Toward a UAS Handling Qualities Specification: Development of UAS-Specific MTEs

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ABSTRACT

Unmanned Aerial Systems (UAS) are becoming more prominent in the airspace and offer solutions to the limitations of manned rotorcraft. The ability to perform autonomous and/or remotely piloted tasks make them popular for both private and public use. As UAS become commonplace, the need to define handling qualities requirements is a critical task. This paper builds upon previous work towards a VTOL-UAS handling qualities framework to propose two UAS-specific maneuvers along with mission-appropriate performance specifications. Flight test results on the University of Portland hexacopter (Group 1 UAS) were collected to validate performance specifications for both the UAS-specific maneuvers and Froude-scaled ADS-33E-PRF mission task elements. A new performance metric based on Froude dynamic scaling of the ADS-33E-PRF attitude bandwidth metric was also developed. This Froude-scaled Level 1 attitude bandwidth criteria was then evaluated in flight test on the UP Hexacopter as a predictive criterion for Level 1 MTE performance. The Synergy 626, a single main rotor helicopter Group 1 UAS, was used to further validate the MTE performance specifications and the scaled attitude bandwidth results, showing this work is applicable beyond multirotor configurations. The key outcomes of the work are the proposed UAS-specific maneuvers, the validation of performance specifications, and validation of the Froude-scaled ADS-33E-PRF Level 1 attitude bandwidth metric as a predictive metric.

NOMENCLATURE

D_{hub}	Hub-to-Hub distance
D_{UAS}	Hub-to-hub distance of UAS
$D_{fullscale}$	Hub-to-Hub distance of full-scale rotorcraft
D_{rotor}	Rotor diameter
L_{scale}	Course length scale factor
L_{path}	Course length of path
N	Characteristic length for Froude scaling
P_{error}	Course position error
p	Roll rate
q	Pitch rate
R_{ψ}	Rotation Matrix
r	Yaw rate
T_{UAS}	Time constant metric of unmanned aerial system
$T_{fullscale}$	Time constant metric of full-scale rotorcraft
t_{scale}	Course time scale factor
w_P	Position error weighting parameter
w_V	Velocity error weighting parameter
V_{scale}	Course velocity scale factor
V_{OA}	Object avoidance velocity
V_{decel}	Emergency stop velocity in which deceleration is initiated
V_{error}	Course velocity error
$V_{max,cmd}$	Maximum commanded velocity
α	Aggressiveness factor
ε	Non-dimensional performance parameter
ζ	Damping ratio

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ω_{BW}	Attitude bandwidth frequency
$\omega_{DRB_{\phi,\theta}}$	Pitch and roll disturbance rejection bandwidth frequency
ω_{UAS}	Frequency for Unmanned Aerial System
ω_c	Broken-loop crossover frequency
$\omega_{fullscale}$	Frequency for full-scale rotorcraft

ACROYNMS

DRB	Disturbance Rejection Bandwidth
HQ	Handling Qualities
MTE	Mission Task Element
PID	Proportional, Integral, Derivative feedback
UAS	Unmanned Aerial Systems
UP	University of Portland
VTOL	Vertical Take-Off and Landing

INTRODUCTION

Unmanned aerial systems (UAS) are increasingly common aircraft that perform autonomous tasks. UAS capable of vertical takeoff and landing offer the ability to perform aerial unmanned missions in various areas such as delivery, surveillance, defense, and public safety. These aircraft are growing more prominent in recreation, commercial and military application, and the need to define handling qualities requirements for VTOL-UAS to meet mission demands is essential for these operators.

Flying and handling qualities criteria are well defined for manned vertical lift aircraft. Prior to flight, predictive handling qualities criteria such as damping ratio, bandwidth, and cross-coupling requirements defined in ADS-33E-PRF [1] as well as proposed requirements for ADS-33F-PRF [2] can be implemented in the control system design. Test pilots evaluate aircraft using the Cooper-Harper Scale to give handling qualities ratings for Mission Task Elements (MTEs) defined in ADS-33E-PRF [1]. A similarly comprehensive process is needed for unmanned aircraft to define design guidelines and give the ability to evaluate UAS control system performance and handling qualities. Although these systems are unmanned and often flown autonomously, their ability to perform missions to operator satisfaction is still referred to as "handling qualities" by the flight control community and herein. As such, building from ADS-33E-PRF the mission task elements should be selected to reflect critical aspects of the VTOL-UAS mission and the predictive handling qualities criteria should result in corresponding Level 1 performance for these MTEs [3].

Handling qualities standards are already established in ADS-33E-PRF for manned full-scale rotorcraft [1] and as such, scaling these standards and applying to UAS makes development of these requirements much more efficient. Scaling rotor dynamics based on the Froude number is already a common similarity requirement for rotorcraft models [4, 5]. Froude dynamic scaling of ADS-33E-PRF predictive metrics is an efficient technique for determining control system design requirements. Disturbance rejection bandwidth is a useful design specification to improve disturbance response that has been proposed for ADS-33F-PRF [2, 6]. In prior works by the authors, the Froude-scaled disturbance rejection bandwidth (DRB) criteria have been validated to predict Level 1 handling qualities in flight [7]. In other prior efforts, Froude scaling was also validated for dynamics and control characteristics of unmanned multicopters [8, 9]. Although manned and unmanned rotorcraft share a range of similar mission demands, UAS have unique demands because they are often smaller than manned vehicles, have minimal human risk, and operate autonomously. MTEs beyond those comprised in ADS-33E-PRF are then required to fully evaluate UAS handling qualities.

This paper will expand on the efforts to build a handing qualities evaluation framework for UAS. The updated framework uses scaled, autonomous ADS-33E-PRF MTEs whenever possible for efficiency with added UAS-specific tasks to fill in the gaps where the missions do not overlap. The goal of the paper is to further develop and validate the proposed handling qualities framework in Ref. [7]. The new work herein proposes scalable UAS specific maneuvers and performance standards, which would be used in addition to the scaled ADS-33E-PRF MTE maneuvers validated in Ref. [7]. Scalability to large and small VTOL-UAS plays a crucial part in the framework and the performance specifications and the MTEs have been developed with this in mind. In this paper, the handling qualities framework for Group 1 UAS is validated with flight test results for two small UAS: a multicopter (UP hexacopter, 3.75 lb) and a single main rotor helicopter (Synergy 626, 10 lb).

As a brief outline of this paper, first, the updated handling qualities evaluation framework will be provided. The scaling methodology and new UAS MTEs are presented in detail. Then, flight evaluation data for the UP hexacopter will be provided to support the new mission-based MTE performance specifications. Next, new validation results for Froude-scaled attitude bandwidth are provided for the UP hexacopter. Finally, the cross-validation of the mission-based MTE specifications and attitude bandwidth predictive criteria is performed on the Synergy 626 Helicopter.

UPDATED HANDLING QUALITIES EVALUATION FRAMEWORK

The handling qualities framework proposed herein builds off the framework presented in Ref. [7]. A similar format is used, but with modification to the performance requirements of the MTEs. The updated handling qualities framework is given in the following sections for both the predicted and assigned levels of handling qualities.

Predicted Handling Qualities Criteria

Predicted handling qualities criteria are available in ADS-33E-PRF. For Group 4 and Group 5 UAS, which are similar in size to full-scale manned rotorcraft, the ADS-33E-PRF predictive criteria can be used directly for the autonomous control system design guidance. For UAS that are smaller than full scale, the criteria can be dynamically Froude-scaled. The scale factor, N is based on the characteristic length. For a multicopter, it is the hub-to-hub distance (D_{hub}), and for a single main rotor helicopter it is the rotor diameter D_{rotor}. The Froude scaling N is relative to a representative full-scale aircraft, where N indicates $1/N^{th}$ scale:

$$N = \frac{D_{fullscale}}{D_{UAS}} \qquad (1)$$

For metrics involving frequency, Froude scaling indicates that dynamic similarity is achieved by:

$$\omega_{UAS} = \omega_{fullscale}\sqrt{N} \qquad (2)$$

This can be applied to metrics like bandwidth, or DRB. Additionally, it can be applied to frequency ranges of interest, such as for example, the frequency range used for application of damping criteria. For any time-constant based criteria:

$$T_{UAS} = \frac{T_{fullscale}}{\sqrt{N}} \qquad (3)$$

Stability margin requirements and non-dimensional criteria like damping ratio can be applied directly without scaling.

Evaluation of Assigned Handling Qualities

The following framework for determining assigned handling qualities for UAS is proposed. A five-step process, that uses a parallel concept to the process of assigning handling qualities for manned aircraft, is given.

1. Select the intended mission of the UAS

Mission task elements in ADS-33E-PRF are assigned to the applicable categories: scout/attack, utility, and cargo. Similar to this format, the UAS framework will consist of three categories: attack, surveillance/scout, and cargo/delivery.

2. Select the appropriate MTEs for the mission

For each category, a list of MTEs consisting of appropriate scaled ADS-33E-PRF maneuvers and UAS specific maneuvers are assigned. Each MTE in the applicable category can be customized for the appropriate level of aggressiveness as demanded by the mission. The desired MTEs would be selected by the procuring agency, but a list of potential appropriate MTEs for the example missions of surveillance/scout, cargo/delivery and attack are given by Table 1. In Appendix I, a detailed description of the MTEs, written in a format similar to ADS-33E-PRF, are given for the maneuvers that have been flight validated.

Table 1. Mission categories and example MTE selections.

MTE	SURVEILLANCE/SCOUT	CARGO/DELIVERY	ATTACK
PIROUETTE*	X		X
LATERAL REPOSITION*	X	X	X
HOVER	X	X	X
DEPART ABORT*	X		X
OBJECT AVOIDANCE*	X	X	X
EMERGENCY STOP*	X	X	X
LOAD PLACEMENT		X	

MTEs that have been flight validated

3. Determine the autonomous trajectories of each MTE via Froude Scaling

After the mission category is selected in Step 2, the MTEs (either ADS-33E-PRF or UAS mission specific) are converted to autonomous trajectories. The MTEs should be scaled with the Froude number to be appropriate for the dynamics of the UAS at hand. The MTE descriptions presented in Appendix I provide the course geometry as a function of N, for ease of use. As an example of how the scaling works, ADS-33E-PRF courses are scaled in length according to the rule:

$$L_{\text{scale}} = \frac{1}{N} \qquad 4$$

The velocity and time scale of the maneuver are also scaled accordingly:

$$V_{\text{scale}} = \alpha \frac{1}{\sqrt{N}} \qquad 5$$

$$t_{\text{scale}} = \alpha^{-1} \frac{1}{\sqrt{N}} \qquad 6$$

The aggressiveness factor α is nominally equal to one, which provides a scaled acceleration that is equivalent to the original maneuver. Aggressiveness factor $\alpha > 1$ has increased scaled aggression, and likewise, $\alpha < 1$ has less scaled aggression. In the work herein, increased aggressiveness was not required, and all maneuvers are found to be reasonably aggressive at $\alpha = 1$. However, the option to use an alternate level of aggression is available to provide flexibility to tailor the MTE to the mission requirements.

4. Autonomously fly the MTEs within the time limit at the required level of aggressiveness and evaluate the performance

Once the appropriate trajectory commands are determined in Step 3, they are programmed into the UAS mission planning software or outer-loop control system command. Then, the aircraft will autonomously complete the intended maneuver at the mission-appropriate aggression level. Position tracking, velocity and time to complete from the maneuver are evaluated against the performance specifications for the MTE. The position tracking requirements are mission-based, not Froude scaled (an explanation is given in the following section). Appendix I provides the flight-validated desired and adequate precision performance metrics for the object avoidance, emergency stop maneuver, and scaled ADS-33E-PRF lateral reposition, depart-abort and pirouette MTEs.

5. Assign a Handling Qualities Level and/or Handling Qualities Rating

After evaluation of the autonomous performance against the MTE, a Handling Qualities Level rating can then be assigned based on the performance of the UAS. Level 1 handling qualities is assigned for the maneuver if desired performance is met, Level 2 is assigned if adequate performance is met, and Level 3 if adequate performance is not achieved. A modified handling qualities rating scale (for UAS) can be used to refine this into an actual handling qualities rating (HQR) if further refinement is needed. A proposed operating handling qualities rating scale is given in Ref. [7].

Update of Performance Specification Parameters

In the previously proposed framework, published in Ref [7], a non-dimensional parameter denoted by the Greek letter epsilon, ε, was used to define the performance requirements. This parameter was given as

$$\varepsilon = w_V \frac{\text{rms}(V_{error})}{V_{max,cmd}} + w_P \frac{\text{rms}(P_{error})}{L_{path}} \qquad 7$$

Where w_V and w_P are velocity and position error weighting terms, respectively. V_{error} and P_{error} are the velocity and position errors, respectively. $V_{max,cmd}$ is the maximum commanded velocity and L_{path} is the path length of the trajectory.

A lower value of ε indicates better performance, with a value of zero indicating perfect tracking. The ε term was found to be easily manipulated by increasing the commanded velocity and the path length, which could artificially reduce its value. Additionally, the root-mean square values of error do not capture maximum values of excursion from the trajectory. The maximum excursion (tracking error) during a maneuver will set the safety limits and determine the ability to autonomously maneuver in narrow passages or cluttered environments. As such, the framework has been re-worked for the scaled ADS-33E-PRF MTEs to focus on maximum excursion. For each MTE, the maximum position bounds of the maneuver are given for the appropriate UAS group, as well as ease of customization to capture alternate mission demands. The new framework evaluates the position error and time-to-complete directly as the performance requirements instead of the normalized parameters, which is aligned with the methodology of ADS-33.

The change in the performance specification addresses feedback from the community that the performance requirements should be mission-based and that the normalized, rms-based epsilon error term was not consistent with ADS-33. It should be noted that although the UAS ADS-33E-PRF courses are Froude scaled, the new performance specifications are not Froude scaled but selected based on mission appropriate bounds for the UAS group. For example, in work done in Ref. [10] it was shown the Froude-scaled ADS-33E-PRF MTE performance specifications for the hover MTE resulted in unreasonable and unachievable tracking requirements. For example, a Level 1 Hover MTE would be required to maintain hover within ± 1.1 inches for a vehicle with a 20-inch hub-to-hub diameter. These stringent performance specifications are not in line with UAS Group 1 mission requirements. As a result of these concerns, new mission-based MTE performance parameters are flight validated herein.

UAS SPECIFIC MANUEVERS

The current state of ADS-33E-PRF includes MTEs appropriate to test manned rotorcraft mission demands. Although these encompass some of the UAS mission, the need for maneuvers specific to the UAS mission remain. Two UAS specific maneuvers were developed and validated to meet this need and will be described herein.

The first proposed MTE is the object avoidance maneuver. This MTE was developed for surveillance, attack, and delivery UAS missions. The object avoidance maneuver includes an ascent/descent while maintaining forward speed to simulate flight above and below objects in a stylized, aggressive maneuver that would capture a critical component of the UAS mission. This is an appropriate maneuver for UAS in urban settings where the aircraft will need to fly above and below obstacles on the terrain and in the airspace. The choice to include three significant altitude changes was motivated by knowledge that as an aircraft progresses through a maneuver, small position errors tend to accumulate. Three significant altitude changes, simulating sequential flights above and below obstacles, is an appropriate measure of the ability to navigate a crowded urban environment. This maneuver is fully described in Appendix I.1 and scaled here for the UP hexacopter as an example, as shown in Figure 1 ($N = 21.7$), relative to the full-scale Chinook.

The second proposed MTE is the emergency stop maneuver. Work done by authors of Ref. [11] was used as a building block for a VTOL emergency stop maneuver. The emergency stop maneuver was developed for surveillance, attack, and delivery UAS mission demands. The goal of the emergency stop is to come to an aggressive stop from a representative autonomous mission speed, while minimizing forward travel and maintaining altitude, to simulate the desire to stop before an unexpected obstacle ahead. A key feature of the maneuver is an allowable turn at the end of the trajectory to potentially give the aircraft more time to stop without sacrificing distance forward. The aircraft can turn the nose or keep it forward after deceleration is initiated, as the method of deceleration is not specified and only the resulting maximum forward travel and altitude tracking are performance parameters. For the UP hexacopter, the maneuver was achievable when keeping the nose forward and veering laterally since the aircraft is symmetric. For a full-scale rotorcraft, turning can reduce forward travel during the deceleration and uses the side area of the aircraft to increase drag.

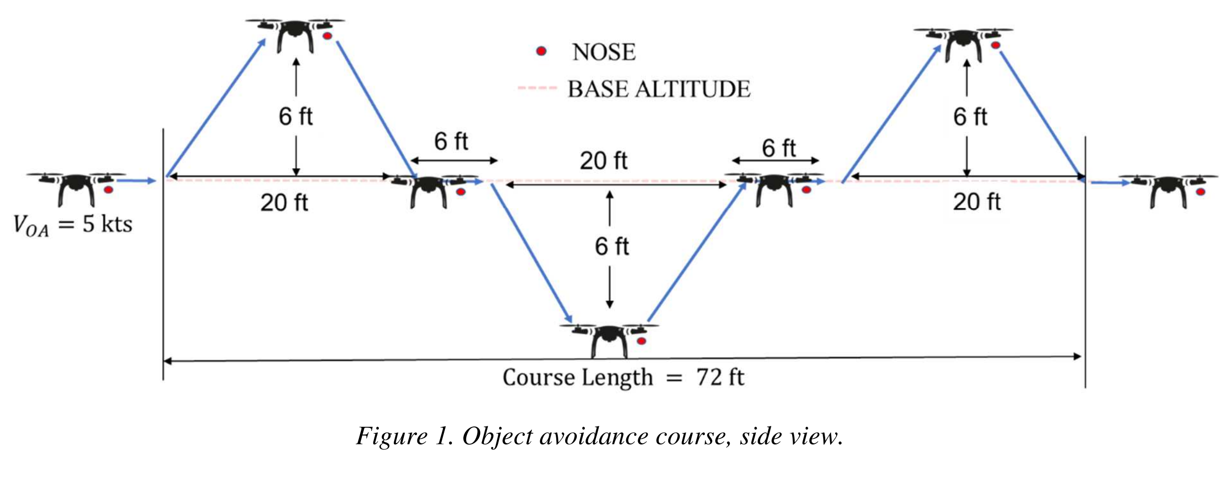

Figure 1. Object avoidance course, side view.

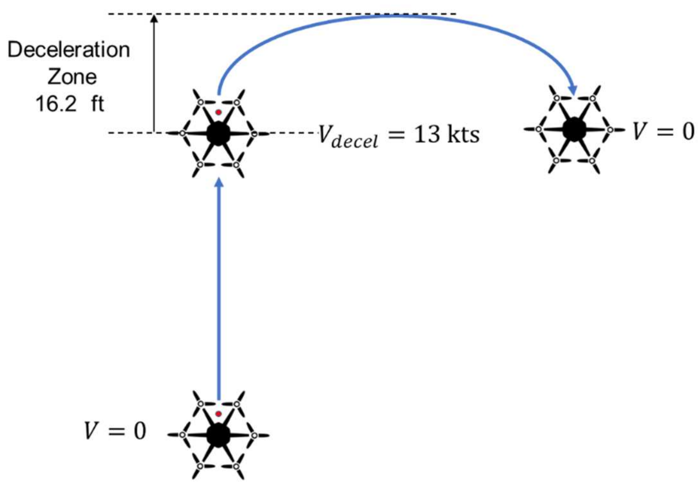

Figure 2. Emergency stop course for the UP Hexacopter, top view.

The scalable emergency stop MTE is fully described in Appendix I.2, and is sized for the UP hexacopter as an example in Figure 2. The maximum forward distance allowed for the UP hexacopter is 16.2 ft and the minimum deceleration velocity is 13 kts, and the aircraft must maintain altitude within 1.35 ft. For reference, the Froude-scaled ADS-33E maneuver depart/abort scaled to the UP hexacopter has a peak velocity of 8.8 kts and forward travel after deceleration of approximately 18.5 ft. In comparison, the emergency stop maneuver is a more aggressive maneuver. This was intentionally done to simulate an emergency procedure where the aircraft needs to stop from a higher speed. Additionally, the turn at the end of the maneuver is a key difference from depart/abort.

HEXACOPTER TEST VEHICLE AND SIMULATION MODELS

The University of Portland (UP) hexacopter, as seen in Figure 3, was used as the primary test bed for this research. The hexacopter was selected for this work due to its mechanical simplicity and capability of vertical lift [12]. Details of the size and specifications for the UP hexacopter are shown in Table 2. A Pixhawk 2.1 (Hex Cube Black) autopilot with open source ArduPilot software [13] is used to control the aircraft. The Pixhawk Cube has three embedded inertial measurement units, dual compasses, and two barometers. An ArduSimple RTK GPS was also installed.

Two flight-accurate state-space models of the vehicle for hover and forward flight at 10 kts were identified from flight data [9, 14] using the CIFER® system identification method [15] and then combined with trim data into a full envelope flight simulation model of the hexacopter via the STITCH software [16]. This allowed for realistic, flight-accurate simulation of the proposed UAS MTEs prior to flight validation.

Figure 3. University of Portland hexacopter.

Table 2. Hexacopter size and specifications.

AIRCRAFT	
WEIGHT, WITH BATTERY	3.75 lb
DIAMETER (HUB-TO-HUB)	1.8 ft
INERTIA (SWING TEST):	
I_{xx}	0.02 slug-ft^2
I_{yy}	0.02 slug-ft^2
I_{zz}	0.04 slug-ft^2
BRUSHLESS MOTORS	
WEIGHT	0.11 lb/motor
KV RATING	930 RPM/V
ELECTRONIC SPEED CONTROLLERS	
CURRENT (CONTINUOUS)	30 A
WEIGHT (EACH)	32 g/ESC
BLADES	
DIAMETER	10 in
PITCH	4.7 in
WEIGHT (EACH)	0.022 lb

HEXACOPTER CONTROL SYSTEM ARCHITECTURE, SCALING, AND OPTIMIZATION

The UP Hexacopter operates the ArduPilot software on-board [13], which is used for flight control. Although there are many stock control modes available on ArduPilot, a new control mode was developed by the authors to allow for a custom control architecture. This allows for a streamlined process where the Simulink block diagram can be used in control system design analysis and then processed directly into flight code via Simulink Coder. This custom control system uses a nested architecture to follow attitude and trajectory commands, the latter of which is important for performing automated MTEs.

The inner attitude-command loop of the control system, shown in Figure 4, has a dynamic inverse applied in each of the four control axes for improved model following and speed of response. The identified state-space model described in [9, 14] provides the A and B matrices for the inverse, which are scheduled with ground speed. The inverted states, which determine the C matrix for the inverse, are p, q, r and w. Proportional-integral-derivative (PID) feedback controllers for the attitudes are wrapped around the dynamic inverse. The proportional and derivative gains were varied during optimization, as was the amount of lead added by the lead filter that is directly downstream of the PID feedback.

In the outer loop, shown in Figure 5, velocity and position proportional-integral controllers are wrapped around the attitude command to track a desired trajectory and enable automated mission task elements. The position feedback path is limited so that the position tracking does not significantly change the direct velocity command of the trajectory, but instead provides smaller inputs to correct for drift. The position commands and feedback are provided in the North-East-Down (NED) frame and then transformed into a coordinate frame aligned with the vehicle heading, via the R_ψ rotation matrix, for velocity control. The low-order feed-forward inverse provides an estimate of the attitude needed to achieve the desired velocity, improving the bandwidth of the closed-loop response.

To determine the control system gains used in the attitude and outer velocity/position controllers, a set of design specifications were selected and the control system parameters were optimized to meet them with CONDUIT® [17]. For the design specifications, Froude scaling of ADS-33E-PRF predicted handling qualities criteria were used. The scaling followed the guidance earlier from Eqs. (1-3). The CH-47 Chinook was selected as the full-scale aircraft for Froude scaling purposes, as described in Ref. [7] because it has multiple main rotors, where characteristic length was defined as the tandem rotor hub-to-hub distance. Therefore, a consistent scaling is achieved between the UP hexacopter and a relevant full-scale configuration:

$$N = \frac{D_{hubChinook}}{D_{hubHexacopter}} = \frac{39.2 \text{ ft}}{1.81 \text{ ft}} = 21.7 \qquad 8$$

This scaling was validated in Ref [7] to be an accurate predictive metric for Level 1 performance based on the disturbance rejection bandwidth in the pitch and the roll axes. Froude-scaled disturbance rejection bandwidth was selected in Ref. [7] for validation because it is a key requirement for unmanned vehicles [17]. In Ref. [7], the ADS-33E-PRF damping requirement of $\zeta \geq 0.35$ was also validated. Later in this paper, flight validation of a scaled UAS requirement based on the inner-loop attitude command bandwidth is presented. Utilizing the CONDUIT® software, the control system was optimized for the UP Hexacopter based on a range of design specifications, which are fully described in Ref. [7].

Design Margin Optimization for Disturbance Rejection Bandwidth

Using CONDUIT®, a design margin optimization was completed for the pitch/roll axes to achieve five designs, two above the Froude-scaled Level 1/2 boundary for DRB, one at the scaled Level 1 boundary for DRB and two below the scaled Level 1/2 boundary. These five designs are shown graphically in Figure 6. The Froude-scaled Level 1 boundary (0% Design Margin) was $\omega_{DRB_{\phi,\theta}} = 0.9\sqrt{N}$ rad/s, using Eq. (2). It should be noted that due to the symmetric configuration of the Hexacopter, the pitch and roll dynamics are nearly identical and therefore both axes were required to meet the more aggressive roll DRB requirement (ω_{DRB_ϕ} =0.9 rad/s for full scale). For each of the five attitude command designs, an outer-loop design was optimized to just meet the Froude-scaled Level 1 handling qualities requirements. This allows only a single parameter to be modified, the attitude disturbance rejection bandwidth, while all other parameters are optimized just to the Level 1/2 boundary.

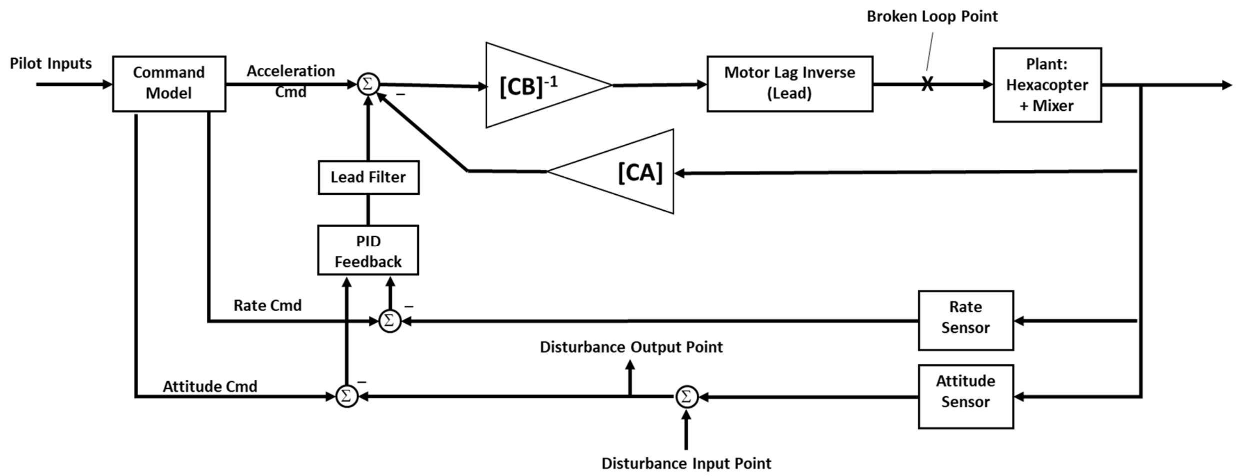

Figure 4. Inner-loop dynamic inverse with PID control for attitude command.

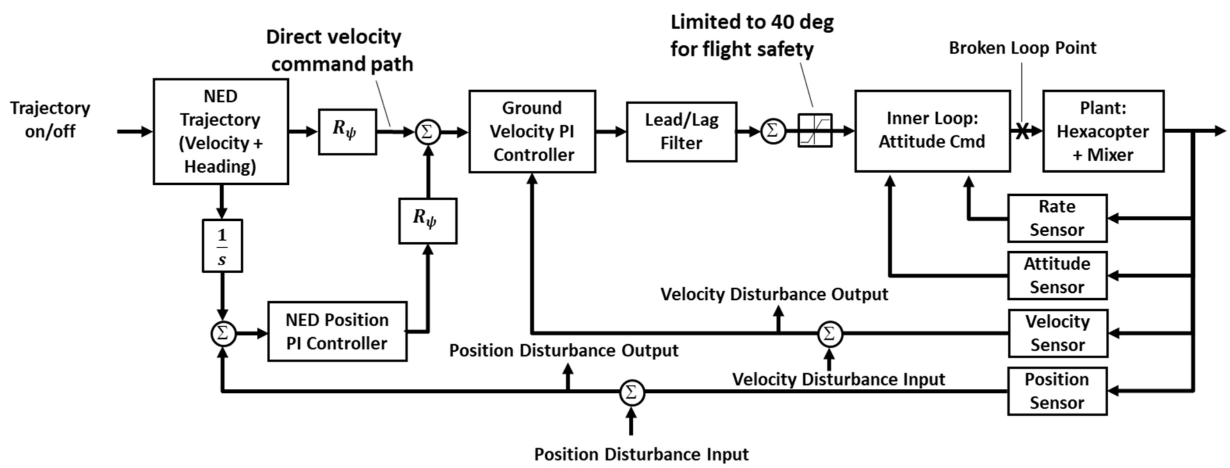

Figure 5. Outer-loop PI control for trajectory velocity and position tracking.

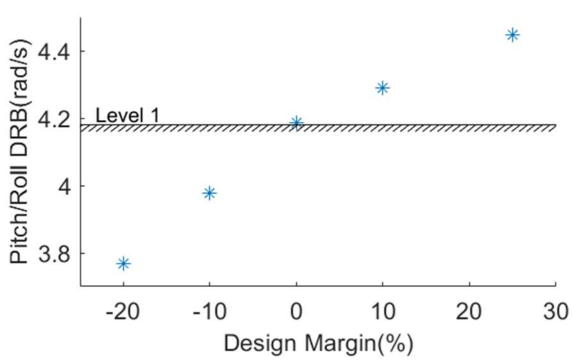

Figure 6. Flight test cases for UP hexacopter, pitch and roll DRB versus design margin.

FLIGHT VALIDATION OF MISSION TASK ELEMENTS

The five control systems from Figure 6 were used to validate the Froude-scaled DRB Level 1/2 predicted handling qualities against Froude-scaled ADS-33E-PRF mission task elements in Ref [7]. As such, these validated control systems provide a benchmark from which new MTEs can be developed and mission-based maximum excursion Level 1 performance requirements can be set. The following sections provide flight test data to show correlation of these updated Level 1 performance specifications against DRB criteria.

Object Avoidance MTE Results

All Object Avoidance MTE data were collected on the UP Hexacopter using the course size and scaling shown in Appendix I.1 ($N = 21.7$). Each of the five cases from Figure 6 were flight tested, completing the Object Avoidance trajectory for each case at least three times. Example flight test results for each DRB case were overlaid and are shown in Figure 7. It can be observed from the graph that the lowest and highest DRBs have the worst tracking, specifically in the z-axis. It should be noted, and as discussed in Ref. [7], that the highest DRB case does not meet the damping requirement and therefore does not provide Level 1 performance in flight. This highlights the need to meet the ADS-33E-PRF damping requirement ($\zeta \geq 0.35$) even for Group 1 UAS.

For each flight test the lateral tracking error, altitude tracking error, and time-to-complete were evaluated to determine an appropriate performance parameter for the MTE. Figure 8 shows the average and standard deviation of (a) the maximum lateral tracking error and (b) the maximum altitude error, relative to the desired course across the three MTE test events for each case.

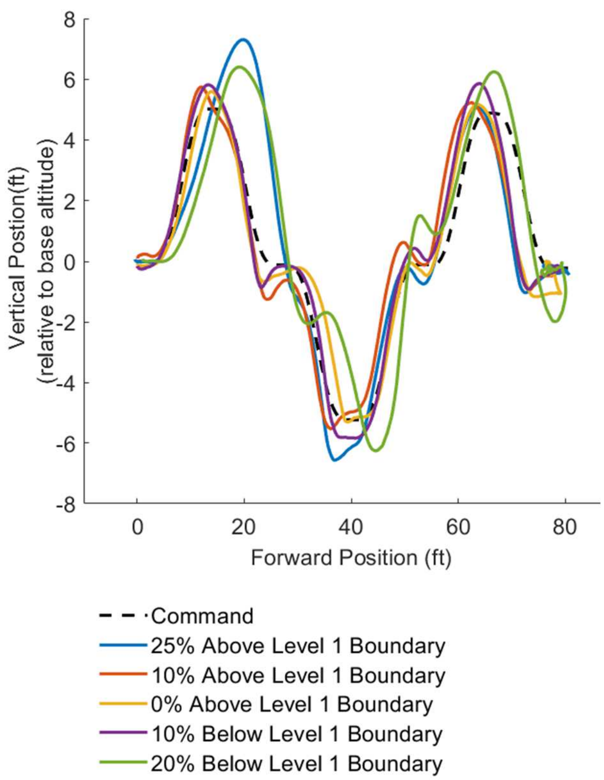

Figure 7. Object avoidance example flight test data.

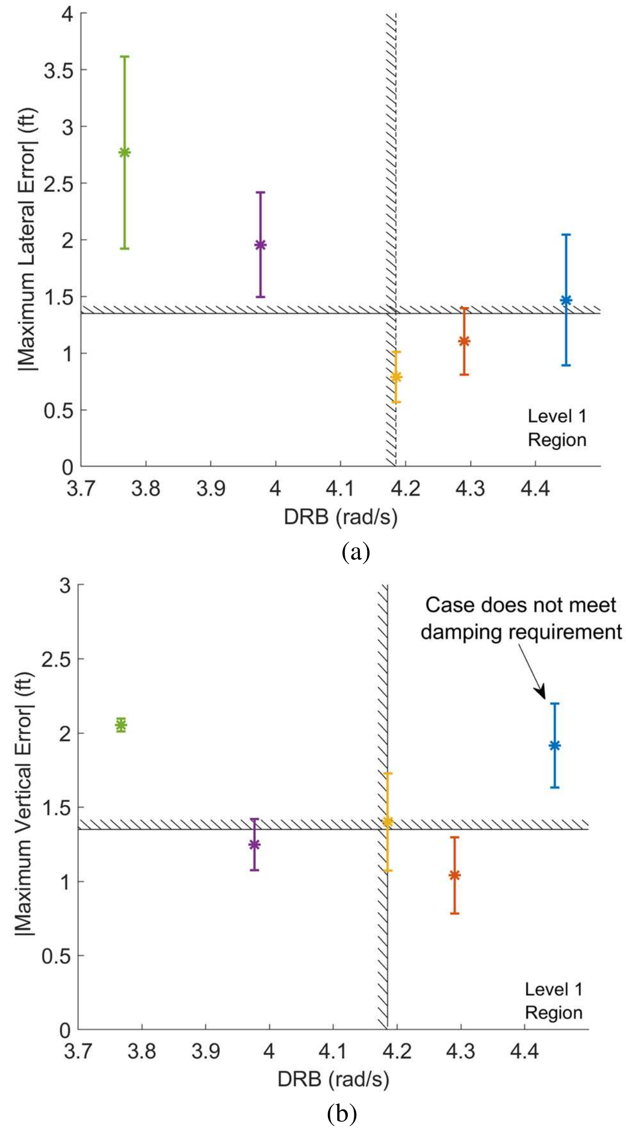

Figure 8. Object avoidance tracking performance versus DRB from flight test.

Generally, the trend holds that the tracking errors decrease as the DRB increases. However, the highest DRB case shown by the blue marker, at 25% above the Level 1 boundary, had a relaxed damping requirement to allow the controller to achieve this high DRB value. As such, the Level 2 ADS-33E-PRF damping requirement results in degraded Level 2 MTE performance. However, the cases that meet the Level 1 predicted metrics (yellow and red markers) should correlate with Level 1 performance. Therefore, a mission-based performance requirement was set to be consistent with the Level 1 predictive requirements, as shown by the hashed horizontal lines at ± 1.35 ft. This boundary of about ± 1 ft correlates well with results by Geyer, which indicate that a reasonable and mission-appropriate boundary is around ± 1 foot for Group 1

UAS [10]. This validates the Level 1 boundaries for vertical and lateral excursion during the obstacle avoidance MTE for a Group 1 UAS. The performance limits for Group 1 UAS are documented in ADS-33E-PRF MTE format in Appendix I.1.

Emergency Stop MTE Results

The Emergency Stop MTE was flight tested three times for each of the five control systems with the varying DRB cases shown in Figure 6. The course size and scaling are shown in Appendix I.2, and were scaled to the UP Hexacopter with $N = 21.7$. An example flight test for each DRB case is shown in Figure 9 and the trend remains that flight performance improves from lowest to highest DRB, except for the highest DRB case (25% above Level 1) because it does not meet the damping requirement, as described in the previous section. Consistent with the object avoidance MTE, the largest tracking errors are seen at the lowest and highest DRB designs.

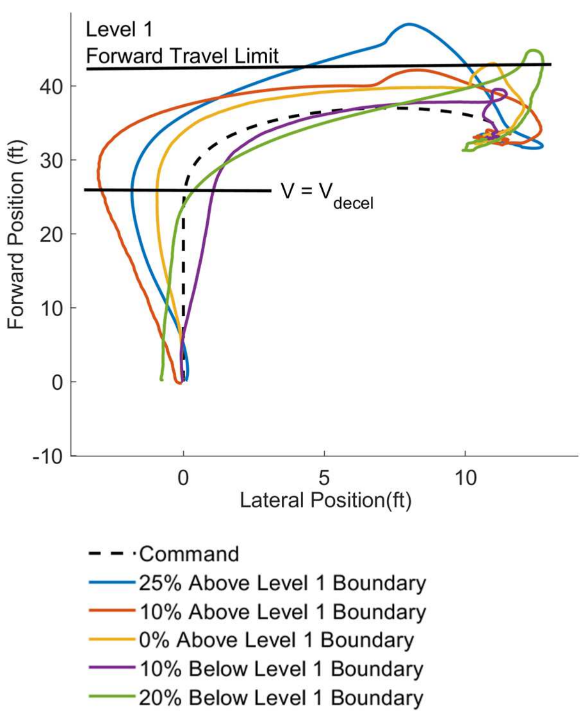

Figure 9. Emergency stop example flight test data.

Recall that during the Emergency Stop MTE, the UAS must be flying at (or above) the desired deceleration velocity when deceleration is initiated. The requirements include an allowable forward distance from the time when the deceleration is initiated while maintaining an altitude tracking requirement. These performance specifications scaled to the UP hexacopter for desired performance are: minimum deceleration speed of 21.5 ft/s, 16 ft of maximum forward travel from point of initial deceleration, and ± 1.35 feet of altitude variation. The average and standard deviation of the forward travel distance for each case (using at least three events) are plotted against the corresponding pitch/roll DRB shown in Figure 10. The forward travel requirement is set based on the Level 1 performance specification as it is in agreement with the Froude-scaled Level 1 DRB. This forward travel requirement should be scaled with UAS characteristic length and associated value of N because the deceleration speed is also scaled.

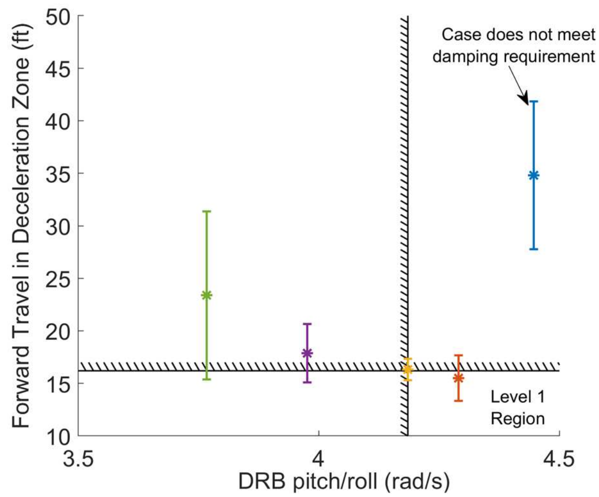

Figure 10. Emergency stop tracking performance versus DRB from flight test.

Updated Scaled ADS-33E MTE Results

In this section, the performance specifications of three Froude-scaled ADS-33E-PRF MTEs: (1) pirouette (2) depart/abort, and (3) lateral reposition have been updated with a mission-based performance specification, which is based on maximum excursion instead of a normalized value, in an effort to be more consistent with the mission requirements and with ADS-33E-PRF. For this update, the maneuver distance, speed and time-to-complete are Froude-scaled, as shown in Appendix I.3, I.4, and I.5, but the tracking performance specifications are mission-based and set by UAS Group.

A similar method to the UAS-specific maneuvers was used to collect data where at least three flight tests for each varying DRB case from Figure 6 were collected and plotted against the corresponding pitch/roll DRB. The following series of figures provide example trajectories recorded on the UP Hexacopter (using RTK GPS) and the resulting mean/standard deviation results across all maneuvers. Figure 11 shows example flight data for the lateral reposition MTE and Figure

12 shows the lateral reposition forward/aft tracking performance metric plotted against the corresponding pitch/roll DRBs. Figure 13 shows example flight data for the depart/abort MTE, and Figure 14 shows the depart/abort lateral tracking performance metric plotted against the corresponding pitch/roll DRBs. It should be noted that the high DRB case does not meet the damping requirement of $\zeta \geq 0.35$ and therefore has Level 2 performance (this behavior is present in the highest DRB case for all longitudinal focused maneuvers due to Level 2 damping). Figure 15 shows example flight data for the pirouette MTE and Figure 16 shows the pirouette radius error performance metric plotted against the corresponding pitch/roll DRBs.

The performance of the UP hexacopter with Froude-scaled Level 1 parameters was used to set the performance limits for Group 1 UAS. In setting these limits, it was important to consider that in ADS-33E-PRF the maximum excursion limits for the longitudinal track in Lateral Reposition, for the lateral track in Depart/Abort and feet for the radial tracking of Pirouette are all ± 10 ft. Because these tracking requirements are the same (± 10 ft) across these three maneuvers it was desired to set these tracking requirements with a consistent value for the UAS MTEs. As such, the Lateral Reposition, Depart/Abort and Pirouette MTEs, seen in Figure 12, Figure 14 and Figure 16 respectively, have a specification for Level 1 tracking performance set at ± 1.35 ft for Group 1 UAS. This value is consistent with Level 1 predicted DRB across the maneuvers and is similar to prior work by Geyer for Group 1 UAS where tracking within about 1 foot was achievable and mission appropriate [10]. As such, this performance metric is consistent with the Froude-scaled metrics for a Froude-scaled MTE, and has mission appropriate tracking for the Group 1 UAS. These performance requirements are also cross-validated again later in the paper for a single main rotor helicopter Group 1 UAS.

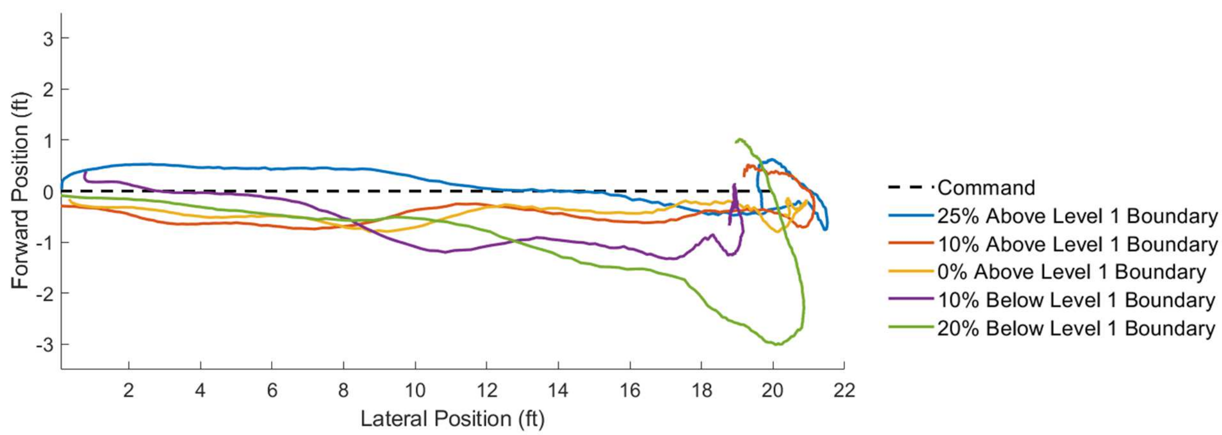

Figure 11. Lateral reposition example flight test data.

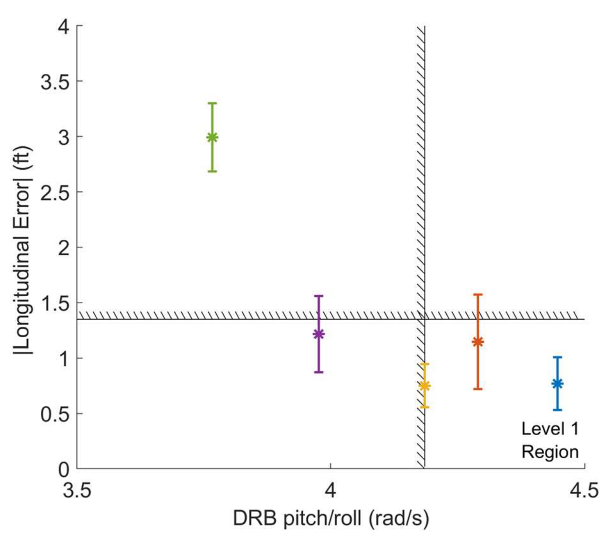

Figure 12. Lateral reposition tracking performance versus DRB from flight test.

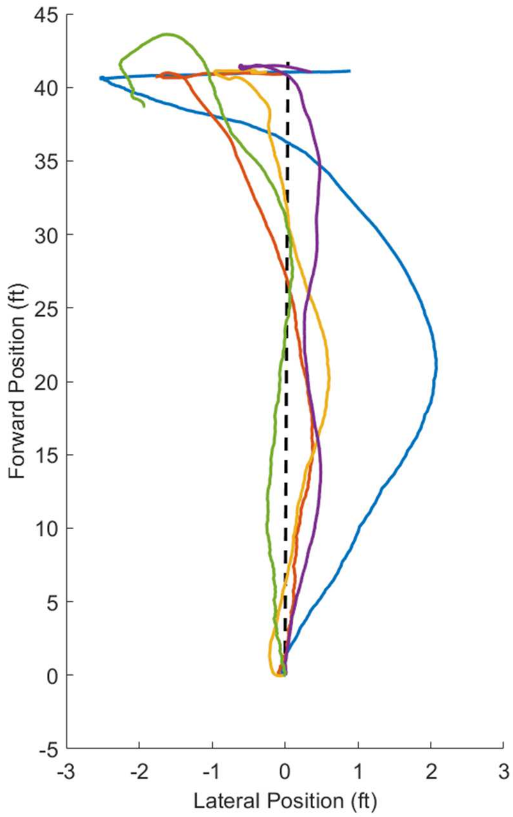

Figure 13. Depart/Abort example flight test data.

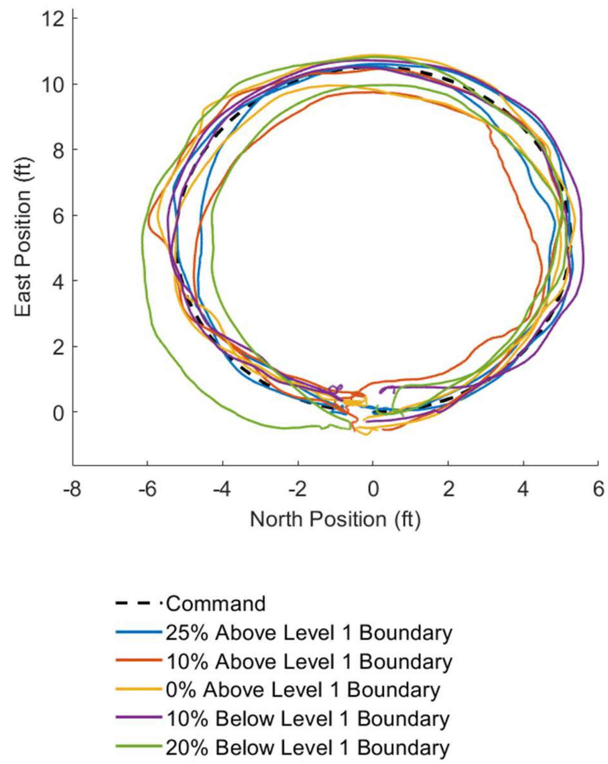

Figure 15. Pirouette example flight test data.

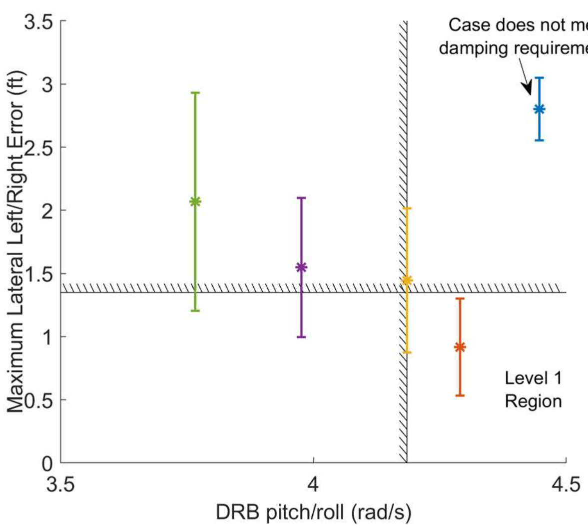

Figure 14. Depart/Abort tracking performance versus DRB from flight test.

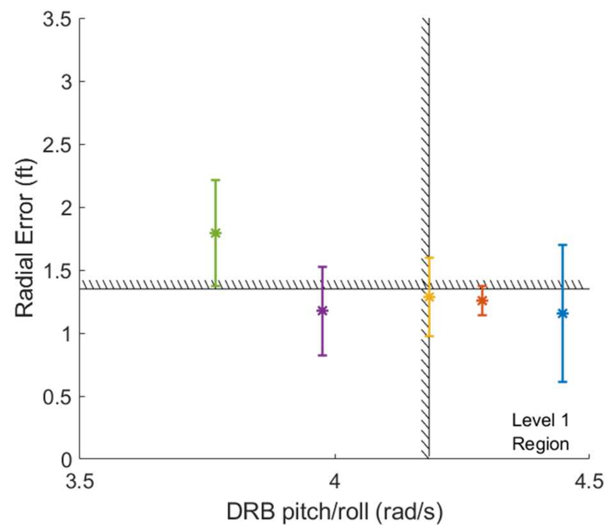

Figure 16. Pirouette tracking performance versus DRB from flight test.

FROUDE-SCALED ATTITUDE BANDWIDTH EVALUATION

For manned aircraft, there are many predictive handling qualities metrics including attitude bandwidth and phase delay, damping ratio, cross-coupling, and disturbance rejection bandwidth. DRB has proven to be a successful predictive metric of unmanned MTE flight performance. However, a larger set of metrics are needed to fully predict UAS handling qualities. In this section, a newly proposed predictive metric for evaluating autonomous MTE tracking for UAS is focused on Froude-scaled attitude bandwidth. In autonomous control systems, the velocity and/or position/waypoint control systems provide the input to the attitude command system. Although the control architecture may vary, the attitude bandwidth affects how quickly the aircraft can achieve a desired trajectory (and reject velocity/position disturbances) because the UAS must rotate in order to achieve an autonomous trajectory and maintain the desired track. As such, there is reason to believe the attitude bandwidth is highly correlated with tracking performance of an autonomous MTE.

Methodology

To validate Froude-scaling of the Level 1 attitude bandwidth, first the appropriate ADS-33E-PRF bandwidth criteria was determined. For Group 1 UAS, including the UP hexacopter, which are largely used for photography purposes, the category of "All other MTEs and Divided Attention" was deemed most appropriate because it is aggressive, but not as highly as target acquisition and tracking. In this category the full-scale requirement is $\omega_{BW} \geq 2$ rad/s (when the phase delay is reasonably small). The bandwidth frequency boundary scales according to Eq. (2). Therefore, the Level 1 Froude-scaled requirement for the UP hexacopter ($N = 21.7$) is

$$\omega_{BW_\phi}, \omega_{BW_\theta} \geq 9.3 \text{ rad/s} \quad (9)$$

Because the control system is a model following architecture, to achieve designs with the desired range of attitude bandwidth spanning above and below the Level 1 boundary, a set of controllers with a range of attitude command model natural frequencies were optimized. The attitude command natural frequencies ranged from 1 rad/s to 8 rad/s, as set in the attitude command model block labeled "2nd Order Command Model" in Figure 17. For each design, the attitude command model frequency was fixed in the CONDUIT® optimization, and all other parameters were optimized using the specifications from Ref. [7]. As such, the PID and lead gains for the inner and outer loops were simultaneously optimized around each command model to ensure both inner and outer-loop design criteria such as stability margin, DRB, damping ratio, cross-coupling, and heave/yaw metrics meet the Level 1 requirements for that case.

The attitude bandwidth was not included explicitly as a design requirement in CONDUIT®, instead all other design specifications were met and then the attitude bandwidth was evaluated for each of the command model cases. The attitude bandwidth is pulled from the frequency response of desired attitude ϕ_{des} input to the actual attitude ϕ output, using the -135 degree phase frequency, with the outer loops broken. Five of the designs were down-selected to provide a good range of cases above and below the Level 1 boundary for the Froude-scaled attitude bandwidth specification. The five selected cases had command model natural frequencies ranging from 3.5 – 5.5 rad/s and associated attitude bandwidth (phase bandwidth) of 8.3 to 10.5 rad/s, as shown in Table 3. In the two cases selected where the attitude bandwidth is below the boundary (Case 1 and Case 2 in Table 3), it is isolated as the only Level 2 predictive metric since all other metrics were optimized to Level 1 by CONDUIT®.

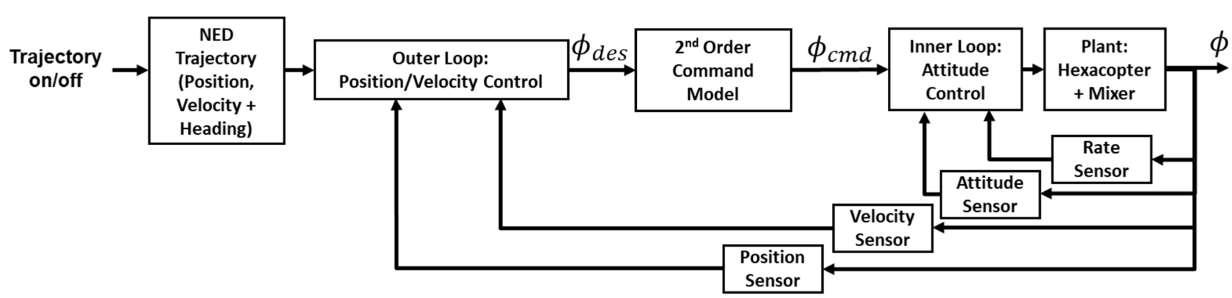

Figure 17. Closed-loop architecture of the UP hexacopter.

Table 3. Selected cases for evaluation of attitude bandwidth metric for UAS.

ATTITUDE COMMAND MODEL $\boldsymbol{\omega_{n_{cmd}}}$	**ATTITUDE BANDWIDTH** $\omega_{BW_{\phi,\theta}}$ (rad/s) (L1 ≥ 9.2)	**ATTITUDE DRB** $\omega_{DRB_{\phi,\theta}}$ (rad/s) (L1 ≥ 4.19)	**OUTER-LOOP DRB** $\omega_{DRB_{u,v}}$ (rad/s) (L1 ≥ 2.5)	$\omega_{DRB_{x,y}}$ (rad/s) (L1 ≥ 0.79)	**DAMPING RATIO** ζ_{min} (L1 > 0.35)
CASE 1: 3.5 rad/s	8.3	4.19 DRP = 3.95 dB	2.51 DRP = 3.7 dB	0.79 DRP = 2.93 dB	0.41
CASE 2: 4 rad/s	8.9	4.19 DRP = 3.93 dB	2.51 DRB = 4.3 dB	0.79 DRP = 2.77 dB	0.42
CASE 3: 4.5 rad/s	9.4	4.19 DRP = 3.82 dB	2.51 DRP = 4.81 dB	0.81 DRP = 2.7 dB	0.38
CASE 4: 5 rad/s	10.0	4.19 DRP = 3.87 dB	2.51 DRP = 5.2 dB	0.79 DRP = 2.6 dB	0.37
CASE 5: 5.5 rad/s	10.5	4.19 DRP = 3.79 dB	2.51 DRP =5.3 dB	0.87 DRP = 2.7 dB	0.35

Flight Testing of Attitude Bandwidth Cases

Flight testing with the five cases from Table 3 was completed on the UP hexacopter to validate attitude bandwidth as a predictive metric. Pirouette was selected as the test maneuver for validating the Level 1 boundary, because it excites many axes simultaneously. At least three test points of the scaled ADS-33E-PRF pirouette were completed for each of the five design configurations. Sample flight data for each of these bandwidth cases is shown in Figure 18. As shown in the figure, the tracking error is higher for the Level 2 attitude bandwidth cases (blue and red).

For each maneuver, the maximum radial error was determined, and the average maximum radial error was then calculated for each attitude bandwidth case (using at least three test events). This radial error, a key performance specification for the pirouette maneuver, was plotted against the attitude bandwidth in Figure 19 (mean and standard deviation). As shown by the Figure, the Froude-scaled Level 1 attitude bandwidth aligns well with the Level 1 performance specification for this maneuver (set earlier in Figure 16). Notably, the case that is significantly below the Level 1 boundary (blue) has Level 2 MTE performance. The case that is just below the Level 1 boundary (orange) just meets the Level 1 performance requirement, indicating that perhaps the divided attention category is a little conservative for the mission of this aircraft (UP hexacopter).

It should also be noted that flight testing for the bandwidth frequencies of the 8.9 rad/s and 10 rad/s cases (orange and purple) were collected on a very calm day while the other flight tests were performed on a day of slight wind. Nonetheless, the overall results show a clear correlation between the Froude-scaled ADS-33E-PRF Level 1 attitude bandwidth and Level 1 MTE performance. These results suggest that Froude-scaled attitude bandwidth, as applied to the inner-loop attitude command system when an outer-loop trajectory controller is present, is an appropriate specification for autonomous UAS handling qualities.

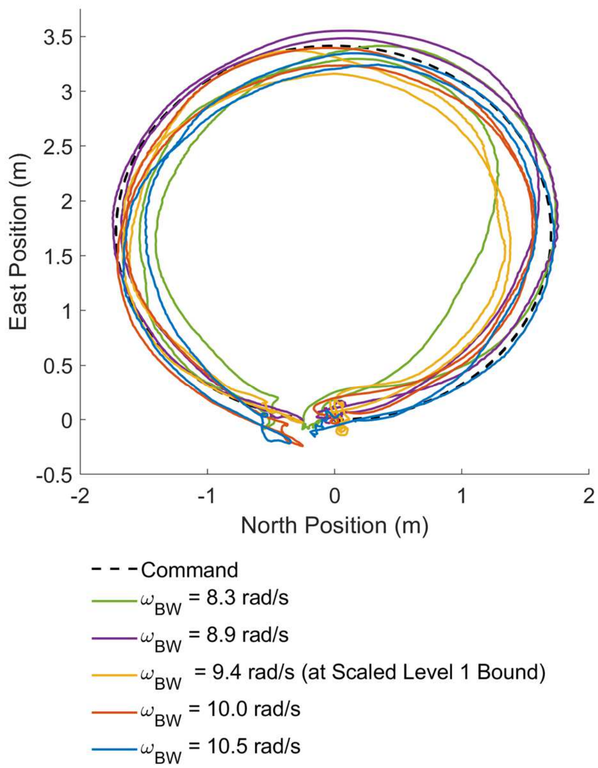

Figure 18. Pirouette example flight test data for attitude bandwidth flight tests.

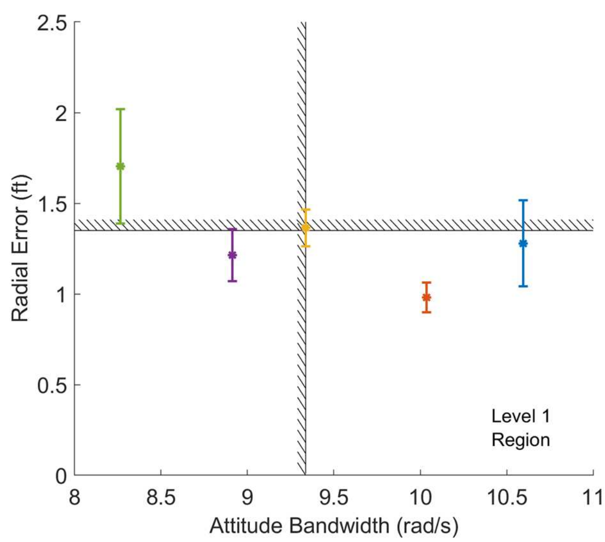

Figure 19. Pirouette tracking performance versus attitude bandwidth from flight test.

VALIDATION WITH THE SYNERGY 626 HELICOPTER

To validate the handling qualities framework and test the Froude scaling beyond multicopters, the methodology presented herein was applied to a Synergy 626 helicopter, shown in Figure 20. This UAS has a gross weight of 10 lb. (Group 1), a fuselage length of 3.56 ft, and a rotor diameter of 4.57 ft. The helicopter rotor is a two-bladed teetering design that uses rubber collars on the spindle to provide flapping stiffness. The effective offset was estimated to be 19%. Taking a Blackhawk H-60 helicopter as a representative full-scale helicopter, this UAS is 1/12 scale or $N = 12$, based on the rotor diameter. The flight controller is a CUAV Pixhawk v5 (similar to Pixhawk 2.1). The ArduCopter control system is flown on the aircraft and enables autonomous trajectories. The ArduCopter Auto mode was used to fly the trajectories by programming waypoints with Mission Planner.

To validate the scaling methodology, three cases with a range of attitude bandwidths above and below the Level 1 boundary were designed. Then the Froude-scaled lateral reposition and depart/abort MTEs were performed for each configuration. The goal was to validate that Froude scaling for the attitude bandwidth criteria for this aircraft results in Level 1 performance for Froude-scaled autonomous MTEs based on the standards defined earlier and given in the Appendix.

Figure 20. Synergy 626 helicopter.

Control System Designs

To determine the control system gains for the Synergy 626 Helicopter, it was first tuned to provide good stability and performance characteristics. Then, a range of command model parameters were manually tuned to achieve the desired attitude bandwidth just at, above and below the Level 1 boundary. Then, the attitude feedback proportional gains were further manually tuned to meet the Level 1 Froude-scaled disturbance rejection bandwidth and a damping ratio of $\zeta \geq 0.35$. A software in the loop (SITL) simulation is available in ArduPilot with a flight identified model of the Synergy 626, such that much of the tuning could be performed in simulation and then adjusted slightly in flight. Frequency sweeps were performed on the aircraft in flight (using the ArduCopter SysID mode) and CIFER® was used to determine flight frequency responses. The attitude bandwidth and disturbance rejection bandwidth were extracted from the appropriate frequency responses using the CIFER® tools. The damping ratio was estimated using a transfer function fit of the closed loop attitude response. The results of this tuning process are shown in Table 4. As shown in the Table, the only requirement that is in the Level 2 range are the bandwidth requirements for the low bandwidth case, although it should be noted that the DRB for the roll axis in this low bandwidth case is just at the boundary. Still, this methodology allows for isolation of the attitude bandwidth parameter, which is the only parameter well into Level 2 for the Low bandwidth case. All other cases meet the Level 1 predictive HQs metrics.

Flight Tests Results: Mission Task Elements

Two Froude-scaled mission task elements were evaluated with the Synergy 626 helicopter, the Lateral Reposition and Depart/Abort. The scaling of the courses was performed according to Appendix I.3. Waypoints were programmed into the Auto mode that would allow the aircraft to complete the MTE autonomously. The waypoint navigation controller maximum acceleration and maximum jerk were tuned in order to achieve the desired time to complete.

The scaled lateral reposition MTE for this UAS is approximately 33 ft long and has a required time to complete of 5.2 s for Level 1 performance. According to work shown earlier in this paper, and in the specification table in Appendix I.3, the Level 1 requirement for the Group 1 UAS is to maintain forward track within ± 1.35 ft. As shown in the example flight test data in Figure 21, the case with Level 1 inner-loop attitude bandwidth cases (red and blue) both meet the performance specification. In the low bandwidth case, the UAS goes outside of the Level 1 performance bound (dash-dot) twice during the maneuver (at ~6 ft and at ~31 ft). It should also be noted that the time to complete was about 7 s for this low bandwidth case, which is Level 2 performance for the MTE.

To validate the performance, at least three test events were conducted for each case, where the maximum forward/aft deviation was recorded for each of the three cases. The error bar lines in Figure 22 represent the mean and standard deviation of these maximum deviations across the repeated maneuvers for each case. As shown in Figure 22, the trend is very clearly correlated to the attitude bandwidth. Additionally, Level 1 performance is achieved for both cases with predicted Level 1 performance, meeting the desired forward/aft tracking requirement and time to complete. For the Level 2 bandwidth case, level 2 tracking forward/aft tracking performance is achieved. It should be noted that for the Level 2 bandwidth case, the time to complete was also in Level 2 for all six test events of this configuration.

The scaled Depart/Abort MTE for this UAS is approximately 66 ft long and has a required time to complete of 7.3 s for Level 1 performance. The tracking requirement is ± 1.35 ft of lateral error. As shown in the example flight test case of Figure 23, the MTE performance is correlated with the attitude bandwidth for roll, and it should be noted that the low bandwidth case does not meet the time requirement and takes around 9 s to complete the maneuver. For the depart/abort, four MTEs were conducted for each of the three bandwidth cases, the error bars on Figure 24 represent the mean and standard deviation of maximum lateral tracking error across each of the four events. As shown in the figure, a good correlation between the Level 1 performance and the attitude bandwidth was found, and it should be noted that for the low bandwidth case, none of the four test events met the time requirement, which is likely why the tracking errors are relatively low.

These results validate the scaling methodology for the MTEs, the UAS Group-based specification boundaries, and using inner-loop attitude bandwidth as a predictive metric. The Level 1 MTE performance bound of ± 1.35 ft for lateral reposition and depart/abort also correlates well with predicted Level 1 handling qualities this Group 1 aircraft. This validation is important because it shows that the scaling method is consistent with Level 1 performance and that the MTEs assess and differentiate performance for a very different UAS than the UP hexacopter – the Synergy 626 weighs more than double the UP hexacopter and has a single main rotor diameter of 4.57 ft, more than twice the hub-to-hub distance of the UP hexacopter.

Table 4. Flight identified handling qualities predictive metrics for the Synergy 626 helicopter.

CASES	ATTITUDE BANDWIDTH		ATTITUDE DRB		DAMPING RATIO	
	ω_{BW_ϕ} (rad/s) (L1 ≥ 6.9)	ω_{BW_θ} (rad/s) (L1 ≥ 6.9)	ω_{DRB_ϕ} (rad/s) (L1 ≥ 3.1)	ω_{DRB_θ} (rad/s) (L1 ≥ 2.4)	ζ_{roll} (L1 ≥ 0.35)	ζ_{pitch} (L1 ≥ 0.35)
LEVEL 2 BANDWIDTH	5.3	4.8	2.9 DRP = 4.7 dB	2.4 DRP = 5.5 dB	0.51	0.49
AT LEVEL 1 BOUNDARY	7.5	6.9	3.1 DRP = 3.6 dB	2.8 DRP = 5.5 dB	0.63	0.56
HIGHER THAN LEVEL 1 BOUNDARY	10.8	8.74	4.0 DRP =3.2 dB	3.8 DRP = 5.4 dB	0.74	0.65

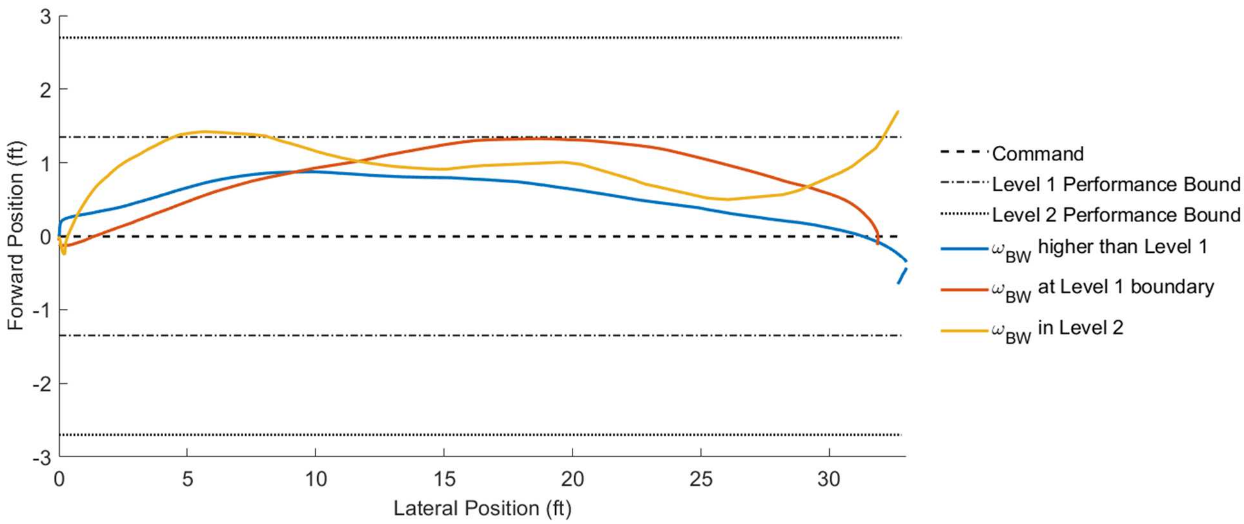

Figure 21. Lateral reposition example flight test data for attitude bandwidth flight tests on the Synergy 626.

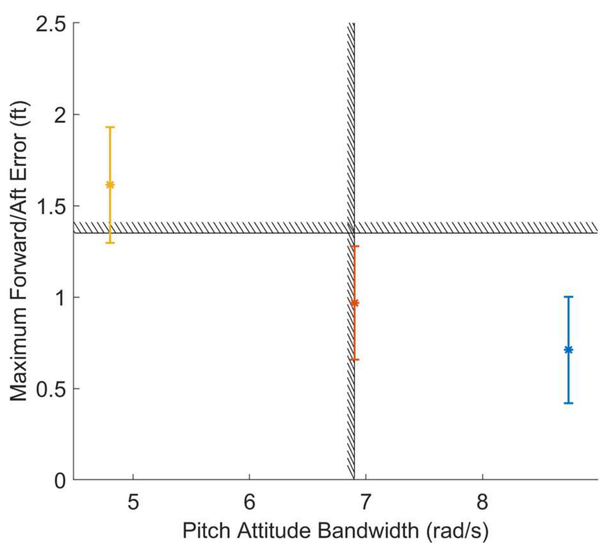

Figure 22. Lateral reposition performance versus attitude bandwidth from flight test on the Synergy 626.

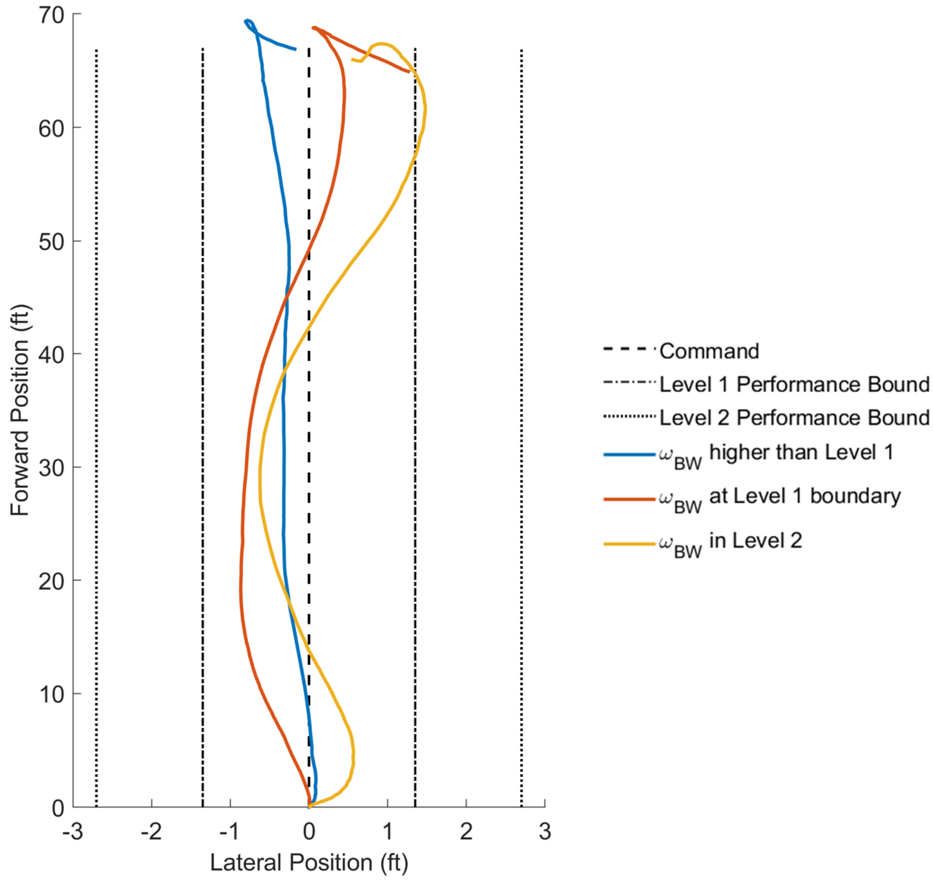

Figure 23. Depart/Abort example flight test data for attitude bandwidth flight tests on the Synergy 626.

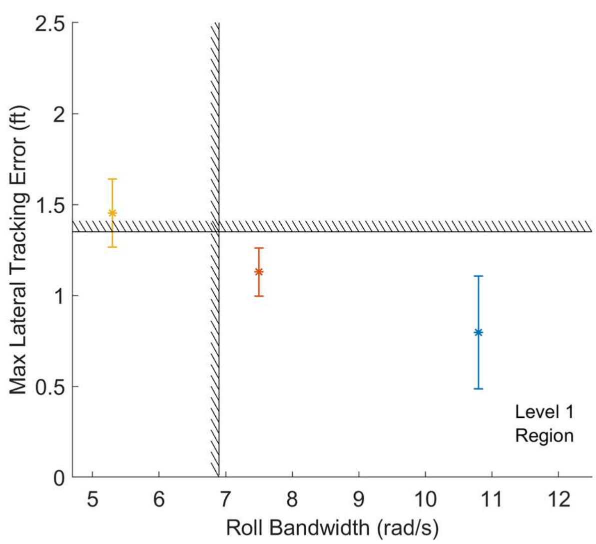

Figure 24. Depart/Abort performance versus attitude bandwidth from flight test on the Synergy 626.

CONCLUSIONS

This work has proposed an updated handling qualities framework, two UAS-specific maneuvers, and a new performance metric. A small hexacopter was flown on the University of Portland's campus to validate the above work. A subset of this method was also validated on the Synergy 626 helicopter. Work previously done by the lead author has validated Froude scaling based on the hub-to-hub distance for ADS-33E-PRF MTEs as well as the disturbance rejection bandwidth predictive performance metric. This paper is a significant contribution to the development of a UAS Handling Qualities Framework through the design and validation of UAS-specific maneuvers and scalable performance requirements that apply to both multicopters and helicopter UAS. The central contributions of this work are:

1. Two scalable UAS-specific maneuvers have been developed and flight tested on the UP hexacopter. The performance specifications have been flight validated to show that Level 1 MTE performance

aligns with the Froude-scaled Level 1 predicted handling qualities.

2. Updated mission-based MTE performance specifications for Group 1 UAS have been flight validated for the Froude-scaled ADS-33E-PRF MTEs. The performance specifications for pirouette, lateral reposition, and depart/abort are compiled in a framework similar to ADS-33 in Appendix I of this document.

3. Froude scaling the ADS-33E-PRF Level 1 attitude bandwidth criteria has been flight validated on two Group 1 UAS, a 4 lb. hexacopter and 10 lb. single main rotor helicopter. A clear trend between the attitude bandwidth predicted Level 1 criteria and Level 1 MTE performance was shown for both aircraft.

AKNOWLEDGEMENTS

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REFERENCES

[1] Anon, "Aeronautical Design Standard, Handling Qualities Criteria For Military Rotorcraft, USAAMCOM, ADS-33E-PRF," US Army, Huntsville, AL, March, 2000.

[2] C. Blanken, M. Tischler, J. Lusardi, C. Ivler and R. Lehmann, "Proposed Reviews to Aeronautical Design Standard - 33E (ADS-33E-PRF) Toward ADS-33F-PRF," Special Report, FCDD-AMV-19-01, September, 2019.

[3] D. Kylde, D. Mitchell and N. Alexandrov, "Development of a Process to Define Unmanned Aircraft Systems Handling Qualities," in *AIAA Atomspheric Flight Mechanics Conference* , Kissimmee, Florida , 2018.

[4] B. Mettler, M. Tischler and T. Kanade, "System Identification of Small-Sized Unmanned Helicopter Dynamics," in *Proceedings of the American Helicopter Society 55th Annual Forum*, Montreal, Quebec, Canada, May 25-27, 1999.

[5] G. Hunt, "Similarity Requirements for Aeroelastic Models or Helicopter Rotors," R.A.E., C.P. No 1245, Farnborough, January 1972.

[6] T. Berger, C. Ivler, M. Berrios, M. Tischler and D. Miller, "Disturbance Rejection Handling Qualities Criteria for Rotorcraft," in *American Helicopter Society Annual Forum*, West Palm Beach, FL, May, 2016.

[7] C. Ivler, K. Truong, D. Kerwin, J. Otomize, D. Parmer, M. Tischler and N. Gowans, "Development and Flight Validation of Proposed Unmanned Aerial System Handling Qualities Requirments," in *Vertical Flight Society Annual Forum*, 2019.

[8] C. Ivler, C. Goerzen, J. Wagster, F. Sanders, K. Cheung and M. Tischler, "Control Design for Tracking of Scaled MTE Trajectories on an IRIS+ Quadcopter," in *AHS 74th Annual Forum Proceedings*, Phoenix, AZ, May, 2017.

[9] C. Ivler, E. Rowe, J. Martin, M. Tischler and M. Lopez, " System Identification Guidance for Multirotor Aircraft: Dynamic Scaling and Test Techniques.," in *Vertical Flight Society International Forum*, Philadelphia, PA, May, 2019.

[10] B. Geyer, "Update on UAS Handling Qualities using FPV Cueing," in *Atmospheric Flight Mechanics Conference, AIAA SciTech* , 2020.

[11] M. Abdulrahim and D. Lisoski, "Performance, Dynamics, and Handling Qualities Flight Testing for Small UAVs," in *UAS Handling Qualities Workshops* , Hampton,Virginia, 2018.

[12] M. Tischler, K. Cohen and W. Wei, "System Identification and Controller Optimization of a Quadrotor UAV," in *AHS International 71st Annual Forum* , Virgina Beach, Virgina , 2015.

[13] anon, "ardupilot.org," [Online]. Available: ardupilot.org/copter/index.htm.

[14] C. Ivler, R. Niemiec, F. Gandhi and F. Sanders, "Multirotor Electric Aerial Vehicle Model Validation with Flight Data: Physics-Based and System Identification Models," in *Vertical Flight Society Annual Forum*, Philadephia, PA, May, 2019.

[15] M. Tischler and R. Remple, Aircraft and Rotorcraft System Identification: Engineering Methods with Flight Test Examples, Reston,VA: AIAA: Education Series, 2012.

[16] E. Tobias, M. Tischler and F. Sander, "Full-Envelope Stitched Simulation Model of a Quadcopter Using STITCH," in *AHS*

International 74th Annual Forum , Phoenix, AZ, 2018.

[17] M. Tischler, T. Berger, C. Ivler, K. Cheung and J. Soong, Practical Methods for Aircrafft and Rotorcraft Flight Control Design: An Optimization-Based Approach, Reston,VA: AIAA, 2017.

[18] M. Takahashi and et. al., "Autonomous Guidance and Flight Control on a Partial-Authority Black Hawk Helicopter," *Journal of Aerospace Information Systems,* vol. 18, no. 10, pp. 686-701, 2021.

APPENDIX I

This appendix presents proposed scaled UAS mission task elements (MTEs) presented in the style of ADS-33E-PRF. Froude scaling is built into the descriptions of the maneuvers, the performance standards and the autonomous course layouts. The performance standards are provided as a function of UAS group. Group 1 has been tested. Group 2 and Group 3 UAS have not been flight tested, therefore the mission-based performance standards are listed as TBD. For Group 4, the ADS-33E-PRF MTEs revert back to ADS-33E-PRF courses and standards so they have been considered tested. In the work in Ref [18], ADS-33 MTEs were performed autonomously on a Black Hawk, indicating that these performance standards are achievable for what would be considered a Group 4 UAS by weight.

The following maneuvers are listed in the Appendix:

I.1 Object Avoidance

I.2 Emergency Stop

I.3 Lateral Reposition

I.4 Depart/Abort

I.5 Pirouette

Froude Scaling of Maneuvers

Scaling is performed relative to a relevant full-scale vehicle, using the characteristic length and the Froude scale N. The following provides guidance on determining an appropriate scale factor N:

- Multicopter: $N = \frac{D_{fullscale}}{D_{hub}}$, where D_{hub} is the hub-to-hub distance of vehicle and $D_{fullscale}$ is the hub-to-hub distance a relevant full-scale multicopter. A suggested value is $D_{fullscale} = 39.2$ ft, based on the CH-47 Chinook.
- Single main rotor: $N = \frac{D_{fullscale}}{D_{rotor}}$, where D_{rotor} is the rotor diameter of the vehicle and $D_{fullscale}$is the hub-to-hub distance of a relevant full-scale helicopter. A suggested value is $D_{fullscale} = 53.7$ ft, based on an H-60 Blackhawk.

Note that if the UAS is “full-scale”, meaning it is of similar size to rotorcraft for which ADS-33E-PRF was designed and has been applied (e.g. Group 4 UAS) then $N = 1$. This will revert back to the ADS-33 courses for the autonomous trajectory.

I.1 Object Avoidance

a. Objectives.

- Check ability to maneuver above and below sequential objects.
- Check ability to track a complex trajectory in the longitudinal and vertical axes while flying forward at nap-of -the-earth speeds and maintaining lateral track.

b. Scaling. Scaling is performed suing Froude number N relative to an appropriate full-scale vehicle as described in Appendix 1.0.

c. Description of maneuver. From level fight at an obstacle avoidance speed of approximately $V_{OA} = \frac{30}{\sqrt{N}}$ kts, the aircraft will simulate a forward trajectory that makes changes in altitude to simulate flight over and under obstacles. The UAS will maintain altitude tracking error within the performance requirements relative to the trajectory given in Figure 25 and within lateral tracking standards. The trajectory course length and performance standards do not include the acceleration or deceleration portion of this maneuver.

d. Description of test course. This maneuver requires no physical test course setup as it is autonomous. The course trajectory/waypoints are programmed to complete the maneuver as shown in Figure 25. Performance is evaluated with a reliable positioning system, such as differential GPS.

e. Performance standards.

Performance standards – Object Avoid

	UAS Group	Desired	Adequate
Maintain lateral track within $\pm$ X ft	1	1.35 ft	2.7 ft
	2, 3, 4	TBD	TBD
Maintain altitude tracking error within $\pm$ X ft:	1	1.35 ft	2.7 ft
	2, 3, 4	TBD	TBD
Maintain heading within +/- X deg	ALL	10 deg	20 deg
Time to complete maneuver	ALL	$\frac{65}{\sqrt{N}}$	$\frac{80}{\sqrt{N}}$

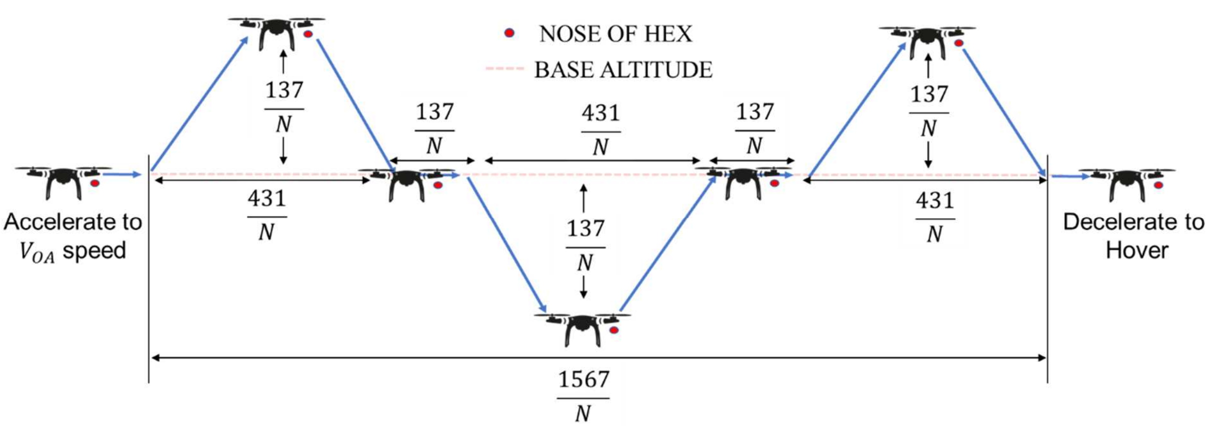

Figure 25. Course trajectory for object avoidance (dimensions are in feet).

I.2 Emergency Stop

a. **Objectives.**
- Check ability to accomplish an unexpected stop from a representative autonomous operational speed with limited forward distance travel.
- Check ability to maintain altitude when undergoing a rapid, possibly turning deceleration.

b. **Scaling.** Scaling is performed suing Froude number N relative to an appropriate full-scale vehicle as described in Appendix 1.0.

c. **Description of maneuver.** From a level flight at a speed of at least V_{decel} knots the aircraft will initiate a rapid deceleration, keeping nose of aircraft forward or completing a turn (coordinated or uncoordinated) as necessary to decelerate with minimal forward travel and maintain altitude. The aircraft will come to a stabilized hover with limited forward travel, while maintaining altitude within the desired limits. The maneuver will end when the aircraft is in a steady hover.

d. **Description of test course.** This maneuver requires no physical test course setup as it is autonomous. The course trajectory/waypoints are programmed to complete the maneuver as shown in Figure 26. Performance is evaluated with a reliable positioning system, such as differential GPS.

e. **Performance standards.**

Performance standards - Emergency Stop

	UAS Group	Desired	Adequate
Maintain altitude within $\pm$ X ft	1	1.35 ft	2.7 ft
	2, 3, 4	TBD	TBD
Minimum velocity from which deceleration is initiated, V_{decel}	ALL	$\frac{60}{\sqrt{N}}$ kts	$\frac{50}{\sqrt{N}}$ kts
Maximum allowable forward travel after deceleration is initiated	ALL	$\frac{350}{N}$ ft	$\frac{600}{N}$ ft

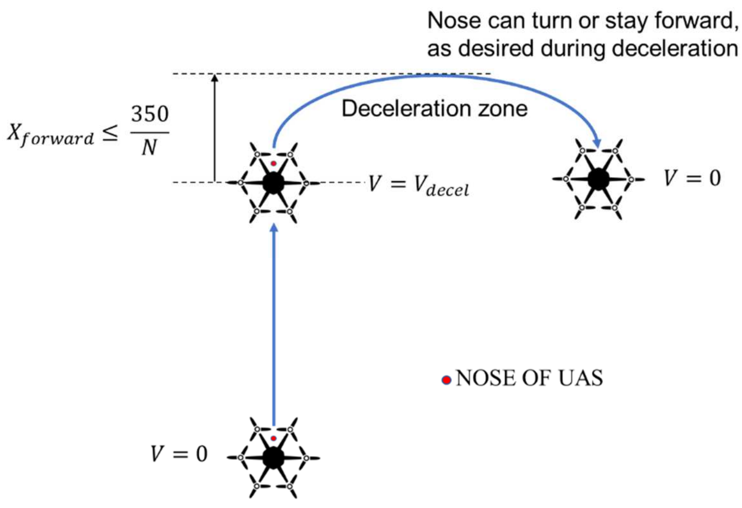

Figure 26. Course trajectory for emergency stop.

I.3 Lateral Reposition

a. Objectives.

- Check roll axis and heave axis autonomous handling qualities during a moderately aggressive maneuver
- Check for undesirable coupling between the roll controller and the other axes

b. Scaling. Scaling is performed suing Froude number N relative to an appropriate full-scale vehicle as described in Appendix 1.0.

c. Description of maneuver. Start in a stabilized hover at an appropriate height with the longitudinal axis of the rotorcraft oriented 90 degrees to the desired direction of travel. The autonomous trajectory will initiate a lateral acceleration to approximately $35/\sqrt{N}$ kts knots groundspeed followed by a deceleration to laterally reposition the UAS in a stabilized hover $400/N$ ft down the course within a specified time. The acceleration and deceleration phases shall be accomplished as single smooth maneuvers. The UAS must be brought to within $\pm 10/N$ ft of the endpoint during the deceleration, terminating in a stable hover within this band. Overshooting is permitted, but will show up as a time penalty. The maneuver is complete when a stabilized hover is achieved.

d. Description of test course. This maneuver requires no physical test course setup as it is autonomous. The course trajectory/waypoints are programmed to complete the maneuver as shown in Figure 27. Performance is evaluated with a reliable positioning system, such as differential GPS.

e. Performance standards.

Performance standards - Lateral Reposition

	UAS Group	Desired	Adequate
Maintain longitudinal track within $\pm$ X ft	1	1.35 ft	2.7 ft
	2, 3	TBD	TBD
	4	10 ft	20 ft
Maintain altitude within $\pm$ X ft:	1	1.35 ft	2.7 ft
	2, 3	TBD	TBD
	4	10 ft	20 ft
Maintain heading within +/- X deg	ALL	10 deg	10 deg
Time to complete maneuver	ALL	$\frac{18}{\sqrt{N}}$	$\frac{25}{\sqrt{N}}$

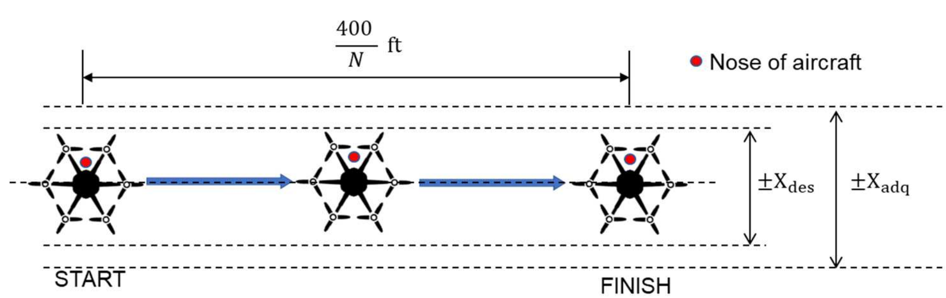

Figure 27. Course trajectory for lateral reposition.

I.4 Depart/Abort

a. Objectives.
- Check pitch axis and heave axis autonomous handling qualities during moderately aggressive maneuvering.
- Check for undesirable coupling between the longitudinal and lateral-directional axes.
- Check for ability to re-establish hover after changing trim

b. Scaling. Scaling is performed suing Froude number N relative to an appropriate full-scale vehicle as described in Appendix 1.0.

c. Description of maneuver. From a stabilized hover at an appropriate altitude, and $800/N$ ft from the intended endpoint, initiate an autonomous longitudinal acceleration to perform a normal departure. At about $40/N$ to $50/N$ knots groundspeed, the autonomous trajectory will begin to decelerate to a hover such the termination of the maneuver, the UAS shall be within $20/N$ ft of the endpoint. It is not permissible to overshoot the intended endpoint and move back. If the UAS stopped short, the maneuver is not complete until it is within $20/N$ ft of the intended endpoint. The acceleration and deceleration phases shall be accomplished in a single smooth autonomous maneuver. The maneuver is complete when control motions have subsided to those necessary to maintain a stable hover.

d. Description of test course. This maneuver requires no physical test course setup as it is autonomous. The course trajectory/waypoints are programmed to complete the maneuver as shown in Figure 28. Performance is evaluated with a reliable positioning system, such as differential GPS.

e. Performance standards.

Performance standards - Depart/Abort

	UAS Group	Desired	Adequate
Maintain lateral track with $\pm$ X ft	1	1.35 ft	2.7 ft
	2, 3	TBD	TBD
	4	10 ft	20 ft
Maintain altitude within $\pm$ X ft:	1	1.35 ft	2.7 ft
	2, 3	TBD	TBD
	4	15 ft	40 ft
Maintain heading within +/- X deg	ALL	10 deg	10 deg
Time to complete maneuver	ALL	$\frac{25}{\sqrt{N}}$	$\frac{30}{\sqrt{N}}$

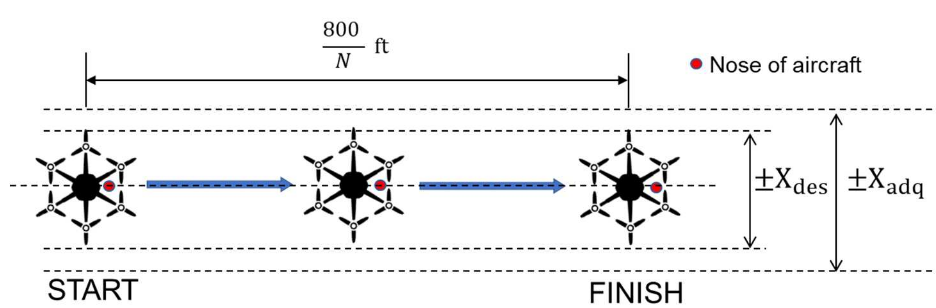

Figure 28. Course trajectory for depart/abort.

I.5 Pirouette

a. Objectives.

- Check ability to achieve precision autonomous control simultaneously in pitch, roll, yaw, and heave.

b. Scaling. Scaling is performed suing Froude number N relative to an appropriate full-scale vehicle as described in Appendix 1.0.

c. Description of maneuver. Initiate the maneuver from a stabilized hover over a point on the circumference of a $100/N$ ft radius circle with the nose of the UAS pointed at a reference point at the center of the circle, and at an appropriate hover altitude. Accomplish a lateral translation around the circle, keeping the nose of UAS pointed at the center of the circle, and the circumference of the circle under a selected point on the UAS. Maintain essentially constant lateral groundspeed throughout the lateral translation (note: nominal lateral velocity will be approximately $8/\sqrt{N}$ knots for the desired and $6/\sqrt{N}$ knots for adequate time-to-complete.) Terminate the maneuver with a stabilized hover over the starting point. Perform the maneuver in both directions.

d. Description of test course. This maneuver requires no physical test course setup as it is autonomous. The course trajectory/waypoints are programmed to complete the maneuver as shown in Figure 29. Performance is evaluated with a reliable positioning system, such as differential GPS.

e. Performance standards.

Performance standards - Pirouette

	UAS Group	Desired	Adequate
Maintain a selected reference point on the UAS within $\pm$ X ft of the circumference of the circle	1	1.35 ft	2.7 ft
	2, 3	TBD	TBD
	4	10 ft	20 ft
Maintain altitude within $\pm$ X ft:	1	1.35 ft	2.7 ft
	2, 3	TBD	TBD
	4	3 ft	10 ft
Maintain heading such that the nose of the UAS points at the center of the circle within +/- X deg	ALL	10 deg	10 deg
Time to complete maneuver	ALL	$\frac{45}{\sqrt{N}}$	$\frac{60}{\sqrt{N}}$

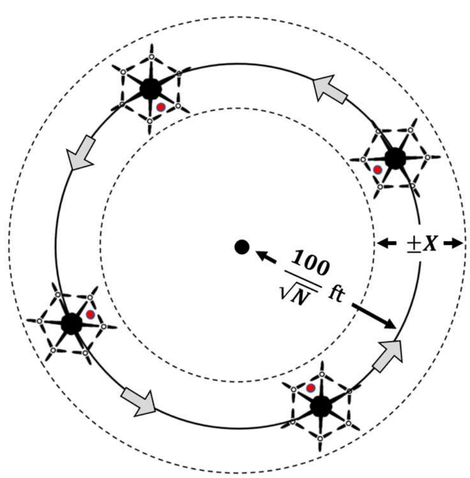

Figure 29. Course trajectory for pirouette.