Analysis of Handling Qualities and Power Consumption for Urban Air Mobility (UAM) eVTOL Quadrotors with Degraded Heave Disturbance Rejection and Control Response

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ABSTRACT

A piloted handling qualities study of urban air mobility (UAM) electric vertical take-off and landing (eVTOL) quadrotors was performed utilizing the Vertical Motion Simulator (VMS) facility at NASA Ames Research Center. Rotor speed and variable pitch-controlled variants of a six-passenger conceptual design vehicle were assessed with different levels of degradation to control response and disturbance rejection bandwidth (DRB) in the heave axis. In previous work, preliminary trends across several handling quality rating categories reflected the effects of these degradations. Additionally, the impact of using different test standards and turbulence on the ratings were discussed. This paper elaborates on those results, but also provides insight into unexpected trends observed during the study including: a disharmony in attitude response, subpar ratings for the baseline Level 1 performance vehicle, and excessive drift and yaw couplings observed in a lateral reposition maneuver. Moreover, shortcomings of the handling quality scales and comparisons of power consumption among the vehicles in the various test conditions are presented.

INTRODUCTION

The objective of the VMS study (Ref. 1) was to investigate the handling qualities of blade pitch-controlled and rotor speed-controlled multirotor eVTOL concept aircraft using advanced flight simulations. Previous studies have shown that the heave axis tends to be more demanding in terms of motor usage (Ref. 2, 3). As such, in this experiment, the heave axis was degraded in terms of control response and DRB to study the trade-offs between handling qualities and power consumption. Analysis of handling quality results from Ref. 1 was limited to a test description, observations from the experiment, and some preliminary analyses of rating patterns. This paper provides additional understanding of rating trends, expands the discussion to include findings related to power consumption, and details the shortcomings of the rating scales used in the study. These topics are organized into Part I of the paper while deeper investigations into unexpected trends are dedicated to Part II.

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BACKGROUND

The study included four vehicle designs: a single blade pitch-controlled configuration and three rotor speed-controlled variants. The key performance settings for each model are represented in Fig. 1. For attitude and heading control, the blade pitch-controlled configuration was designed to achieve Level 1 small and moderate-amplitude metrics (per ADS-33E [Ref. 4]) as well as Level 1 disturbance rejection bandwidth (DRB) and disturbance rejection peak (DRP) requirements (per proposed ADS-33F standards [Ref. 5]). These performance metrics were all given a margin of 10% with respect to the Level 1 / Level 2 boundary apart from pitch, which was originally designed to achieve 10% margin, but ended up falling to 4% for reasons described in the Test Preparation section of Ref. 1. Similarly, attitude and direction control for the rotor speed-controlled configurations were tuned to boundary Level 1 performance. Heave performance was determined using a combination of phase delay from ADS-33E, DRB and DRP from proposed revisional standards (ADS-33F), and an inverse time constant metric from findings by Franklin and Stortz (Ref. 6). The first and second rotor speed configurations (referred to here as "RPM1" and "RPM2", respectively) were designed for

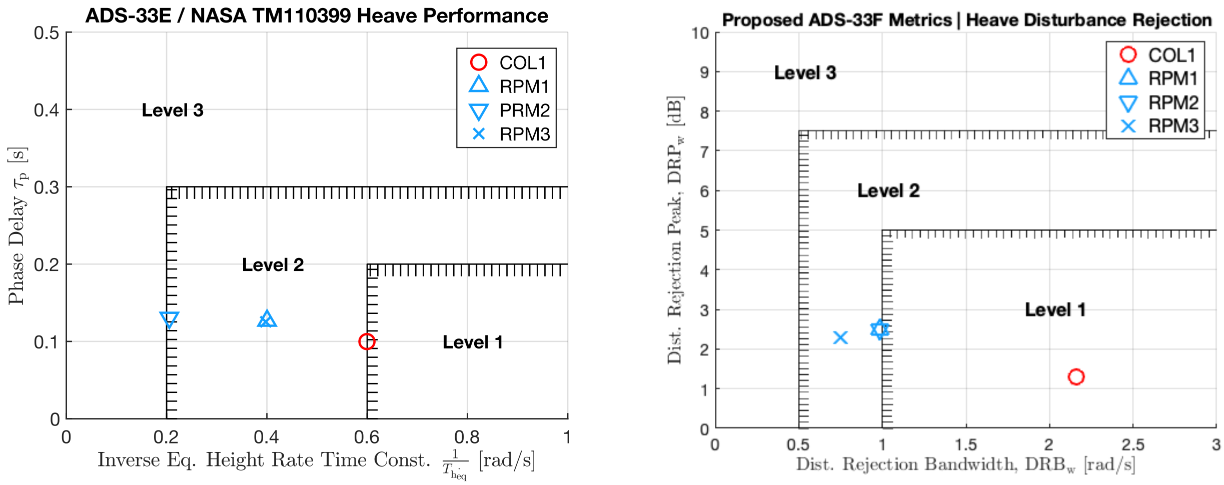


Fig. 1. Heave performance for the four vehicle configurations.

borderline Level 1 / Level 2 DRB along with heave response time constants of 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 of approximately 0.75 rad/s.

Four maneuvers or mission task elements (MTEs) using two standards were explored. These included a Hover task, a Lateral Reposition, and a Vertical Maneuver, which were all derived from ADS-33E for hover and low-speed regimes. The fourth maneuver was a custom UAM approach and landing scenario in downtown San Francisco, which is not analyzed in this paper; however, some discussion regarding pilot workload for the MTE can be found in Ref. 1. The first of the two standards studied were the traditional ADS-33 requirements (Ref. 4). The second set of benchmarks utilized smaller targets as well as shorter course distances, and/or more allotted time to demand higher precision while relaxing aggressiveness. These were thought to be more representative of a UAM mission compared to the ADS-33 standards, which were developed for military rotorcraft; hence, this second set will be referred to as the UAM standards throughout the paper. More details on these MTEs and the requirements imposed by each standard can be found in the appendix of Ref. 1.

The low altitude Dryden turbulence model was selected for its ease of implementation and used to generate wind disturbance inputs to the u, v, w body-axis airspeed components and the p, q, r body-axis rotational rates. The model is well documented in a previous study (Ref. 7), where it was used as a baseline model for comparison against an alternative method, with demonstration on a motion-based simulation of a UH60A Blackhawk. It is recognized that the Dryden model can be ill-suited for rotorcraft simulation, especially at slow airspeeds, due to its underlying assumption that the vehicle's airspeed must be large compared to the turbulent flow (Ref. 8, 9). However, by tuning a minimum airspeed parameter as a surrogate for the rotorcraft's actual airspeed, the Dryden model produced light turbulence inputs with acceptable spectral content and feel as judged by a pilot subject matter expert. The parameters used for the study were 60 kts minimum airspeed, 60 ft span, and turbulence magnitude settings for a mean wind speed of 15 kts at 20 ft AGL per the low altitude Dryden model specification (Ref. 10). Table 1 shows the resulting RMS airspeeds and rotational rates for the rotorcraft simulated in a hover condition at 20ft AGL.

Table 1. RMS airspeeds and rotational rates from the Dryden model.

Dryden Model RMS Airspeeds & Rotational Rates						
Altitude [ft]	u [ft/sec]	v [ft/sec]	w [ft/sec]	p [deg/sec]	q [deg/sec]	r [deg/sec]
20.00	2.75	2.75	1.42	1.87	0.99	1.71

Attitude Command-Attitude Hold (ACAH) and Translational Rate Command (TRC) control modes were compared using the Hover MTE. TRC was utilized in the Vertical Maneuver to allow pilots to focus primarily on the heave axis response while ACAH was the primary control mode for the Lateral Reposition. In terms of directional and heave control, Rate Command-Direction Hold (RCDH) and Rate Command-Height Hold (RCHH) were used, respectively. Additionally, the UAM approach MTE utilized Rate Command-Attitude Hold (RCAH) and Turn Coordination (TC) at the beginning of the maneuver before pilots manually transitioned to RCDH and ACAH or TRC for the low-speed portion of the maneuver. Lastly, the TRC mode was tuned to three configurations: TRC1a, TRC1b, and TRC2. TRC1a and TRC1b have nearly indistinguishable differences in the outer-loop filter shaping while TRC2 had higher speed limitations that dramatically improved its performance. More specific details on the TRC modes can be found in Ref. 1.

PART I

COOPER-HARPER HANDLING QUALITY RATINGS

Causes of Higher Ratings

When considering the Cooper-Harper Handling Quality Ratings (HQRs), the baseline COL1 vehicle received average ratings that were Level 2 despite being tuned to Level 1 performance with margin. This trend can be seen in the ratings for both the Lateral Reposition and Hover MTEs (Fig. 2). Recall that COL1 had a borderline time constant for heave (see Fig. 1). As such, the vehicle performed as expected for the Vertical Maneuver with average HQRs that met or exceeded borderline Level 1 / Level 2 performance.

For the Lateral Reposition, pilots commented that all four of the vehicle configurations tended to drift longitudinally despite almost purely lateral inputs being made. This effect was ultimately traced back to a stitched dynamics model implementation issue, which is further discussed later in this paper. Additionally, pilots found that the fixed-pitch RPM configurations were susceptible to yaw coupling due to roll inputs. This coupling was especially prevalent when pilots made more aggressive control inputs and was also more common in runs involving turbulence. These effects created additional workload for the pilots and ultimately resulted in higher HQRs. This issue is further discussed under the Yaw Coupling section in Part II.

For the Hover MTE, pilots were asked to reposition the aircraft along a 45° track to a hover location and maintain their position within tolerance for 30 seconds. In both the translation and station-keeping segments of the operation, pilots assessed both the pitch and roll components of the attitude control system. The feedback from pilots was that there was a disharmony in the response between the two axes.

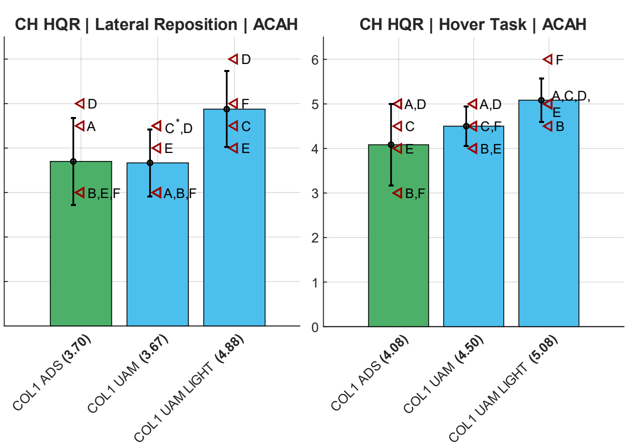


Fig. 2. COL1 Cooper-Harper HQRs for the Lateral Reposition (left) and Hover MTE (right). Note that borderline Level 1 / Level 2 ADS-33 metrics are associated with a Cooper-Harper HQR of 3.5.

Pitch was described as lethargic and difficult to control while roll was said to be quick and jerky. This additional workload for pitch is reflected by the larger spread of side-stick control inputs along the longitudinal axis as seen in Fig. 3. COL1 and RPM3 are shown as they have the most prominent differences between longitudinal and lateral variation, but it should be noted that RPM1 and RPM2 also have larger longitudinal variation, albeit smaller in magnitude. Plots for these additional vehicles and evaluations in the presence of turbulence can be found in Appendix B. Another factor that may be contributing to the longitudinal workload is the drifting issue mentioned earlier for the Lateral Reposition (see Stitched Model Implementation Issue for more discussion).

Similarly, some pilots also noted the presence of yaw coupling when making more aggressive control inputs for the

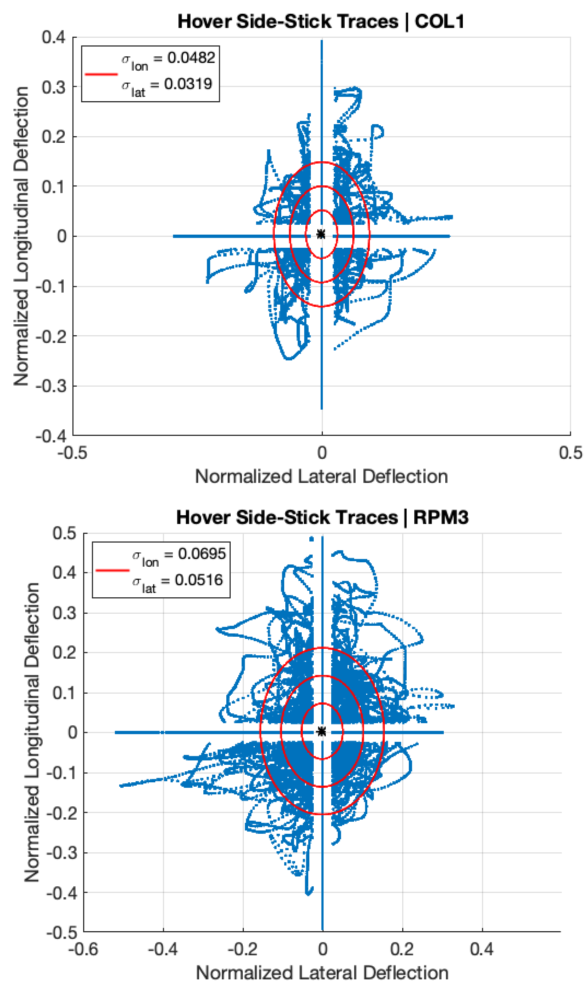


Fig. 3. Hover MTE side-stick traces for evaluation runs under ADS-33 & UAM standards without turbulence using the COL1 and RPM3 configurations. The black asterisk shows the mean while the surrounding red ellipses portray the first three standard deviations. The amounts for one standard deviation (σ) in the longitudinal and lateral directions are shown in the legend.

RPM vehicles during the Hover MTE. As before, turbulence amplified these effects and resulted in higher HQR ratings from the pilots. More information regarding the disharmony in attitude response and yaw coupling effects can be found under the Attitude Disharmony and Yaw Coupling sections, respectively.

UAM Versus ADS-33 Standards

Average Cooper-Harper ratings for the Hover and Lateral Reposition MTEs were slightly higher for the UAM standards compared to the traditional ADS-33 standards for the further degraded RPM2 and RPM3 configurations. Based on individual pilot ratings, the same could not be said for the RPM1 and COL1 configurations. This is thought to be driven by the higher precision requirements imposed by the UAM standards which can cause pilots to increase their compensation gain and bring out the attitude disharmony and yaw coupling effects discussed in the previous section. This notion is supported by similar trends observed in the Precision and Aggressiveness ratings.

As mentioned in Ref. 1, this trend was reversed for the ADS-33 Vertical Maneuver runs which received higher average ratings (see appendix Fig. A4). While pilots were required to maintain a more precise altitude for UAM standards, the additional allotted time was sufficient to complete the task without increasing their demand for control authority (ADS-33 had a desired performance time limit of 13 seconds while UAM standards imposed 30 seconds). Again, this trend was also reflected in the Precision and Aggressiveness ratings received from the pilots.

AGGRESSIVENESS & PRECISION

Correlation Between the Two Scales

When considering the ratings for all applicable maneuvers, Aggressiveness and Precision were initially found to be strongly correlated with one another with a coefficient of determination[*] (r^2) value of ~78%. This is partially a product of both scales using a similar rating range of one to five and the fact that any evaluation run where the pilot could not achieve desired performance in all target requirements (e.g. physical position, time to completion, etc.) was forced by each of the scales to rate the vehicle a five (see appendix Fig. A1). Therefore, the ratings obtained from the scales do not distinguish the quality of precision or aggression for runs where performance was only adequate. This artificially inflated the correlation values. As a result, the calculations were performed once more with the ratings of 5 removed.

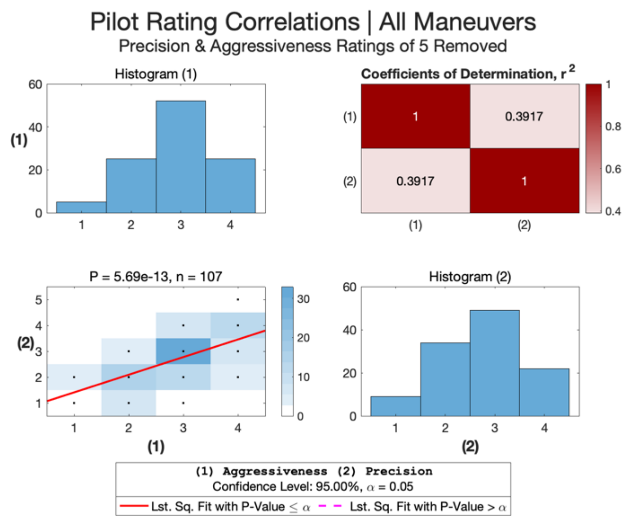


Fig. 4. Pilot Rating Correlations for Aggressiveness & Precision with Ratings of 5 Removed.

Fig. 4 shows combinations of the two ratings which are depicted as black dots in the lower-left scatter plot. The frequency of each combination is shown as a heatmap behind the scatter where boxes with darker shades of blue indicate more occurrences. Additionally, the corresponding P-value[†] and number of samples, n, are listed in the chart title. The histograms on the upper left and bottom right of Fig. 4. depict the distribution of ratings for Aggressiveness and Precision, respectively. A summary of the coefficients of determination for Aggressiveness versus Precision is also shown in the upper-right.

Removing the ratings of five caused the coefficient of determination to drop from ~78% to ~39%. While this is a significant decrease, there is still a moderate correlation between the two rating scales. In addition, the spread of the histogram data, the strong heatmap values along the best-fit line of the combination plots, and the similarity of the patterns seen in the Precision & Aggressiveness rating summaries (see Appendix A) all show how closely related the scales are to one another. While this is not necessarily indicative that the information provided from the Aggressiveness and Precision ratings were the same, it might be more efficient to use scales that are less correlated to maximize the usefulness and uniqueness of the data collected in the future. Statistics regarding the correlation between all of the rating categories, including the ratings of five for Precision and Aggressiveness, are shown in appendix Fig. C1. Appendix Fig. C2 portrays the same analysis but omits the previously mentioned ratings of five.

[*] The coefficient of determination (r^2) measures percentagewise how much variation in one variable can be explained by the variation of another.

[†] In this context the P-value represents the probability that an observed correlation occurred due to chance. Lower P-values show that a result (i.e., correlation) is more reliable and not random.

Effects of Turbulence

When turbulence was introduced for the Hover and Lateral Reposition MTEs, pilots were required to make more frequent and abrupt inputs which, subsequently, aggravated adverse effects (yaw coupling, pitch/roll disharmony, drift, etc.) and compounded the overall workload. Given these factors and the tight position tolerances for the UAM standards, it is not surprising that pilots were unable to meet the desired performance criteria using any of the vehicle configurations. The lone exception to this pattern was the COL1 vehicle for the Lateral Reposition (Fig. 5) which has approximately 10% more roll margin compared to the RPM configurations (shown in Fig. 15b). This gives COL1 a slight advantage, but it is suspected that the primary driver behind the higher ratings for the RPM vehicles was a combination of maintaining tight UAM tolerances and inherent yaw couplings, which both were further complicated by the presence of turbulent conditions.

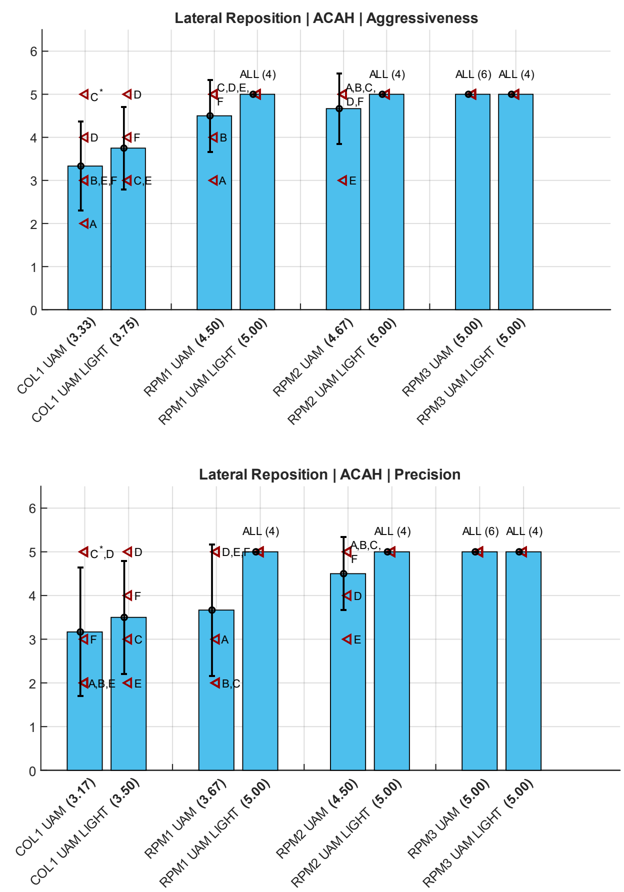


Fig. 5. UAM standard Aggressiveness (top) & Precision (bottom) ratings for the Lateral Reposition MTE.

Vertical Maneuver

Under ADS-33 standards, average Precision and Aggressiveness ratings for the vertical maneuver were about the same between RPM2 and RPM3, but noticeably worse compared to the baseline RPM1 vehicle. Pilots flying the RPM2 (degraded time constant) configuration observed that the vehicle was sluggish in response to their collective stick inputs and several of them noted a tendency to overshoot the target boards. For the RPM3 (degraded DRB) configuration, pilots found that heave responses became substantially out-of-phase with their inputs and created pilot induced oscillation (PIO) tendencies. This issue is identified in the pilot comments and is clearly visible in both PIO (appendix Fig. A19) and predictability ratings for RPM3 compared to RPM1 (appendix Fig. A13).

RIDE QUALITY

Scale Limitations

Unlike the Aggressiveness and Precision ratings, Ride Quality was rated on a one to nine scale where a one indicated a "smooth" ride experience and a nine indicated a "jerky" encounter (see Fig. A1). However, the ratings in between (values two through eight) lack explicit delineation, and as a result, observations regarding Ride Quality must be prefaced with the fact that the rating scale leaves a substantial amount of ambiguity for what each number represents. As a result, pilots often relied on individual mental models of what each value represented, which may not match how other pilots viewed each run. This was evident in how some pilots exhibited unique rating tendencies. This can be seen for the Vertical Maneuver MTE in Fig. 6 where pilot F tended to give the lowest ratings for the no turbulence cases and the highest ratings for the setups involving turbulence. Furthermore, pilot B tended to consistently provide higher ratings than the aggregate mean.

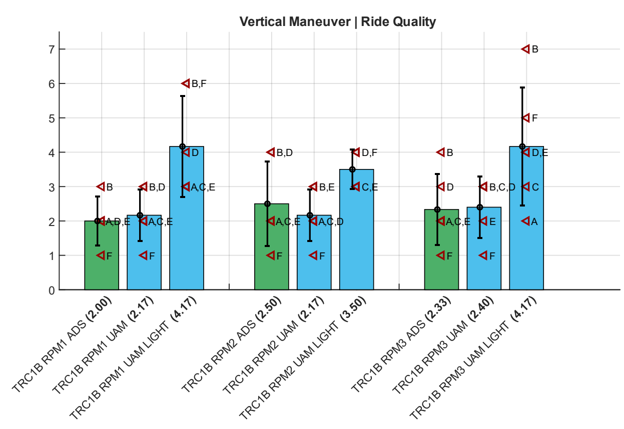


Fig. 6. Vertical Maneuver Ride Quality ratings for the RPM configurations.

Relation to Other Ratings

To better characterize the handling and ride qualities of UAM vehicles, it is of interest to obtain data that provides novel information that cannot be similarly predicted from other rating scales. In contrast to the moderate correlation of Aggressiveness and Precision ratings, the Ride Quality rating seems to be the least correlated with every other rating. This can be seen in Fig. 7 where the Ride Quality has the lowest coefficient of determination with every other rating (except overall Cooper-Harper HQR). As a result, Ride Quality represents a unique vehicle characteristic that is not already captured by the other handling qualities ratings discussed in this paper. Thus, it is imperative that future tests utilize a more rigorous approach to characterizing ride quality.

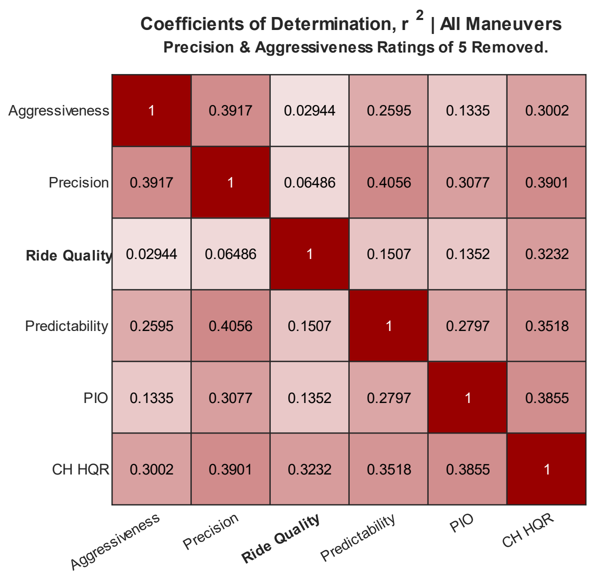


Fig. 7. Coefficients of determination between Ride Quality and the other five rating categories. Precision & Aggressiveness ratings of 5 have been removed.

PREDICTABILITY

Scale Limitations

Predictability was rated on a simplistic one to nine ordinal scale identical to Ride Quality, but with descriptors of "predictable" for one and "unpredictable" for non. The lack of distinctive labels for ratings two through eight means that there was no basic definition to agree upon, leaving the interpretation up to the individual pilots' opinions. Thus, pilots may tend to cluster their ratings towards one end of the scale versus another because of prior experiences or first encounters with a vehicle featuring relatively poor (or exceptional) handling qualities. Within the experiment, the order that the pilots received the configurations was varied in an attempt to reduce biases; however, evidence of this effect can be seen in Fig. 8 where pilot F tended to give lower ratings while pilot D gave relatively higher ratings.

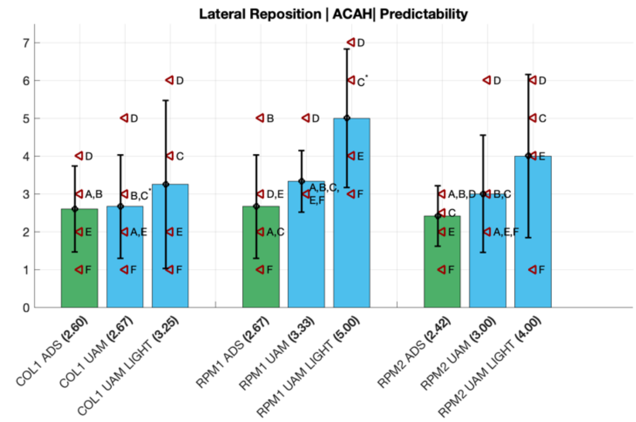


Fig. 8. Sample Predictability ratings from the Lateral Reposition MTE. RPM3 has been excluded to make the figure more legible, but full results are presented in Fig. A12.

While predictability itself is a qualitative metric, the large range of the scale and lack of descriptors blurs underlying trends. That said, the average rating trends for Predictability were fairly similar to those of Precision. In fact, the coefficient of determination (r^2) values between the two ratings were ~25% when Precision ratings of 5 were included and ~41% with the 5 ratings removed (see Appendix C). Likewise, Predictability had similar overall average rating trends as Aggressiveness; however, the correlation values were not as strong (~22% with ratings of 5 included and ~26% with ratings of 5 excluded).

Perception of RPM2 Differences

Average Predictability ratings rose with the addition of turbulence across all MTEs and affected the RPM configurations the most. Some of the more favorable Predictability ratings under UAM standards with turbulence were for the RPM1 configuration in the Vertical Maneuver; the RPM2 & RPM3 configurations in the Hover MTE; and the RPM1 & RPM3 configurations in the Lateral Reposition.

Average RPM2 Predictability ratings were slightly lower than RPM1 & RPM3 for the Lateral Reposition (see Fig. 8). Looking to the individual pilot trends, this pattern only holds true for the UAM standards with turbulence. It is also interesting to note that the average PIO, Precision, Aggressiveness, and Cooper-Harper ratings for the Lateral Reposition under ADS-33 standards also show favorability towards the RPM2 configuration; however, these differences are small and not universally substantiated when looking at corresponding individual pilot trends.

Notwithstanding the lack of sizeable rating differences, this trend was further investigated, and it was found that pilots utilized the collective stick to a much greater extent in the RPM2 vehicle compared to the other RPM configurations. This is illustrated in Fig. 9 where traces of the collective stick inputs for all Lateral Reposition evaluation runs under ADS-33 standards are aligned at their first nonzero value and characterized by a thick, black line representing the average. Red shading is used to depict a one standard deviation spread of the data. When comparing the individual lines for RPM1 and RPM2 of Fig. 9 in detail, there were only six nonzero traces among nineteen evaluation runs for RPM1 which involved three of the six pilots. RPM2 on the other hand, elicited collective inputs from five of the six pilots during fifteen of the twenty evaluation runs.

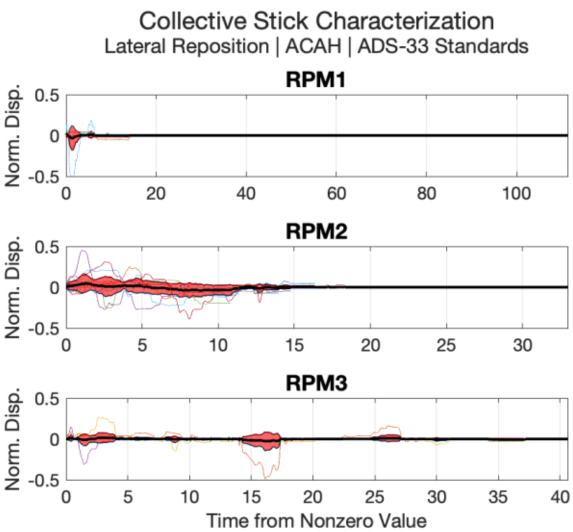


Fig. 9. Collective stick characterizations for the RPM configurations in the Lateral Reposition under ADS-33 standards.

It was also observed that pilots C, E, and F improved their average completion time for the Lateral Reposition under ADS-33 standards by about a second compared to RPM1. This is somewhat significant since the time for desired performance under ADS-33 standards was 18 seconds and many of the baseline RPM1 evaluation runs were up against that boundary (see Table 2).

Table 2. Average completion times for Lateral Reposition evaluation runs under ADS-33 standards. The first row shows the combined average from each of the six pilots and the trend in those times matches the pattern seen in the pilot ratings for Aggressiveness under the same conditions (See Fig. A6).

Average Completion Times Lateral Reposition | ADS-33 Standards				
Pilot	COL1 [sec]	RPM1 [sec]	RPM2 [sec]	RPM3 [sec]
ALL	18.35	18.64	18.18	19.20
A	19.33	18.00	18.33	18.67
B	17.67	18.33	18.33	18.50
C	N/A	19.33	18.33	19.33
D	20.00	20.00	20.33	19.67
E	17.00	16.67	15.75	19.00
F	17.75	19.50	18.00	20.00

PIO TENDENCIES & DRB

The PIO tendency scale was an optional rating for the pilots, so the results shown are only for the ratings received when the pilot judged the configuration to be PIO prone. With this in mind, the significance of any observed pattern can be evaluated by the number of pilots who were compelled to give a rating. It should also be noted that any PIO experienced by the pilots would be Category I PIO, which is associated with any potential high-frequency phase roll-off. This is because control saturation and rate limiting (Category II causes) were not modeled in this study. Among the four configurations, RPM3 received the largest number of individual pilot ratings while COL1 received the least (see Fig. 10).

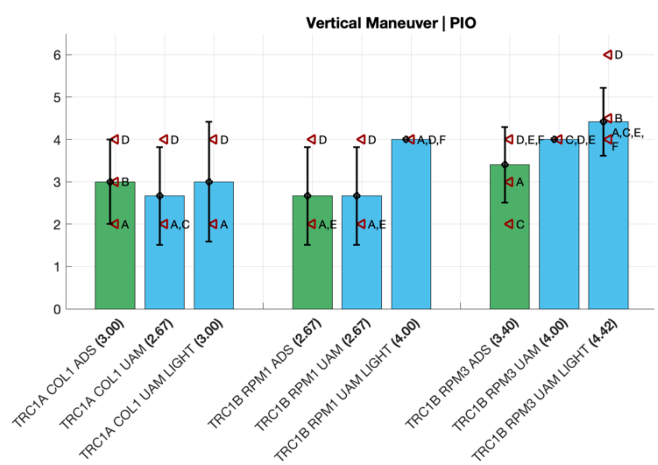


Fig. 10. Vertical Maneuver PIO ratings for the RPM3 vehicle compared to the baseline models.

Looking to the Vertical Maneuver under UAM standards with turbulence, it is evident that pilots were perceptive of the degraded DRB for RPM3. The lack of control system support to filter out the environmental disturbances made the maneuver extremely challenging and had a large impact on the Predictability (Fig. 11) as well as overall Cooper-Harper HQRs (appendix Fig. A4). Additionally, there were PIO rating spikes for the RPM3 vehicle in the Vertical Maneuver under ADS-33 and UAM standards without turbulence. Pilots commented that increased aggressiveness excited a PIO tendency, which suggests that the more time-constrained ADS-33 standards should elicit more PIO ratings from the pilots. However, this appears to only be true for the RPM3 vehicle where half of the pilots gave a PIO rating for the UAM standards, but five of the six pilots gave a PIO rating for the ADS-33 standards. The high sensitivity of RPM3 to PIO tendencies even when evaluated in runs without turbulence highlights the importance of considering DRB in control design.

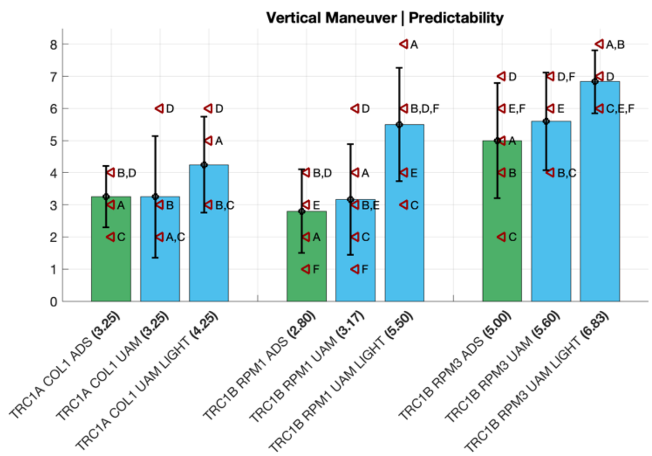


Fig. 11. Vertical Maneuver Predictability ratings for the RPM3 vehicle compared to the baseline models.

When examining the Hover MTE, RPM3 displays higher PIO tendency for the UAM standards with turbulence and there appears to be very little difference in PIO ratings between the different standards for the RPM vehicles, but aside from these trends, there are simply not enough ratings to justify other observations. Similarly, the Lateral Reposition MTE also lacks a significant number of ratings. Future studies should not make rating scales of interest optional.

POWER CONSUMPTION

Previous work explored the relationship between the motor model and control system design for rotor speed-controlled vehicles (Ref. 11). Modeling of the power system for the RPM configurations must be integrated directly into the control loop. Thus, the power and torque required of each individual rotor to execute a maneuver becomes a potential limiting factor for these configurations in terms of control authority as well as vehicle selection and design. This study utilized the same bare-airframe quadrotor model and expanded the scope to compare against a baseline blade pitch-controlled configuration (Ref. 12). While RPM quadrotors utilized four independent rotor/motor pairs, the COL1 design connected all four rotors to a single gearbox, which effectively centralized both torque and power. To this end, the limitations to power and torque were assessed per rotor for the RPM configurations, but collectively for the COL1 vehicle.

Effects of Vehicle Architecture

The COL1 configuration had a higher single rotor trim power, and therefore mean power, compared to the RPM vehicles across all MTEs tested (see Table 3). Since mean power for the RPM vehicles were lower compared to COL1, one may be tempted to say RPM vehicles were more efficient overall; however, there are other factors that should be considered. While mean power can be useful for gauging consumption rates, it only represents a steady-state like condition. It is important to realize that there were significant power and torque peaks which occurred when pilots accelerated or changed direction (transient states). These are exemplified in Fig. 12 for the Vertical Maneuver MTE. Six peaks in the top plot represent power draws that correspond to points in the lower plot where the pilot: (1) initiated the climb, (2) maintained altitude for the top target with additional power, (3) arrested the descent rate, and (4-6) coarsely corrected altitude at the bottom target through power adjustments.

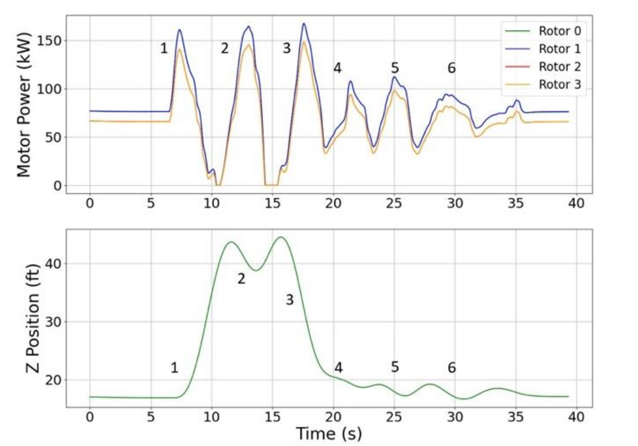


Fig. 12. Power and Z-Position Time History for an RPM3 vehicle performing a Vertical Maneuver run.

The peak power for a single rotor of the RPM vehicles varied based on the maneuver. The largest peak power demands for the RPM vehicles came from the Lateral Reposition maneuver which ranged from 220 to 320 kW per rotor (Fig. 13). For the Hover and Vertical Maneuver MTEs, the peak power per rotor ranged from 170 to 300 kW and 100 to 190 kW, respectively (Table 4). Compared to the representative COL1 value, the RPM vehicles reached 1.5 to 3 times the peak power.

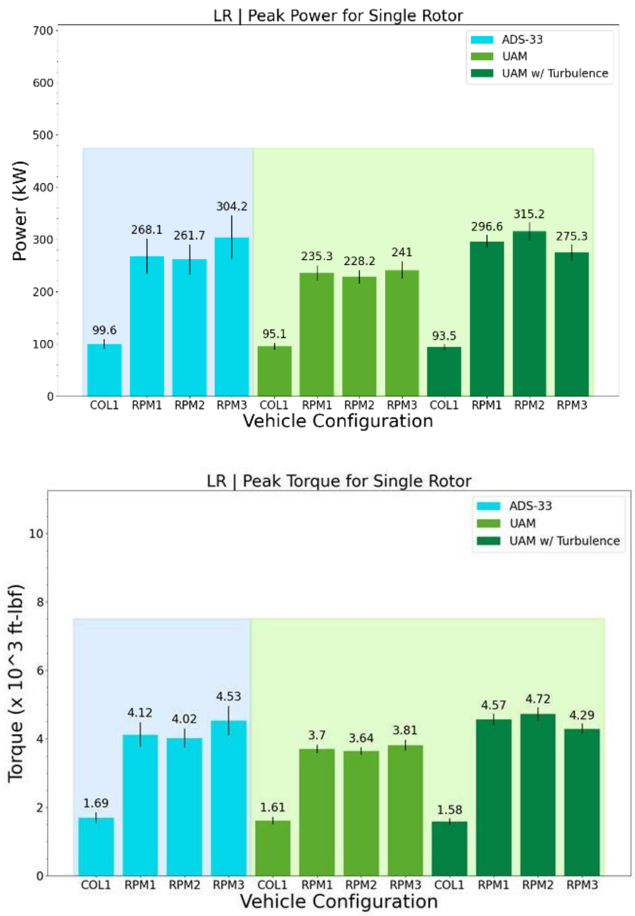


Fig. 13. Peak power (top) and torque (bottom) for a single rotor during the Lateral Reposition maneuver. The COL1 is a representative single rotor power for comparison to the RPM values.

Control Authority Limitations

Without control over the pitch of the blades, the RPM configurations are forced to spool up their rotors to impart motion. This effect resulted in substantially higher peak power draws when compared to the COL1 vehicle. Since this study did not model any motor limitations, peak power demands were viewed with respect to the maximum rated power (MRP) of the conceptual designs to determine if the motors would have saturated. For COL1 the MRP for all four motors was 168 hp. The MRP for the RPM configurations differed between the front (131 hp) and rear (165 hp) pairs of motors to optimize for a lighter gross weight design. In the following analyses, the ratio of peak power to MRP was calculated for each rotor. The largest ratio (i.e., worst-case scenario) will be used in comparing the vehicles.

Average single rotor MRP ratios were assessed across all maneuvers and standards. For the COL1 vehicle, the MRP ratios ranged from 0.7 to 0.9, indicating that control authority demanded by the pilot for the maneuvers did not exceed the available power for the conceptual design. For the RPM configurations, the MRP ratios ranged from 1.2 to 3.6 for the front rotors and 0.8 to 2.6 for the rear rotors. As before, the Lateral Reposition MTE necessitated the most power from the RPM configurations (see Fig. 14). Evidently, for the required level of agility, the RPM vehicles would not be feasible in a real-world scenario as they each exceed their physical limitations. Without increasing available power, tuning the control laws to avoid saturation would only worsen the performance of the RPM vehicles which, as shown previously, is already adequate at best.

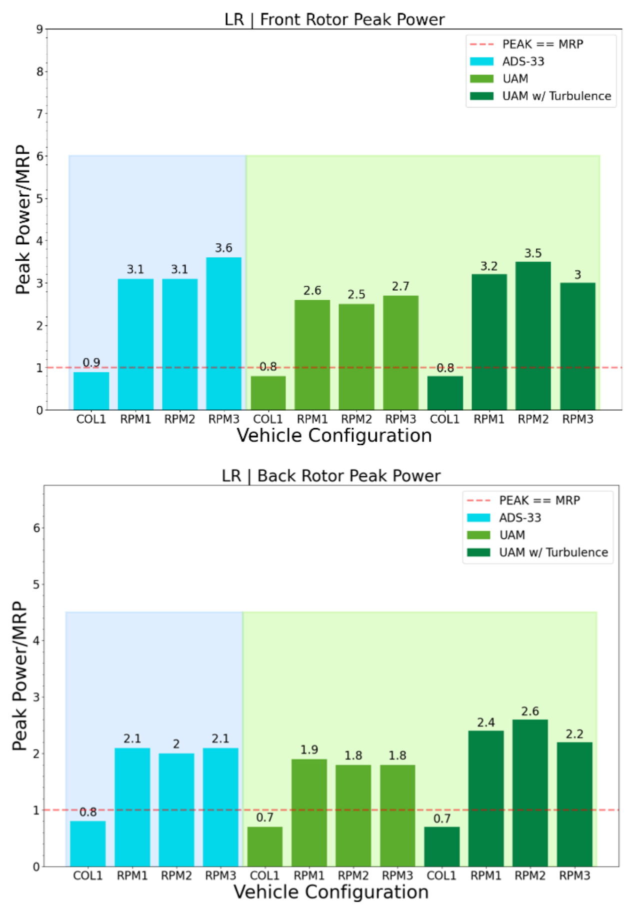


Fig. 14. Front (top) and back (bottom) rotor peak power to MRP ratios for the Lateral Reposition MTE.

Table 3. Mean power for a single rotor (kW).

Vehicle	COL1			RPM1			RPM2			RPM3		
Standard	ADS-33	UAM	UAM w/ Turb.	ADS-33	UAM	UAM w/ Turb.	ADS-33	UAM	UAM w/ Turb.	ADS-33	UAM	UAM w/ Turb.
Hover	75.2	76.2	73.9	56.8	61.8	98.3	40.2	29.3	85.3	47.5	47.1	88.6
Vertical Maneuver	54.0	67.6	66.8	38.6	26.1	18.4	21.8	32.9	27.5	30.9	36.2	24.3
Lateral Reposition	71.3	72.8	72.9	90.2	55.8	101.1	87.4	57.8	97.7	88.8	67.2	80.4

Table 4. Peak power for a single rotor (kW).

Vehicle	COL1			RPM1			RPM2			RPM3		
Standard	ADS-33	UAM	UAM w/ Turb.	ADS-33	UAM	UAM w/ Turb.	ADS-33	UAM	UAM w/ Turb.	ADS-33	UAM	UAM w/ Turb.
Hover	88.2	87.3	88.9	219.5	225.6	291.8	190.2	178.7	274.3	202.7	206.7	277.1
Vertical Maneuver	108.2	96.9	95.6	188.0	121.5	136.3	155.4	107.0	108.4	168.2	108.5	142.8
Lateral Reposition	99.6	95.1	93.5	268.1	235.3	296.6	261.7	228.2	315.2	304.2	241.0	275.3

Table 5. Minimum power for a single rotor (kW).

Vehicle	COL1			RPM1			RPM2			RPM3		
Standard	ADS-33	UAM	UAM w/ Turb.	ADS-33	UAM	UAM w/ Turb.	ADS-33	UAM	UAM w/ Turb.	ADS-33	UAM	UAM w/ Turb.
Hover	81.5	81.5	81.5	70.4	70.5	71.0	70.3	70.3	70.9	70.3	70.4	71.0
Vertical Maneuver	82.3	82.3	82.2	72.1	71.0	71.1	71.4	71.1	71.0	72.2	71.0	71.3
Lateral Reposition	84.4	83.4	83.3	74.4	62.4	72.7	74.6	72.3	72.9	74.7	72.4	72.9

Previous theoretical work concluded that the heave axis would be the most demanding (Ref. 2, 3). As a result, the design of the experiments for this work focused on varying heave response time and DRB between the three RPM configurations. However, results of this study show greater average power peaks for the Lateral Reposition rather than the Vertical Maneuver (Table 4). It may be that the aggressive nature of the maneuver, rather than the axis the maneuver was performed in, drove the higher power requirements. The Lateral Reposition maneuver requires large inputs to complete the course in the targeted time and when pilots used a rapid lateral input to decelerate, yaw coupling was reported. This, along with corrective action for an inherent longitudinal drift of the vehicles, could also contribute to the high peak power and torque values, especially if the adjustments were abrupt. This effect is still being analyzed and will be addressed in future work.

On average, across all the different MTEs and standards (with the lone exception of the Lateral Reposition under UAM standards with turbulence), RPM2 had lower or equivalent peak power demands compared to RPM1 and RPM3 (Table 4). A potential hypothesis for this may be that the command shaping used to tune RPM2's degraded time constant dampened some of the stronger peak demands at the cost of a response delay.

Differences in peak power between the two standards tested arose for the Vertical Maneuver and Lateral Reposition MTEs, but not for the Hover MTE. For the Vertical Maneuver and Lateral Reposition, the ADS-33 standards produced higher peak power demands than the UAM standards without turbulence. The Hover MTE, on the other hand, demonstrated less variation between the two standards tested, with peak power demands being within one standard deviation of each other (Hover and Vertical Maneuver single rotor peak power charts are in appendix Fig. E4, the Lateral Reposition equivalent is in top of Fig. 13).

Furthermore, the impact of turbulence varied based on the configuration. Looking at the difference between the peak, mean, and minimum power for the UAM runs with and without turbulence for all MTEs, the COL1 vehicle showed the least variation with the introduction of turbulence (Table 3-Table 5). The presence of turbulence only changed peak power consumption for COL1 by about 1% while the RPM1 and RPM3 vehicles averaged approximately 22% and 17% more power draw in the presence of turbulence, respectively. RPM2 was the most impacted by turbulence, averaging nearly 38% more power when turbulence was present. The impact of turbulence also varied slightly between the MTEs, where turbulence seemed to impact the Hover and Lateral Reposition MTEs to a greater extent than the Vertical Maneuver MTE.

PART II

ATTITUDE DISHARMONY

During the Hover MTE, pilots noticed a disharmony between pitch and roll response to their inputs. Pitch was described as sluggish whereas roll was jerky. This asymmetry was frequently noted by the pilots and drove up their HQRs. Pilots also commented that the two axes might be coupled. ADS-33 provides metrics for pitch and roll couplings, which were analyzed and shown not to be a factor. These metrics however were tailored to aggressive agility maneuvers that were beyond the intended capabilities of the vehicles in this study (see Appendix D for results). As such, a more generalized approach was taken to estimate the magnitude of cross-axis couplings in the primary flight controls. This was accomplished by recording the ranges of the off-axis responses to step and exponential chirp inputs and normalizing them to ranges of their respective on-axis counterparts. For example, pitch due to roll would be estimated by dividing the range of a pitch response to a lateral stick input with the range of a roll response to the same input. Estimates for the cross-couplings between pitch and roll were again shown to be negligible (see Table 6).

Further diagnosis of the disharmony led to a review the ADS-33E metrics for which the attitude responses were tuned. One of the most glaring findings was that moderate-amplitude pitch boundary for Level 1 performance was significantly lower than the same boundary for roll (see Fig. 15). ADS-33E's supplement, the Background Information Users Guide or "BIUG" (Ref. 13) provided rationale behind each of the standards. Specifically, section 3.3.3 of Ref. 13 describes the moderate-amplitude boundary. In essence, it is designed to connect small-amplitude bandwidths (y-intercepts) on the left-side of the plot with large-amplitude angular rates at the right-side. Examples of these large-amplitude rates are depicted by the red and blue lines in Fig. 16a which can be described by the equation below.

Table 6. Pitch & Roll Cross-Coupling Estimates.

Roll due to Pitch					
Airspeed	Input	COL1	RPM1	RPM2	RPM3
CAS: 0 kts	30% Step	0.00%	0.00%	0.00%	0.00%
	10% Chirp	0.00%	0.00%	0.00%	0.00%
CAS: 10 kts	30% Step	0.00%	0.00%	0.00%	0.00%
	10% Chirp	0.00%	0.01%	0.01%	0.00%
CAS: 20 kts	30% Step	0.00%	0.01%	0.01%	0.01%
	10% Chirp	0.00%	0.02%	0.02%	0.01%
Pitch due to Roll					
Airspeed	Input	COL1	RPM1	RPM2	RPM3
CAS: 0 kts	30% Step	0.27%	0.89%	0.89%	0.77%
	10% Chirp	0.09%	0.87%	0.87%	0.87%
CAS: 10 kts	30% Step	0.34%	1.60%	1.59%	1.67%
	10% Chirp	0.09%	1.71%	1.71%	1.71%
CAS: 20 kts	30% Step	0.56%	3.17%	3.17%	3.28%
	10% Chirp	0.15%	3.08%	2.89%	3.08%

$$\frac{q_{\text{pk}}}{\Delta\theta} = \frac{q_{\text{pk}}\text{ (large-amplitude angular rate)}}{\Delta\theta_{\text{min}}}\,^{‡}$$

For roll, the right-side intercepts are defined as where the angular rates for Level 1 / Level 2 ($p_{\text{pk}} = 50$ deg/sec) and Level 2 / Level 3 ($p_{\text{pk}} = 21$ deg/sec) cross the minimum attitude change ($\Delta\phi_{\text{min}}$) of 60° ($\Delta\theta_{\text{min}} = 30°$ for pitch). For roll, the shape of the boundaries between these two points is informed by flight and simulation tests analyzed in a U.S. Army / NASA contractor report (Ref. 14). This report

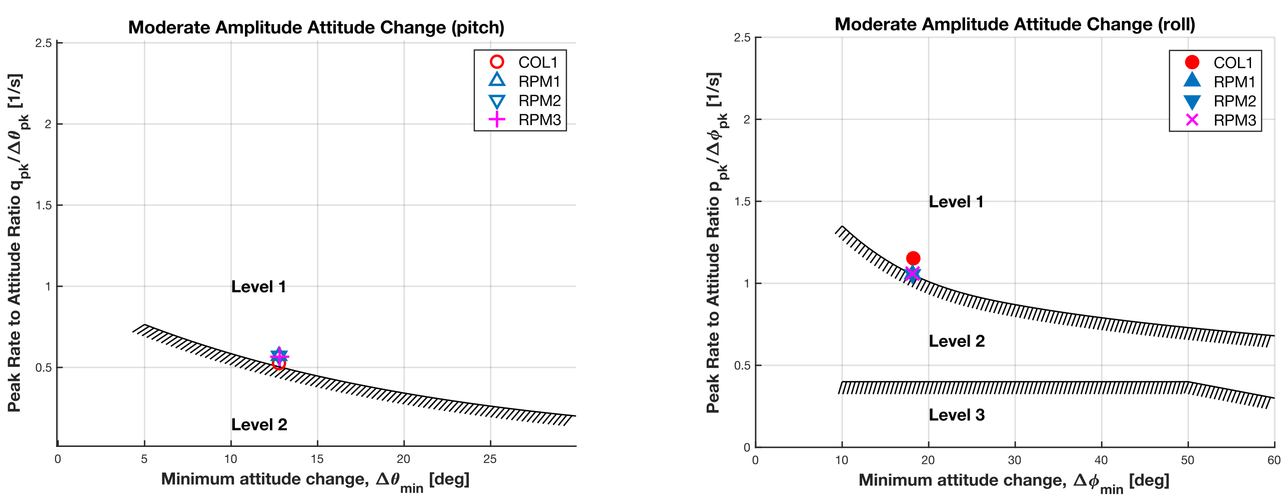
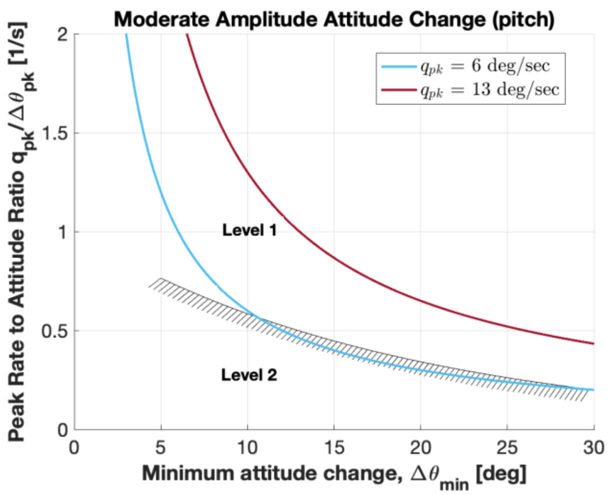
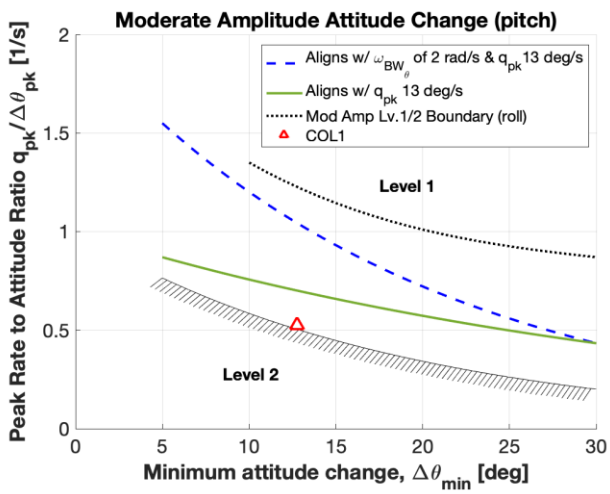


Fig. 15. ADS-33E moderate-amplitude pitch (left) and roll (right) requirements overlaid with vehicles from the VMS study. Note that these plots are adapted from Figure 8c and 8d, respectively, in Ref. 4. The UAM vehicles in this study did not require target acquisition and tracking capabilities, so they were designed to the ADS-33E metrics for "All Other MTEs".

‡ Note that this equation is written in terms of pitch, but it is equivalent for roll.



(a) Discrepancy at the right side of the moderate-amplitude pitch metric for alignment to large-amplitude angular rates.



(b) Depictions of alternative level 1 / level 2 moderate-amplitude pitch boundaries.

Fig. 16. Discrepancies and alternative boundaries for the ADS-33E moderate-amplitude pitch metric.

focused on roll control authority as pilots from prior studies of VTOL aircraft found lateral response to be insufficient.

For pitch, no equivalent report exists, so assumptions were made as to the shape of the boundary. Specifically, the BIUG describes the moderate-amplitude pitch (left-most plot of Fig. 15 as follows:

> <u>All Other MTEs (pitch):</u> The lower end of the Level 1 limit in Figure 4c (3.3) has been set to allow a natural reduction in bandwidth from the small-amplitude limit of 1 rad/sec (at $\Delta\theta \doteq 0$) to a value consistent with the angular rate requirement for moderate maneuvering (Table 1(3.3)) at the upper end. (Ref. 13, p.251).

Looking to the referenced table, the angular rate (q_{pk}) is 13 deg/sec for Level 1 and 6 deg/sec for Level 2 & 3. Since the moderate-amplitude plot only depicts a boundary between Level 1 / Level 2, one would expect the right side of the moderate-amplitude plot to coincide with the angular rate of 13 deg/sec at $\Delta\theta_{\min} = 30°$ yet the actual plot appears to align with an angular rate of 6 deg/sec (see Fig. 16a). Correction for this discrepancy is shown in Fig. 16b by a green line. For reference, the performance of COL1 is depicted by a red triangle and the equivalent Level 1 / Level 2 moderate-amplitude boundary for roll is shown by a black dotted line.

Furthermore, a discrepancy also exists at the left-side of the moderate-amplitude metric. In this case, the description from the BIUG matches the figure and the boundary decays from a y-intercept of 1 rad/sec. However, when looking to the small-amplitude metrics that this plot connects to, it seems that the assumption was based on bandwidth for fully-attended pitch operations ($\omega_{BW_\theta} = 1$ rad/sec). This conflicts with the Hover MTE flown in this study as is involves pilot workload in both pitch and roll. Taking this into consideration, the boundary for pitch may also need to be corrected to align with the Level 1/Level 2 small-amplitude metric for divided attention at $\omega_{BW_\theta} = 2$ rad/sec (as depicted in Figure 5e of Ref. 4). A line correcting for both the large-amplitude angular rate ($q_{\text{pk}} = 13$ deg/sec) and small-amplitude bandwidth ($\omega_{BW_\theta} = 2$ rad/sec) is illustrated by the dashed blue line in Fig. 16b.

While this paper was not designed to assess the location of ADS-33 boundaries, the contradictory information in the BIUG combined with the pilot feedback from this study suggest that the boundaries for pitch performance should be revisited in future work so that they can be harmonized with the performance criteria for roll.

STITCHED MODEL IMPLEMENTATION ISSUE

During the Lateral Reposition pilots stated that they experienced an unexpected longitudinal drift in all four vehicle configurations. The drifting behavior was reproduced in simulation using lateral step inputs and it was subsequently discovered that a quasi-Linear Parameter Varying (qLPV) model implementation detail was to blame.

The bare airframe stability and control derivatives for the concept vehicle were linearized over a set of trim points and stitched together in a qLPV model framework. This modeling approach is commonly used, as it provides computationally fast, and sufficient nonlinear representation of the vehicle's dynamics across the full-flight envelope. The qLPV model as implemented in the VMS, was stitched based on the vehicle's true airspeed, which by definition includes all three of the body-axis airspeed components (i.e., *u*, *v*, and *w*). However, because the qLPV model was developed for forward flight, the trimmed linearized models only included pitch trim effects and corresponding *u*, *w* body-axis airspeed components. As a result, lateral airspeed components were interpreted as longitudinal motion by the qLPV model, and the vehicle would subsequently trim for forward pitch. This gave rise to the longitudinal drift experienced by the pilots. This effect was confirmed post study, when it was shown that removing the lateral velocity component from the airspeed input for the qLPV model corrected the longitudinal drift (see Fig. 17).

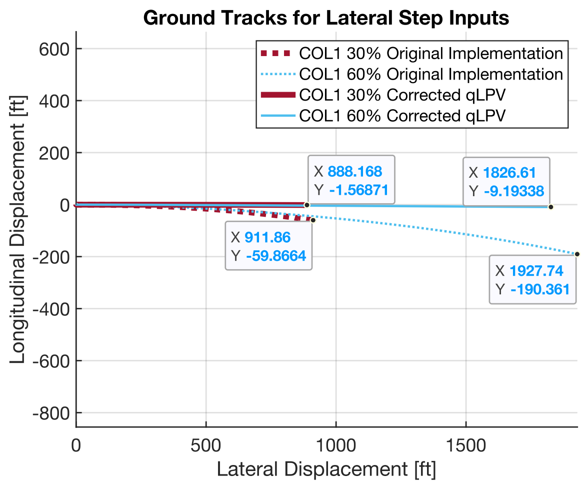


Fig. 17. Longitudinal drifts and corrections for 30% and 60% lateral step inputs. Steps lasted 10 seconds and were followed by a 20 second period with no inputs to allow the vehicle to move freely.

Of course, this drifting effect required additional pilot compensation for the Lateral Reposition, but it also likely contributed to the asymmetric longitudinal workload pilots experienced during the Hover MTE. Given that the error in the qLPV airspeed parameter for the Hover MTE was lower compared to the Lateral Reposition and the fact that pilots consistently commented on the sluggishness of the pitch response, it is suspected that reduced bandwidth in pitch played a larger role.

YAW COUPLING

Yaw coupling effects were experienced in both the Lateral Reposition and Hover MTEs for the RPM configurations The Lateral Reposition evoked most of the pilot responses and comments indicated that the coupling was triggered by aggressive roll inputs, especially when control was reversed during the deceleration phase of the MTE.

There were at least two contributing factors to the observed yaw coupling due to roll command. The first is the qLPV modeling issue discussed above. At the point of deceleration for the Lateral Reposition, the qLPV model incorrectly trims the vehicle for forward flight, which is shown to have amplified the coupling. The second is that the control system design used a model order reduction technique with steady-state matching to remove blade-flapping states which were hidden from the controller. The flapping dynamics however were only faster than the attitude dynamic modes by a factor of two, so additional error was introduced between the model used to derive the controller and the simulated model, which included the flapping dynamics. It was shown in an offline analysis that this produced error in the low frequency model approximation used to design the controller that reflected poorly on the full order yaw due to roll command coupling. Furthermore, in the offline analysis, improvement (but not elimination) was obtained by using model order reduction with truncation instead of steady-state matching.

Cross coupling between lateral stick inputs and yaw response for the RPM models was confirmed using the same technique employed for estimating attitude couplings. Step and chirp signals were injected to the lateral stick for the four vehicles and ranges for the yaw rate responses were collected. These ranges were then normalized to the range of the yaw rate response from the same signal inputs on the pedals to obtain coupling estimates. Results are summarized in Table 7 below.

Table 7. Yaw due to lateral stick coupling estimates.

Yaw due to Roll					
Airspeed	Input	COL1	RPM1	RPM2	RPM3
CAS: 0 kts	30% Step	0.14%	11.96%	12.24%	7.94%
	10% Chirp	0.19%	3.18%	3.18%	3.15%
CAS: 10 kts	30% Step	2.82%	47.32%	47.34%	46.61%
	10% Chirp	3.93%	51.08%	51.08%	51.02%
CAS: 20 kts	30% Step	4.86%	102.65%	102.64%	98.75%
	10% Chirp	6.73%	110.72%	73.38%	110.51%

It was apparent from these results that there were some underlying dynamics strongly tied to the fixed-pitch RPM configurations that were exciting the yaw coupling. In order to quantify the degree of coupling due to the qLPV implementation issue, a doublet signal (Fig. 18) was placed on the lateral stick input to mimic the Lateral Reposition MTE. The qLPV model was analyzed in its original implementation as well as the corrected version to see how the baseline vehicles would respond (see Fig. 19).

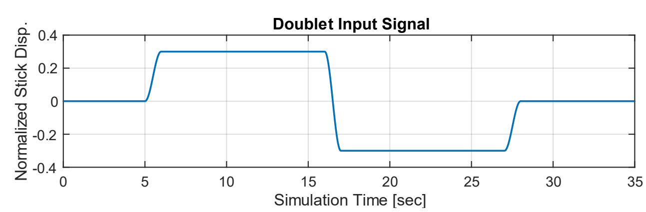


Fig. 18. Smoothed doublet signal used in the analysis for yaw coupling.

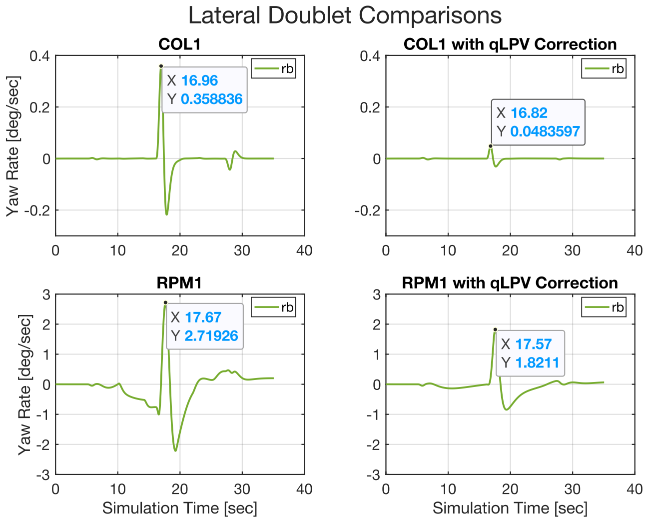


Fig. 19. Comparisons of yaw rates coupled to lateral stick doublets.

With the qLPV correction in place, the COL1 configuration peak yaw rate was reduced by ~86% while the peak yaw rate for the RPM1 configuration only dropped by ~33%. Regardless, the yaw coupling due to roll remains even after the qLPV issue is addressed.

SUMMARY

Several observations made in the preceding paper (Ref. 1) as well as some new ones have been discussed. Three major root causes for most of the unexpected results were identified and analyzed in detail. First, was an adverse drifting effect caused by a flaw in the airspeed calculation fed to the qLPV model that primarily affected ratings for the Lateral Reposition. Second, was a disharmony observed by the pilots in the attitude response for the Hover MTE. This disharmony provoked pilots to comment on their difficulties in controlling the “sluggish” longitudinal axis compared to the “jerky” lateral response. The longitudinal drift issue in the qLPV model was likely a contributing factor in the challenge pilots faced with the longitudinal axis, but it did not explain the difference in the quality of the responses. Instead, a discrepancy in the ADS-33E standards is likely to have resulted in suboptimal control tuning for the pitch response. The third root cause was yaw couplings mainly observed in the Lateral Reposition that resulted in lower HQRs. This effect was found to be inherent to the fixed-pitch RPM vehicles and potentially exacerbated by the qLPV modeling issue.

In addition to the ratings, new analysis revealed key insights on differences in power consumption and torque demands between the COL1 and RPM vehicles, the individual RPM vehicles, and the various MTEs. One of the key findings was that the peak power for all RPM configurations exceeded the MRP of the conceptual motors for all MTEs while the power demands for the COL1 vehicle did not. The largest MRP violations seemed to be associated with the front rotors and ranged from 1.2 to 3.6 times the motor saturation limits. As a result, while the COL1 vehicle demanded higher mean power per rotor, the RPM vehicles used a significantly larger range of power values per rotor. This included power spikes 1.5 to 3 times that of the COL1 vehicle. Among the RPM vehicles, it was often found that the RPM2 configuration demanded the smallest peak power and peak torque for most maneuvers, while RPM1 (for Hover, Vertical Maneuver MTEs) and RPM3 (for Lateral Reposition) typically demanded the most. Additionally, turbulence generally increased the power necessary to maneuver for RPM vehicles, while leaving the COL1 vehicles largely unaffected.

In terms of the test standards, the more precise and less time sensitive UAM standards evoked higher Cooper-Harper HQRs from the RPM2 and RPM3 vehicles in the Hover and Lateral Reposition MTEs. For the Vertical Maneuver, the additional allotted time from the UAM standards was ample enough for pilots to complete the maneuver without requiring control authority to maintain their precision. Additionally, ADS-33 power demands were most noticeable in the peak power trends for the Lateral Reposition and to a lesser extent for the Vertical Maneuver. Peak power demands for Hover were not as distinguishable between the two standards.

There were several rating scales and methods that should be revisited in the planning of future studies. First are the simplistic Ride Quality and Predictability scales, which fell victim to biases of the pilots. Adding descriptors to the indistinctive values on the scales would give some form of consistency as pilots would be able to agree on a set definition. Another solution may be to parse the questions into more specific elements of interest to researchers. For example, a controls engineer may want to divide Ride Quality into ratings for high-frequency vibrations and low-frequency oscillations while a human factors investigator may be more interested in noise levels or ergonomics of the inceptors. Second are the Aggressiveness and Precision scales, which limited pilot feedback to evaluation runs with desired performance. Modifying the decision tree of these scales to encompass adequate performance (or even to be rated independently of the task performance) would allow pilots to continue distinguishing precision and aggression characteristics for each test configuration (vehicle, MTE, course standard, etc.) despite potentially subpar behavior. Additionally, scales that were not consistently used such as the Bedford Workload Scale (BWS) or PIO tendency should be either eliminated or thoroughly applied in order to gather the most data from the often-limited sample size of pilots available.

Improving responses from these categorized scales provides valuable data that can help identify which particular factors may be affecting overall Cooper-Harper ratings. As introduced in this study, calculating the correlation between these categories has the benefit of uncovering how unique and useful each scale may be, such as the Ride Quality metric. Since Ride Quality was not strongly correlated to the other rating categories, expanding the scope of this scale may provide more unique data that could be used for assessing passenger acceptance. Conversely, it may also be worth exploring options for combining the most correlated scales in order to accentuate underlying causes as efficiently as possible.

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APPENDIX A

Features of the Pilot Rating Charts

Throughout this report there are figures representing average pilot ratings which may be vague. The title of the chart should indicate the MTE being shown. The title will also include the control mode for plots where only a single mode is analyzed. The solid bars in these plots represent the magnitude of the average pilot rating for each combination specified along the X-axis. The average can also be found written out bold and in parentheses of its respective X-axis label. Each label contains the control mode (if not in the title), vehicle configuration, and MTE performance standard. The label will include the word “Light” following the performance standard if turbulence was present during the evaluation. The black error bars represent 1 standard deviation from the average pilot rating. Please note this is strictly for visualizing the spread of the ratings received and not making statistical conclusions. Dark red triangles represent individual pilot ratings for each evaluation combination (e.g., Lateral Reposition using the RPM1 configuration under ADS-33 standards, etc.) 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 evaluation combination 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 ADS-33 standards while blue bars represent UAM standards.

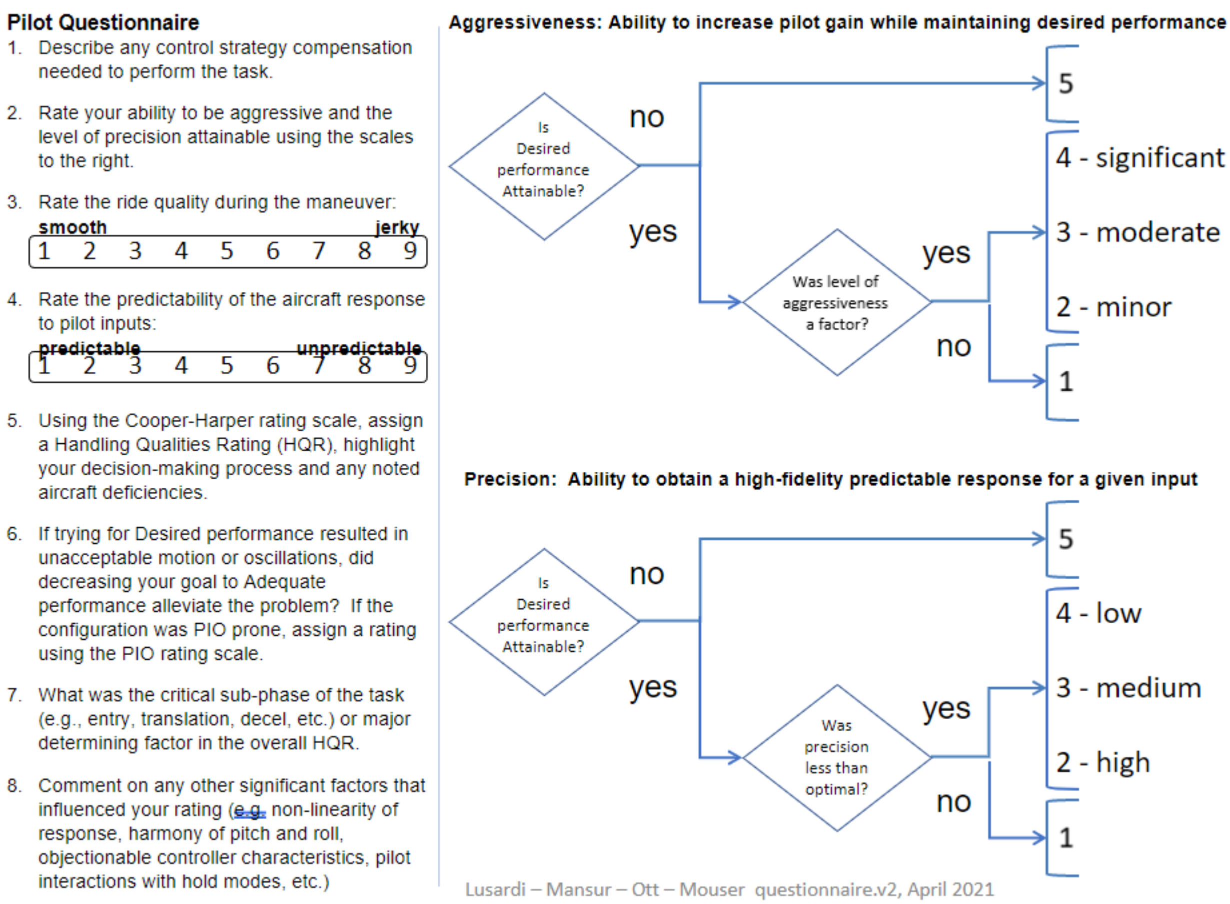

Fig. A1. Pilot Questionnaire for Ride Quality, Predictability, Aggressiveness, and Precision Rating Scales.

Cooper-Harper Handling Quality Ratings

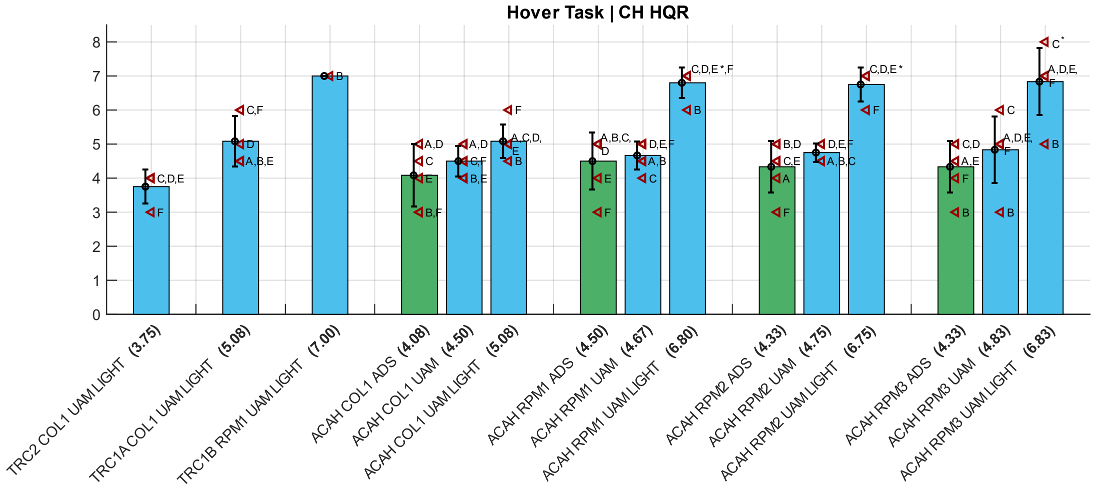

Fig. A2. Cooper-Harper HQRs: Hover MTE.

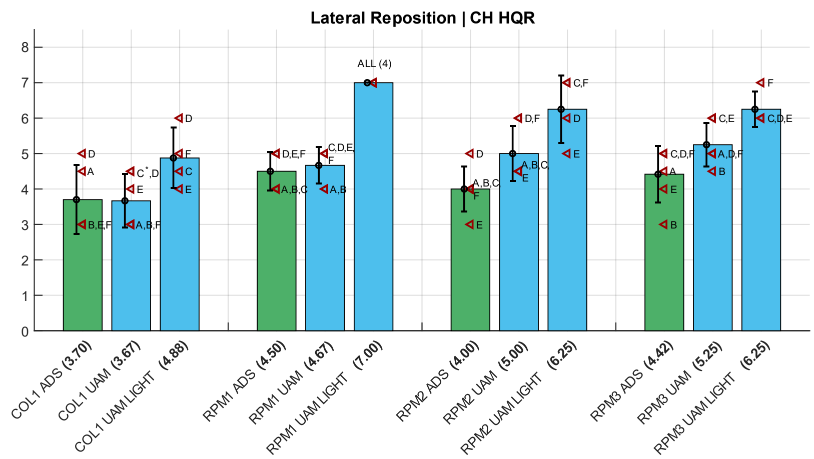

Fig. A3. Cooper-Harper HQRs: Lateral Reposition.

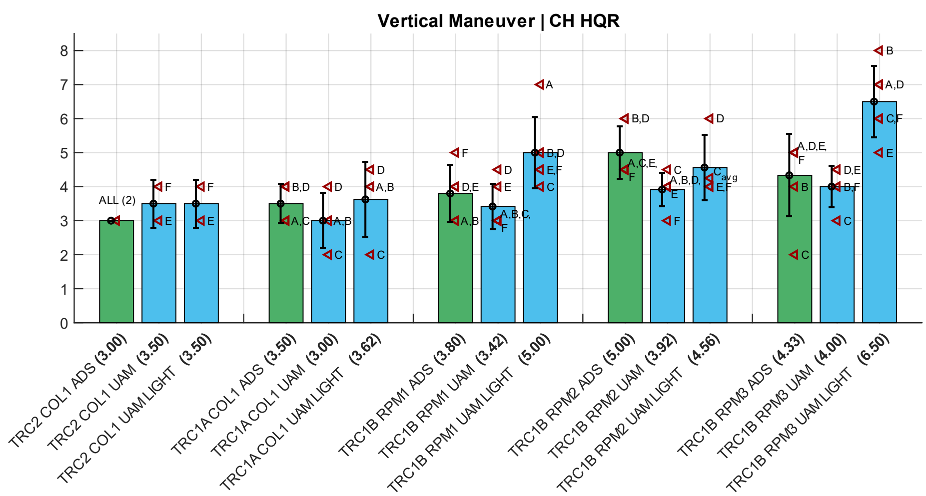

Fig. A4. Cooper-Harper HQRs: Vertical Maneuver.

Aggressiveness Ratings

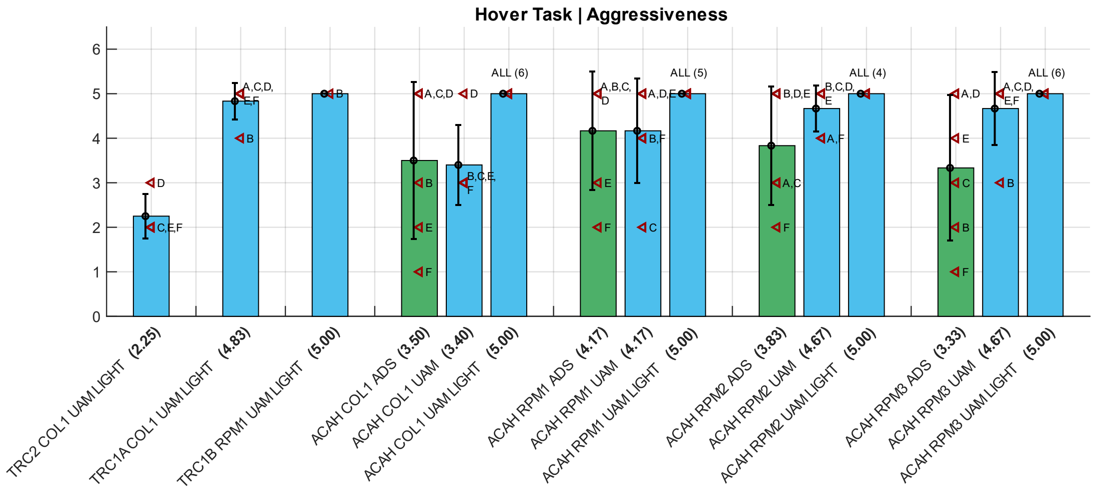

Fig. A5. Aggressiveness Ratings: Hover MTE.

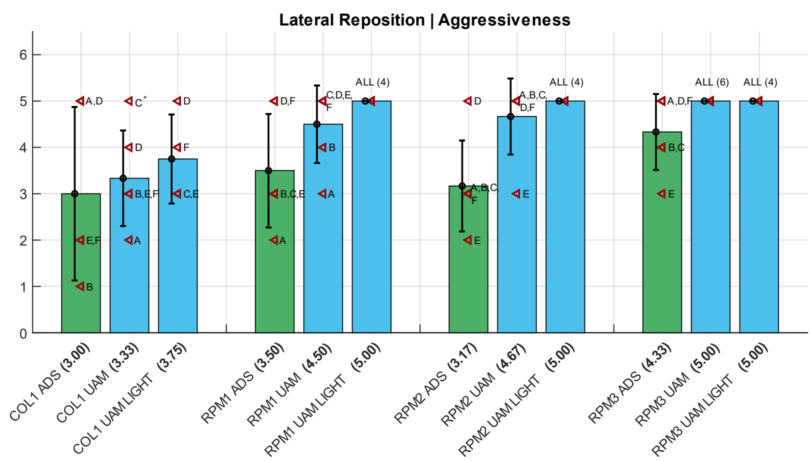

Fig. A6. Aggressiveness Ratings: Lateral Reposition.

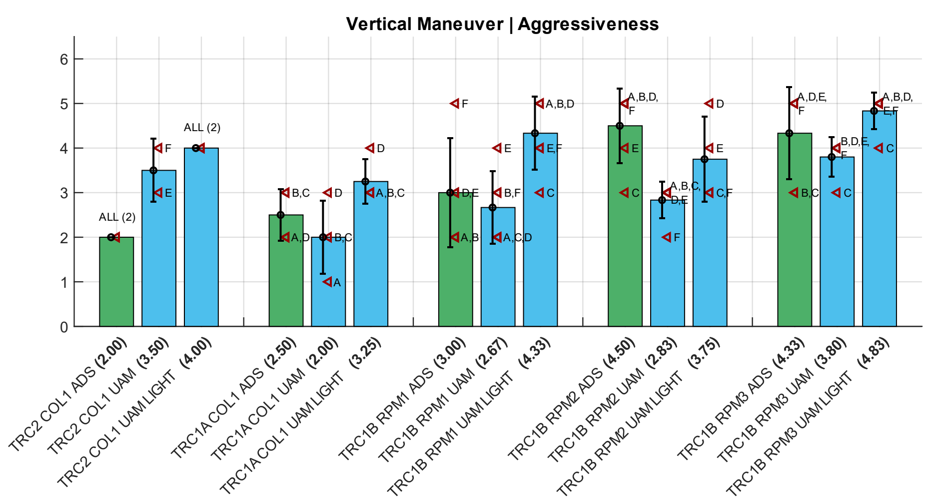

Fig. A7. Aggressiveness Ratings: Vertical Maneuver.

Precision Ratings

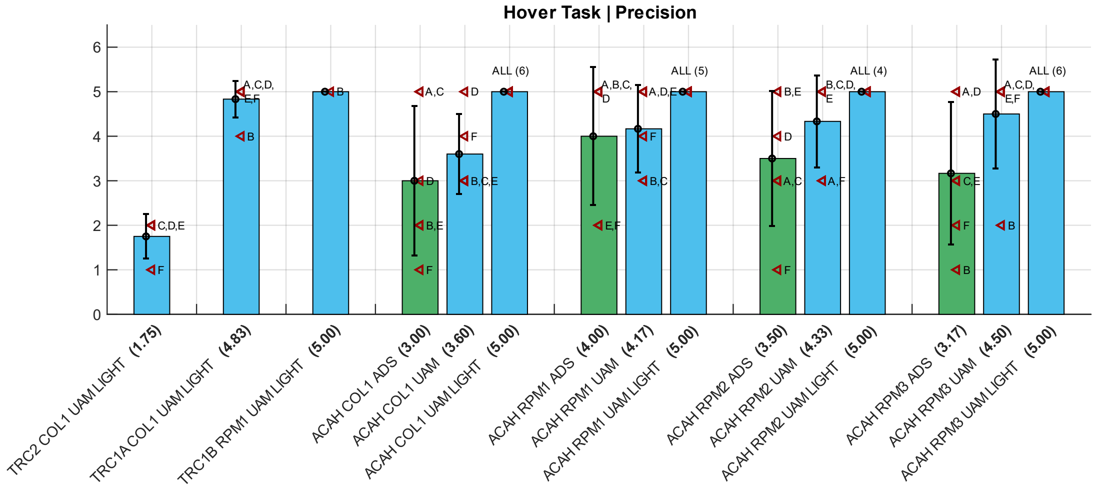

Fig. A8. Precision Ratings: Hover MTE.

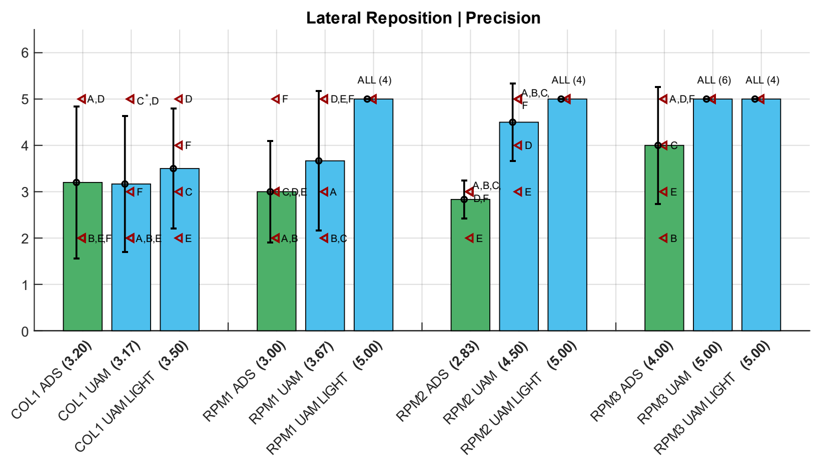

Fig. A9. Precision Ratings: Lateral Reposition.

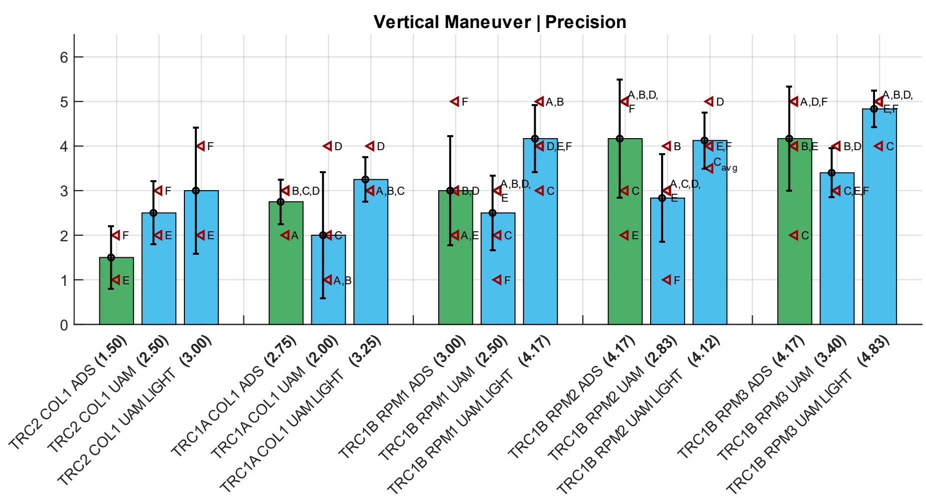

Fig. A10. Precision Ratings: Vertical Maneuver.

Predictability Ratings

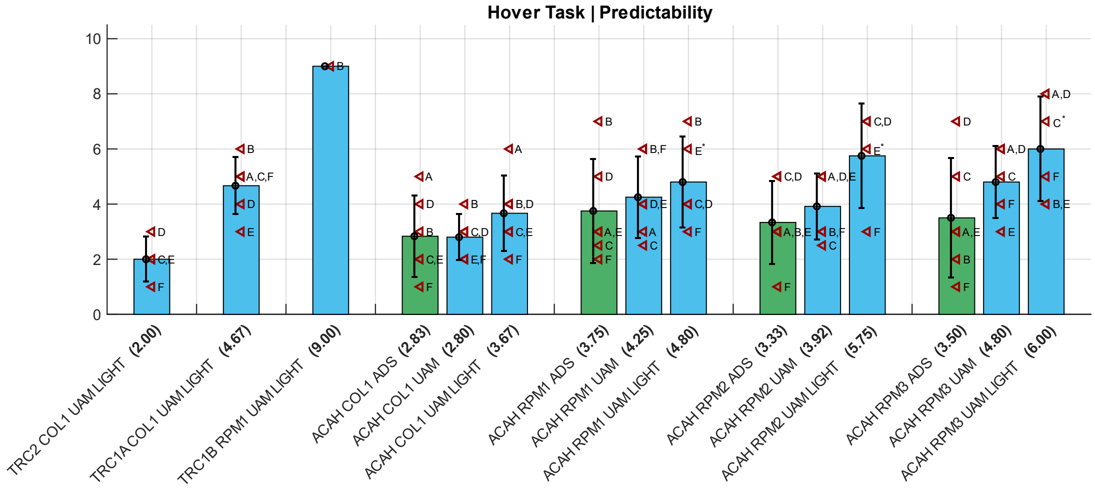

Fig. A11. Predictability Ratings: Hover MTE.

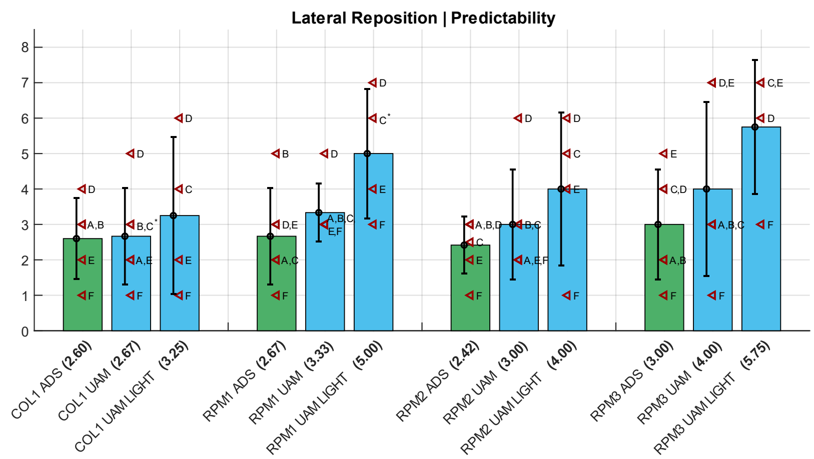

Fig. A12. Predictability Ratings: Lateral Reposition.

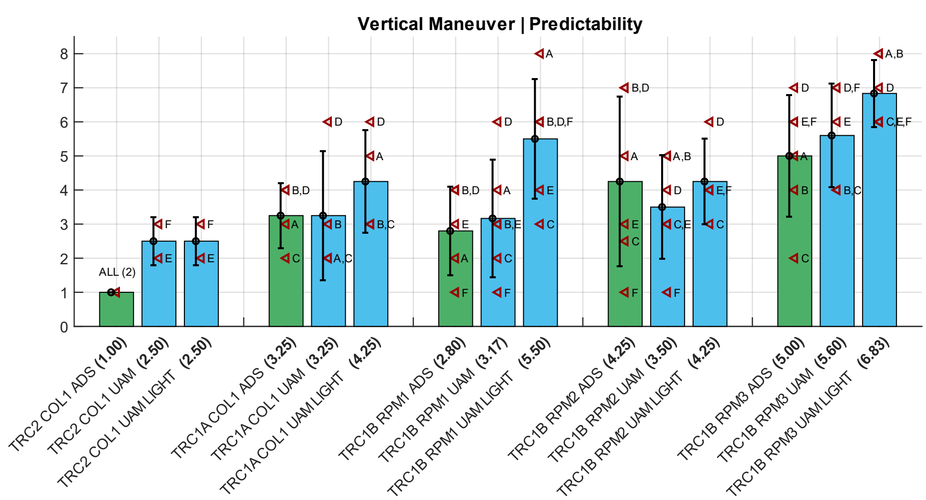

Fig. A13. Predictability Ratings: Vertical Maneuver.

Ride Quality Ratings

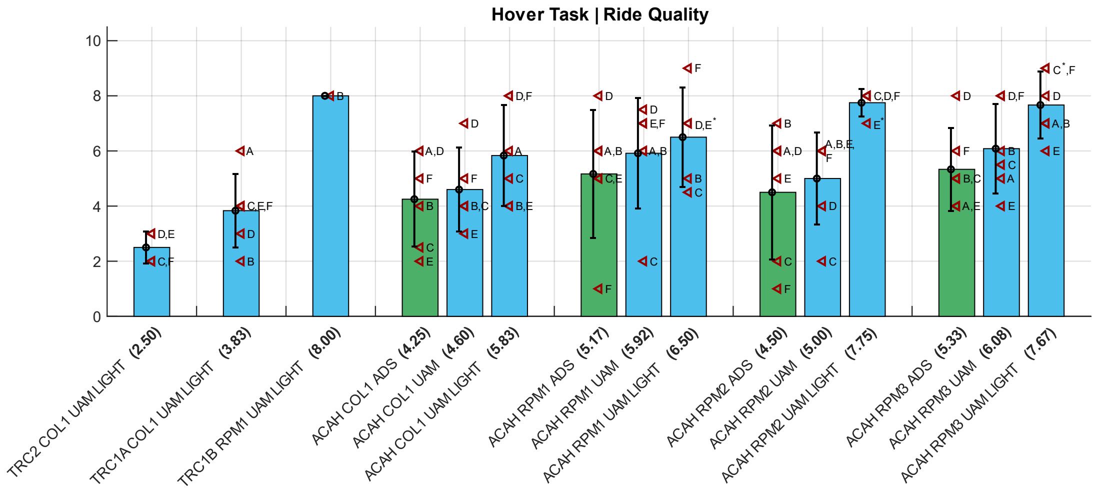

Fig. A14. Ride Quality Ratings: Hover MTE.

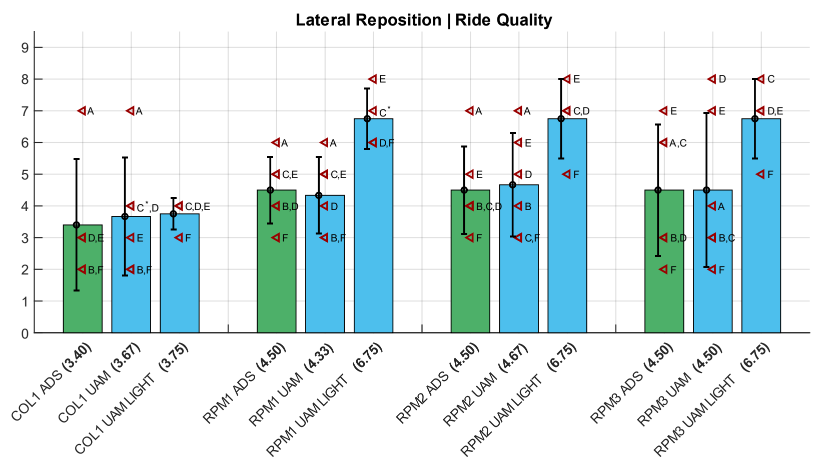

Fig. A15. Ride Quality Ratings: Lateral Reposition.

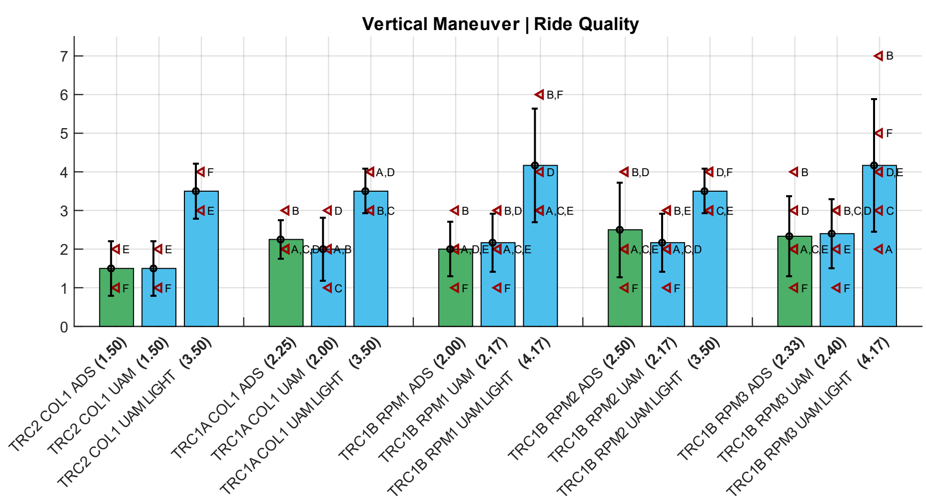

Fig. A16. Ride Quality Ratings: Vertical Maneuver.

Pilot Induced Oscillations (PIO) Ratings

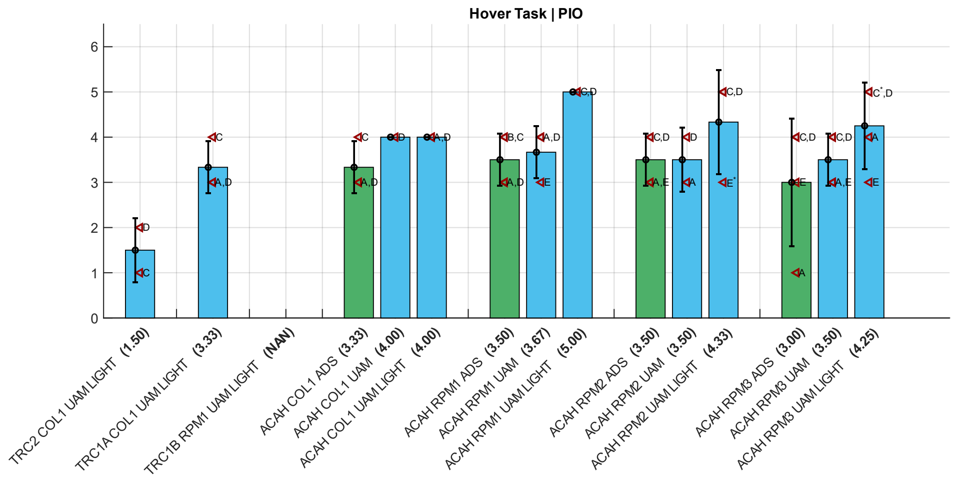

Fig. A17. PIO Ratings: Hover MTE.

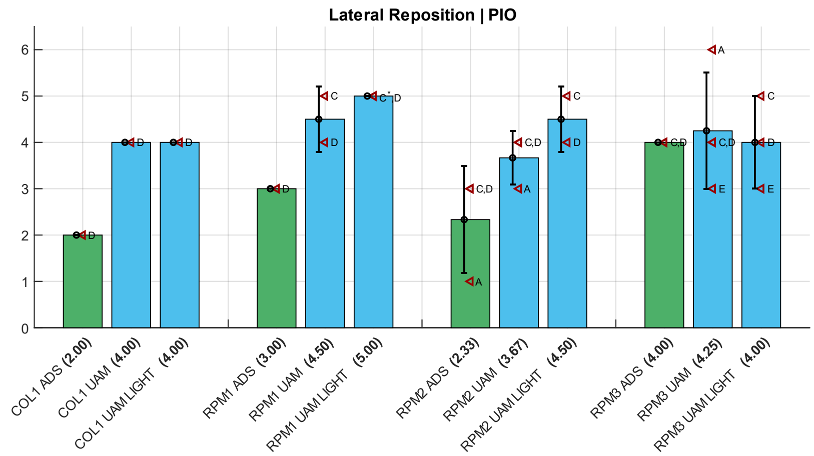

Fig. A18. PIO Ratings: Lateral Reposition.

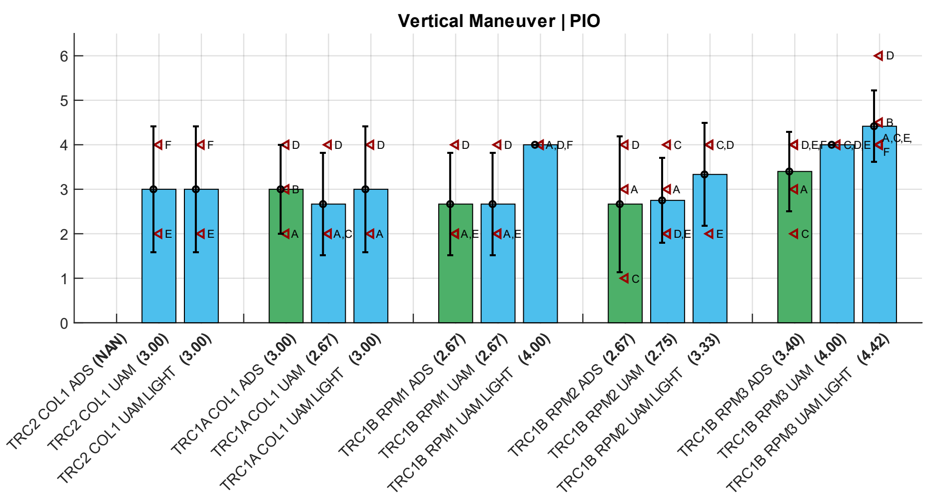

Fig. A19. PIO Ratings: Vertical Maneuver.

APPENDIX B

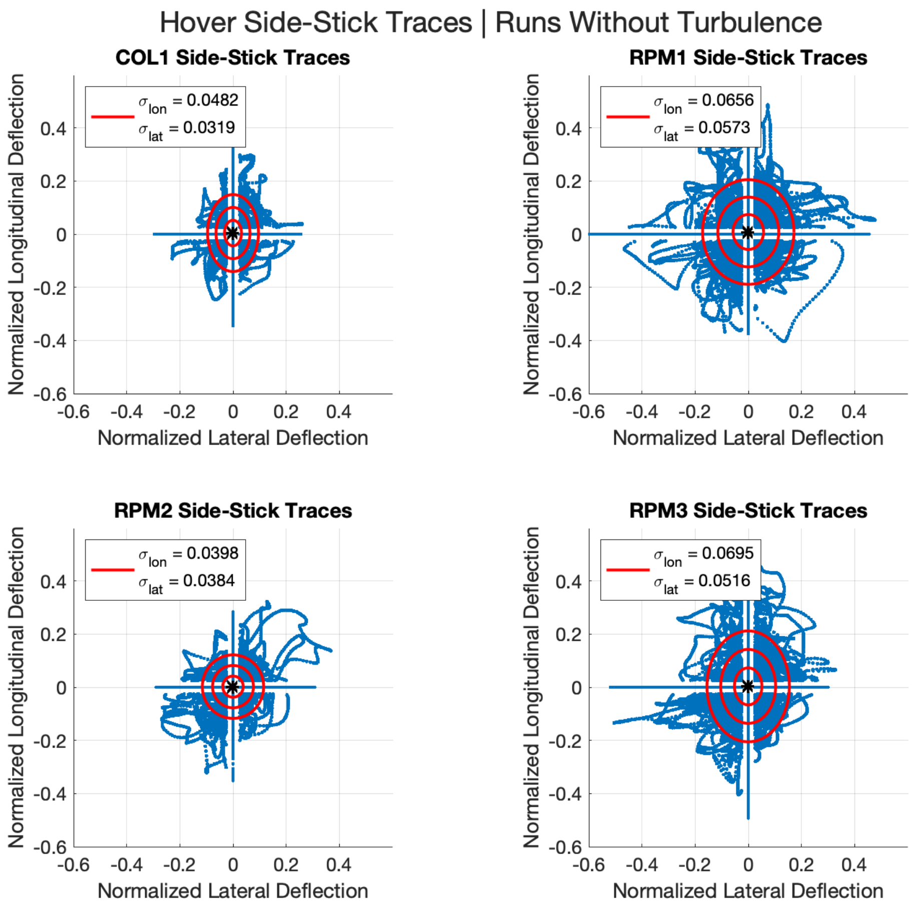

Fig. B1. Hover MTE side-stick traces in evaluation runs without turbulence.

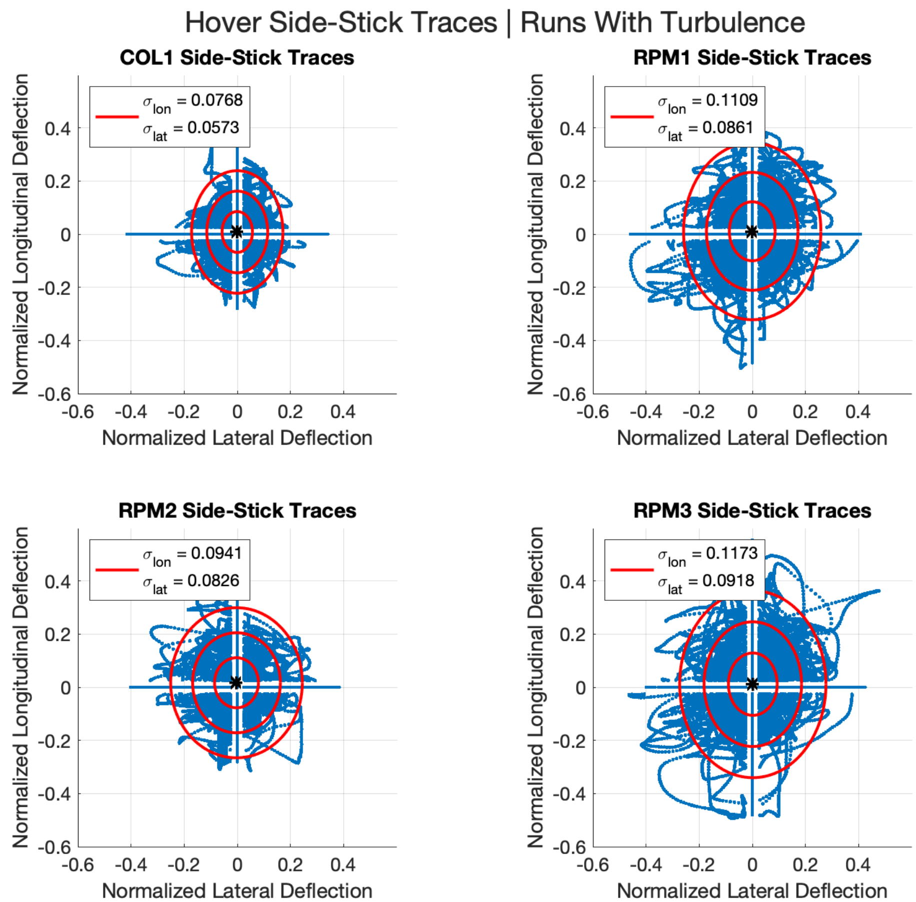

Fig. B2. Hover MTE side-stick traces in evaluation runs with turbulence.

APPENDIX C

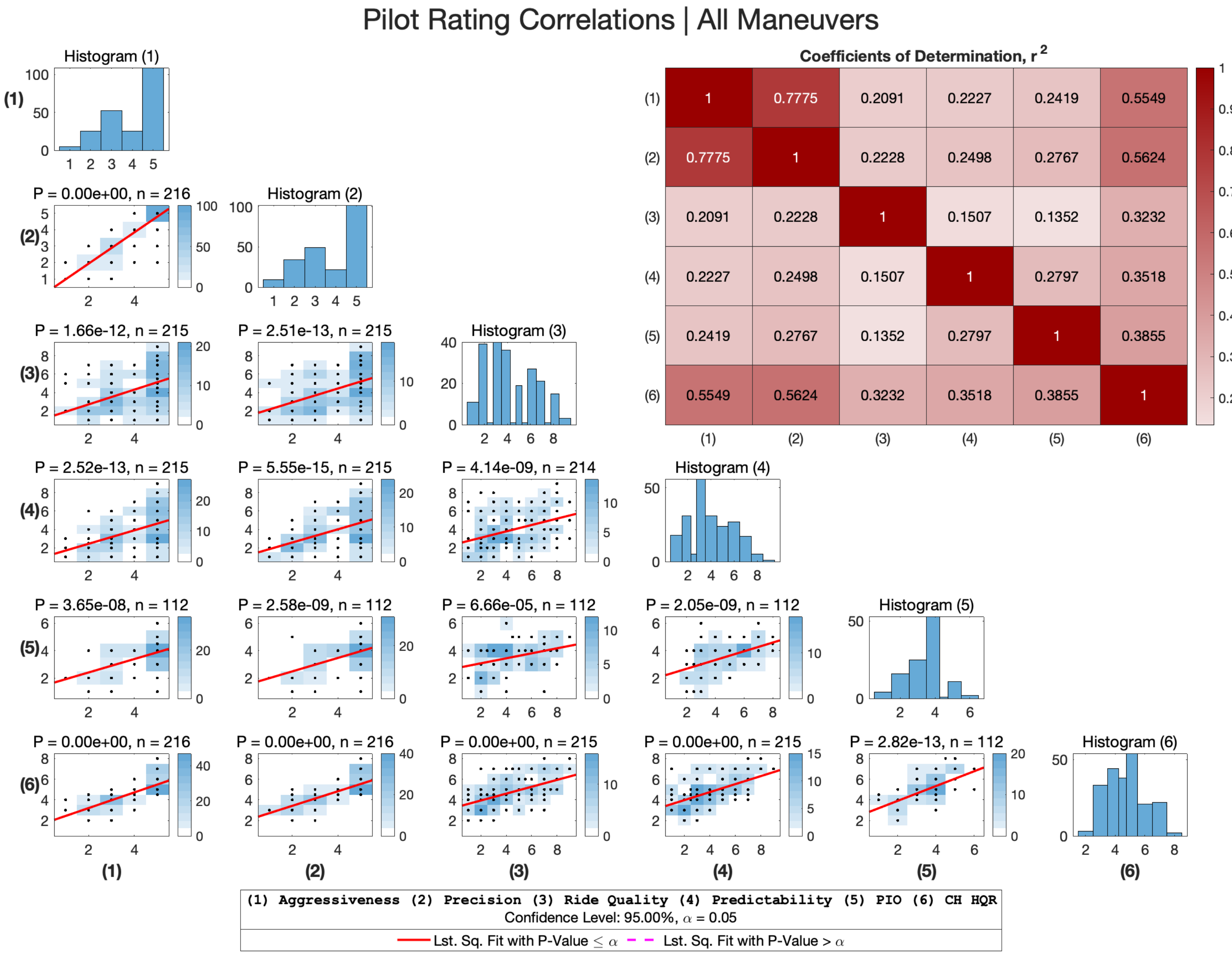

Fig. C1. Pilot rating correlations for all evaluation runs with Precision and Aggressiveness ratings of five removed.

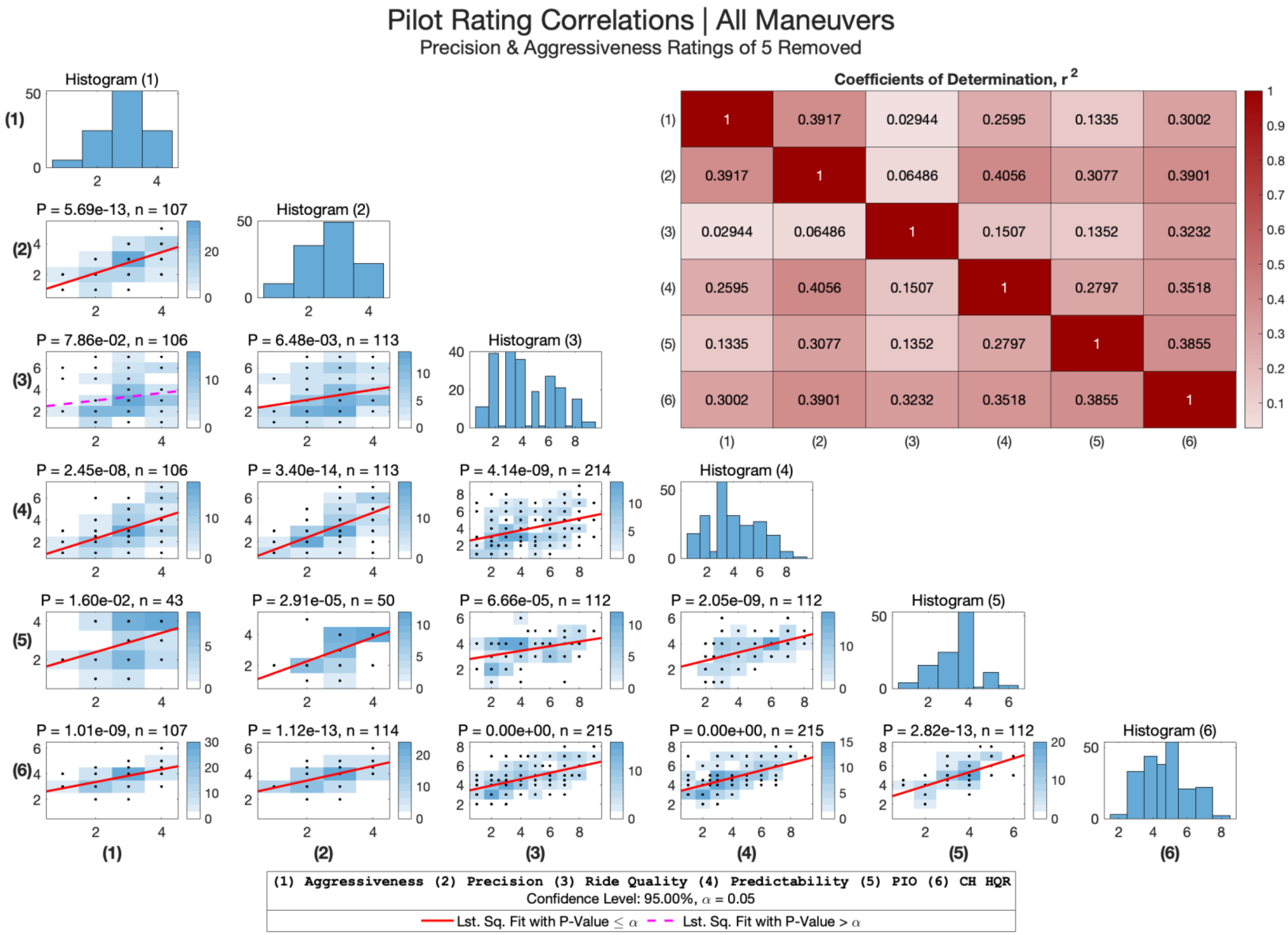

Fig. C2. Pilot rating correlations for all evaluation runs.

APPENDIX D

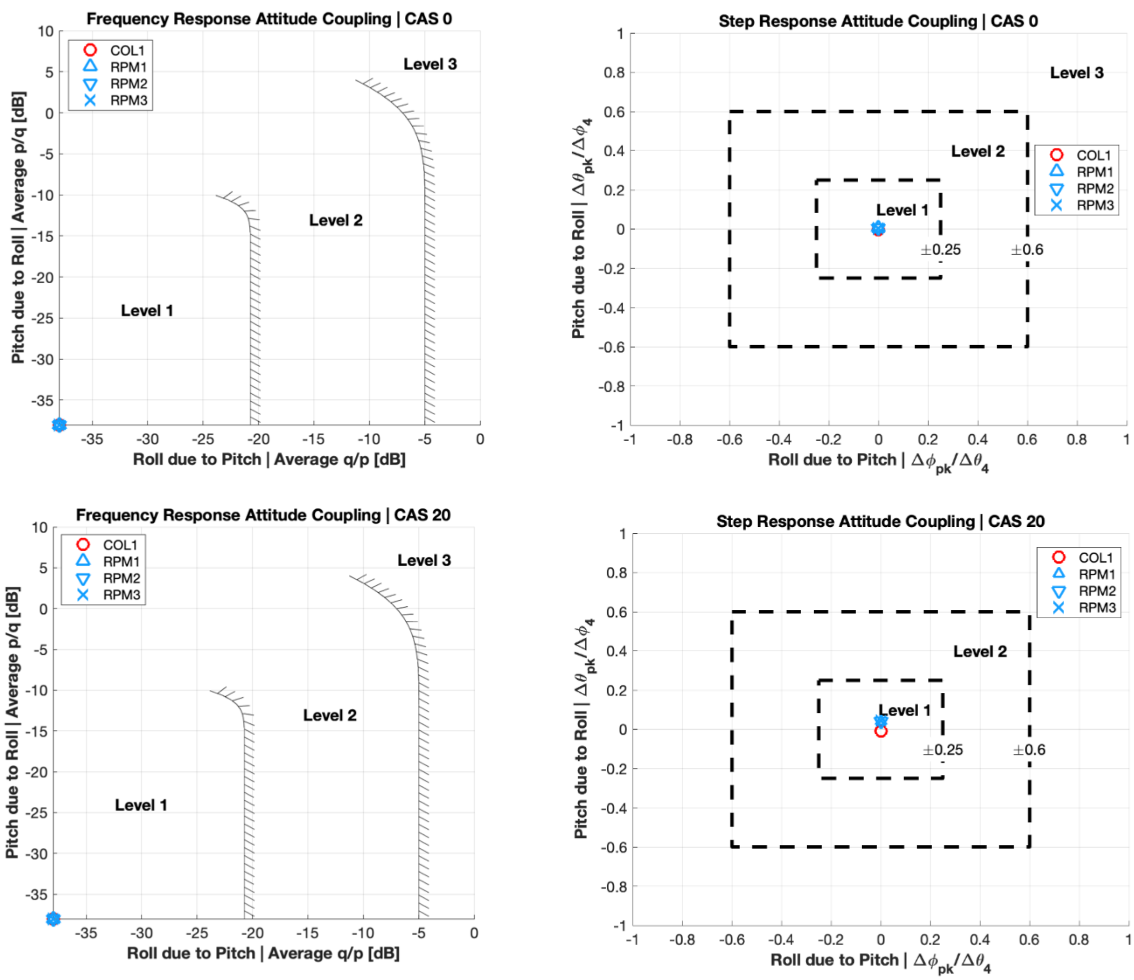

Fig. D1. ADS-33 metrics for pitch-due-to-roll and roll-due-to-pitch coupling at 0 and 20 knots. Note that all the vehicles in the left plots fell deep inside Level 1 and exceeded the limits of the plotting window. As such, they were repositioned to fit within the bounds of the chart.

APPENDIX E

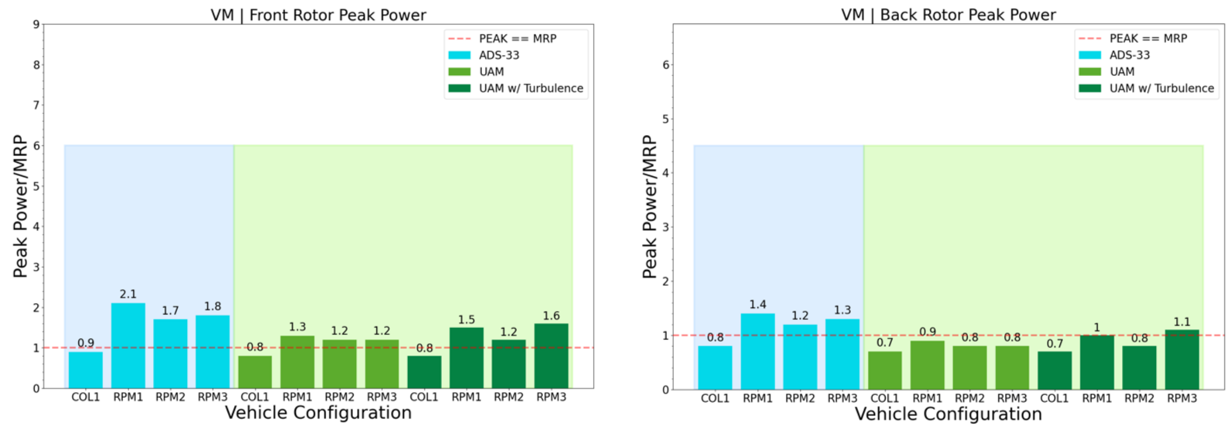

Fig. E1. Vertical Maneuver Peak Power to MRP Ratio for Front (left) and Rear (right) Rotor Pairs.

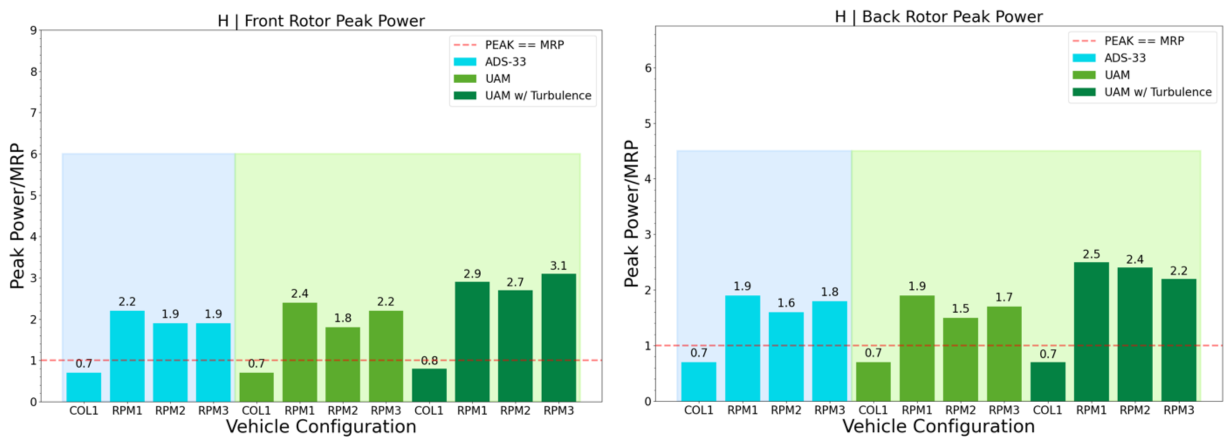

Fig. E2. Hover Peak Power to MRP Ratio for Front (left) and Rear (right) Rotor Pairs.

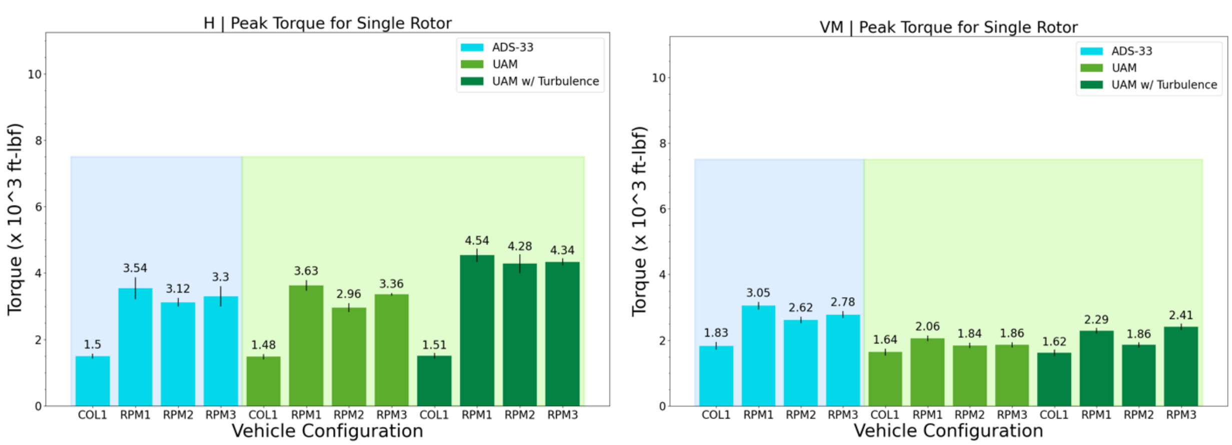

Fig. E3. Peak Single Rotor Torque for Hover (left) and Vertical Maneuver (right).

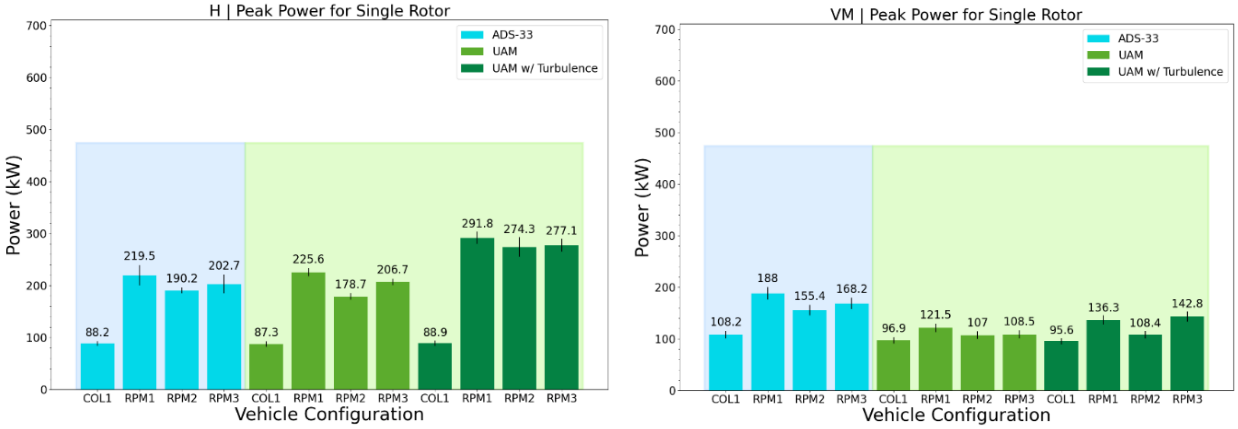

Fig. E4. Peak Single Rotor Power for Hover (left) and Vertical Maneuver (right).