task MTE under UAM standards with turbulence. The fact that no one pilot rated both TRC2 and TRC1a for the Vertical Maneuver along with the relatively close ratings between the control modes (see Fig. E17) makes it difficult to conclusively say whether TRC2 improved ride quality.

Perhaps the ride quality scale, in the context of this experiment (question 3 in Fig. C4), lacks the structure needed to differentiate the numerical values. While ride quality is arguably matter of pilot opinion, a scale that associates definitions or characteristics to each of the values would help in distinguishing trends. This should be corrected for future studies.

Overall, the high ride quality ratings, particularly in the turbulence cases, highlight the need to consider the passengers' ride experience, in addition to the controllability of the vehicle, in the design of future urban air mobility vehicles.

Ability to be Aggressive and Precise

It is beneficial to consider the results of the aggressiveness and precision ratings concurrently. Low aggressiveness ratings correspond to satisfactory control system response to abrupt pilot inputs, and high aggressiveness ratings correspond to introduction of unwanted motion with more aggressive pilot inputs. Low precision ratings correspond to the ability to be more precise as needed, while high precision ratings correspond with difficulty in handling the vehicle precisely.

The UAM light turbulence case for both aggressiveness and precision average ratings were the same value across all vehicles for the Hover Task and Lateral Reposition apart from the COL1 configuration for the Lateral Reposition MTE (Tables D2 and D3). This likely means that the turbulence degraded vehicle performance such that the Precision and Aggressiveness scales were not sufficient to provide more refined evaluation and that performance was not desirable. Overall, the pilots were able to fly the marginal Level 1, COL1 configuration with more aggression and more precisely without inducing undesirable motion of the vehicle compared to the RPM configurations.

The tighter tolerances of the UAM standards required more precision than ADS-33 standards, but pilots were allotted more time to accomplish the maneuver. When pilots attempted to be more aggressive to achieve the higher precision required of the UAM standards, the performance often degraded for the Hover and Lateral Reposition cases. The addition of turbulence amplified the challenge. For the Vertical Maneuver under UAM standards without turbulence, the precision and aggressiveness ratings for all vehicles (apart from RPM1, which was rated about the same when comparing individual pilot ratings) received lower precision ratings than the ADS-33 standard cases, suggesting that a pilot's ability to be precise and demanding was the most likely to benefit from longer time to complete the maneuver.

Predictability

Predictability is a measure of the pilot's ability to anticipate the behavior of the vehicle dynamics to a given input. In general, the predictability followed the trends of the other characteristics studied. The marginal Level 1, COL1 configuration behaved more ideally than the borderline configurations. In most of those cases, the vehicle was more predictable when flying ADS-33 standard tasks than the UAM standard counterparts. However, for the COL1, marginal Level 1 configuration, little to no difference existed between the averages for the ADS-33 and UAM standard cases without turbulence. Predictability decreased with the addition of turbulence. This effect was most noticeable in the RPM3 configuration where the DRB in the heave axis was degraded.

Pilot Induced Oscillation (PIO) Tendency Rating

The pilot-induced oscillation (PIO) tendency rating scale ranges from 1 – 6 and is defined in Fig. C3. Lower ratings correlate to a lower tendency for the pilot to induce oscillations. Conversely, higher ratings may indicate that the induced oscillations may preclude the pilot from accomplishing the maneuver at hand. One important caveat is the lack of data present from the PIO ratings. For example, some configurations only had three separate pilot ratings. As a result, preliminary observations should be taken cautiously, and more extensive research is needed to confirm findings. From the data that is available, it appears that the configuration with Level 2 heave disturbance rejection bandwidth (RPM3) had a higher average PIO rating than configurations with borderline Level 1 or marginal Level 1 disturbance rejection bandwidth (COL1, RPM1, and RPM2) across all Vertical Maneuver runs.

Pilots' Comments

Lateral Reposition Trends

The Lateral Reposition task was flown with all vehicle configurations in the ACAH control mode. The primary challenge dictated by pilots was timing the roll back/deceleration of the lateral stick to avoid overshoot. This was especially evident in the RPM2 configuration (degraded heave rise time) where pilots mentioned that they needed to avoid large inputs due to the jerky reactions in the roll axis. Generally, pilots reported that COL1 provided the best amount of precision and aggressiveness (i.e., had the lowest handling quality ratings).

Another frequent comment across many of the runs was the tendency for the vehicles to drift. Pilots mentioned that the COL1 configuration tended to drift aft, while the RPM configurations sometimes drifted forward. Furthermore, some pilots mentioned specifically that roll inputs induced yaw and that the presence of turbulence exacerbated the couplings. A more in-depth study should be performed to diagnose the causes of the coupling.

Table 6. Summary of Pilot Comments for Lateral Reposition.

COL1	Little mention of PIO, primary challenge was timing the deceleration and adapting to the longitudinal drift (aft wards). Turbulence only added a moderate challenge.
RPM1	It was challenging to judge the timing of deceleration- needed to modulate lateral inputs. Strong coupling at the end/during deceleration. With turbulence, the task was very challenging. PIO and workload to manage coupling were challenging.
RPM2	Roll inputs seemed tighter and often excited coupling. Both entry and deceleration were challenging. Ride quality was jerky. Fore drift and need to correct attitude reported. With turbulence, longitudinal drift was more apparent, and inputs induced yaw. Could not be aggressive.
RPM3	Timing the roll back was critical since lateral inputs were limited in aggressiveness. Heading and roll coupling reported. Maneuvers using UAM standards were more challenging than ADS-33 standards. With turbulence, couplings were exacerbated, and pilots could not be too aggressive without degrading performance.

Vertical Maneuver Trends

Pilots indicated that the most challenging part of the Vertical Maneuver was capturing the top target. For the RPM2 configuration, pilots mentioned that the heave response tended to be more sluggish which often led to overshooting the target. As a result, the pilots noted the need to use smaller inputs, especially for the smaller targets of the UAM tasks. However, pilots generally found that, for the runs without turbulence, the ADS-33 runs required more aggression than the UAM runs while attempting to achieve desired performance. The mention of increased aggression often paired with comments of a tendency to PIO at the top target. This was especially evident in runs with the RPM3 configuration and runs with turbulence. As a result, pilots indicated that the addition of turbulence increased the challenge of station-keeping at the top. Some pilots noted that the presence of turbulence reduced their bandwidth to control and maneuver the vehicle. Pilots also identified that the lack of visibility (due to the limited vertical geometry of the T-cab windows) and visual cueing often made timing the deceleration to capture the top target more challenging.

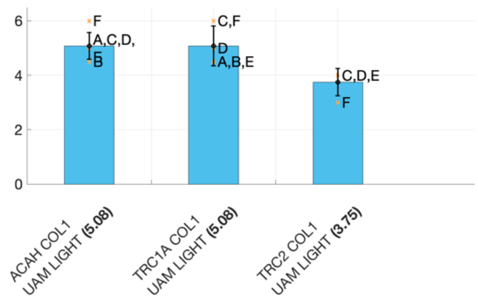
Table 7. Summary of Pilot Comments for Vertical Maneuver (TRC1b).

RPM1	Configuration required pilots to use small inputs, and the risk of PIO seemed greater in general. The addition of turbulence, which made the maneuver much more challenging much more challenging, required pilots to use slow inputs and made PIO more common. Pilots have to "let aircraft bobble a bit" to stay in desired constraints.
RPM2	Aggressive inputs were needed or else the heave response was more sluggish/delayed. PIO was not as prevalent, but overshoot at the top was prevalent. For maneuvers with UAM standards, smaller inputs seem to be better. With turbulence, pilots needed to be just slightly more aggressive, but being more aggressive increased difficulty to control vehicle. Generally lower bandwidth for control.
RPM3	Capture of the bottom board was the most challenging part of the maneuver. Pilots mentioned PIO tendencies more frequently as well as potential obstruction of view at top which may contribute to higher HQR ratings, but pilots were still able to achieve desired performance. For UAM standards, pilots found that being aggressive led to PIO tendencies. With turbulence, abrupt inputs along with the smaller UAM target boards also excited heave PIO tendencies.

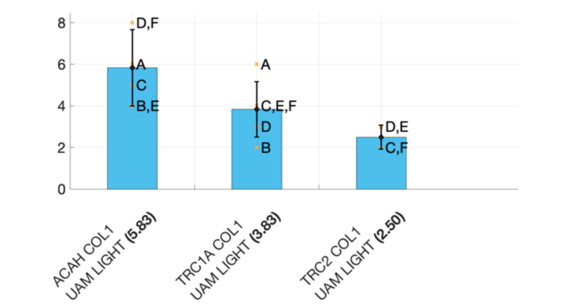
Hover Trends

The Hover task was flown with all vehicle configurations in the ACAH control mode. The most challenging portion of the maneuver for the pilots was the deceleration and station-keeping. Pilots also noted a disharmony between pitch and roll response where the roll response felt jerky while the pitch response was a bit "lethargic" and gave the sensation of a PIO tendency that degraded the overall task performance. For the rotor speed-controlled vehicles there were some comments regarding yaw couplings or heading hold deviations that were most prominent in the RPM2 configuration as well as the UAM task that included light turbulence.

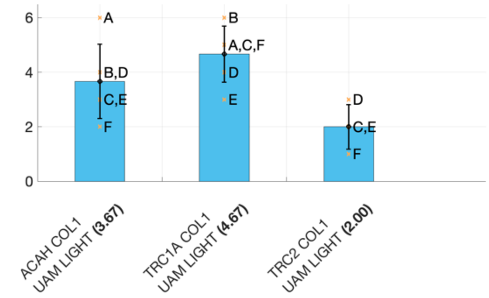
The Hover task was also flown with both the TRC1a and TRC2 control modes for the COL1 vehicle in the UAM standards course with light turbulence. TRC1a did not improve upon ACAH in terms of overall CH HQR and was worse in terms of predictability; however, pilots did seem to give better ratings for TRC1a's ride quality and PIO tendency characteristics. For TRC1a, pilots felt the response they required was insufficient and that they needed to add lead in the lateral axis. The additional workload of fighting the TRC may have been the reason for the higher predictability rating. The TRC1a mode was given a PIO rating of 3 by pilots A & D who both rated the ACAH version 4. As a reminder, the main difference between 3 & 4 on the PIO scale is the presence of oscillatory motion. Conversely, the higher rate limits for TRC2 were a significant improvement to the vehicle performance in not only overall HQR, but every other rating metric from the pilots as well.



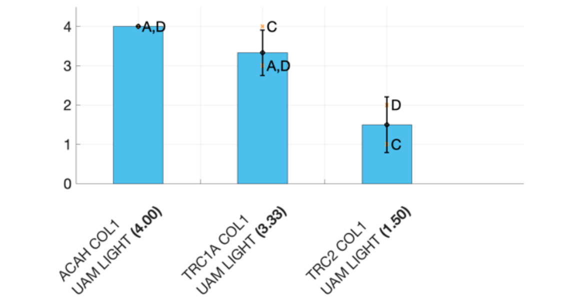
(a) Handling Qualities Ratings for Hover



(b) Ride Quality Ratings for Hover



(c) Predictability Ratings for Hover



(d) PIO Ratings for Hover

Fig. 12. Comparing ACAH, TRC1a, and TRC2 control modes for the Hover MTE.

Table 8. Summary of Pilot Comments for Hover (ACAH).

COL1	Jerky lateral (roll) response which was especially noticeable with increased aggression/speeds was noted. The sluggishness of the longitudinal (pitch) axis compared to the quicker roll response may be causing the discrepancy or "disharmony".
RPM1	Pitch/roll disharmony, jerky lateral response, and difficulty in longitudinal control were reported. Yaw couplings began to present themselves with the addition of turbulence.
RPM2	Yaw couplings / heading drifts were more prominent for this configuration. pitch/roll disharmony, jerky lateral response, and difficulty in longitudinal control were reported.
RPM3	Pilots mentioned a disharmony between pitch and roll where the lateral response was jerky and that there was difficulty in controlling the longitudinal axis. Pilots also made comments on Yaw couplings which presented themselves with the addition of turbulence

Bedford Workload Ratings of UAM Approach

As previously mentioned in the Test Procedure section, a representative UAM approach and landing was flown with both an instrumented guidance system and a visual approach for each vehicle configuration. The purpose of these runs was to correlate experiences from the formal HQ evaluations with a an operationally relatable mission scenario. Secondarily, it allowed researchers to evaluate how a, theoretically, more intuitive guidance system affected pilot workload. For this series of cases, the Bedford Workload scale was used (Ref. 15).

Comparing the instrumented and visual approach, the two methods received similar workload ratings for the marginal Level 1 configuration, COL1. The RPM configurations all received significantly better ratings ("tolerable" by pilot ratings of 6 or lower) for the visual approach method compared to the instrument approach. The baseline vehicle, RPM1, was rated slightly better than RPM2 and RPM3 for the instrument approach, but about the same as RPM2 and RPM3 for the visual approach. The degraded RPM configurations seemed to create additional workload for the pilots during the instrument approach; however, no such burden existed when the maneuver was flown visually. While the RPM2 and RPM3 configurations produced relatively similar workload ratings, it is hypothesized that if pilots were time-constrained that the workload ratings for the RPM2 case may degrade further. This is based on the sluggishness of the RPM2 case which is somewhat prominent in the ratings and comments of the Vertical Maneuver MTE (see discussion under the Handling Quality Ratings HQRs subsection).

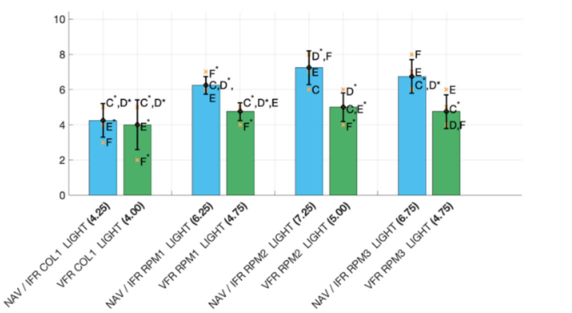


Fig. 13. Bedford Workload Scale comparing Navigational and Visual approaches to the UAM Approach MTE.

NEXT STEPS

The trends described in this paper will be further discussed and analyzed in a subsequent paper that has been accepted for the 2022 Vertical Flight Society Forum. Additional discussion points will likely include power and torque demands on the motor/rotor system and the effect of coupling motion of the ratings. A second Vertical Motion Simulator test is planned for calendar year 2023 which will explore an alternative UAM vehicle configuration. Other future work potentially includes exploring the effect or limiting the motor input and failure analysis for multirotor vehicles. Data from these studies and lessons learning will be shared, as appropriate, with other government (FAA and Army) and industry partners.

CONCLUSIONS

Preliminary trends have been identified from the Spring 2021 VMS test of a six-passenger quadrotor for a UAM mission. Of the four configurations explored, one (COL1) was tuned to marginal Level 1 handling qualities and three other configurations were tuned to degraded variations in borderline Level 1/Level 2 handling qualities ratings. Three MTEs and a representative approach and landing were performed. COL1 received more desirable ratings and was more agreeable overall to pilots for most cases. However, ratings were not always within Level 1 boundaries. Performance of all vehicles were degraded by adding turbulence.

Two standards were examined: the traditional ADS-33 standards and a theoretically representative UAM alternative. Under these two metrics, the same vehicle configurations received different handling qualities ratings, emphasizing the need to further understand the standards required for safe and desirable vehicle performance. The degradation of the response time and DRB in the heave axis also produced different handling quality ratings. The RPM1 configuration was expected to perform better than the RPM2 and RPM3 in the Vertical Maneuver (since RPM2 and RPM3 were further degraded in the heave axis). This was true for most Vertical Maneuver HQR ratings, however, in context of the other ratings (precision, aggressiveness, ride quality, and predictability) the effect of the TRC mode and additional side effects of these configurations should be further considered. When more aggressive maneuvering was employed, some of the cases with the more precise UAM standards produced less desirable handling qualities ratings.

Ride quality ratings were some of the least desirable of all the trends, emphasizing the need to consider passenger response as part of the vehicle design. Turbulence exaggerated these trends. The RPM3 case, with degraded DRB, was more prone to PIO. The slower response of the RPM2 configuration led to less PIO compared to the base RPM1 configuration. For the UAM approach and landing, the RPM cases produced higher workload ratings when using the instrumented guidance system, emphasizing the need for additional research into future navigation systems. Other future work includes additional discussion of these trends, as well as including more realistic power system limitations.

APPENDIX

The appendix contains supplemental figures, tables, and charts related to the experiment set up, the requirements for rating the various MTEs, and averaged pilot ratings. There are five sections: A) Description of Visual Display for Guided Approach and Landing, B) Mission Task Element (MTE) Descriptions, C) Pilot Rating Scales and Questionnaire, D) Pilot Rating Tables, and E) Pilot Rating Statistics Figures.

A. Description of Visual Display for Guided Approach and Landing

CDTI-PFD

- Flightpath symbol: Represents the trajectory of the aircraft in the earth-frame. At speeds above 33.9kts, the symbol is a circle and indicates vertical and horizontal flight path in degrees. Below 33.9kts, the symbol is a diamond and indicates vertical and lateral speed in deg/fps.
- Ghost aircraft symbol: Represents the ideal flight path with a lead time-constant for the pilot to capture and follow. The symbol changes from a circle to a diamond at 35kts. Additionally, the symbol is scaled to fit inside the flightpath symbol.
- Glide slope and localizer raw data: Shown as dots on the bottom and right side of the ADI. When the magenta diamond is on the center marker then the aircraft is on localizer and/or the 6-degree glide slope.
- Glide slope: The dashed white line indicates a 6-degree glide slope in the earth-frame.
- Velocity error tape: The rectangular symbol on the left wing of the flightpath symbol assists the pilot in decelerating during the approach. The velocity error tape above the wing is too fast, below the wing is too slow, and no tape is on speed.
- Acceleration caret: The arrow symbol on the tip of the left wing represents the forward acceleration in the same manner as the velocity tape. When the caret is aligned with the wing, the aircraft is at zero acceleration. The caret above the wing indicates acceleration and caret below the wing is deceleration.

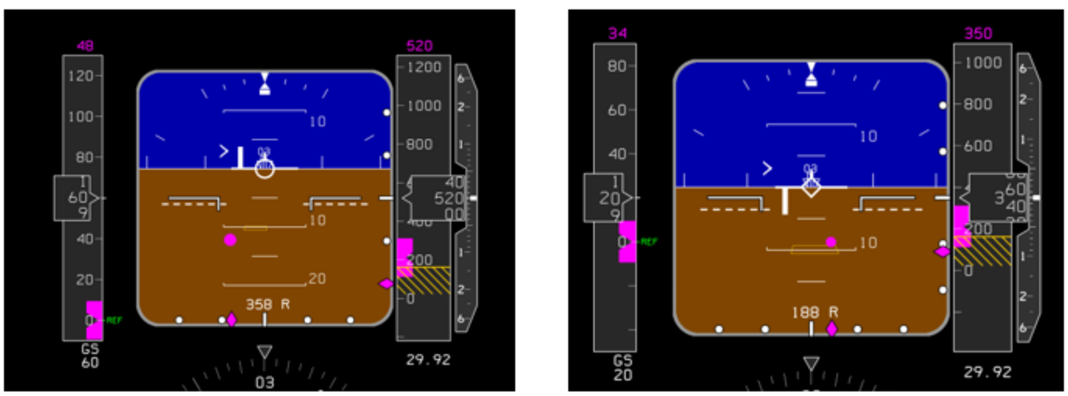


Fig. A1. PFD, >33.9kts (left), <33.9kts (right).

B. Mission Task Elements (MTE) Descriptions

Mission Task Elements (MTEs) for evaluation of the quadrotor configuration handling qualities were selected primarily from the ADS-33. The study focused on the Cargo/Utility performance standards for the Good Visual Environment (GVE) conditions, for all MTEs, as the default performance standards. An additional set of performance metrics were developed to account for UAM mission-specific conditions. The following pages present, for quick reference, descriptions and performance requirements for a selection of evaluation tasks: Hover, Vertical Maneuver, Lateral Reposition MTEs, and the custom UAM approach and landing. The MTEs enforce a broad range of maneuvering aggressiveness and precision, in single and multiple axes, to assess controllability and ability to accomplish precision control. The UAM Approach and Landing task presents a complete mission-relatable scenario to serve as a basis of comparison with the MTE evaluations.

3.10.1 Hover

a. Objectives.

- Check ability to transition from translating flight to a stabilized hover with precision and a reasonable amount of aggressiveness.
- Check ability to maintain precise position, heading, and altitude in the presence of a moderate wind from the most critical direction in the GVE; and with calm winds allowed in the DVE.

b. Description of maneuver. Initiate the maneuver at a ground speed of between 6 and 10 knots, at an altitude less than 20 ft. For rotorcraft carrying external loads, the altitude will have to be adjusted to provide a 10 ft load clearance. The target hover point shall be oriented approximately 45 degrees relative to the heading of the rotorcraft. The target hover point is a repeatable, ground-referenced point from which rotorcraft deviations are measured. The ground track should be such that the rotorcraft will arrive over the target hover point (see illustration in Figure 29). In the GVE, the maneuver shall be accomplished in calm winds and in light winds from the most critical direction. If a critical direction has not been defined, the hover shall be accomplished with the wind blowing directly from the rear of the rotorcraft.

c. Description of test course. The suggested test course for this maneuver is shown in Figure 29. Note that the hover altitude depends on the height of the hover sight and the distance between the sight, the hover target, and the rotorcraft. These dimensions may be adjusted to achieve a desired hover altitude.

d. Performance standards. Accomplish the transition to hover in one smooth maneuver. It is not acceptable to accomplish most of the deceleration well before the hover point and then to creep up to the final position.

Fig. B1. Description of Hover MTE in ADS-33F-PRF.

Performance Standards: ADS-33E-PRF 3.11.1 Hover GVE, Cargo/Utility	Desired	Adequate
Attain a stabilized hover within X seconds of initiation of deceleration	5 seconds	8 seconds
Maintain a stabilized hover for at least	30 seconds	30 seconds
Maintain the longitudinal and lateral position within X feet of the point on the ground	±3 ft	±6 ft
Maintain altitude within:	±2 ft	±4 ft
Maintain heading within X degree	±5 deg	±10 deg

Performance Standards: UAM Hover GVE, Cargo/Utility	Desired	Adequate
Attain a stabilized hover within X seconds of initiation of deceleration	10 seconds	15 seconds
Maintain a stabilized hover for at least	30 seconds	30 seconds
Maintain the longitudinal and lateral position within X feet of the point on the ground	±1.5 ft	±3.9 ft
Maintain altitude within:	±1 ft	±2.6 ft
Maintain heading within X degree	±5 deg	±10 deg

Fig. B2. Desired and Adequate Requirements of Hover MTE in ADS-33 and UAM Standards.

3.10.7 Vertical Maneuver

a. Objectives.

For a scout/attack rotorcraft this maneuver is to simulate a rapid unmask/remask maneuver, with an aiming task at the unmask. For a utility or cargo rotorcraft, the maneuver is to assess the heave axis controllability with precision station keeping.

- Check for adequate heave damping, i.e., the ability to precisely start and stop a vertical rate.
- Check for adequate vertical control power.
- Check for undesirable coupling between collective and the pitch, roll, and yaw axes.
- Check the characteristics of the heave axis controller, especially if a non-conventional controller is used, e.g., a four-axis sidestick.
- With an external load, check for undesirable effects between the heave controller and the other axes of the rotorcraft and complications caused by the external load dynamics.

b. Description of maneuver. From a stabilized hover at an altitude of 15 ft, initiate a vertical ascent of 25 ft, stabilize for 2 seconds, and then descend back to the initial hover position. With an external load, the maneuver is initiated from a higher altitude to assure a 10 ft load clearance. In the GVE, the maneuver shall be accomplished in calm winds and in light winds from the most critical direction. If a critical direction has not been defined, the hover shall be accomplished with the wind blowing directly from the rear of the rotorcraft.

c. Description of test course. The test course shall consist of markings on the ground that clearly define desired and adequate performance. It is suggested that this maneuver use the hover course (Figure 29) with a second reference symbol or hover board set to align at the upper reference.

d. Performance standards.

Fig. B3. Description of Vertical Maneuver MTE in ADS-33F-PRF.

Performance Standards: ADS-33E-PRF 3.11.6 Vertical Maneuver GVE	**Desired**	**Adequate**
Maintain the longitudinal and lateral position within X ft of a point on the ground	±3 ft	±6 ft
Maintain start/finish altitude within X ft	±3 ft	±6 ft
Maintain heading within X ft	±5 deg	±10 deg
Complete the maneuver within	13 sec	18 sec
Performance Standards: UAM Vertical Maneuver GVE	**Desired**	**Adequate**
Maintain the longitudinal and lateral position within X ft of a point on the ground	±1.5 ft	±3.9 ft
Maintain start/finish altitude within X ft	±1 ft	±2.6 ft
Maintain heading within X ft	±5 deg	±10 deg
Complete the maneuver within	30 sec	40 sec

Fig. B4. Desired and Adequate Requirements of Vertical Maneuver MTE in ADS-33 and UAM Standards.

ADS-33F-PRF

3.10.9 Lateral Reposition

a. Objectives.

- Check roll axis and heave axis handling qualities during moderately aggressive maneuvering.
- Check for undesirable coupling between the roll controller and the other axes.
- With an external load, check for dynamic problem resulting from the external load configuration.

b. Description of maneuver. Start in a stabilized hover at 35 ft wheel height (or no greater than 35 ft external load height) with the longitudinal axis of the rotorcraft oriented 90 degrees to a reference line marked on the ground. Initiate a lateral acceleration followed by a deceleration to laterally reposition the rotorcraft in a stabilized hover 400 ft down the course within a specified time. The acceleration and deceleration phases shall be accomplished as single smooth maneuvers. The rotorcraft must be brought to within ±10 ft of the endpoint during the deceleration, terminating in a stable hover within this band. Overshooting is permitted during the deceleration, but will show up as a time penalty when the pilot moves back within ±10 ft of the endpoint. The maneuver is complete when a stabilized hover is achieved. Perform the maneuver both to the right and to the left. For a cockpit with side-by-side seating, the evaluation pilot should be allowed to sit in either seat to assess potential detrimental cueing effects on the handling qualities rating.

c. Description of test course. The test course shall consist of any reference lines or markers on the ground indicating the desired track and tolerances for the acceleration and deceleration, and markers to denote the starting and endpoint of the maneuver. The course should also include reference lines or markers parallel to the course reference line to allow the pilot and observers to perceive the desired and adequate longitudinal tracking performance, such as the example shown in Figure 32.

d. Performance standards.

Fig. B5. Description of Lateral Reposition MTE in ADS-33.

Performance Standards: ADS-33E-PRF 3.11.8 Lateral Reposition GVE	**Desired**	**Adequate**
Maintain longitudinal track within X ft	±10 ft	±20 ft
Maintain altitude within X ft	±10 ft	±15 ft
Maintain heading within X deg	±10 deg	±15 deg
Time to complete maneuver	18 sec	22 sec

Performance Standards: UAM Lateral Reposition GVE	**Desired**	**Adequate**
Maintain longitudinal track within X ft	±3 ft	±6 ft
Maintain altitude within X ft	±2 ft	±4 ft
Maintain heading within X deg	±5 deg	±10 deg
Time to complete maneuver	12 sec	18 sec

Fig. B6. Desired and Adequate Requirements of Lateral Reposition MTE in ADS-33 and UAM Standards.

Performance Standards: UAM Approach Task GVE	Desired	Adequate
Maintain glideslope and localizer within:	1/2 dot	1 dot
Prior to glideslope intercept, maintain altitude within:	± 50 ft	± 100 ft
Maintain lateral/longitudinal hover position within:	±10 ft	±20 ft
Maintain speed within:	±5 kts	±10 kts
Maintain initial hover altitude within:	±5 ft	±10 ft
Attain an aircraft heading at touchdown that is aligned with the reference heading within:	±5 deg	±10 deg

Fig. B7. Desired and Adequate Requirements of UAM Approach and Landing MTE in UAM Standards.

C. Pilot Rating Scales and Questionaire

The figures below present the standardized questionnaires that the pilots used to generate their various ratings. As aforementioned, note that some rating scales provide definitions for each value while others do not.

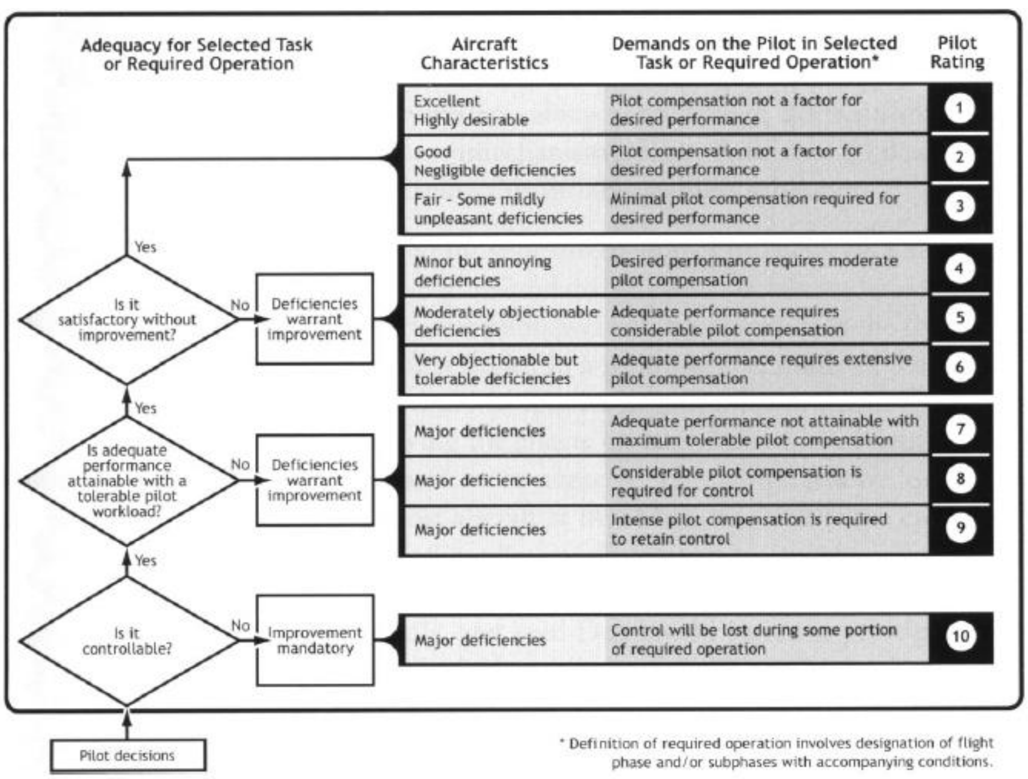


Fig. C1. Cooper-Harper Handling Qualities Rating Scale.

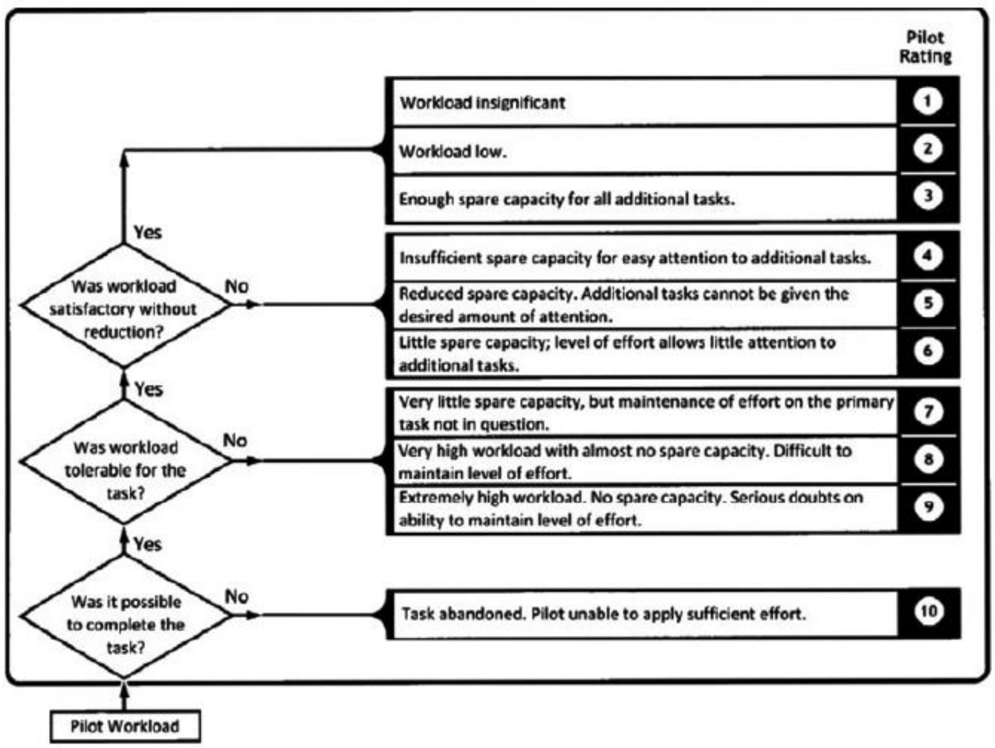


Fig. C2. Bedford Workload Scale.

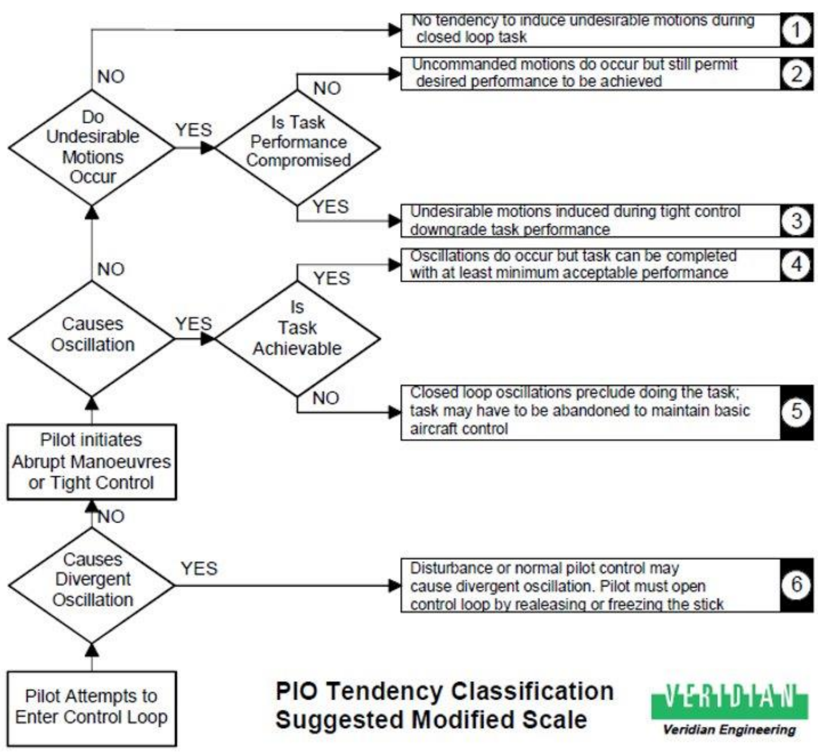


Fig. C3. PIO Tendency Classification Rating Scale.

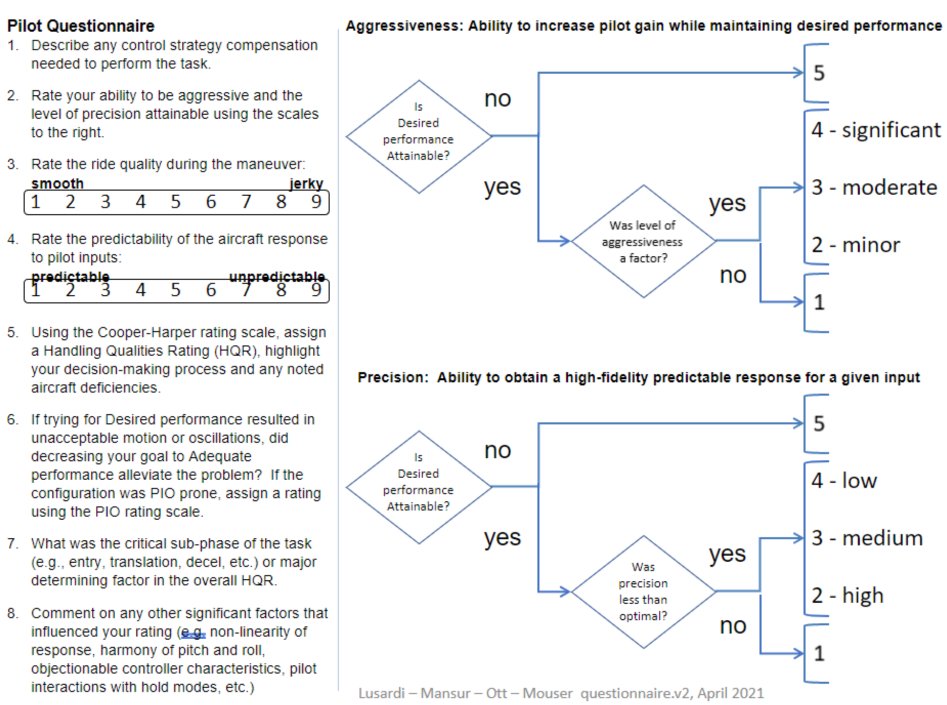


Fig. C4. Pilot Questionnaire for Ride Quality, Predictability, Aggressiveness, and Precision Rating Scales.

D. Pilot Rating Tables

The tables below summarize the average pilot ratings for all the MTEs apart from the UAM approach (since that maneuver focused on recording Bedford Workload Scale (BWS)).

Table D1. Average Ride Quality Rating.

Vehicle	COL1					RPM1			RPM2			RPM3		
Standard	ADS-33	UAM	UAM			ADS-33	UAM	UAM	ADS-33	UAM	UAM	ADS-33	UAM	UAM
Turbulence	None	None	Light			None	None	Light	None	None	Light	None	None	Light
Hover	4.3	4.6	5.8	3.8	2.5	5.2	5.9	6.5	4.5	5.0	7.8	5.3	6.1	7.7
Vertical Maneuver	2.3	2.0	3.5			2.0	2.2	4.2	2.5	2.2	3.5	2.3	2.4	4.2
	1.5	1.5	3.5											
Lateral Reposition	3.4	3.7	3.8			4.5	4.3	6.8	4.5	4.7	6.8	4.5	4.5	6.8
Control Mode Color Legend			ACAH			TRC1a			TRC1b			TRC2		

Table D2. Average Aggressiveness Rating.

Vehicle	COL1			RPM1			RPM2			RPM3		
Standard	ADS-33	UAM	UAM	ADS-33	UAM	UAM	ADS-33	UAM	UAM	ADS-33	UAM	UAM
Turbulence	None	None	Light	None	None	Light	None	None	Light	None	None	Light
Hover	3.5	3.4	5.0 / 4.8 / 2.3	4.2	4.2	5.0	3.8	4.7	5.0	3.3	4.7	5.0
Vertical Maneuver	2.5	2.0	3.3	3.0	2.7	4.3	4.5	2.8	3.8	4.3	3.8	4.8
	2.0	3.5	4.0									
Lateral Reposition	3.0	3.3	3.8	3.5	4.5	5.0	3.2	4.7	5.0	4.3	5.0	5.0
Control Mode Color Legend	ACAH			TRC1a			TRC1b			TRC2		

Table D3. Average Precision Rating.

Vehicle	COL1			RPM1			RPM2			RPM3		
Standard	ADS-33	UAM	UAM	ADS-33	UAM	UAM	ADS-33	UAM	UAM	ADS-33	UAM	UAM
Turbulence	None	None	Light	None	None	Light	None	None	Light	None	None	Light
Hover	3.0	3.6	5.0 / 4.8 / 1.8	4.0	4.2	5.0	3.5	4.3	5.0	3.2	4.5	5.0
Vertical Maneuver	2.8	2.0	3.3	3.0	2.5	4.2	4.2	2.8	4.2	4.2	3.4	4.8
	1.5	2.5	3.0									
Lateral Reposition	3.2	3.2	3.5	3.0	3.7	5.0	2.8	4.5	5.0	4.0	5.0	5.0
Control Mode Color Legend	ACAH			TRC1a			TRC1b			TRC2		

Table D4. Average Predictability Rating.

Vehicle	COL1			RPM1			RPM2			RPM3		
Standard	ADS-33	UAM	UAM	ADS-33	UAM	UAM	ADS-33	UAM	UAM	ADS-33	UAM	UAM
Turbulence	None	None	Light	None	None	Light	None	None	Light	None	None	Light
Hover	2.8	2.8	3.7 / 4.7 / 2.0	3.8	4.3	4.8	3.3	3.9	5.8	3.5	4.8	6.0
Vertical Maneuver	3.3	3.3	4.3	2.8	3.2	5.5	4.3	3.5	4.3	5.0	5.6	6.8
	1.0	2.5	2.5									
Lateral Reposition	2.6	2.7	3.3	2.7	3.3	5.0	2.4	3.0	4.0	3.0	4.0	5.8
Control Mode Color Legend	ACAH			TRC1a			TRC1b			TRC2		

Table D5. Average PIO Rating.

Vehicle	COL1					RPM1			RPM2			RPM3		
Standard	ADS-33	UAM	UAM			ADS-33	UAM	UAM	ADS-33	UAM	UAM	ADS-33	UAM	UAM
Turbulence	None	None	Light			None	None	Light	None	None	Light	None	None	Light
Hover	3.3	4.0*	4.0	3.3	1.5	3.5	3.7	5.0	3.5	3.5	4.3	3.0	3.5	4.3
Vertical Maneuver	3.0	2.7	3.0			2.7	2.7	4.0	2.7	2.8	3.3	3.4	4.0	4.4
	N/A	3.0	3.0											
Lateral Reposition	2.0*	4.0*	4.0*			3.0*	4.5	5.0	2.3	3.7	4.5	4.0	4.3	4.0

Control Mode Color Legend	ACAH	TRC1a	TRC1b	TRC2

*Only rated by pilot D

E. Pilot Rating Statistics Figures

The following section of figures represent pilot ratings for each simulation combination and are organized by MTE. The figures include bars representing the magnitude of the average pilot rating for each combination specified along the X-axis. The average is also bold and in parentheses of its respective X-axis label. Each label contains the control mode, vehicle configuration, and MTE performance standard. The label will include the word "Light" following the performance standard if turbulence was on during the evaluation. The black error bars represent ±1 standard deviation from the average pilot rating. Faint orange x's represent individual pilot ratings for each maneuver and the corresponding pilot(s) are shown by adjacent letters. Letters with a superscript asterisk represent pilots who performed less than three evaluation runs. Letters with the subscript "avg" notation represent an average rating of a single pilot who performed and evaluated the same maneuver more than once. In some cases, all of the pilots gave the same rating for a maneuver. If such is the case and there are at least two pilot ratings, the value will be represented by the word "ALL" followed by the number of pilots who evaluated the maneuver. Finally, the green bars represent the ADS-33 standard while the blue bars represent the UAM standard.

UAM approach plots have some minor differences from the other MTEs. UAM approaches made under visual flight rules (VFR) are represented by green bars while those made using the navigational cueing under instrument flight rules (IFR) are represented by blue bars. Since there is no unique control mode for the UAM approaches, the X-axis label specifies the type of approach (VFR or IFR / NAV) instead. It should be noted that because of the long amount of time required to complete this MTE, many pilots only flew one or two approaches of each type (VFR and IFR / NAV)

Hover Task Figures

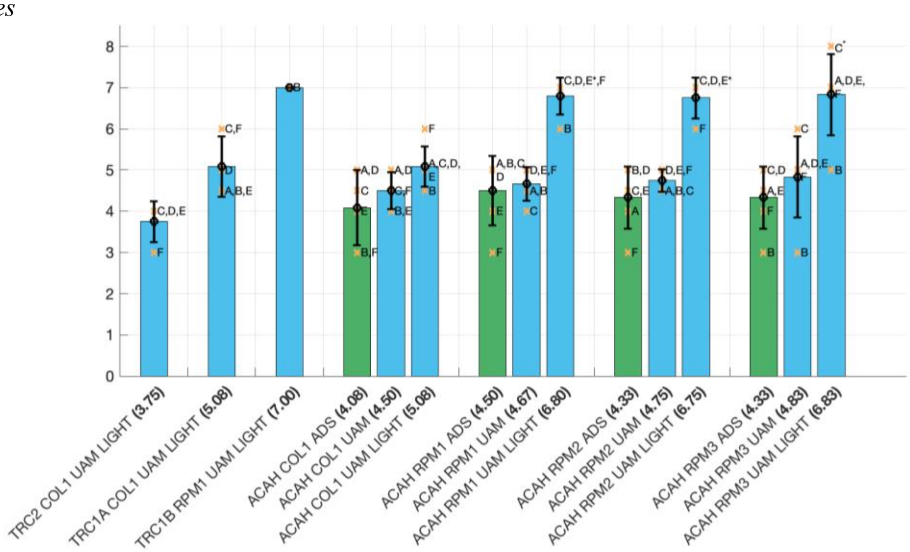


Fig. E1. Hover Task: Cooper-Harper HQRs

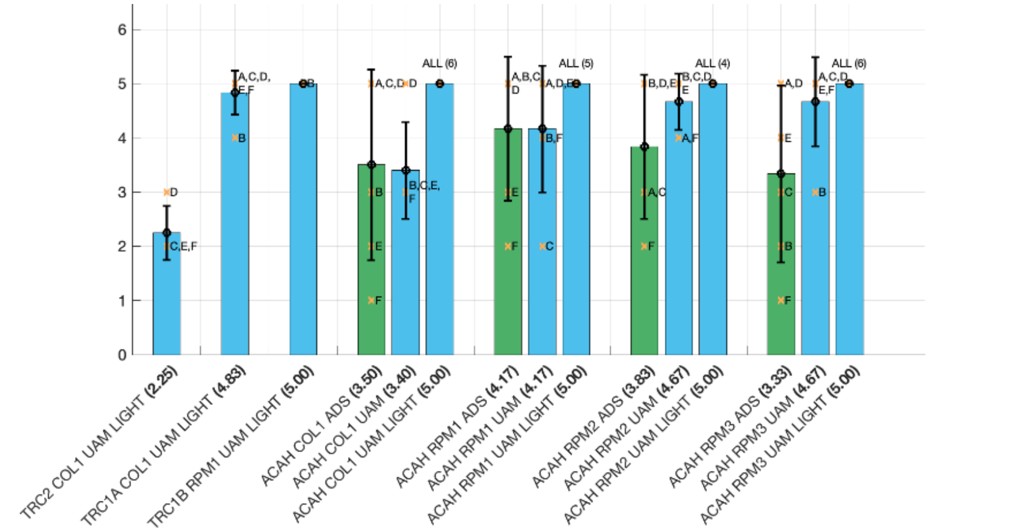


Fig. E2. Hover Task: Aggressiveness Ratings.

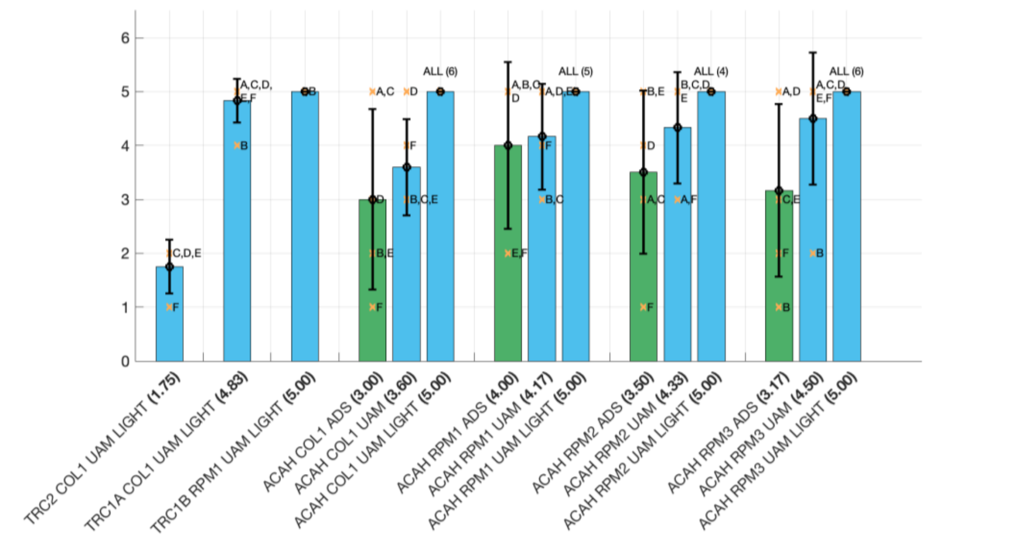


Fig. E3. Hover Task: Precision Ratings.

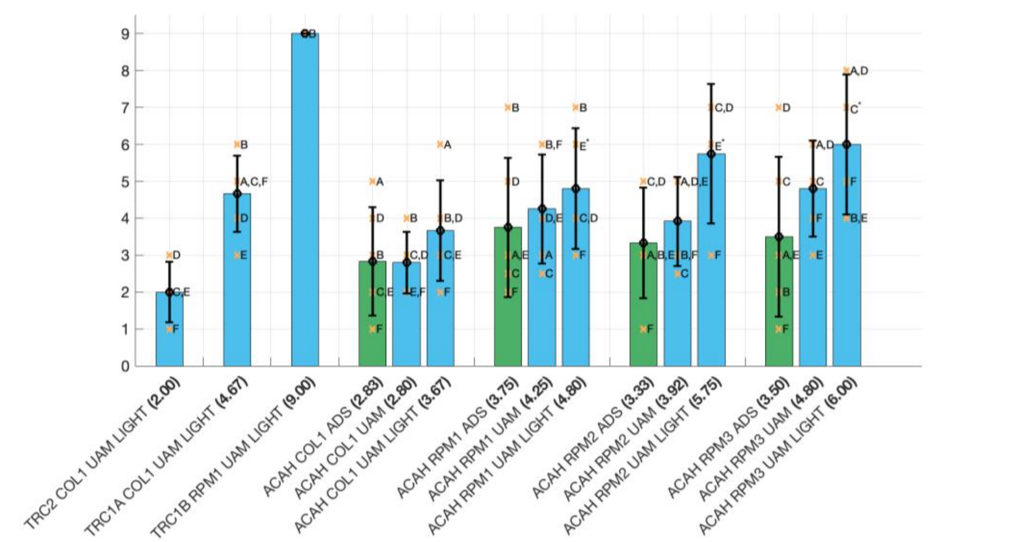


Fig. E4. Hover Task: Predictability Ratings.

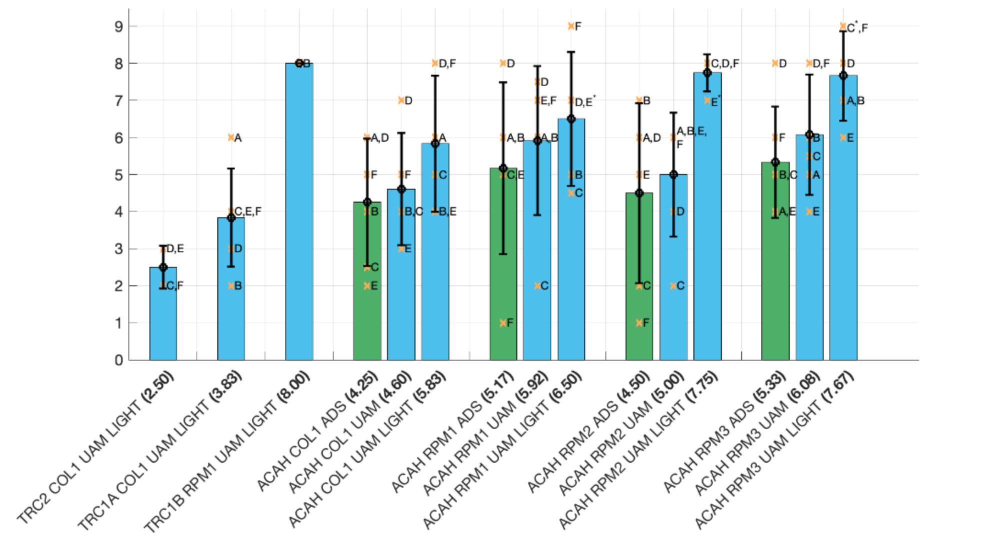


Fig. E5. Hover Task: Ride Quality Ratings.

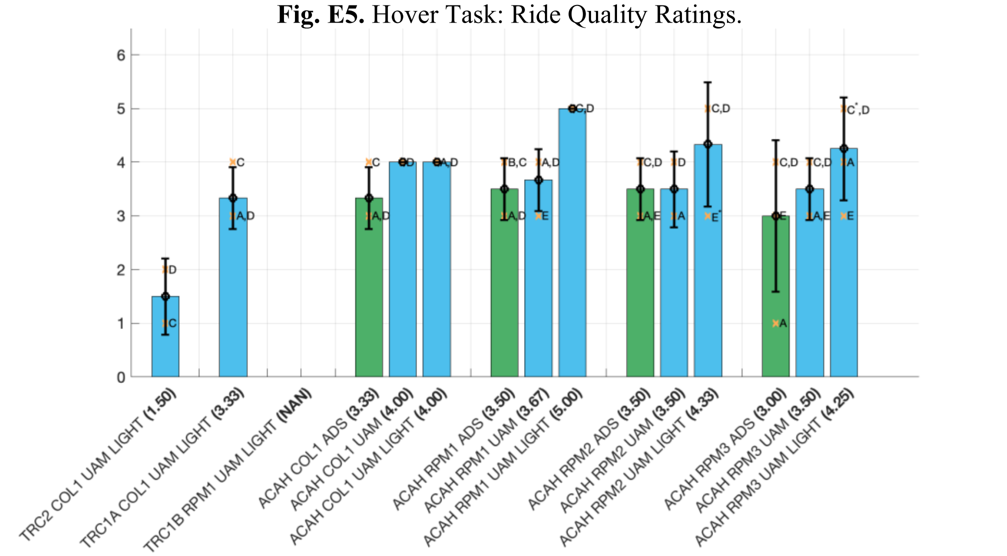


Fig. E6. Hover Task: PIO Ratings.

Lateral Reposition Figures

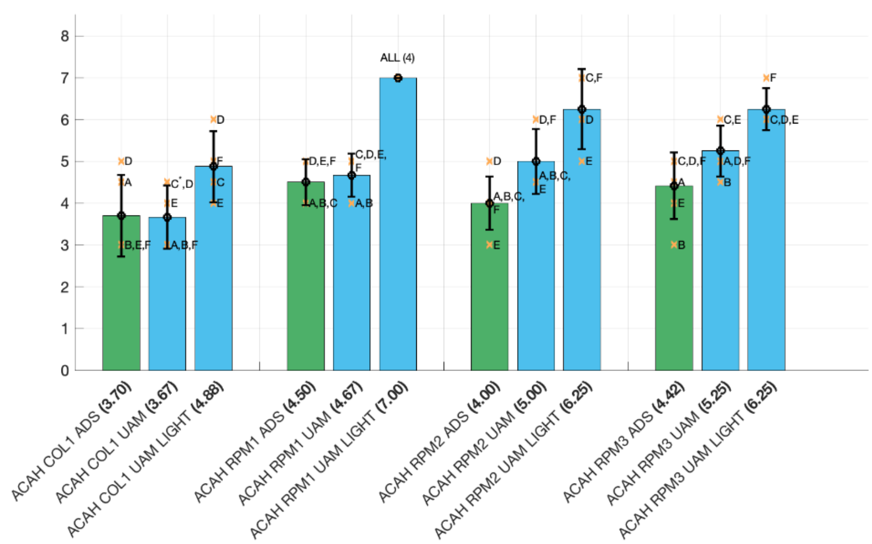


Fig. E7. Lateral Reposition: Cooper-Harper HQRs.

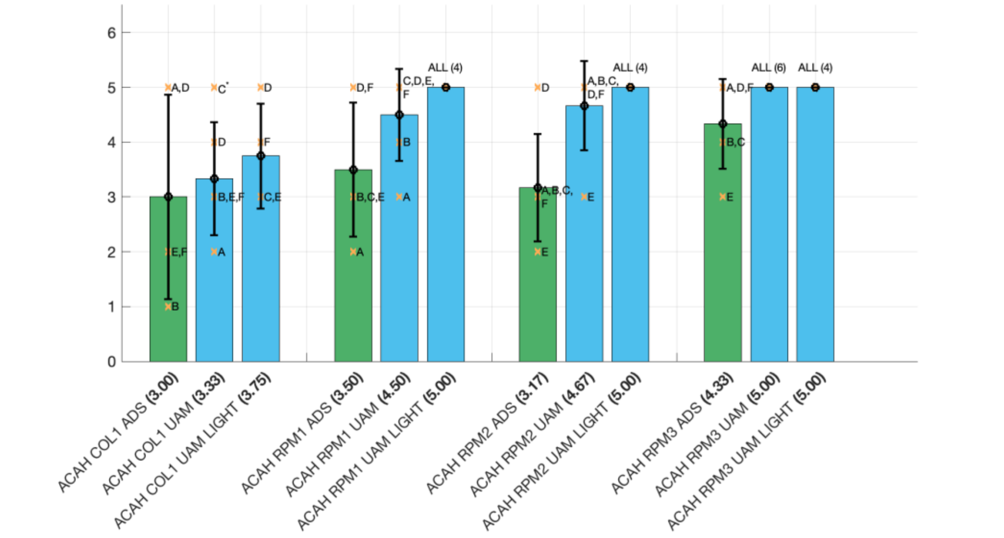


Fig. E8. Lateral Reposition: Aggressiveness Ratings.

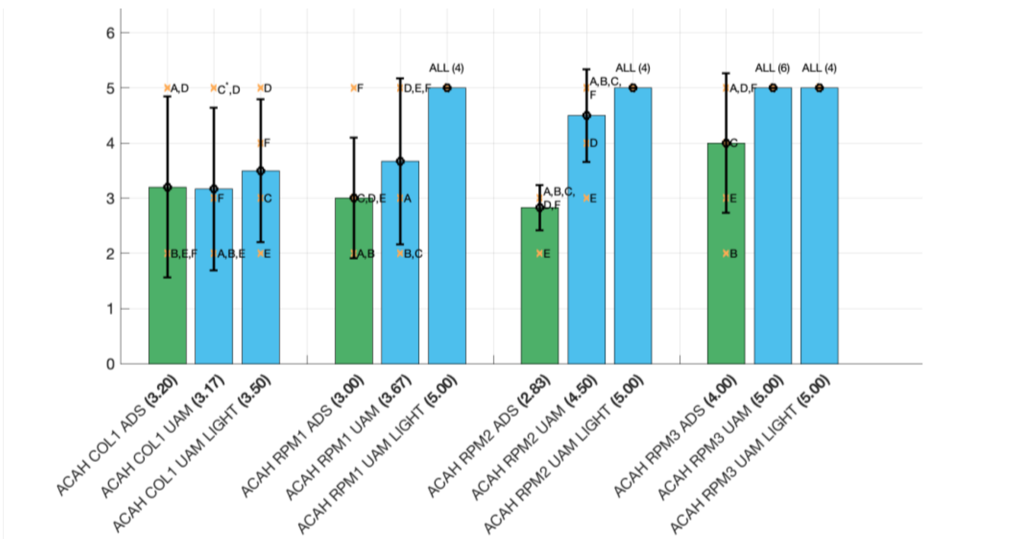


Fig. E9. Lateral Reposition: Precision Ratings.

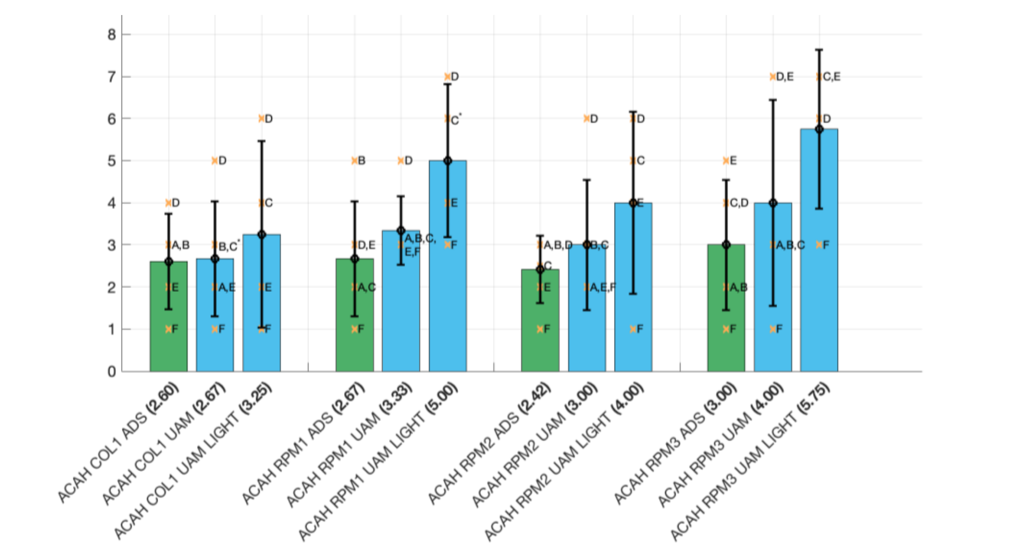


Fig. E10. Lateral Reposition: Predictability Ratings.

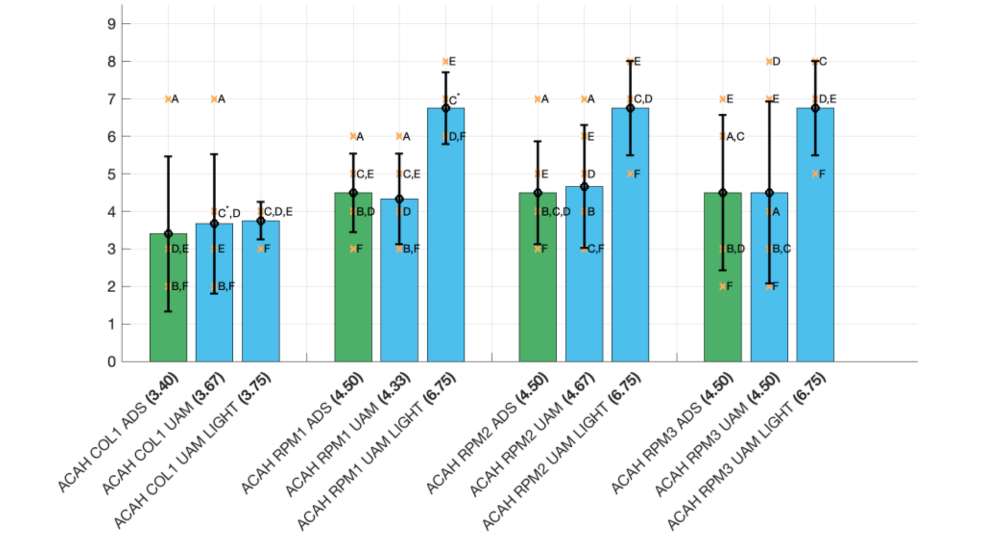


Fig. E11. Lateral Reposition: Predictability Ratings.

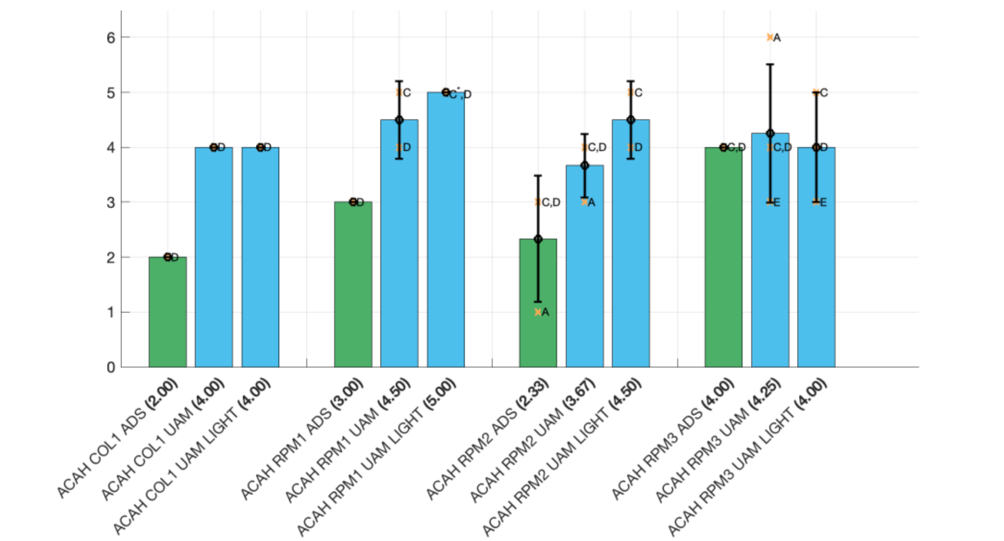


Fig. E12. Lateral Reposition: PIO Ratings.

Vertical Maneuver Figures

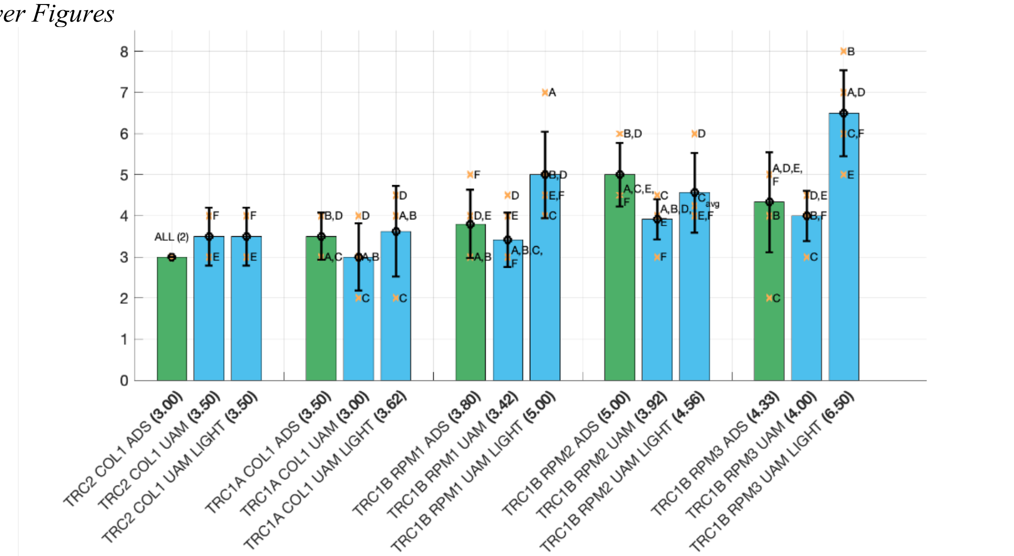


Fig. E13. Vertical Maneuver: Cooper-Harper HQRs.

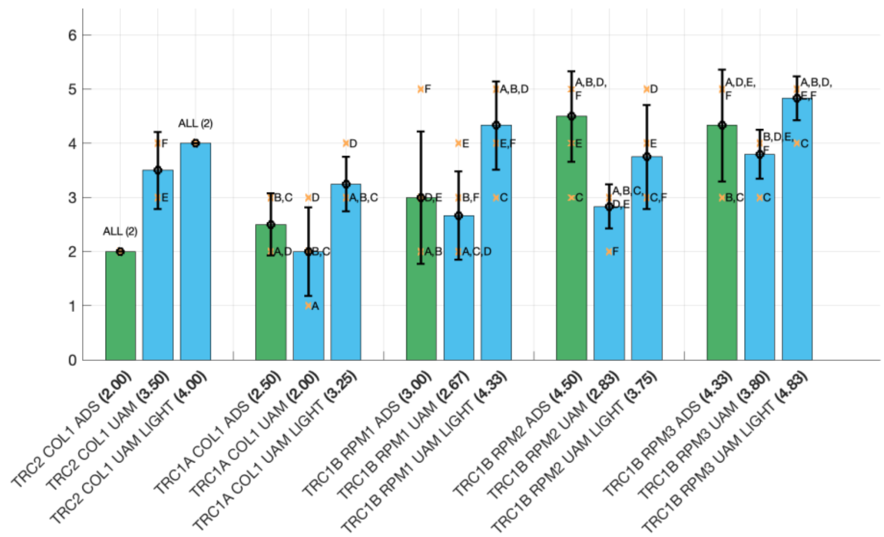


Fig. E14. Vertical Maneuver: Aggressiveness Ratings.

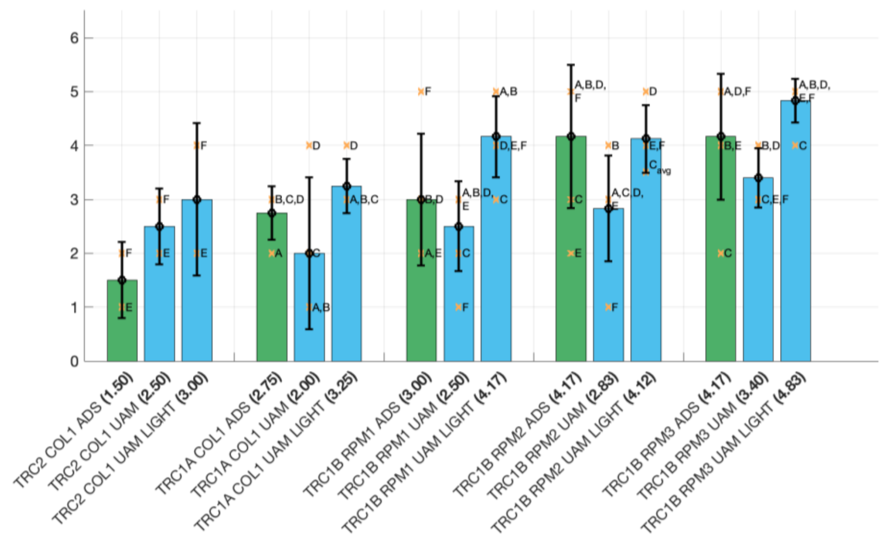


Fig. E15. Vertical Maneuver: Precision Ratings.

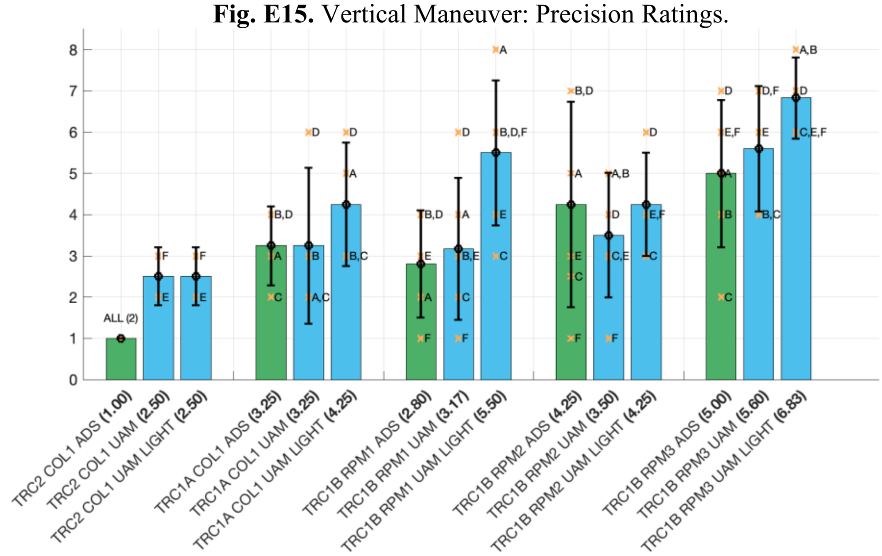


Fig. E16. Vertical Maneuver: Predictability Ratings.

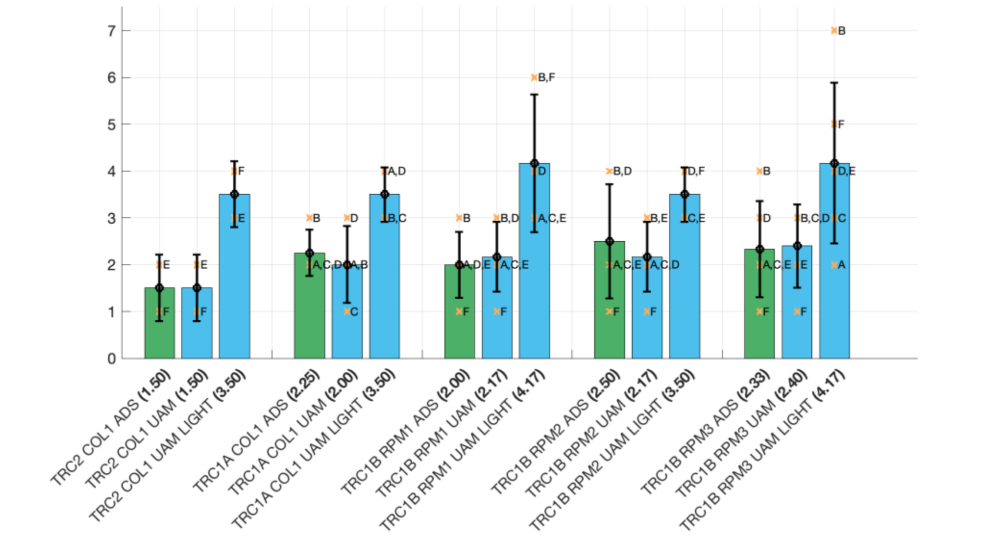


Fig. E17. Vertical Maneuver: Ride Quality Ratings.

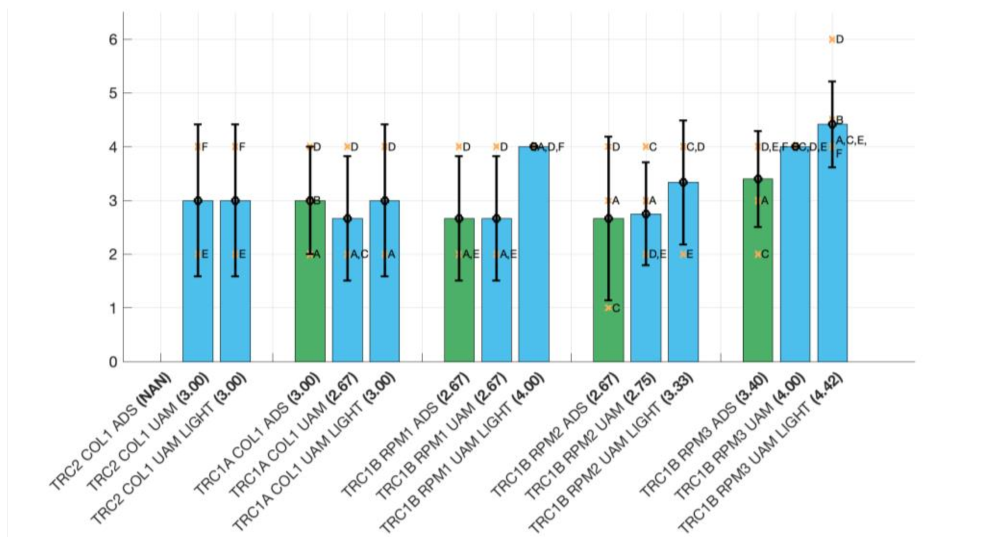


Fig. E18. Vertical Maneuver: PIO Ratings.

UAM Approach Figures

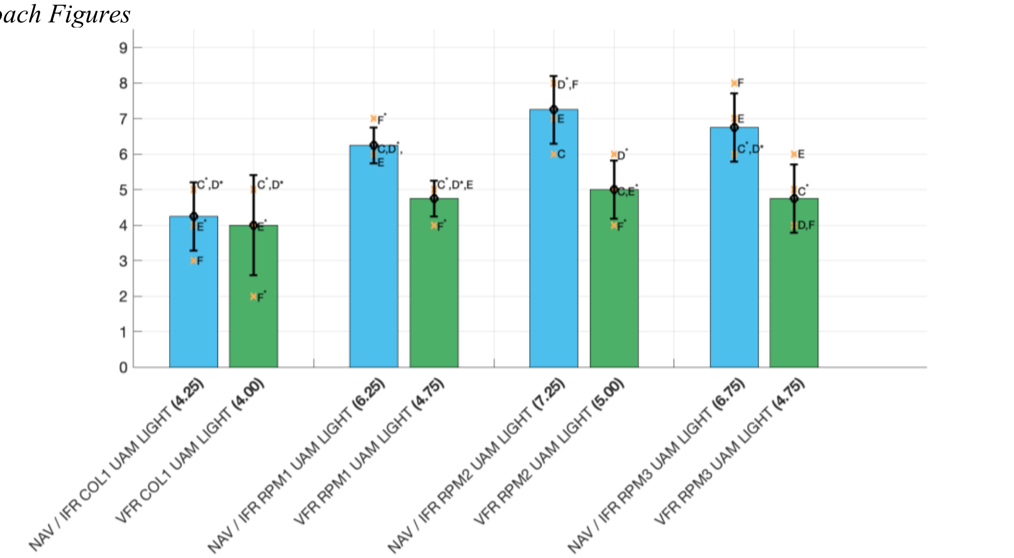


Fig. E19. UAM Approach: Bedford Work Scale Ratings.

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