# Handling Qualities Based Assessment of Scalability for Variable-RPM Electric Multi-Rotor Aircraft


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## ABSTRACT

An examination is conducted into the effects of increasing rotor diameter on the handling qualities of a quadcopter with fixed-pitch, variable-RPM rotors. Five aircraft are simulated, with rotors ranging from 1 to 8 feet in diameter. The flight characteristics of the aircraft are quantified using Froude-scaled handling qualities metrics. Several scaled ADS-33E-PRF handling qualities metrics are evaluated, including response to a collective controller, disturbance rejection, and bandwidth in roll, pitch, and yaw. It is concluded that aircraft performance is limited by disturbance rejection requirements in yaw as well as actuator saturation limitations that are present in other control channels, and a quadcopter with rotors over 2 feet in diameter will need greater installed power than what is currently estimated in order to meet handling qualities metrics without violating actuator constraints.


## INTRODUCTION

There is growing demand for the development of large-scale electric VTOL (eVTOL) aircraft for use as transport vehicles, including unmanned cargo aircraft as well as passenger vehicles. This demand is exemplified by the release of NASA's Urban Mobility Grand Challenge (Ref. 1) as well as the Uber Elevate program (Ref. 2), both of which call for the development of eVTOL aircraft at a much larger scale than exists commercially today.

The development of eVTOL aircraft for use as short-range transport vehicles has the potential to revolutionize the transportation industry, but these aircraft face a multitude of technical challenges that must be addressed before they are commercially available. Some of these challenges, described by Johnson et al. (Ref. 3), include the safety, operational effectiveness, and overall aircraft performance. All of these relate to the responsiveness and maneuverability of the aircraft, which are quantified through the use of handling qualities metrics.

The scaling up of traditionally small multicopters brings with it significant changes in the responsiveness and controlability of the aircraft. Typical multicopters are controlled through the creation of differential thrust by changing the speeds of the fixed-pitch rotors. Through this control strategy negates the need for the mechanical complexity of swash plates, the responsiveness of a multicopter is dependent on the speed at which changes in rotor thrust can be achieved. As a result of greater rotational inertia, the use of larger diameter rotors will delay how quickly changes in rotor thrust can be produced, which will hinder the aircraft's ability to meet handling qualities requirements.

The development and refinement of handling qualities for the evaluation of multicopter performance is an active area of research. This is a research gap that must be addressed before eVTOL aircraft can be used as large-scale transport vehicles. Traditional handling qualities for helicopters typically focus primarily on pilot workload and comfort. Several groups (Refs. 4–7) have proposed alternate handling qualities for unmanned aircraft that focus more on mission satisfaction rather than the satisfaction of the pilot.

Ivler et al. (Ref. 8) utilized a scaled version of the ADS-33E-PRF Mission Task Elements (MTEs) to evaluate the performance of a 3.75 lb quadcopter and successfully showed that, to quantitatively evaluate the response of the aircraft, kinematically scaled (based on the maximum velocity of the aircraft) ADS-33E-PRF requirements were effective. This kinematic


Presented at the Unmanned VTOL Session of the 75th Vertical Flight Society Annual Forum, Philadelphia, PA, May 13-16, 2019

scaling cannot be implemented if the maximum forward flight speed of the aircraft is unknown. However, another option lies in Froude-scaled MTEs based on the length scale of the aircraft. This method, described by Alveranga et al. (Ref. 9), changes the bounds of Level 1 and Level 2 handling qualities requirements based on a relative length scaling.

A previous study by Walter et al. (Ref. 10) examined the effects of increasing rotor diameter on the heave response to a change in collective command by simulating a single, isolated rotor. Based on Froude-scaled ADS-33E-PRF requirements, it was concluded that rotors greater than 6 feet in diameter would not be able to produce changes in thrust quickly enough to have a satisfactory response along the heave axis. The present study moves forward from this previous research by simulating a full quadcopter in order to examine handling qualities metrics along the pitch, roll, and yaw axes, as well as heave.

## MODELING

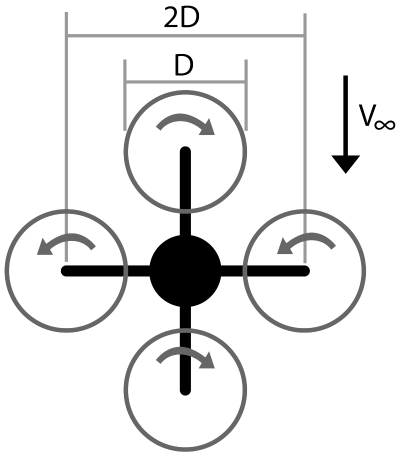


**Fig. 1. Plus Type Quadcopter Configuration**

In the present study, plus-configuration quadcopters (Fig. 1) with rotors ranging from 1 to 8 feet in diameter are simulated using the Rensselaer Multicopter Analysis Code (RMAC) (Ref. 11).

### Aircraft Dynamics Model

RMAC models the aircraft as a 6DOF rigid body, with point forces representing gravity, fuselage drag, and rotor forces and moments. Rotor loads are calculated using blade element theory, with a 3x4 Peters-He finite-state dynamic wake model. Motor dynamics are modeled by conservation of angular momentum, as shown in Eq. 1. Instead of the aerodynamic torque being transferred to the aircraft as a yawing moment, the torque produced by the motors is transmitted, which captures the net effect of rotor acceleration and aerodynamic torque.

$$I\dot{\Omega} = \tau_{motor} - \tau_{aero} \tag{1}$$

For each aircraft size, the dynamics are numerically linearized about a steady hover into a linear time-invariant state-space representation in order to design control laws that stabilize the aircraft. The higher frequency inflow dynamics are reduced out of the model via static condensation, resulting in a state space model comprised only of the rigid body and motor dynamics. Controllers are designed about this reduced linear model, which are then validated with the fully nonlinear model in Simulink.

### Aircraft Parameter Scaling

The simulated quadcopters are based on the AeroQuad Cyclone, shown in Fig. 2. The nominal specifications of the Cyclone are given in Table 1. The aircraft, which has 1 foot diameter rotors, is scaled up to have 2, 4, 6, and 8 foot diameter rotors. The rest of the aircraft geometry is scaled as shown in Table 1, with gross weight scaled to maintain a constant disk loading across all simulated vehicles.

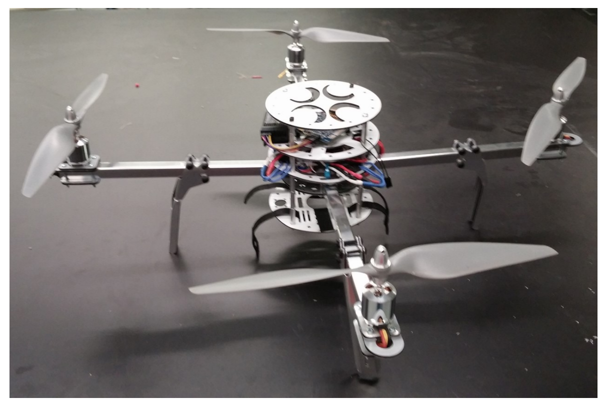

**Fig. 2. AeroQuad Cyclone Quadcopter**

**Table 1. Nominal Aircraft Parameters**

| Parameter | Value | Scaling Factor |
|---|---|---|
| Rotor Diameter | 12 in | $D$ |
| Gross Weight | 4.41 lb | $D^2$ |
| Hub-to-Hub Distance | 24 in | $D$ |
| Boom Weight | 0.066 lb | $D^3$ |
| Motor Weight | 0.14 lb | $D^3$ |
| Rotor Weight | 0.007 lb | $D^3$ |
| Root Airfoil | NACA 4412 | – |
| Tip Airfoil | Clark Y | – |
| Root Chord | 0.866 in | $D$ |
| Tip Chord | 0.343 in | $D$ |
| Root Pitch | 21.5° | – |
| Tip Pitch | 11.1° | – |
| Rotor Solidity | 0.09 | – |

### Rotor & Motor Properties

Combined rotor and motor inertia is estimated based on existing hardware components (Ref. 10), and is given in Eq. 2, where $D$ is the rotor diameter in feet and $I$ is the rotational inertia of the system in slug·ft$^2$. The maximum available power predicted for a given rotor diameter is given by Eq. 3 (Ref. 10).

$$I = 4.8x10^{-5}D^5 \tag{2}$$

$$P_{max} = 0.39D^{1.5} \tag{3}$$

**Handling Qualities: Damping Ratio and Stability Margins**

Control laws are designed to meet the damping ratio and stability margin requirements given in Table 2. The damping ratio metric comes from the hover and low speed requirements in the ADS-33E-PRF (Ref. 12), and the stability margin requirements come from SAE-AS94900 (Ref. 13).

**Table 2. Damping Ratio and Stability Margin Requirements**

| Metric | Requirement |
|---|---|
| Damping Ratio | $\geq 0.35$ |
| Gain Margin | $\geq 6$ dB |
| Phase Margin | $\geq 45°$ |

**Handling Qualities: Heave Step Response**

The heave step response of the system is evaluated using the hover and low speed requirement of heave response to a collective input in the ADS-33E-PRF (Ref. 12). A step command in vertical velocity is input into the nonlinear simulation of the aircraft, and a curve in the form of a first order response (Eq. 4) is fit to the response in order to extract the time constant $T$ and time delay $\tau$. These values are then compared to the requirements given in Table 3 to determine if the response is acceptable.

$$w_{est}(t) = K[1 - exp(-\frac{t-\tau}{T})] \tag{4}$$

**Table 3. Heave Rate Response Requirements**

| Level | Time Constant $T$ (s) | Time Delay $\tau$ (s) |
|---|---|---|
| 1 | 5.0 | 0.20 |
| 2 | $\infty$ | 0.30 |

**Handling Qualities: Roll/Pitch/Yaw Frequency Response**

Unlike the heave evaluation, which is performed in the time domain, the evaluation of the roll, pitch, and yaw handling qualities ratings of the aircraft is evaluated in the frequency domain. A chirp signal is input to a quasi-linear (linearized dynamics, nonlinear actuator) system model, and the response recorded. The phase delay and bandwidth are then extracted from the resultant bode plot, as described in the ADS-33E-PRF (Ref. 12) and compared to requirements.

**Handling Qualities Metrics: Disturbance Rejection**

Disturbance rejection is also considered along all aircraft axes, which tests the aircraft's ability to hold a steady state despite a disturbance. As explained in Ref. 14, a chirp signal is input into the feedback loop and the frequency response recorded. The disturbance rejection bandwidth (frequency at which the magnitude crosses -3 dB) and the disturbance rejection peak (maximum magnitude) are extracted from the disturbance rejection bode plot and compared to the metrics in Table 4.

**Table 4. Disturbance Rejection Requirements (Ref. 15)**

| Hold Variable | DRB (rad/s) | DRP (dB) |
|---|---|---|
| Heave (w) | $\geq 1.0$ | $\leq 5.0$ |
| Roll ($\phi$) | $\geq 0.9$ | $\leq 5.0$ |
| Pitch ($\theta$) | $\geq 0.5$ | $\leq 5.0$ |
| Yaw ($\psi$) | $\geq 0.7$ | $\leq 5.0$ |

**Scaling of Handling Qualities Metrics**

Froude scaling based on the size of the aircraft (Refs. 8, 9) is used to apply traditional handling qualities metrics to these smaller multirotor aircraft. The size of the quadcopter is compared to the size of the UH-60 Black Hawk to get a scaling factor, $F$, using Eq. 5.

$$F = \sqrt{\frac{\text{Hub-to-Hub Distance}}{\text{UH-60 Rotor Diameter}}} \tag{5}$$

This factor is used to scale the handling qualities metrics based on their dimensions. For example, the time constant (s) is divided by the scaling factor before being compared to the requirements, while the bandwidth (rad/s) is multiplied by the scaling factor. This scaling is applied to the various handling qualities metrics described above before being compared to the required values.

**Controller Architecture**

The controller architecture (Fig. 3) utilizes two nested control loops, with an inner RPM-governing loop to regulate the rotor speeds and an outer stabilization loop for the aircraft attitudes and heave rate. The aircraft dynamics model, as previously described, takes the torques of each motor as an input ($u_{sat}$), and outputs the aircraft state. The saturation block is used to model the power limitations of the motor (Eq. 3), based on the total input torques commanded by the control law (u) and the current rotor speeds ($\Omega_I$). The delay block is used to model phenomena such as sensor delay and sampling rates on the aircraft. A time delay of 5 ms is chosen, corresponding to a sampling frequency of 200 Hz. A mixer is used to transform from multi-rotor coordinates (which simplify the stabilization loop to a series of decoupled SISO systems) to individual rotor coordinates (in which RPM governing is SISO).

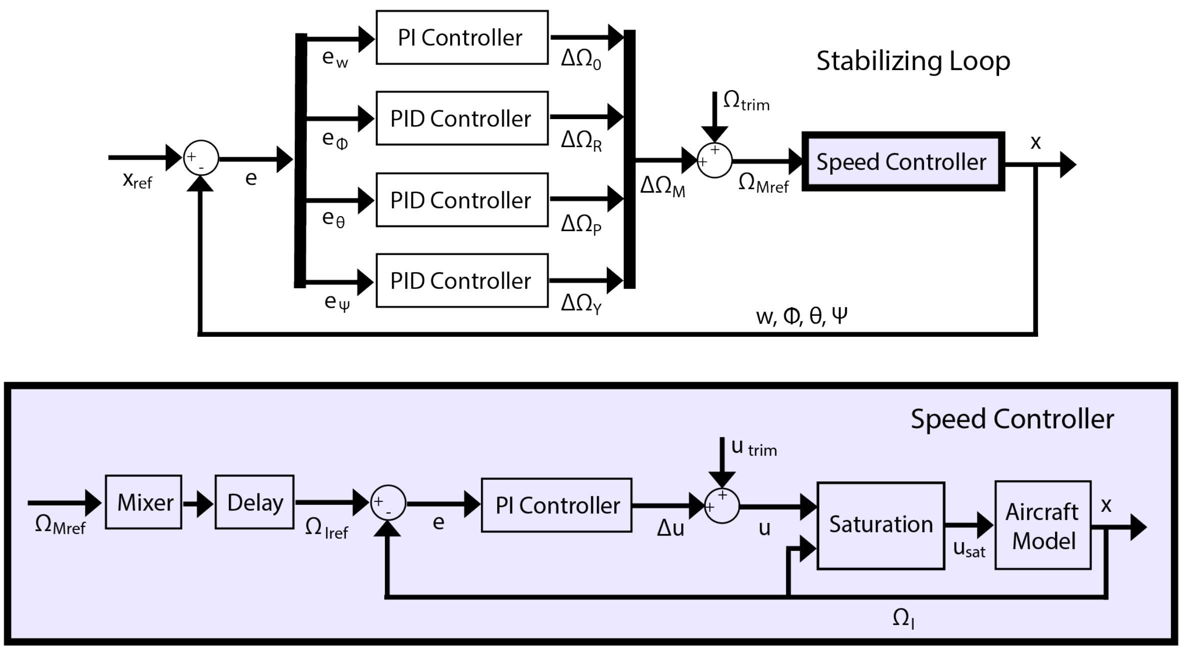


**Fig. 3. Controller Architecture**

The attitudes and heave rate are fed back in the stabilization loop, where a PID (PI for heave) controller determines a command for the multirotor speeds in terms of a deviation from a reference speed. To obtain the total value of the rotor speeds, the reference condition (trimmed hover speeds) is added to this command, which is used as the reference input in the RPM-governing loop. The RPM-governing loop determines the error between the commanded rotor speeds and the actual rotor speeds, and produces a change in torque input (Δu) for the plant. A hover trim reference ($u_{trim}$) is added to get the total torque input. If the total commanded torque exceeds the limits of the motor, saturation is applied to meet the restrictions of the hardware.

**Controller Design**

Five unique PI/PID controllers are required for each aircraft size that is simulated. In order to be able to compare the performance of the different aircraft sizes, gains must be chosen systematically. Controllers are designed on the linearized models. The gains are selected to minimize settling time while maintaining appropriate damping ratio and stability margins (Table 2). The gains are optimized for each controller using a particle swarm optimization routine. For a given set of gains, Eq. 6 (Ref. 14) can be evaluated for settling time, gain margin, phase margin, and minimum damping ratio, with "good" and "bad" values for each normalization chosen based on knowledge of the system and its required performance. For example, a "bad" damping ratio for the heave response of the system would be anything less than one (as it is expected to be first order), while a "bad" damping ratio for the roll response would be 0.35, as per ADS-33E-PRF requirements (Ref. 12). A normalized value of 1 for any metric represents the minimum acceptable performance. The optimization routine minimizes the maximum value of $f$ for the settling time, gain/phase margin, and damping ratio, similar to Ref. 14.

$$\overline{f_i} = \frac{f_i - good_i}{bad_i - good_i} \tag{6}$$

**Table 5. Good and Bad Values for Optimization**

| Metric | Units | good | bad |
|---|---|---|---|
| Gain Margin | dB | 7 | 6 |
| Phase Margin | deg | 60 | 45 |
| $\zeta$ (heave) | - | 1 | 0.95 |
| $\zeta$ (roll/pitch/yaw) | - | 0.6 | 0.35 |
| heave $\tau_s$/F | s | 5.2 | 10.4 |
| roll/pitch $\tau_s$/F | s | 12.9 | 25.9 |
| yaw $\tau_s$/F | s | 18.3 | 55 |

Because it minimizes settling time, this method of choosing gains ignores the limitations of the actuators and may violate motor torque limits for sufficiently large command inputs. The maximum and minimum gains allowable for consideration by the optimization routine are therefore limited based on system knowledge.

# RESULTS

**Heave Step Response**

The controllers are designed for the heave axis such that the responses have a damping ratio of 1. This is done so that a first-order response can be fit to the response (as required by ADS-33). The open loop response to a collective controller is already predominately first-order, so a variety of different gains exist that are able to meet the damping ratio and stability requirements. The gains are limited such that there is minimal overshoot in the step response of the nonlinear system. The stability margins in heave are given in Table 6.

**Table 6. Margins for Heave Feedback Loop**

| Rotor Diameter (ft) | Damping Ratio | Gain Margin (dB) | Phase Margin (deg) |
|---|---|---|---|
| 1 | 1 | 25.2 | 86.2 |
| 2 | 1 | 26.8 | 86.7 |
| 4 | 1 | 27.7 | 87.5 |
| 6 | 1 | 27.6 | 89.6 |
| 8 | 1 | 27.7 | 83.2 |

From a steady hover, a climb rate of 10 ft/s is commanded for each aircraft size. Input torque is shown in Fig. 4. All aircraft saturate, with the larger rotor diameters remaining saturated for longer times. Despite their greater control effort, the larger aircraft are unable to match the settling time of the smaller, lighter aircraft without overshoot (Fig. 5).

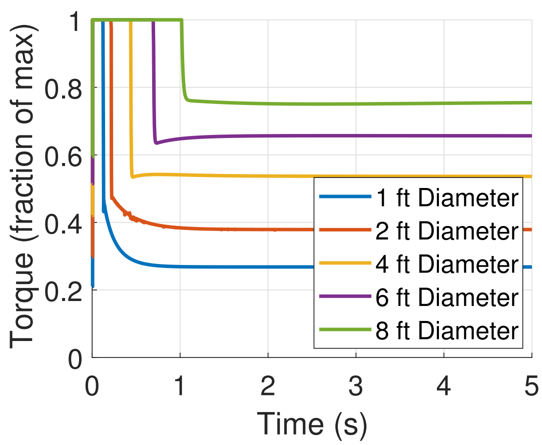


**Fig. 4. Input Torque for Heave Response**

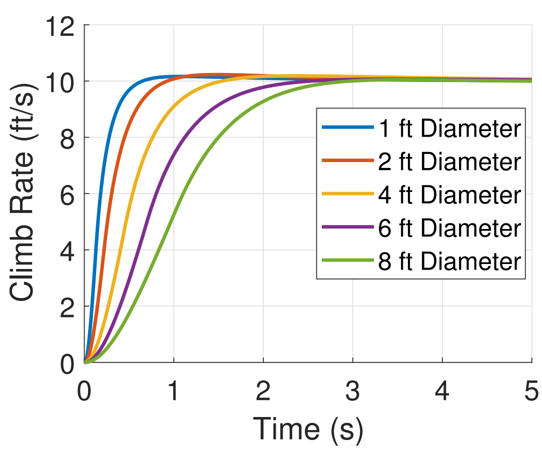


**Fig. 5. Heave Step Response**

For each aircraft size, the time delay and time constant are found using Eq. 4, with the values given in Table 7. These values are then scaled by dividing by the Froude scaling factor from Eq. 5 and compared to the ADS-33E-PRF requirements in Fig. 6.

**Table 7. Time Delay & Time Constant of Closed Loop Heave Response**

| Rotor Diameter (ft) | Time Constant (s) | Time Delay (s) |
|---|---|---|
| 1 | 0.18 | 0.017 |
| 2 | 0.27 | 0.039 |
| 4 | 0.48 | 0.074 |
| 6 | 0.72 | 0.112 |
| 8 | 0.99 | 0.159 |

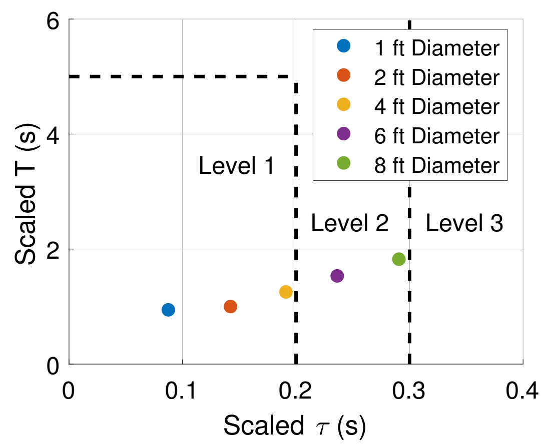


**Fig. 6. Scaled Hover and Low-Speed Target Acquisition and Tracking Heave Metrics**

The aircraft with 6 and 8 foot rotors are not able to meet the Level 1 heave requirements, and instead fall in Level 2. The responsiveness of these two aircraft is undesirable due to the time delay caused by the rotor dynamics. This time delay is associated with the part of the response where the motors are saturated, so even with a different controller design, these aircraft would likely not be able to meet the heave requirements. However, an increase in installed power, or a decrease in rotor rotational inertia, would likely allow a quadcopter with 6 or 8 foot diameter rotors to meet the time delay requirements. These results corroborate those presented in (Ref. 10), where an isolated rotor was considered in heave.

Along with the step response, disturbance rejection was also considered for the heave axis. The response to a disturbance input was used to extract the disturbance rejection bandwidth (DRB) and disturbance rejection peak (DRP), with the values listed for each aircraft size in Table 8. Both the Froude-scaled and un-scaled DRB values are listed.

For the heave velocity, the DRB is required to be greater than 1 rad/s, and the DRP is required to be less than 5 dB. The

**Table 8. Disturbance Rejection Metrics for Heave**

| Rotor Diameter (ft) | DRB (rad/s) | Scaled DRB (rad/s) | DRP (dB) |
|---|---|---|---|
| 1 | 6.23 | 1.20 | 0.255 |
| 2 | 4.29 | 1.17 | 0.175 |
| 4 | 2.98 | 1.15 | 0.153 |
| 6 | 2.24 | 1.06 | 0.134 |
| 8 | 1.50 | 0.82 | 0.120 |

DRP and scaled DRB of each simulated aircraft are compared to these requirements in Fig. 7. All except the aircraft with 8-foot diameter rotors are able to meet the Level 1 disturbance rejection requirements in heave. The disturbance rejection of this aircraft could likely be improved by increasing gains, but this would cause too much overshoot in the step response and change the requisite first order behavior in this axis.

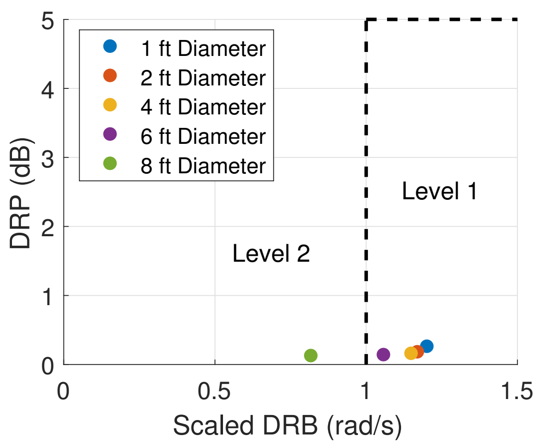


**Fig. 7. Scaled Heave Disturbance Rejection Metrics**

### Roll & Pitch

For the simulated aircraft, roll and pitch have identical dynamics in hover due to the symmetry of the quadcopter, and thus only one of the two needs to be evaluated. Because the handling qualities metrics considered have stricter requirements for roll than for pitch, only the roll response is presented, as an aircraft that is Level 1 in roll (combat/target acquisition and tracking) is also Level 1 in pitch.

For each aircraft size, controllers were designed to meet the required damping ratio and stability margins. The closed-loop damping ratio, as well as the gain and phase margins are tabulated for each aircraft in Table 9.

To evaluate the roll bandwidth and phase delay, a chirp signal was commanded in the roll channel of the nonlinear model. For all aircraft sizes, the scaled closed loop bandwidth and phase delay criteria met the ADS-33E-PRF Level 1 requirements for hover and low-speed roll target acquisition and tracking, as shown in Fig. 8. Note that in this evaluation of the roll/pitch handling qualities through the frequency response, the effects of saturation are not included, as the chirp input was sized to avoid large input.

**Table 9. Damping Ratios and Margins for Roll Feedback Loop**

| Rotor Diameter (ft) | Damping Ratio | Gain Margin (dB) | Phase Margin (deg) |
|---|---|---|---|
| 1 | 0.69 | 18.2 | 52.9 |
| 2 | 0.70 | 22.0 | 57.0 |
| 4 | 0.85 | 24.3 | 63.5 |
| 6 | 0.93 | 24.1 | 69.9 |
| 8 | 0.75 | 24.2 | 70.1 |

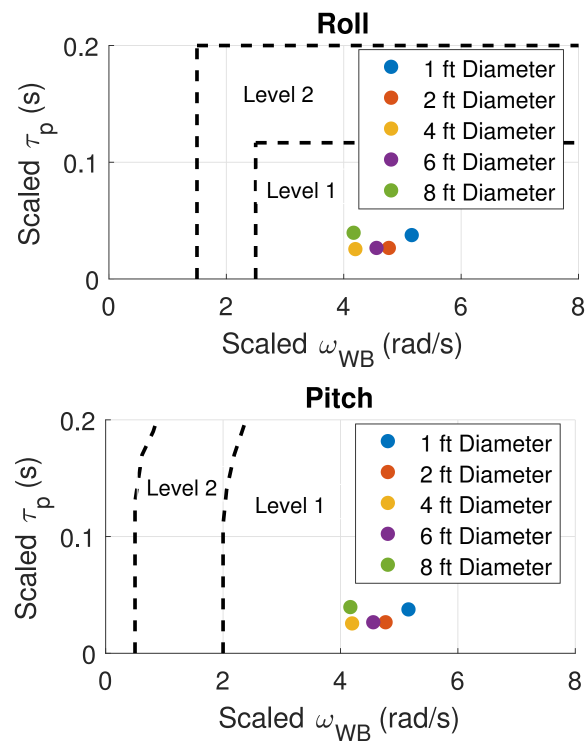


**Fig. 8. Hover and Low-Speed Roll and Pitch Target Acquisition and Tracking Metrics**

To observe these saturation effects, a roll attitude of 5° to the right is commanded, beginning from a steady hover. Though the aircraft response is stable and well-damped for all rotor sizes, the overshoot and settling time generally increase with the rotor size (Fig. 9). This behavior is caused by the saturation of the control inputs, shown for each rotor size in Fig. 10, where the solid lines correspond to the left-side rotors (which produce a positive roll moment) and the dotted lines correspond to the right-side rotors (which produce a negative roll moment). For rotors exceeding 4ft in diameter, the left-side rotors reach their maximum torque, delaying the response.

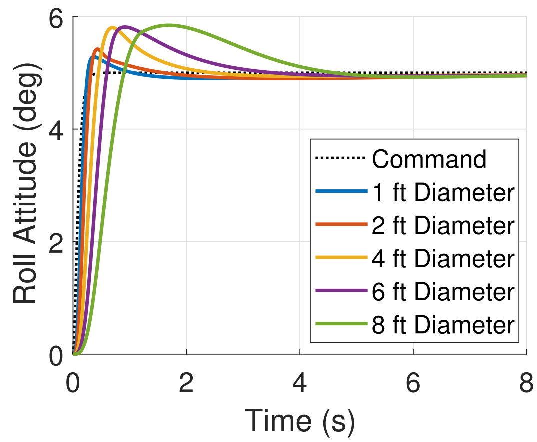


**Fig. 9. Response of Quadcopters to a Commanded Step Change of 5° in Roll Attitude**

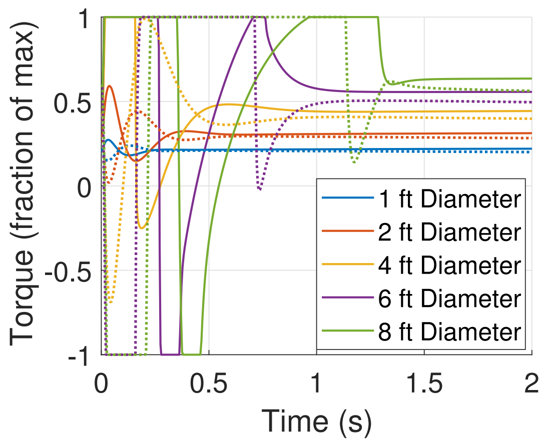


**Fig. 10. Input Torque for 5° Roll Step Response**

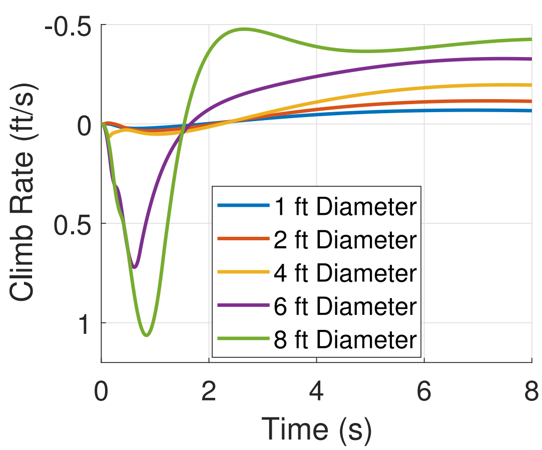


**Fig. 11. Resulting Heave During Roll Step**

Additionally, motor saturation can introduce undesirable off-axis effects from the control inputs. For example, when the left-side rotors saturate due to a large roll command, the right-side rotors will continue to slow down, as the control law is unaware that motors have saturated. Consequently, there is a net loss in thrust, so the aircraft begins to descend, as shown in Fig. 11.

To avoid saturation and these off-axis effects, the roll control laws of the aircraft with 4, 6, and 8-foot diameter rotors were re-tuned with lower gains, such that the motors no longer saturate during the 5° step response, shown in Fig. 12. With the re-tuned controllers, the step responses of the larger rotors oscillate significantly more, shown in Fig. 13.

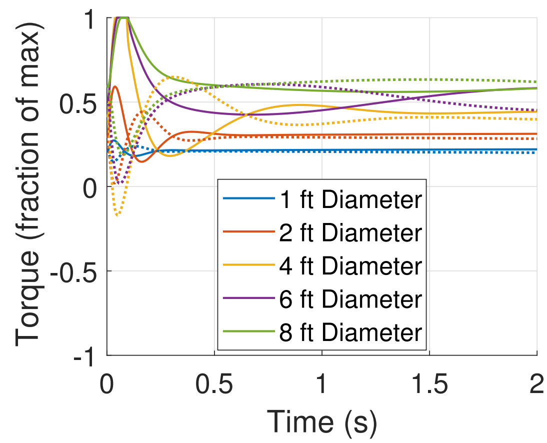


**Fig. 12. Input Torque for 5° Roll Step Response- Reduced Gains**

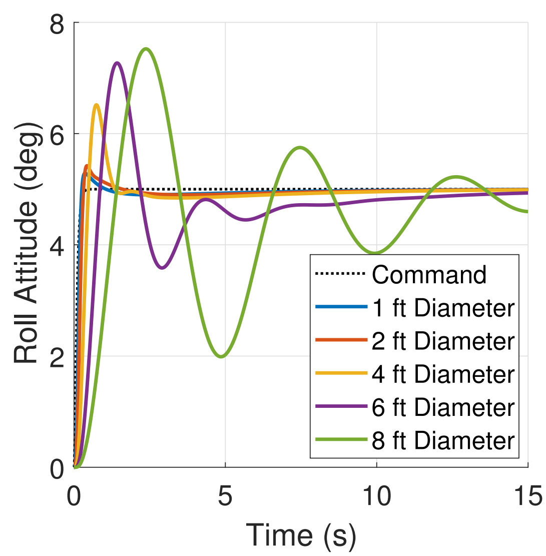


**Fig. 13. Response of Quadcopters to a Commanded Step Change of 5° in Roll Attitude - Reduced Gains**

Though reducing the gains avoids saturation of the motor torque for a 5° roll command, these controllers are unacceptable due to their poor damping ratio and margins, as shown in Table 10 (unacceptable values in red).

**Table 10. Margins for Roll Feedback Loop - Reduced Gains**

| Rotor Diameter (ft) | Damping Ratio | Gain Margin (dB) | Phase Margin (deg) |
|---|---|---|---|
| 1 | 0.69 | 18.2 | 52.9 |
| 2 | 0.70 | 22.0 | 57.0 |
| 4 | 0.52 | -17.5 | 50.1 |
| 6 | 0.309 | -9.75 | 35.9 |
| 8 | 0.152 | -4.31 | 27.2 |

Additionally, with the re-tuned controllers, the frequency response of the aircraft with rotors of 4 feet in diameter or greater no longer meet the Level 1 roll requirements (Fig. 14), though the 4-foot diameter rotor is Level 1 in pitch.

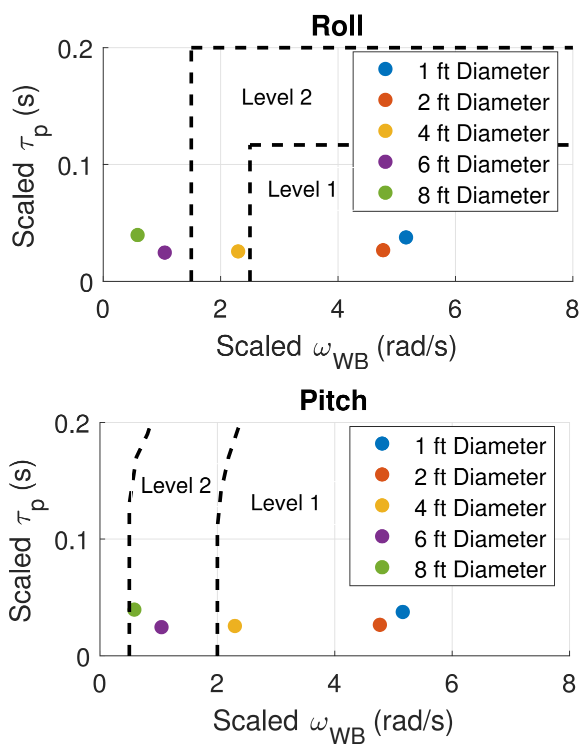


**Fig. 14. Hover and Low-Speed Roll and Pitch Target Acquisition and Tracking Metric - Reduced Gains**

Roll/pitch attitude disturbance rejection is also considered with the original controllers (that allow saturation during the step response). Shown in Fig. 15, all aircraft are able to meet the disturbance rejection requirements for both roll and pitch.

**Table 11. Disturbance Rejection Metrics for Roll - Reduced Gains**

| Rotor Diameter (ft) | DRB (rad/s) | Scaled DRB (rad/s) | DRP (dB) |
|---|---|---|---|
| 1 | 13.25 | 2.57 | 2.87 |
| 2 | 8.16 | 2.23 | 2.61 |
| 4 | 4.69 | 1.81 | 2.04 |
| 6 | 3.07 | 1.45 | 1.34 |
| 8 | 1.87 | 1.02 | 0.99 |

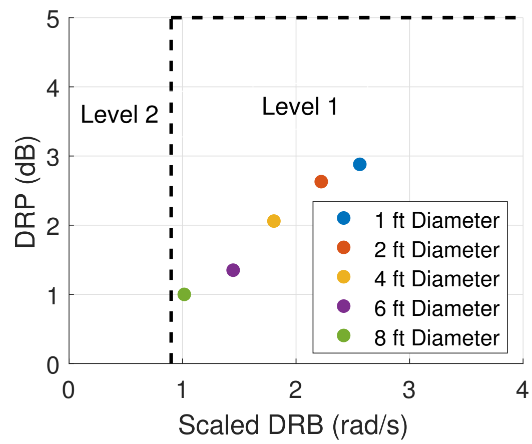


**Fig. 15. Scaled Roll Disturbance Rejection Metrics Compared to Requirements**

Disturbance rejection of roll/pitch attitude is considered with the reduced gains (that avoid saturation during the step response) as well. With the reduced gains, the aircraft with rotors of 6 and 8 feet in diameter no longer meet the roll/pitch attitude disturbance rejection requirements, shown in Fig. 16. Despite its gains also being reduced, the aircraft with 4-foot rotors is still able to meet the Level 1 requirements.

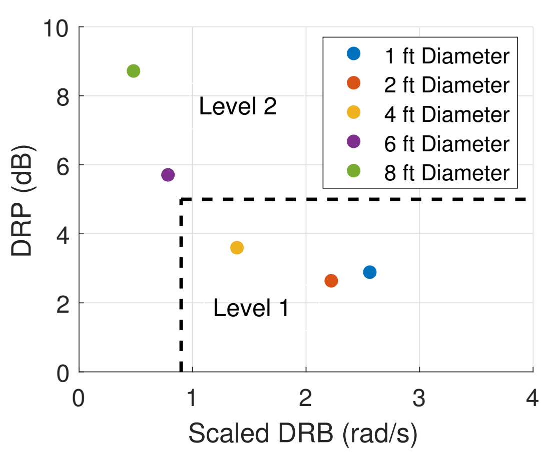


**Fig. 16. Scaled Roll Disturbance Rejection Metrics Compared to Requirements - Reduced Gains**

Overall, the limiting factor to the roll/pitch response is the inability to find an adequate control law that does not violate actuator constraints for larger rotor sizes. Therefore, in order for the larger aircraft to meet Level 1 requirements in roll and pitch, either larger motors (increasing the maximum torque available), reduced rotor rotational inertia, or collective pitch variation (circumventing the need to rapidly change the rotor speed) is necessary.

**Yaw/Heading**

Unlike in roll/pitch, stabilizing control laws exist in yaw that avoid significant saturation of the motors. Aircraft at each of the considered scales are able to meet the damping ratio and stability margin requirements for the yaw axis, given in Table 12.

**Table 12. Margins for Yaw Feedback Loop**

| Rotor Diameter (ft) | Damping Ratio | Gain Margin (dB) | Phase Margin (deg) |
|---|---|---|---|
| 1 | 0.58 | 18.4 | 62.2 |
| 2 | 0.57 | 13.7 | 70.7 |
| 4 | 0.53 | 14.0 | 74.1 |
| 6 | 0.37 | 25.0 | 45.2 |
| 8 | 0.38 | 30.9 | 47.0 |

A 10° heading change is commanded as a step input. The input torque for the response of each aircraft is shown in Fig. 17, and the response in Fig. 18. Though they all meet the stability margins and damping ratio requirements, the larger diameter aircraft overshoot the commanded heading significantly more than the smaller ones, and take significantly longer to settle. Based on the frequency response in yaw, all aircraft are able to meet the ADS-33E-PRF requirements in yaw (Fig. 19).

However, only the 1 and 2 foot rotor sizes meet the DRB requirements in yaw (Fig. 20, Table 13). Increasing gains may result in a Level 1 designation for the larger aircraft, but would come at the expense of more severe input saturation.

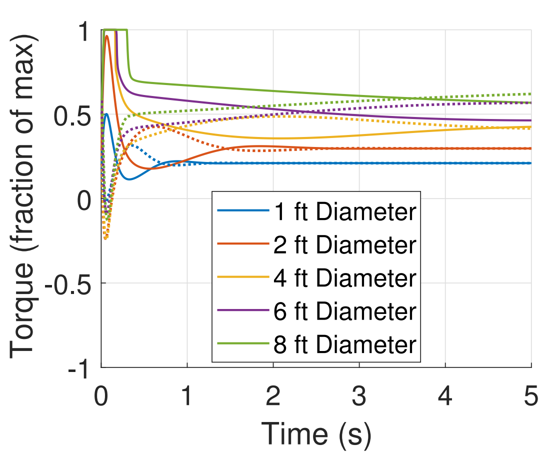


**Fig. 17. Input Torque for Yaw Response**

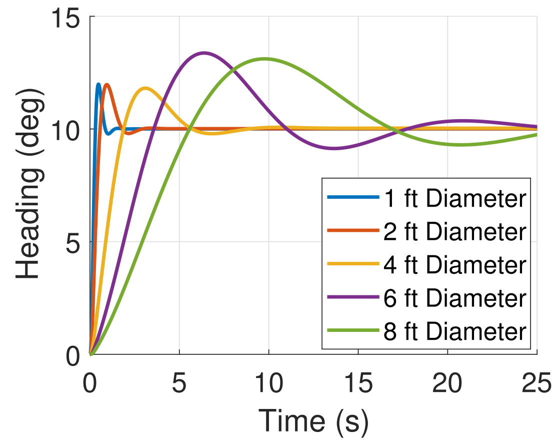


**Fig. 18. Yaw Step Response**

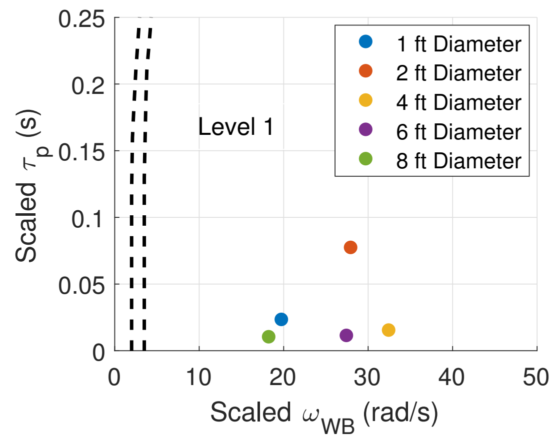


**Fig. 19. Hover and Low-Speed Yaw Target Acquisition and Tracking**

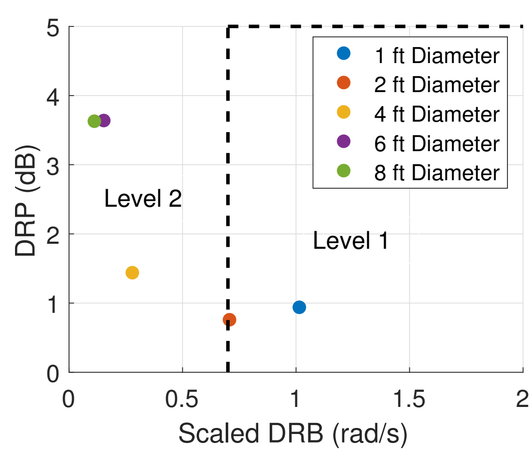


**Fig. 20. Scaled Yaw Disturbance Rejection Metrics Compared to Requirements**

**Table 13. Disturbance Rejection Metrics for Yaw**

| Rotor Diameter (ft) | DRB (rad/s) | Scaled DRB (rad/s) | DRP (dB) |
|---|---|---|---|
| 1 | 5.72 | 1.02 | 0.93 |
| 2 | 2.58 | 0.70 | 0.75 |
| 4 | 0.73 | 0.28 | 1.43 |
| 6 | 0.33 | 0.16 | 3.63 |
| 8 | 0.21 | 0.11 | 3.62 |

## CONCLUSIONS

The effects of rotor rotational dynamics on the Froude-scaled handling qualities of multicopters of various sizes have been assessed through simulation. In heave, quadcopters with rotors of up to 4 feet in diameter reach Level 1 in low-speed target acquisition and tracking, while those up to 6 feet can meet Level 1 disturbance rejection requirements. In yaw, only quadcopters with 2 foot diameter rotors or less meet scaled disturbance rejection requirements, though all sizes meet Level 1 pilot bandwidth and phase delay requirements in target acquisition and tracking.

For the quadcopters with rotors of 4 feet or greater in diameter in roll/pitch, no control laws could be obtained that simultaneously satisfy handling qualities requirements while avoiding input saturation in response to even modest commands in roll attitude. This saturation revealed undesirable off-axis couplings that are not referenced in the ADS-33E-PRF requirements.

To meet handling qualities requirements with larger rotors (over 2 feet in diameter), while not saturating the motor inputs, either larger motors must be used (at the expense of empty weight), the rotational inertia of the rotors reduced, or alternate control methodologies (such as feathering rotors or dedicated maneuvering rotors) must be explored.

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## ACKNOWLEDGEMENTS


The RPI authors are grateful for the funding support provided for this work by Terrafugia Corp. The authors would also like to acknowledge the Department of Defense and STI for sponsoring Mr. McKay through the National Defense Science and Engineering Graduate Fellowship.


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