

Integrated Handling Qualities Safety Analysis For Conceptual Design of Urban Air Mobility Vehicles

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The recent emergence of distributed electric propulsion Vertical Takeoff and Landing (VTOL) aircraft has created a rapid introduction of new design concepts with unique stability and control characteristics. A challenge to realizing the full potential of these vehicles for urban transportation is to gain public acceptance which is largely driven by flight safety. This paper describes ongoing research to address the feasibility of integrating flying qualities safety metrics into conceptual design of VTOL Urban Air Mobility (UAM) vehicles. The discussion is composed of the approach and progress toward a toolbox that integrates with existing NASA rotorcraft design software and processes. Several key challenges are highlighted including modeling requirements for failures, identification of critical failures, and capturing critical failures, with robustness to model uncertainty. A discussion of requirements for safety metrics, specific to UAM vehicles, as well as the effects of the control system design is also included. Results to date have demonstrated the degradation in flying qualities metrics due to propulsion failures.

I. Nomenclature

ACAH	=	attitude command, attitude hold
$\tilde{A}$	=	augmented stability matrix
BEMT	=	blade element momentum theory
$\tilde{B}$	=	augmented control matrix
DRB	=	disturbance rejection bandwidth, rad/s
DRP	=	disturbance rejection peak, dB
GP	=	Gaussian Process
k	=	number of rotors
LQR	=	linear quadratic regulator
LQI	=	linear quadratic integrator
MTE	=	Mission Task Element
NDARC	=	NASA Design and Analysis of RotorCraft
p, q, r	=	body-axis angular rates, rad/s
RCDH	=	rate command, direction hold
RVLT	=	Revolutionary Vertical Lift Technology
T_{rec}	=	Time span of frequency sweep, seconds
UAM	=	Urban Air Mobility
u, v, w	=	body-axis translational velocity components, ft/s
VTOL	=	vertical takeoff and landing
VSTOL	=	vertical short takeoff and landing
β_0	=	coning angle, rad or deg
β_{1c}	=	longitudinal flap angle, rad or deg

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β_{1s}	= lateral flap angle, rad or deg
Ω	= rotor speed, rad/s
λ_0	= uniform component of inflow
λ_{1c}	= longitudinal component of inflow
λ_{1s}	= lateral component of inflow
ϕ	= roll angle, rad or deg
θ	= pitch angle, rad or degrees
θ_{75}	= rotor collective pitch at 75% radius, rad or deg
θ_d	= pitch disturbance sweep, rad or deg
ψ	= yaw angle, rad or deg
$\vec{u}$	= control input vector
ω_{min}	= minimum frequency for frequency sweep, rad/s
ω_{max}	= max frequency for frequency sweep, rad/s
ω_{BW}	= piloted bandwidth frequency, rad/s
τ	= rotor shaft torque input, ft-lb
τ_p	= phase delay, seconds
$\vec{u}$	= control input vector
$\vec{x}$	= state vector
$\vec{x}_{CMD}$	= state command vector

II. Background and Objectives

The recent emergence of distributed electric propulsion VTOL aircraft has created a rapid introduction of new design concepts with unique stability and control characteristics. Many of these vehicles are targeted for use in high density, low altitude urban environments known as Urban Air Mobility (UAM). The development and integration of UAM vehicles is presenting new challenges regarding safety and certification compared to existing commercial and general aviation vehicles. The eventual goal of fully autonomous vehicles will have a significant impact on this effort.

NASA has been continuing research to advance design methods specific to UAM vehicles. This work builds on legacy rotorcraft design codes and processes aimed at concept definitions that will support related research for air traffic management, public acceptance and vehicle system requirements. Typically, conceptual design is aimed at defining vehicle geometry, mass properties, propulsion requirements and basic control system characteristics. NASA has recognized a need for safety assessments during conceptual design to reduce costly design iterations due to unmitigated safety issues. Ultimately, this research is aimed at accelerating public acceptance of the emerging UAM market in addition to the development of airworthiness certification criteria. The key objectives of this research include the following:

- Development of simulation-based tools to assess the impact of failures or hazardous conditions on handling qualities and flight safety. This step involves modeling of flight dynamics and the effects due to failures, as well as identification of critical failures and uncertainties that can be mitigated by vehicle design features.
- Identification and development of critical safety metrics that are suitable for a conceptual design framework
- Demonstration of a proof-of-concept toolbox for integrating safety metrics into NASA conceptual design processes using existing design codes

This paper is organized as follows. Section III provides a discussion of the current state of the art in aircraft conceptual design and highlights challenges regarding flight safety considerations for UAM vehicles. A discussion of design tools used by NASA and proposed modifications to those tools based on this research is included. Section IV provides a discussion of proposed safety metrics based on existing military flying qualities specifications. Section V provides an overview of tools used for this research including flight simulations, control system design and uncertainty analysis. Lastly, Section VI presents recent results and key findings to date.

III. Description of Conceptual Design Tools and Framework

NASA has developed and currently uses numerous design codes and processes that represent the state of the art in rotorcraft design. This work builds on decades of research and experimental validation data. An illustration of the integrated conceptual design framework including proposed safety assessment tools is shown in Fig. 1. The proposed modification to this framework is highlighted in green where a safety assessment step is added to inform a vehicle design modification based on a failure analysis. This paper will describe the development of these proposed safety

assessment tools, namely failure mode simulations, definitions of safety metrics, and the introduction of uncertainty modeling that can be provided by machine learning methods.

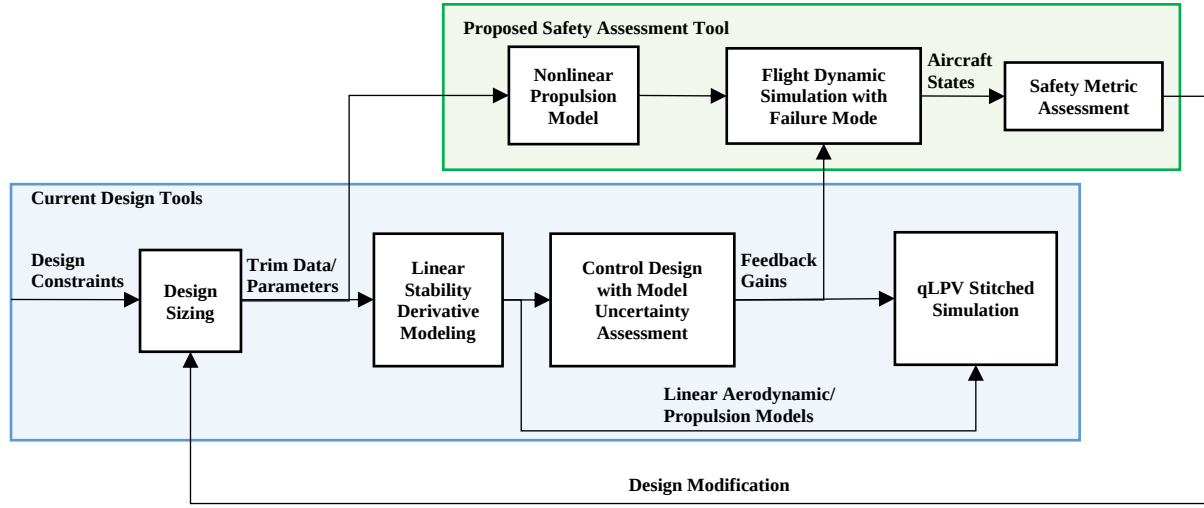


Figure 1. Illustration of conceptual design framework and proposed safety analysis tools.

The aircraft design process must balance many competing requirements to produce an aircraft that is strong, lightweight and economical, while being reliable enough to safely accomplish the intended operational mission. The process involves a combination of component and system testing and analysis, and is generally overseen by an airworthiness authority. Analysis tools vary in complexity depending on the phase of design, and are oftentimes tailored to corporate expertise bias, that is, they lack generality and are specifically tuned to a specific aircraft configuration.

Major refinement of the control systems usually is done at the preliminary phase of design, and, in the case of rotorcraft, is enabled by comprehensive analysis and computational fluid dynamics tools. Design iteration at this stage is computationally intensive but significantly less costly than iterating on a manufactured design. It is desirable to enter into the preliminary phase of design with an aircraft geometry that has been carefully assessed for as many foreseeable issues as possible.

This has been historically challenging to achieve at the conceptual design phase, because of a general lack of adequate tools. During the conceptual design, engineers must balance high level mission requirements and make decisions that define the basic geometry (number of rotors, rotor radius, speed, location, number of blades, blade solidity and twist, and wing configuration and location), installed power, number, size and type of engine, fuel storage, and ultimately, an estimate of component and system weights.

Tools for conceptual design must enable the rapid assessment of the effects of these various design parameters on aircraft performance and control within the Operational Flight Envelope (OFE). The NASA Design and Analysis of Rotorcraft (NDARC) tool was developed precisely for this purpose [1]. NDARC enables the iterative automated sizing of arbitrary rotorcraft configurations constrained by design flight conditions and mission profiles. NDARC is complemented by the **F**light dynamics and control modeling tool for **C**onceptual **D**esign (FlightCODE, under development, following the philosophy defined in SIMPLI-FLYD) [2]. FlightCODE (same as SIMPLI-FLYD) interprets vehicle trim and aerodynamic calculations from NDARC to calculate, in a linear sense, the stability and control characteristics of the aircraft for a pre-defined set of operating conditions. To date, several UAM concepts have been designed, exercising these tools, as focus vehicles to enable relevant research such as control system design, trajectory performance modeling, and handling qualities requirements [3] [4] [5] [6] [7] .

Modern advanced rotorcraft, for instance electric VTOL (eVTOL) in the context of UAM, will rely on fly-by-wire control laws. Assessment of an aircraft's design handling qualities, and the required actuator control authority, cannot be separated from the flight control laws. FlightCODE therefore includes an automated control synthesis step to assess whether viable control laws can be designed around a given configuration and flight condition. Although not constrained uniquely to this approach, FlightCODE does include an interface to the **C**ontrol **D**esigner's **U**nified **I**nTeface (CONDUIT [8]). The latter enables a handling qualities-centric multi-objective control system optimization

design approach that guarantees a top-down design approach from high level operational mission-driven requirements down to the individual components.

A full-envelope time-domain simulation capability rounds off the base analysis. This is enabled by “stitching” multiple trim and linear flight dynamics state-space models together in a quasi-Linear Parameter Varying (qLPV) framework. Time domain simulation capabilities are essential to conduct the examination of a control system design.

The handling qualities-based flight dynamics and control assessment methodology in FlightCODE has been exercised and demonstrated to support rotorcraft design for nominal flight conditions within the OFE and in normal operating states [2]. Handling qualities-based design must also consider the handling qualities of rotorcraft in the Service Flight Envelope (SFE), as derived from rotorcraft limits, and the allowable degradation due to system failures with uncertainty. These considerations are important to assess flight safety. It is argued then that a robust flight control assessment design tool, even at the conceptual level, must also consider model uncertainty, rotorcraft limits and system failures.

IV. Safety Metrics For Conceptual Design

An objective of this research is to identify metrics that quantify a degradation in safety due to failures or onset of hazardous flight conditions. Such metrics also need to inform design modifications to mitigate the degradation. Efforts to date have focused on existing military specifications that consider failures and safety with degraded handling qualities. Because many UAM concepts are hybrid rotorcraft and fixed wing vehicles, consideration has been given to specifications for both classes such as ADS-33E-PRF [9] (rotorcraft), Mil-F-8785 [10] (fixed wing), and Mil-F-83300 [11](VSTOL aircraft). ADS-33E is the most modern and comprehensive specification for rotorcraft and was selected as the baseline source of metrics for the purposes of this research. None of the existing specifications have been validated specifically for UAM vehicles. However, it was assumed that rotorcraft handling qualities requirements would be suitable for the purposes of this research as they address hover/low-speed and forward flight conditions [12]. Currently ADS-33E does not address transition flying qualities for variable configuration rotorcraft and remains a topic for future research. In addition, it should be considered that validation of metrics for failed conditions is limited due to the practical limitations and risks of acquiring flight data with a control anomaly. Another consideration is that handling qualities requirements may be highly dependent on certification requirements that have not yet been defined for UAM vehicles. Nonetheless, any proposed safety metrics must include failures, contingencies and flight envelope definitions, including loss of control, which are all important parts of this research.

The specifications above all use objective flying qualities requirements designed to achieve acceptable piloted handling qualities for the intended mission task. ADS-33E makes the distinction between “flying qualities” and “handling qualities” where flying qualities are the inherent dynamic behavior of the vehicle and handling qualities refers to the ability of a pilot to perform a task. The specifications are based on the premise that meeting Level 1 flying qualities parameters is required to achieve Level 1 piloted handling qualities. In addition, it is noted that violation of multiple flying qualities parameters may have a synergistic impact on handling qualities and the potential of degrading to Level 3.

A degradation in flying qualities due to a failure is permitted and is based on the probability of occurrence to fairly account for those failures that are less likely to occur. In addition, ADS-33E addresses the requirement for “specific failures” that are defined without regard to the probability of occurrence. To date, this research is only considering specific failures that include full or partial engine failures and flight control failures. Lastly, ADS-33E considers flight envelopes previously introduced, namely the Operational Flight Envelope and Service Flight Envelope. This research is focused on the Operational Flight Envelope where Level 1 handling qualities are required.

ADS-33E addresses flying qualities degradation due to failures ranging from abrupt transients through requirements for maneuvering flight. Figure 2 illustrates a conceptual description of the range of applicable flying qualities requirements beginning with an initial transient response, recovering and re-trimming for stable flight, and maneuvering to “get home”. Handling qualities during failures would be assessed by evaluating mission tasks, termed Mission Task Elements (MTE’s), as defined in the specifications. This latter step would require a high-fidelity piloted simulation, or an analytical pilot model, to fully assess the impact of failures on handling qualities and remains a topic for future research.

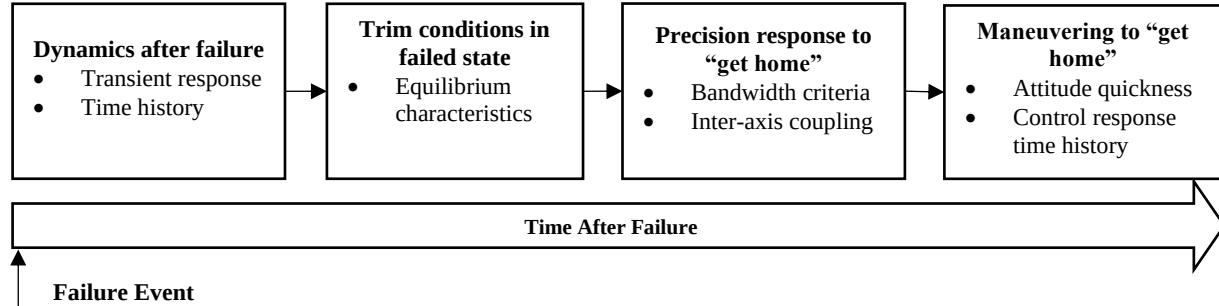


Figure 2. Illustration of applicable ADS-33E metrics following a failure.

For this research, 19 preliminary requirements were selected from ADS-33E to demonstrate an approach to integrating safety metrics and to determine the most critical metrics relevant to conceptual design. These metrics are listed in Table 1 and include control bandwidth, attitude quickness, cross axis coupling and response precision for all vehicle axes and for hover/low-speed and forward flight conditions. An additional metric proposed in [13], disturbance rejection, is also being considered because of the relevance to passenger ride qualities as well as handling qualities. Also, other metrics will be considered as this research progresses. Simulation analysis, as described in the following section, was aimed at assessing each criterion and identifying critical criteria that would be key drivers for conceptual design. For example, each metric was correlated with specific vehicle design parameters, such as rotor geometry, and evaluated for the impact on the configuration design. An important goal is to show that the safety metrics are informative to the conceptual vehicle design process.

Table 1. ADS-33E Preliminary Criteria Used For Failure Response Analysis.
Paragraph and requirement refers to criteria provided in Ref. [9].

Paragraph	Criteria	Requirement
3.1.14.4	Transients following failures	Table III
3.3 (<i>hover and low speed</i>)		
3.3.2.1	Pitch/roll bandwidth, PIO tendency	Fig. 5
3.3.2.3.2	Pitch/roll frequency and damping	Fig. 7
3.3.3	Attitude quickness (pitch, roll)	Fig. 8
3.3.5.1	Yaw bandwidth	Fig. 9
3.3.6	Attitude quickness (yaw)	Fig. 10
3.3.9	Interaxis coupling	Figs. 11,12
3.3.10.2	Collective response	Fig. 14
3.3.12	Translational response	Fig. 15
3.4 (<i>forward flight</i>)		
3.4.1.1, 3.4.6.1	Pitch/roll bandwidth	Figs. 16,17
3.4.1.2	Pitch frequency and damping	Fig. 7
3.4.3	Flight path control	3.4.3.1, 3.4.3.2
3.4.4	Longitudinal stability	Described in text
3.4.5	Interaxis coupling	Fig. 12
3.4.6.2	Attitude quickness (roll)	Fig. 18
3.4.7.1	Bank angle oscillations	Fig. 20
3.4.7.2	Turn coordination	Fig. 21
3.4.9.1	Lateral/directional frequency and damping	Fig. 23
3.4.9.2	Spiral stability	Described in texts

V. Safety Analysis Tools

The primary objective of this research was to demonstrate a safety assessment methodology for UAM vehicles in the conceptual design phase and to develop approaches that are compatible with current design tools such as NDARC and FlightCODE. The proposed safety analysis approach involves evaluating vehicle specification compliance in the presence of a failure or off-nominal operating conditions. This requires a flight dynamic simulation with failure mode implementation, flight control system design, and software for computation of specification compliance. Accounting for uncertainty is especially important for models concerning degradation or failure, and tools for including model uncertainty in the analysis are needed for a more robust assessment. This section will describe the methods used for simulation development and computation of safety metrics.

A. Simulation Description

Two NASA-developed concept vehicles [3, 4], the six passenger collective-controlled quadrotor and RPM-controlled Lift+Cruise configurations were selected to demonstrate handling qualities and stability analysis in nominal and off-nominal conditions. Renderings of these vehicles are shown in Figs. 3 and 4, and aircraft parameters for each vehicle are provided in Table 2.

Previous baseline control system studies [14] and pilot-in-the-loop handling qualities evaluations have utilized a “stitched” simulation framework. This approach uses quasi-linear parameter varying (qLPV) aerodynamic and propulsion models (typically generated from FlightCODE), while retaining nonlinear gravitational forces and nonlinear rigid-body equations of motion. This has been a useful model structure for real-time simulation applications and rapid assessment of stability and control performance. Assessment of specification compliance in the presence of failures requires vehicle models that accurately predict off-nominal performance characteristics, particularly when the control inputs and aircraft states deviate from reference trim conditions. In this work, linear models were used for control design purposes; however, to avoid potential violations of linear theory when assessing the impact of failures, nonlinear blade element momentum theory (BEMT) propulsion models based on NDARC theory [1] were implemented to capture the rotor performance at a wider range of operating conditions. Future work may explore the feasibility of integrating models that were linearized about a failure condition into the existing qLPV framework.

Table 2. Aircraft Parameters.

Parameter	Quadrotor	Lift+Cruise
Gross Weight (<i>lb</i>)	6,480	5,795
Number of Rotors	4	9
Number of Blades	3	2
Rotor Radius (<i>ft</i>)	13.1	5
Aircraft moments of Inertia (<i>slug – ft²</i>)		
I_{xx}	15,540	6,893
I_{yy}	16,963	4,500
I_{zz}	20525	9,611
I_{xy}	0	0
I_{yz}	0	0
I_{xz} (to be updated)	0	0
Rotor Inertia (<i>slug – ft²</i>)	265.8	13.49



Figure 3. Rendering of quadrotor reference design.



Figure 4. Rendering of Lift+Cruise reference design.

The required inputs to the nonlinear BEMT propulsion models are consistent with NDARC and FlightCODE. These include parameters such as rotor radius, chord taper, blade twist, blade solidity, flap frequency, lock number, and rotor inertia. Efforts were made to ensure that the propulsion model predictions were consistent with NDARC for the same

operating conditions. Output of a trim sweep for the collective controlled quadrotor from NDARC was compared to the BEMT predictions. Figures 5 and 6 show comparisons of longitudinal/lateral flap angles (β_{1c}, β_{1s}), mean inflow ratio (λ_0), and hub frame forces and moments. The largest percent difference in thrust and torque are approximately 3% and 10% respectively. Current analysis is focused on hover and low speed (less than 45 knots), and these models provided reasonable predictions for the first phase of safety assessment tool development.

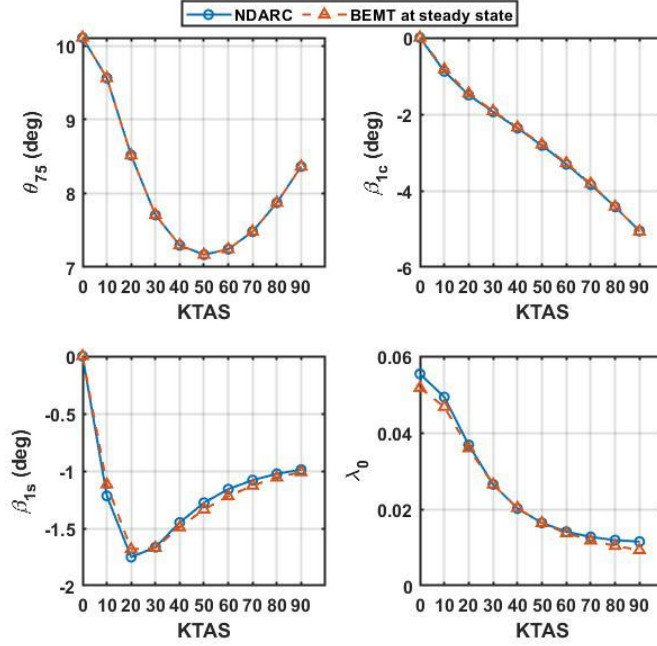


Figure 5. Comparison between NDARC output and BEMT rotor flapping and inflow predictions for collective-controlled quadrotor.

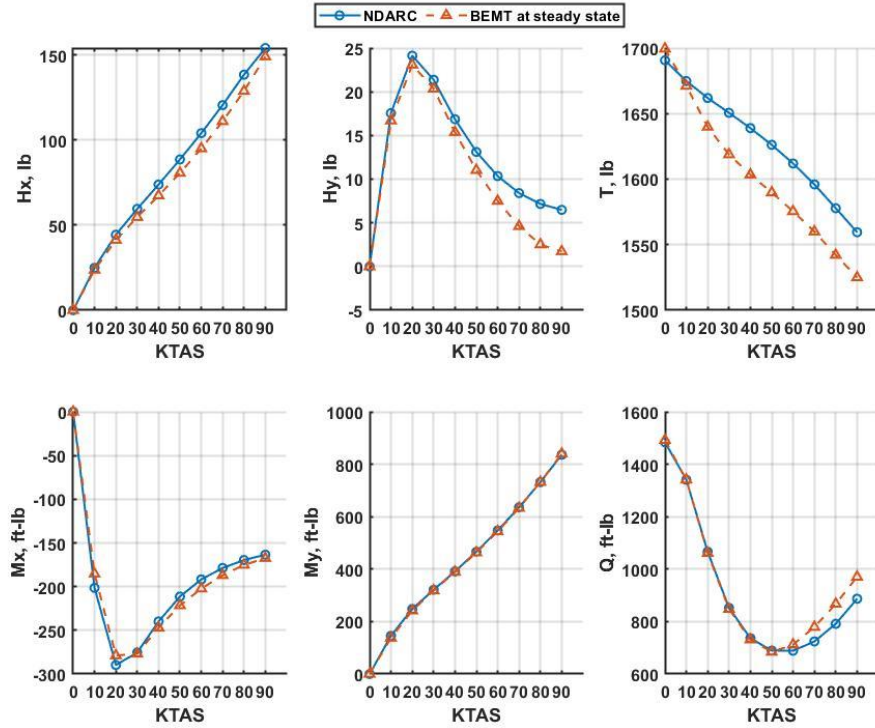


Figure 6. Comparison between NDARC output and BEMT hub-load predictions for collective controlled quadrotor.

Each rotor model includes states for flap angles in the non-rotating coordinate frame ($\beta_0, \beta_{1c}, \beta_{1s}$), inflow ratios ($\lambda_0, \lambda_{1c}, \lambda_{1s}$), and rotor speed (Ω). The blade flapping equation of motion in the rotating coordinate frame was constructed by considering the forces acting on the blade section. The forces and moments considered include an inertial force opposing the flap motion, a centrifugal force directed radially outward, and an aerodynamic force normal to the blade which causes a moment of the flap hinge [15]. Inflow states were computed using a Pitt and Peters dynamic inflow model. Each rotor contains seven states. The state vector for both vehicles includes rotor and aircraft states and is given as $\vec{x} = [\beta_{0k}, \beta_{1ck}, \beta_{1sk}, \lambda_{0k}, \lambda_{1ck}, \lambda_{1sk}, \Omega_k, u, v, w, p, q, r, \phi, \theta, \psi]$ where k ranges from one to the total number of rotors.

The control input vector for the collective controlled quadrotor is $\vec{u} = [\delta_{lat}, \delta_{lon}, \delta_{ped}, \delta_{col}, V_k]$ where δ_{lat} , δ_{lon} , δ_{ped} , and δ_{col} are the lateral, longitudinal, pedal, and collective inputs in radians. The rotor collective actuators are represented with a second order linear model, including rate and position limits. The input motor voltage for the k^{th} rotor is given as V_k . The electric motor characteristics were added using a procedure outlined in previous work [14]. This approach allows each rotor RPM to be unique, and is not fully consistent with the cross-shafted propulsion system described in [4].

The control input vector for the Lift+Cruise vehicle is $\vec{u} = [\tau_k, \delta_E, \delta_{A_L}, \delta_{A_R}, \delta_R]$ where τ_k is the k^{th} rotor shaft torque input in ft-lb. The elevator, left/right aileron, and rudder control surface deflections are represented with δ_E , δ_{A_L} , δ_{A_R} , and δ_R .

B. Control System Design Approach

The control system will have a significant impact on flight behavior following a failure. Although the scope of this research does not include an in depth design of failure accommodating controls, the interpretation of results will depend on the baseline control structure and performance. Therefore, selection of control mode and feedback gains were made to target specific performance metrics such as attitude quickness, disturbance rejection bandwidth, and stability margin criteria as defined in Ref. [9]. A model following architecture with feedback error was used for both vehicles to achieve the desired response type in each axis [16]. A top level block diagram of the simulation structure is shown in Fig. 7. Command models were used to achieve Attitude Command Attitude Hold (ACAH) response types in the pitch and roll axes, while a Rate Command Direction Hold (RCDH) response type was implemented in the yaw axis.

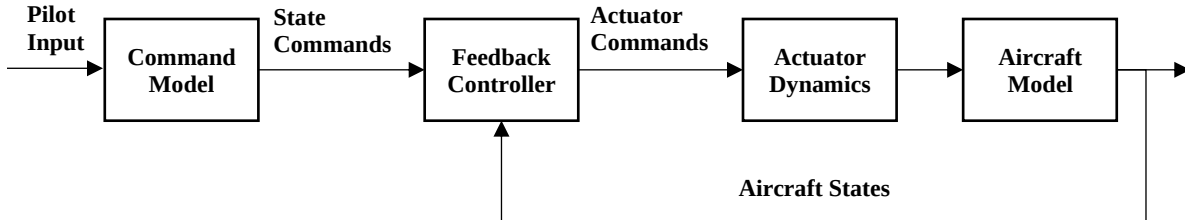


Figure 7. Top level block diagram representation of control system for longitudinal inputs.

Linear quadratic integral (LQI) feedback gains were computed to enable tracking capability for command following and feedback stabilization [17]. The LQI implementation requires augmentation of the original state-space representation to add states that represent an error signal for a particular aircraft state. Error signals for ϕ , θ and ψ were added to provide zero steady-state error command tracking. The error states ($\vec{x}_{err}$) are defined as the integral between a reference command ($\phi_{CMD}, \theta_{CMD}, \psi_{CMD}$) and the response variable. This results in an augmented stability matrix ($\tilde{A}$) and control matrix ($\tilde{B}$), which are then input into the conventional LQR algorithm available in MATLAB®. The cost matrices, Q and R , were determined by sweeping the diagonal terms associated with the error states and computing the resulting time domain and handling qualities specifications. Figures 8 and 9 show example results of the control design approach applied to the six passenger collective controlled quadrotor for pitch and roll axes. For this example, the controller was designed to achieve Level 1 handling qualities, using small and moderate amplitude attitude change control criteria as defined in ADS-33E for hover and low speed conditions. This is a time domain-based metric that was evaluated using a step response for each axis. For example, to compute the attitude quickness specification for the roll axis in Fig. 8, a 15 degree roll angle step command was input to the command model. The

ratio of peak roll rate (p_{pk}) to maximum roll angle relative to the trim condition ($\Delta\phi_{pk}$) was then plotted against the undershoot ($\Delta\phi_{min}$). Small amplitude control response characteristics are computed using the Bandwidth criteria and results are provided in Fig. 9. This is a frequency based metric which evaluates the bandwidth frequency (ω_{BW}) and the phase delay (τ_p) parameters. For an ACAH response type, the bandwidth frequency is evaluated where the phase curve crosses -135 degrees. The phase delay is computed using the phase curve at frequencies greater than the bandwidth frequency, and describes the slope of the curve beyond -180 degrees. Further information regarding these specifications and calculation methods may be found in [9] and [13].

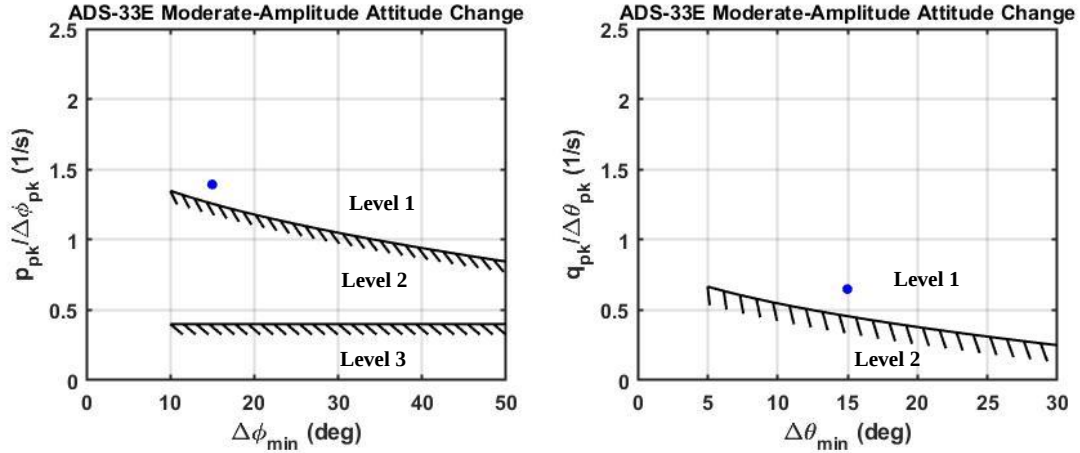


Figure 8. Nominal roll (left) and pitch (right) moderate-amplitude attitude control responses for collective controlled quadrotor. The blue circle represents the vehicle response using the model following controller.

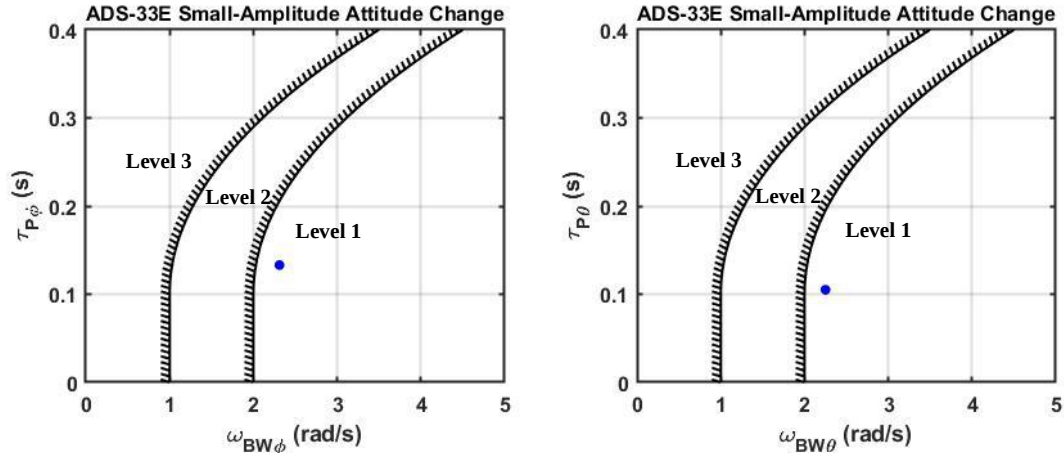


Figure 9. Nominal roll (left) and pitch (right) small-amplitude attitude control responses for collective controlled quadrotor. The blue circle represents the vehicle response using the model following controller.

C. Uncertainty Quantification

Uncertainty quantification is an important component to any safety analysis. To establish viability of a conceptual design, one seeks to first ensure that the vehicle can be operated safely for the nominal design, and then for a given (possibly large) set of failures that is needed to complete a safety qualification. In any case, the analysis should ensure robustness to uncertainty present in the system. In general, one cannot prove that a system is safe under all circumstances. However, it is possible to prove that a system is not safe for a known condition, to make safe the design for that condition, and to iterate until the design is safe for all known conditions of importance.

Uncertainty can enter analysis in many ways. For concreteness here, the effect of uncertainty is considered for a given design point, such as the nominal design in a particular flight condition, or any envisioned failure condition. It is further assumed here that parametric uncertainty is provided to the analysis from external methods, such as system identification (that estimates parameters with uncertainty), physical experiment where one directly measures the variation of a parameter over operating condition, or through a physics-based analysis possibly leveraging a higher-

fidelity numerical method. Methodologies used for managing uncertainty in machine learning and high-fidelity simulation are also being leveraged for handling qualities analysis, including Polynomial Chaos [18], and Koopman operator theory-based [19] methodologies. Another such approach tailored to managing uncertainty directly with qLPV models was explored in [20]. Here a Gaussian Process machine learning framework was used to obtain parameter uncertainty in the stability and control derivatives for a set of reference flight conditions. Figure 10 provides an example of trim state and stability derivative perturbations as a function of airspeed for the six-passenger collective-controlled quadrotor. The blue line represents the nominal trim and stability derivatives. The red lines represent each perturbed sample, and the $\pm 3\sigma$ bounds computed from the Gaussian Process predictive variance are shown in green and black. The feedback gains were computed using the nominal bare-airframe linear models and scheduled with airspeed. The controller performance was then evaluated using the perturbed models output from the GP. For example, Fig. 11 shows an assessment of pitch disturbance rejection for each perturbed sample at a trim speed of 15 knots.

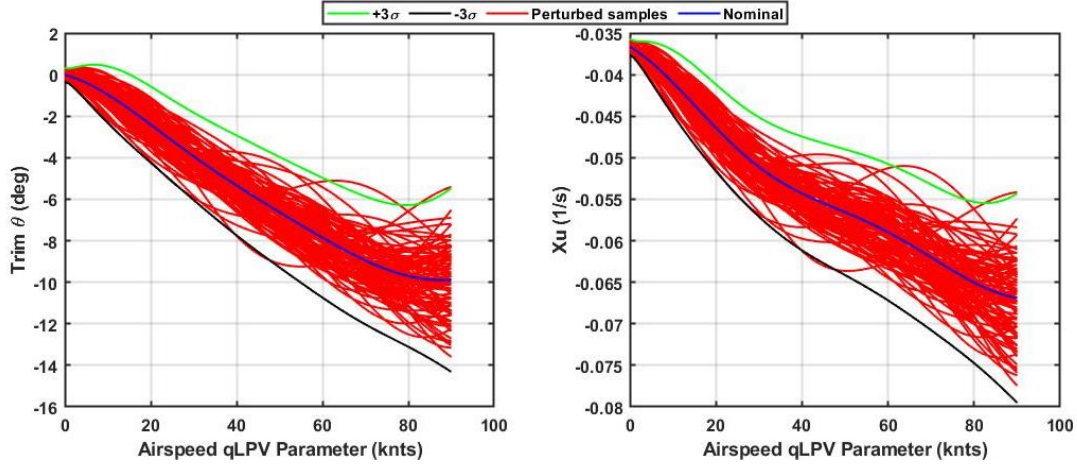


Figure 10. Example output of machine learning Gaussian Process for collective controlled quadrotor.

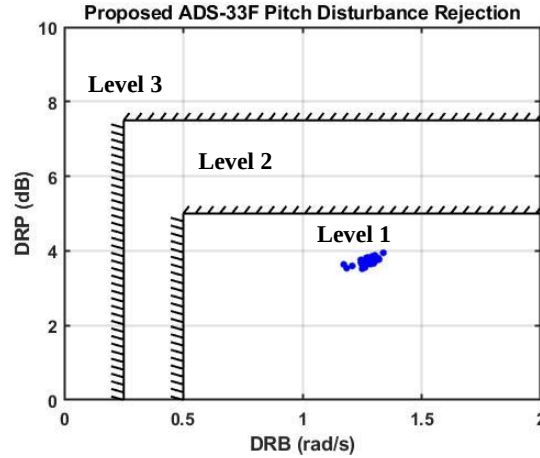


Figure 11. Pitch disturbance rejection criteria with model uncertainty for collective controlled quadrotor.

Monte-Carlo analysis is generally an applicable, and easy to use tool for checking output behavior to uncertainty in the input, as in the previous example. While such tools should be employed frequently, they are typically not exhaustive, and in many applications can fail to identify critical inputs that would cause a system output to exceed acceptable bounds. The underlying reason for this is the curse-of-dimensionality. For example, with only six uncertain input parameters, taking 10 values each, there are already a million parameter combinations to check – and if each check requires a simulation that takes only one second to run, the overall analysis will take 11.5 days to complete. In some cases, it is possible to circumvent the curse-of-dimensionality. For example, branch-and-bound methods can eliminate subsets of combinations to check. There are also cases where the form of the model can be exploited. The

most important example of the latter case is linear systems, where H_∞ and μ -analysis methods enable a rigorous exploration of the effect of model and input uncertainties on worst-case control stability and performance [21] [22] [23]. Furthermore, linear system analysis is a core component for vehicle handling qualities standards, and safe operation of a vehicle requires it to behave, for the most part, in a linearly predictable manner. Here we demonstrate one such analysis to make clear, in a more specific way, the need for these types of methods in safety analysis.

A scenario with the NASA Lift + Cruise vehicle [3] in hover is considered. The vehicle dynamics are linearized with state vector $x = [\psi, x_e, y_e, h, \Omega_1, \dots, \Omega_8, \phi, \theta, u, v, w, p, q, r]$, and with the bare airframe shaft torques $u = [\tau_1, \dots, \tau_8]$. These physical variables are then normalized depending on the intended application for the analysis. The focus here will be on disturbance rejection with rotor-speed control, so the variables are normalized either to reasonable maximum values, or to trim values. The values selected for this example are shown in Table 3 and Table 4. The rotor rates $\Omega_1, \dots, \Omega_8$ are the trim rates (which are not maximums), and the maximum rotor-torque values shown are 1.5 times the torque required for trim. The factor of 1.5 establishes the torque required to meet proposed ADS-33E-PRF disturbance rejection requirements [13], with a constant gain feedback, Linear-Quadratic Integrator (LQI) architecture [24] for rotational-rate control. A Translation-Rate Command (TRC) controller for earth-relative position x_e, y_e, h and a Rate-Command Direction Hold (RCDH) controller for yaw ψ was implemented. The maximum torque limits assumed here exceed the maximum torque initially envisioned for the concept vehicle, which did not consider the need to meet disturbance rejection requirements.

Table 3. State variable normalization factors.

ψ	x_e	y_e	h	$\Omega_1, \dots, \Omega_8$	ϕ	θ	u	v	w	p	q	r
5 deg	10 ft	10 ft	10 ft	80.5 rad/s	5 deg	5 deg	5 ft/s	5 ft/s	5 ft/s	3 deg/s	3 deg/s	3 deg/s

Table 4. Input variable normalization factors (notional maximum permitted rotor-torque).

τ_1	τ_2	τ_3	τ_4	τ_5	τ_6	τ_7	τ_8
662.97 ft-lb	662.97 ft-lb	662.97 ft-lb	662.97 ft-lb	660.05 ft-lb	660.05 ft-lb	660.05 ft-lb	660.05 ft-lb

Uncertainty is added to the linear model in the form of a 50% variation in the torque-to-rotor rate control derivatives (i.e., $\partial\Omega_i/\partial\tau_i, i = 1, \dots, 8$). A μ -analysis is then performed using the MATLAB Robust Controls toolbox, first to check robust stability (the design is stable up to 122% of the modeled uncertainty but not including the rotor-torque limits), and then to establish worst-case performance for specific outputs. Figure 12 shows results for height-hold performance and the corresponding rotor 1 torque – the case is similar for the other command channels and rotor torques. On the left-side plot the disturbance rejection capability for height-hold meets the bandwidth and peak design requirements of greater than 0.17 rad/sec (where the sensitivity plot first crosses -3dB from below) with less than 3dB peak [13]. Interestingly, this performance characteristic is not sensitive to the modeled uncertainty, as the plots for nominal and worst-case limits all lie on top of one another. The plot to the right captures the critical effect of the uncertainty. It shows the gain from the worst-case commanded input to the torque required on rotor 1. A potential safety issue occurs where the graph crosses 0 dB, corresponding to the maximum torque permitted for the normalized system. The plot shows that the nominal system is safe for the worst-case command vector, but that the modeled uncertainty may cause the rotor torque to exceed its design capability by up to 10 dB (i.e., a factor of 3).

Figure 13 shows the critical effect of the torque limits on the system’s overall response. Here a normalized simultaneous disturbance (or pilot command) to both x_e and h is applied to the system input at 4.48 rad/s. The robust stability analysis identified this frequency as the most susceptible to producing an unstable response. The right-side plot in Fig. 12 shows that this frequency also causes the controller to drive rotor 1 torque above the defined limit. The left-side plot of Fig. 13 shows the linear system response when the torque limit is not enforced. Here, the vehicle has almost no response because 4.48 rad/s exceeds the bandwidth of the closed-loop system. However, when the torque limit is imposed, the system goes unstable, as shown on the right-side of Fig. 13. An instability such as this, if present and excitable in a real system, can cause Pilot Induced Oscillation [25] and/or a severe mishap or crash. A key take away here, is that the linear system analysis with uncertainty shows where the system’s linear behavior will end in a practically informative way.

There was much in this example that was notional. In particular, the torque limits, control derivative uncertainty, and degree to which the unsafe frequency zone 3-9 rad/s (right-side Fig. 12) is susceptible to excitation. More sophisticated physics-based models can drive this information, and these may include machine learning methods for

interpolating between validated analysis points (which are costly to require) and providing uncertainty as discussed above. The purpose here was to concretely show the need for more work in these areas, and the importance of uncertainty quantification and rigorous worst-case analysis as components in an overall system safety analysis.

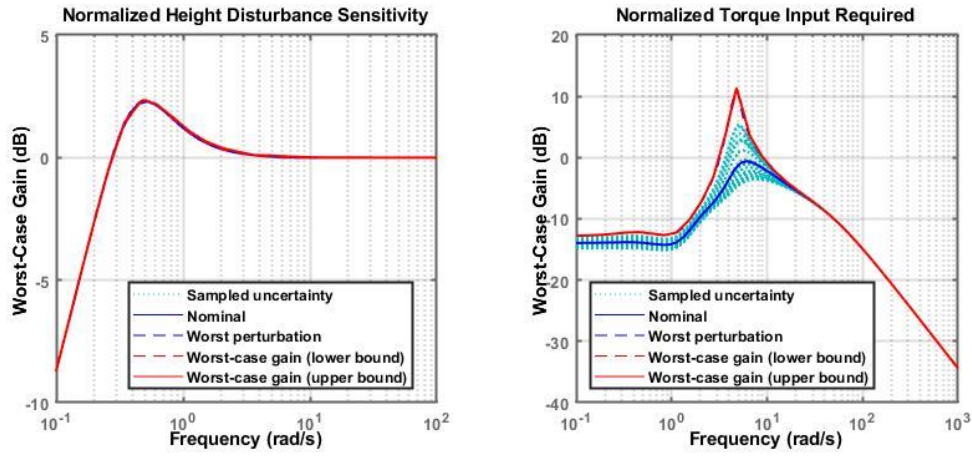


Figure 12. [Left] Normalized height-hold response sensitivity to worst-case normalized disturbance input. [Right] Gain to rotor 1 torque due to normalized worst-case disturbance (or commanded) input for Lift+Cruise.

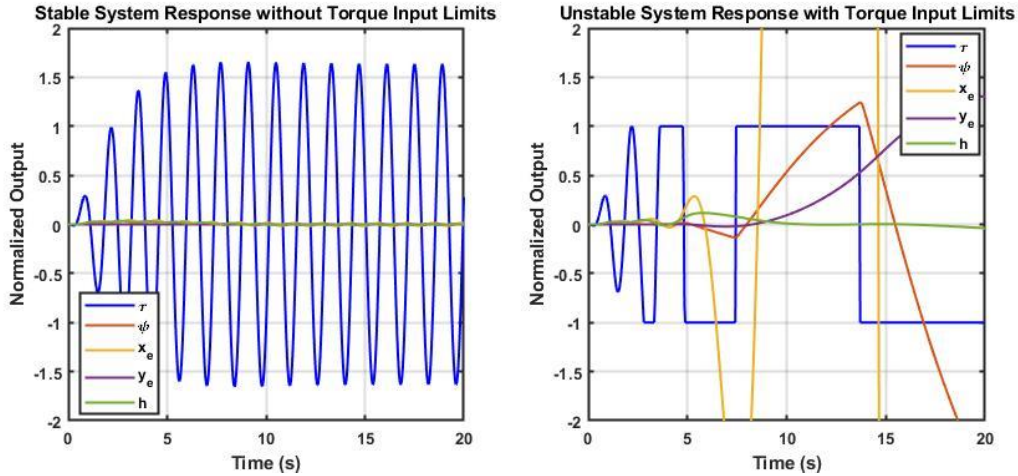


Figure 13. [Left] Simulated system response to normalized worst-case disturbance without torque limits. [Right] Same simulation except with torque limits enforced for Lift+Cruise.

VI. Simulation Test Results

The final component of the simulation-based tools is that for data analysis. This includes software that calculates values for specific metrics and compares that to the specification requirements for both nominal and off-nominal conditions. These calculations generally fall into two broad categories, time history-based analysis and frequency-based metrics. Time history metrics such as moderate amplitude attitude change are computed using step or impulse commands. Bandwidth metrics such as disturbance rejection and pilot bandwidth are computed by applying frequency sweep or chirp signals to pilot inputs or feedback states. The approach of applying sweeps in a time marching simulation was taken to enable the implementation of failures in various components of the simulation. Additionally, this approach could be used to assess the effects of rate limiters and saturation limits on specification compliance, which may be critical for vehicles relying on variable RPM electric motors. Figure 14 depicts the simulation structure, and the location of frequency inputs such as a pilot sweep (δ_{lon_p}), or disturbance sweep (θ_d).

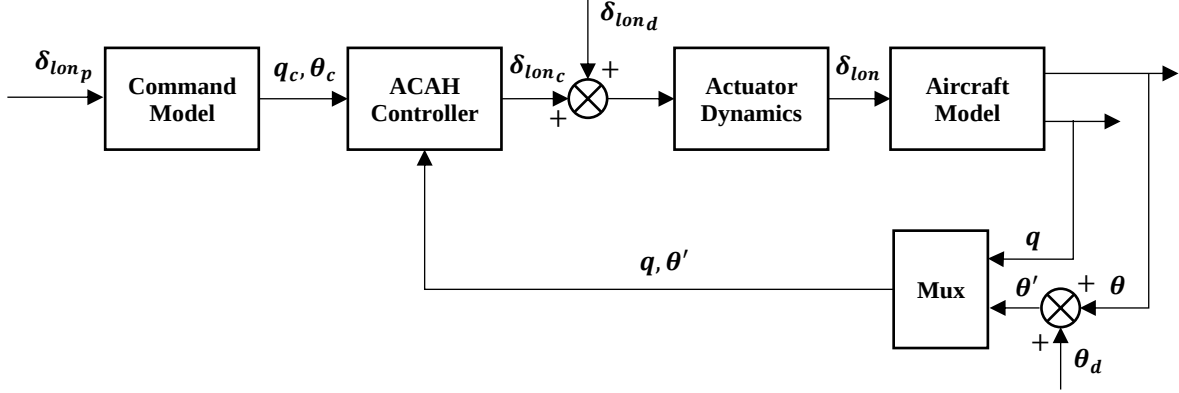


Figure 14. Block diagram of simulation with sweep inputs.

Computer generated frequency sweep signals were implemented using the approach outlined in [26]. Equations (1)-(3) show how the disturbance sweep (θ_d) is computed as a function of the desired amplitude (A_d) and exponentially increasing frequency ($\omega(t)$). The length of each sweep (T_{rec}) was 100 seconds, the minimum frequency (ω_{min}) was 0.3 rad/s, the maximum frequency (ω_{max}) was 12 rad/s. Constant terms (C_1 and C_2) were set to 4 and 0.0187, respectively [26]. Fade in and fade out functions were applied to the beginning and end of each sweep to avoid abrupt inputs. Additionally, three seconds of trim was applied at the beginning and end of each run.

$$\theta_d(t) = A_d \sin(\theta(t)) \quad (1)$$

$$\theta(t) = \int \omega(t) dt \quad (2)$$

$$\omega(t) = \omega_{min} + C_2 \left(e^{\frac{C_1 t}{T_{rec}}} - 1 \right) (\omega_{max} - \omega_{min}) \quad (3)$$

Figures 15 and 16 show time history and frequency response examples for disturbance rejection criteria and pilot bandwidth using the collective controlled quadrotor simulation. An amplitude of five degrees was used for both θ_d and δ_{lon} sweeps. Figure 15 shows Level 1 disturbance rejection compliance with a peak of 3.8 dB, and a disturbance rejection bandwidth of 1.25 rad/s evaluated at -3dB. Spectral content beyond ω_{max} was not used for computation of the specifications. Similarly, in Fig. 16, Level 1 small-amplitude attitude change criteria are met with a bandwidth of approximately 2.2 rad/s evaluated at a phase of minus 135 degrees.

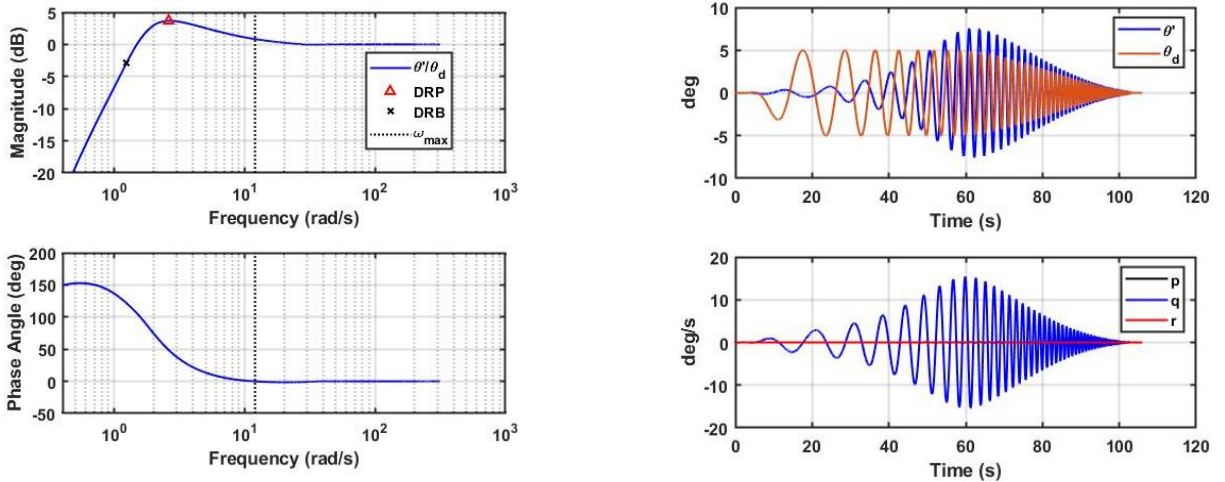


Figure 15. Frequency and time history responses of pitch disturbance sweep for collective controlled quadrotor.

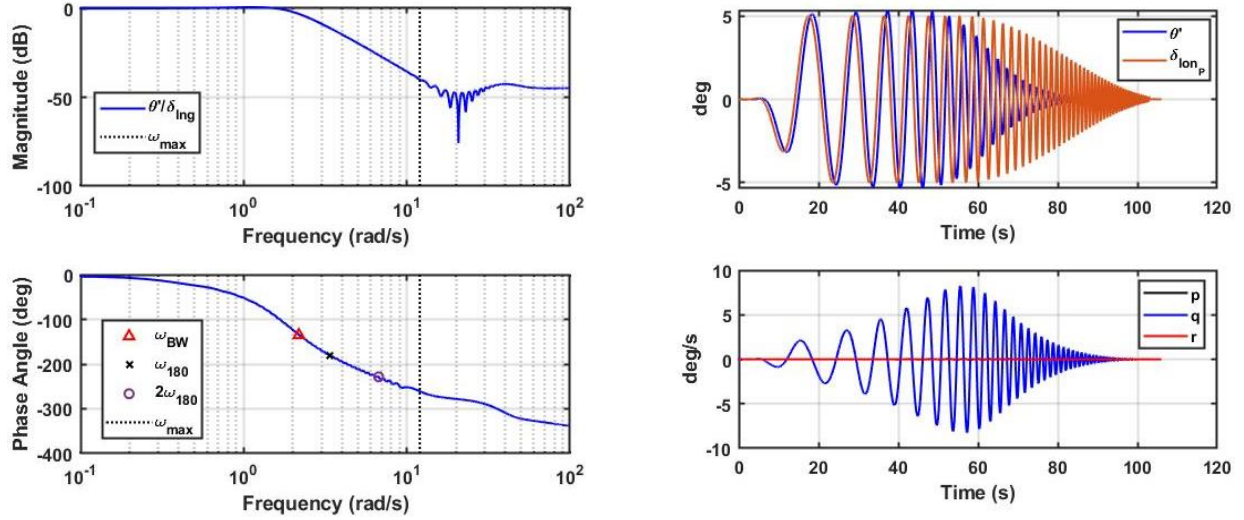
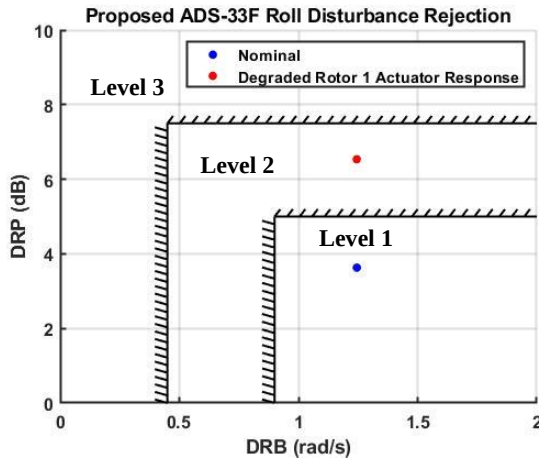
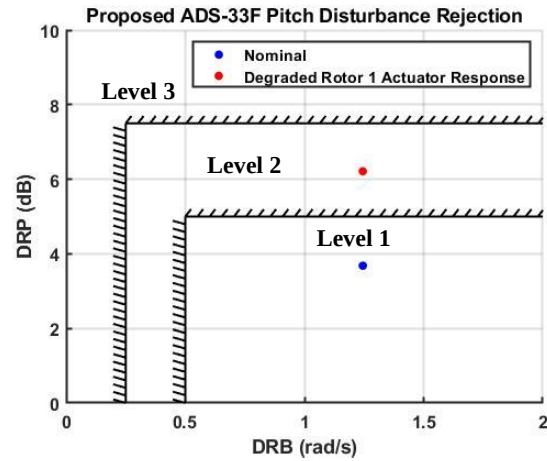


Figure 16. Frequency and time history responses of longitudinal pilot sweep for collective controlled quadrotor.

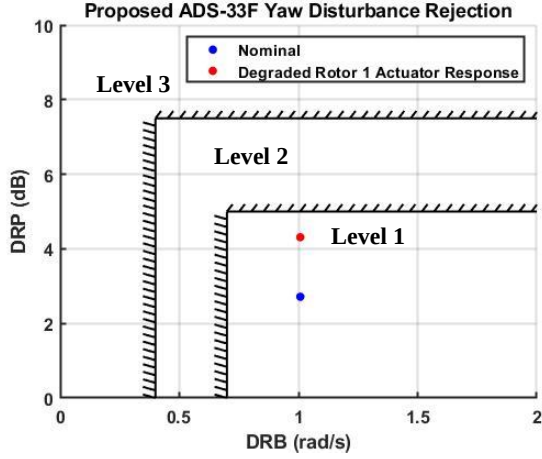
An example of degradation in specification compliance was studied using the collective controlled quadrotor simulation. Nominal disturbance rejection, pilot bandwidth, and interaxis coupling criteria were compared to performance with a degraded rotor actuator response. The time constant of rotor 1 (front left rotor) was increased significantly from 0.04 seconds to 0.19 seconds to introduce unexpected asymmetries in rotor response. Figure 17 shows disturbance rejection criteria for the roll, pitch, yaw and heave axes. Roll and pitch criteria degrade to level two due to the increase in Disturbance Rejection Peak (DRP) from approximately 3.8 dB to 6.2 dB. DRP characterizes overshoot in the initial response [13] and degraded stability margin. The yaw and heave axes experience an increase in DRP; however, it is not significant enough to degrade to Level 2. No significant changes in DRB were observed.



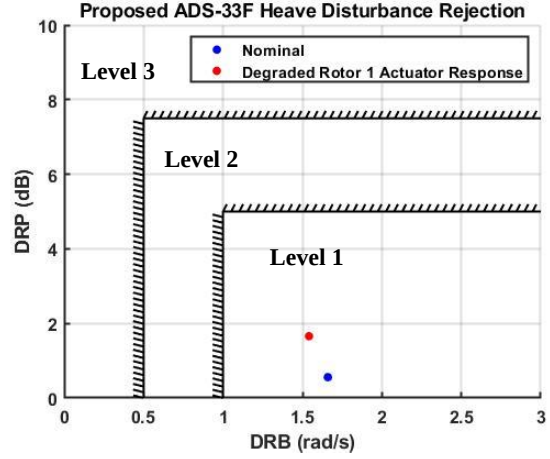
(a) Roll disturbance rejection



(b) Pitch disturbance rejection



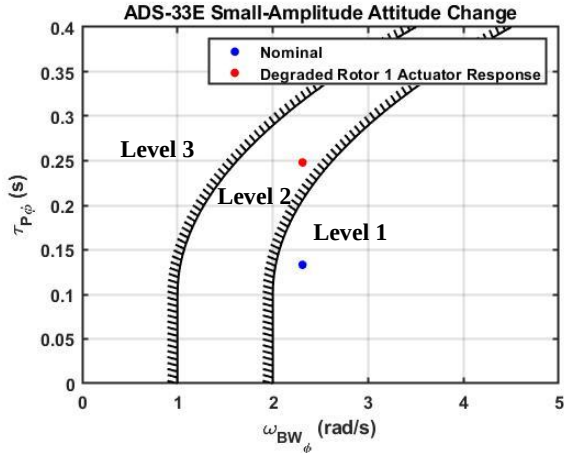
(c) Yaw disturbance rejection



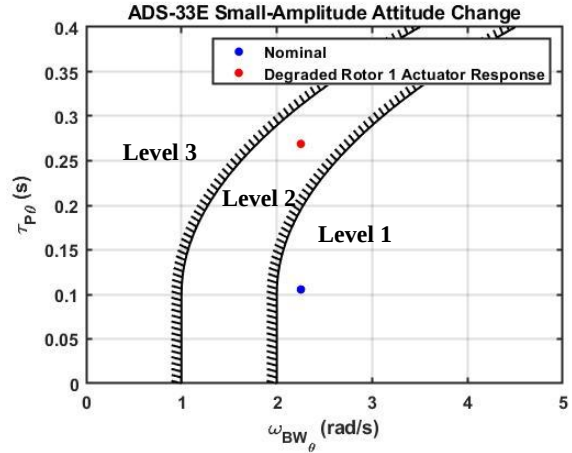
(d) Heave disturbance rejection

Figure 17. Disturbance rejection specifications for collective controlled quadrotor.

Figure 18 shows pitch and roll small-amplitude attitude change criteria for the pitch and roll axes. An increase in phase delay for each axis is observed, falling into the Level 2 region. At hover, the dynamics in the roll and pitch axes have similarities that likely contribute to their symmetric performance in failed conditions. Interaxis coupling criteria also showed degradation to Level 2. This criterion requires a plot of the average magnitude of roll-due-to-pitch (p/q) versus pitch-due-to-roll (q/p) between the phase bandwidth and neutral stability frequencies of the pitch-due-to-pitch (θ'/δ_{lon}) control inputs [9].



(a) Roll disturbance rejection



(b) Pitch disturbance rejection

Figure 18. Small-amplitude attitude change criteria for collective controlled quadrotor.

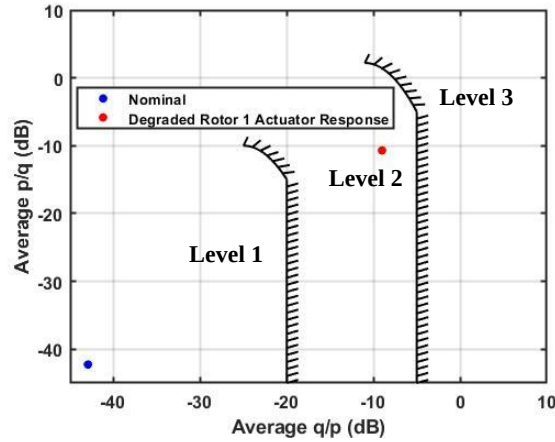


Figure 19. Interaxis coupling for collective controlled quadrotor.

VII. Summary And Future Work

To date, safety metrics derived from existing handling qualities specifications have been successfully applied in a simulation-based framework and a preliminary study of selected actuator failures with a collective controlled quadrotor configuration has been completed. The potential for a significant degradation in handling qualities has been demonstrated and ongoing research is focused on identifying critical criteria and demonstrating configuration design changes based on compliance with these metrics. Furthermore, uncertainty analysis has demonstrated the potential for vehicle instability due to implementation of practical operating considerations such as rotor torque limits. This research has also shown that hybrid rotorcraft/fixed wing configurations present unique safety considerations during failures. For example, interaxis coupling has been identified as a potential critical safety metric due to the loss of control symmetry with a propulsion failure. Research will be needed to identify metrics that are more specifically suitable for UAM configurations and to address the role of failure accommodating control systems and autonomous systems.

Simulation modeling is a key enabling technology and aerodynamic modeling requirements and accuracy, specific to failures, remains a topic for research. This study has developed simulation modeling approaches for certain types of failures, but further work is needed to define and model a full range of critical failures. This work has also addressed the role of the control system on the degradation in handling qualities due to failures. To date, this work has looked at how an example degradation can affect a nominal controller design, but not how a system might address more substantial failures.

Future research will be aimed at demonstrating the feasibility of a conceptual design process that includes safety metrics developed in this work. Validation of these results is a future objective that would require piloted simulation studies to assess the degradation in handling qualities due to a failure. Recent research on pilot modeling has the potential to be integrated into the design framework that could provide validation for some cases and include handling qualities prediction and assessment of ride qualities/passenger comfort during failures.

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