Forward Flight & MTE Simulation of a UAM-Scale Quadcopter with Hybrid RPM & Pitch Control

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ABSTRACT

The handling qualities of a 1200-lb gross weight, UAM-scale quadcopter with both variable rotor speed and collective pitch control are examined in simulation. With these redundant controls, the forward flight trim space is analyzed and three trim modes are defined, where power consumption can be increased to improve mobility with pitch control inputs. Explicit model following control laws are optimized using CONDUIT® to meet ADS-33E-PRF handling qualities specifications in hover, with design margin optimization on each axis. Three control strategies are compared for heave, roll, and pitch control: pure RPM-control, pure pitch-control, and hybrid-control using a complementary filter (allowing pitch inputs to be used for maneuvers and changes in RPM to be used for trim). Hybrid trim control is also defined to maintain pitch actuator margin from stall in forward flight trim conditions. Based on standard handling qualities metrics, the hover control laws are found to be robust enough to provide adequate performance in forward flight at cruise speed. The lateral/longitudinal performance of the trim modes and control strategies are then compared through simulation of the ADS-33E-PRF Mission Task Element (MTE): lateral reposition. Outer loop control design is performed in order to simulate pilot inputs during the maneuver and provide aggressive acceleration with minimal oscillation about the end point. Based on results from simulation of a lateral reposition maneuver, two of the three trim modes considered were able to complete the maneuver with satisfactory handling qualities.

NOTATION

Symbols

c_T	Rotor Thrust Coefficient
K	Input Scaling
p	Roll Rate, Body Axis
q	Pitch Rate, Body Axis
r	Yaw Rate, Body Axis
R	Rotor Radius
u	Longitudinal Velocity, Body Axis
U	Control Inputs
v	Lateral Velocity, Body Axis
V	Motor Voltage
w	Heave Rate, Body Axis
x, y, z	Aircraft Position
X	Dynamic States
α	Complementary Filter Cutoff Frequency
δ	Acceleration Input
θ	Pitch Attitude
Θ	Blade Root Pitch
μ	Advance Ratio
τ	Time Constant
ϕ	Roll Attitude
ψ	Heading
Ψ	Azimuthal Location
ω_N	Natural Frequency
Ω	Rotor Speed
ζ	Damping Ratio

Acronyms

ACAH	Attitude Command, Attitude Hold
DRB	Disturbance Rejection Bandwidth
DRP	Disturbance Rejection Peak
EMF	Explicit Model Following
eVTOL	Electric Vertical Takeoff and Landing
MRC	Multi-Rotor Coordinate
MTE	Mission Task Element
OLOP	Open-Loop-Onset-Point

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RMAC	Rensselaer Multicopter Analysis Code
RMS	Root Mean Square
RPM	Revolutions Per Minute
RCDH	Rate Command Direction Hold
RCHH	Rate Command Height Hold
TRC	Translational Rate Command
UAM	Urban Air Mobility

INTRODUCTION

With many new eVTOL configurations for Urban Air Mobility applications in development, an essential consideration is the handling qualities of these aircraft. The traditional definition of handling qualities relies on pilot ratings based on perceived work load during flight to determine whether the aircraft is satisfactory. Extracted from these pilot ratings, standard handling qualities metrics (such as those in ADS-33E-PRF, Ref. 1) define quantifiable characteristics that correlate to pilot satisfaction. Thus, control laws can be designed on simulation models to meet these metrics and ensure satisfactory maneuverability in flight. Evaluation of these metrics is split into three regions: Level 1 (satisfactory), Level 2 (adequate), and Level 3 (unacceptable).

Previous studies (Refs. 2–4), have shown that the fixed-pitch, variable-RPM rotors traditionally used in small-scale vehicles are not as effective as control actuators at larger scales, due to increased rotor inertia influencing the aircraft dynamics. Large spikes in motor current/torque are required to accelerate the large rotors and provide satisfactory maneuverability. The detrimental effect of rotor inertia on aircraft agility has been shown to increase with larger rotor sizes (Ref. 5), leading to relatively large, high-torque motors being required to meet handling qualities requirements (Ref. 2).

Rather than changing thrust with rotor speed, another option for control of UAM-scale multi-rotor aircraft is variation of collective feathering. Like the collective pitch input used on conventional rotorcraft tail rotors, changing the root blade pitch controls the thrust without requiring rotor acceleration. In Ref. 3, Malpica and Withrow-Maser found that UAM-scale aircraft with variable collective pitch were able meet handling qualities requirements, while aircraft with variable-RPM alone could not (with assumed torque limitations). Niemiec et al. (Ref. 4) also considered both variable rotor speed and collective pitch control for a large multirotor aircraft, but found that both control configurations were equally limited by the yaw maneuverability, as this axis relies directly on motor reaction torque, and therefore, current.

Variable-RPM and variable-pitch control were compared for a 1200 lb quadcopter in Ref. 6 at several different hover trim points. With higher trim rotor speed and lower trim blade pitch, higher trim power was traded for increased heave, roll, and pitch maneuverability with variable-pitch control (due to increased pitch actuator margin). For these thrust-driven maneuvers, pitch control was able to eliminate the spikes in motor current associated with rotor acceleration and simultaneously provide greater maneuverability. However, similar to the findings in Ref.4, pitch control provided no benefit when considering the torque-driven yaw axis.

Variable-RPM control can be more power-efficient when considering changes in trim condition, shown by McKay et al. (Ref. 7) and Walter et al. (Ref. 6), though it is generally worse for the maneuverability of the aircraft. First implemented in Ref. 8, a hybrid control scheme utilizing a complementary filter for mixing can allow the aircraft to take advantage of the faster pitch-control for maneuvers while still trimming the aircraft with variable-RPM.

With optimized Explicit-Model-Following (EMF) control laws designed to meet standard ADS-33E-PRF (Ref. 1) handling qualities metrics, the hybrid control scheme was able to match the increased maneuverability associated with pitch control without causing the spikes in motor current caused by RPM-control. However, by using RPM-control to trim the aircraft, the hybrid control scheme was able to trade stall margin for reduced power when operating in favorable trim conditions, as well as maintain stall margin and maneuverability in adverse (i.e., hot/high/heavy) conditions.

This study extends the hybrid control simulations from Ref. 6 to include consideration of trim in forward flight, as well as simulation of Mission Task Elements (MTEs). Again, several trim points are considered, and the simulated maneuverability and performance of the aircraft are compared with pitch, RPM, and hybrid control.

MODELING AND ANALYSIS

Platform

Using the same aircraft platform as in (Ref. 6), a hybrid control scheme is applied to a 1200 lb quadcopter. Each rotor is directly driven by an electric motor with variable-RPM, and has actuation of the collective pitch. Shown in Fig. 1, the aircraft is flown in a cross-configuration with basic parameters listed in Table 1.

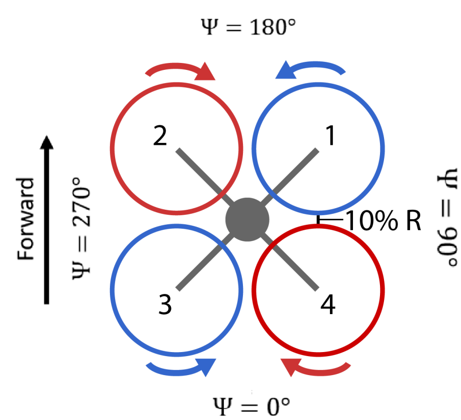


Figure 1: Quadcopter Configuration with Rotor Numbering

Table 1: Aircraft Parameters

Parameter	Value
Gross Weight	1200 lb
Disk Loading	6 psf
Rotor Radius	4 ft
Rotor Inertia	47 lb ft^2
Blade Twist	-10.3°
Rotor Solidity	0.09
Blade Taper Ratio	2.5

Simulation Model

Physics-based simulation models are developed using the Rensselaer Multicopter Analysis Code (Ref. 9), which uses a Peters-He finite state dynamic inflow model (Ref. 10) and blade element theory. The reduced linear dynamics include 16 states: 12 rigid body and 4 rotor speeds, with the inflow states removed via static condensation, listed in Eq. 1. With two control inputs on each rotor, the dynamics model has 8 inputs, listed in Eq. 2.

$$\mathrm{X} = [x\ y\ z\ \phi\ \theta\ \psi\ u\ v\ w\ p\ q\ r\ \Omega_1\ \Omega_2\ \Omega_3\ \Omega_4]^T \quad (1)$$

$$\mathrm{U} = [V_1\ V_2\ V_3\ V_4\ \Theta_1\ \Theta_2\ \Theta_3\ \Theta_4]^T \quad (2)$$

Control mixing is defined using a multi-rotor coordinate transform (Eq. 3, Ref. 11), where Ψ_k represents the azimuthal location of rotor hub k (Fig. 1, Eq. 4). This transform is applied to the voltage inputs in Eq. 3. V_0 represents mean voltage, used to control the heave axis. V_{1s}/V_{1c} represent lateral/longitudinal variation in voltage input, and thus control roll/pitch. V_d alternates sign with rotor rotational direction, producing a yaw moment on the aircraft. The same transform is used for the pitch inputs, defining Θ_0, Θ_{1c}, Θ_{1s}, and Θ_d. Using the multi-rotor coordinate transform decouples the dynamics of the quadcopter, resulting in two inputs (voltage and root pitch) that affect each of the four aircraft axes.

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} 1 & \sin(\Psi_1) & \cos(\Psi_1) & 1 \\ 1 & \sin(\Psi_2) & \cos(\Psi_2) & -1 \\ 1 & \sin(\Psi_3) & \cos(\Psi_3) & 1 \\ 1 & \sin(\Psi_4) & \cos(\Psi_4) & -1 \end{bmatrix} \begin{bmatrix} V_0 \\ V_{1s} \\ V_{1c} \\ V_d \end{bmatrix} \quad (3)$$

$$\Psi_k = (90k + 45)^\circ \quad \text{for} \quad k = 1,2,3,4 \quad (4)$$

Control Architecture

Explicit-Model-Following (EMF) control architecture is implemented with Rate-Command/Height-Hold (heave), Attitude-Command/Attitude-Hold (roll and pitch), and /Rate-Command/Direction-Hold (yaw) response types to stabilize and control the aircraft (Fig. 2).

In the EMF architecture, pilot inputs are passed through a command filter (first-order for heave and yaw, second-order for roll and pitch). The feedforward path consists of an inverse of an approximated aircraft dynamics model. An additional lag is included in the yaw feedforward path in order to account for the direct effect differential voltage inputs have on yaw rate.

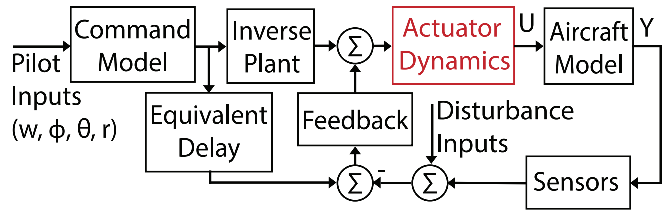


Figure 2: EMF Control Architecture

An equivalent delay is included that accounts for the effects of higher-order dynamics excluded from the approximated model inverse. Proportional-Integral-Derivative (PID) feedback control is implemented to stabilize the vehicle, mitigate errors, and reject disturbances. A sensor delay is included on the output signals from the simulation model (as in Ref. 12). These delays account for expected filtering on sensor outputs (anti-aliasing, structural and rotor notch filters, etc.).

The sum of the feedforward and feedback paths is designed as a virtual acceleration command δ for each axis, rather than specifically a rotor speed or blade pitch input:

$$\delta = [\delta_0\ \ \delta_{1s}\ \ \delta_{1c}\ \ \delta_d].^T \quad (5)$$

This allows each aircraft axis to be treated as a Single-Input-Single-Output (SISO) system despite having two control inputs (motor voltage and root pitch in multi-rotor coordinates). Control mixing for the hybrid control system takes this input acceleration command for each axis and outputs both the motor voltage values (RPM-control) and blade pitch values (pitch-control) to give input U (Eq. 2) to the simulation model.

Table 2: Input Scaling

	Heave	Roll	Pitch	Yaw
$K^{(\Omega)}$	$1/Z_\Omega$	$1/L_\Omega$	$1/M_\Omega$	T_V/N_V
$K^{(\Theta)}$	$1/Z_\Theta$	$1/L_\Theta$	$1/M_\Theta$	0

The hybrid control mixer is illustrated by the block diagram in Fig. 3. The acceleration command δ for each multi-rotor input is split into two paths: one corresponding to the rotor speed control path and the other corresponding to the blade pitch control path. Appropriate scaling is applied to input δ based on the bare-airframe dynamics (Table 2, Ref. 6) and then passed through a complementary filter.

As was shown in Ref. 6, pitch and hybrid control provide no benefit over RPM control for the yaw axis, due to the yaw response being driven by changes in motor torque rather than thrust. Thus, only RPM control is considered for the yaw axis and the complementary filter is bypassed for yaw inputs.

The complementary filter separates the signal into high- and low-frequency content, taking the form

$$\text{High Pass} = \frac{s}{s+\alpha}, \qquad \text{Low Pass} = \frac{\alpha}{s+\alpha}. \quad (6)$$

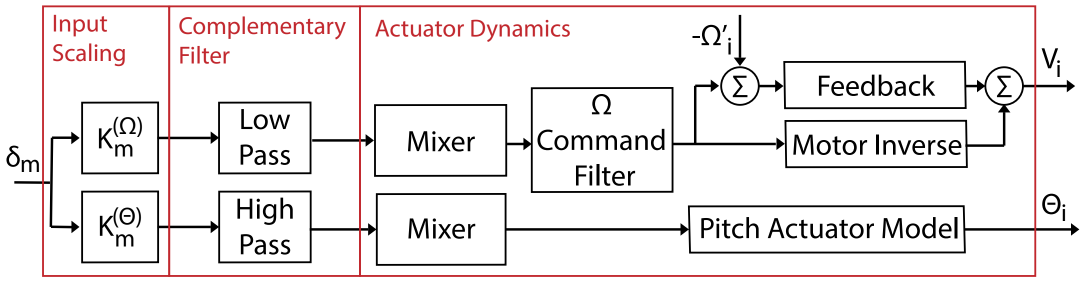


Figure 3: Hybrid Control Mixing and Actuator Dynamics

For each rotor, the blade pitch actuator receives the high-frequency (maneuver) content, while the low-frequency (trim) content is allocated to the motor speed controller. This will essentially allow the aircraft to use changes in blade pitch for short-term responses, such as the acceleration at the beginning of a maneuver, while the rotor speed is used for longer-term responses, such as changes in trim condition.

The complementary filter cutoff frequency α dictates the frequency at which the transition from RPM-control to pitch-control occurs, illustrated in Fig. 4. For frequencies less than α, the low-pass path has higher gain, while for frequencies greater than α, the high-pass path has higher gain. For frequencies further than a decade from α, the frequency content is effectively routed entirely to either the low- or high-pass path. When summed together, the low- and high-pass filters result in 0 dB (unity) gain and 0° phase lag for all frequencies. Lower values of α will route relatively more content to the high-pass (pitch-control) path, allowing the rotor speed to change more slowly.

After passing through the complementary filter, both paths are transformed into individual rotor coordinates before the actuator dynamics. Another EMF control loop is implemented on the rotor speed, including an equivalent delay to account for sensing of the rotor speed. Though the motor dynamics model can be perfectly inverted, feedback control on the rotor speed is included in order to account for other effects, such as changing blade pitch. This is similar to an engine governor or Electronic Speed Controller, driving any error in rotor speed to zero.

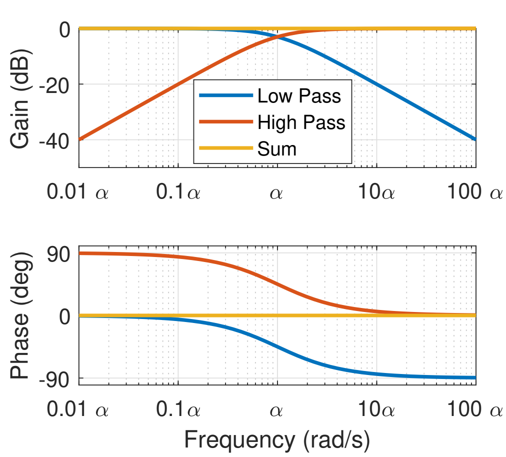


Figure 4: Complementary Filter Frequency Response

Pitch actuator dynamics are included in the blade pitch control path based on a Froude-scaling of the UH-60A tail rotor actutator model presented in Ref. 13. The pitch actuators are assumed to be second-order with an assumed damping ratio of $\zeta = \sqrt{2}/2$ and natural frequency of $\omega_N = 82$ rad/s:

$$G_\Theta = \frac{\Theta}{\Theta_{cmd}} = \frac{\omega_N^2}{s^2 + 2\zeta\omega_N s + \omega_N^2} \tag{7}$$

Control Optimization

As recommended in Ref. 12, the remaining control system parameters (feedback gains and command model parameters) are optimized in CONDUIT® to meet a comprehensive set of stability, handling qualities, and performance requirements (Table 3). The optimization routine seeks to minimize the actuator effort (defined by the summed objectives), without violating any hard (stability) or soft (handling qualities) constraints that are designed to ensure satisfactory performance.

In addition to several ADS-33E-PRF hover and low speed requirements (e.g. piloted bandwidth and minimum damping ratios), disturbance rejection requirements (Ref. 14) and Open-Loop Onset Point (OLOP, Ref. 15) specifications are also included. In addition to typical actuator RMS objective functions, additional objective functions associated with the motor current during heave, pitch, and yaw step responses are included. These are included with the aim of minimizing the peak current during maneuvers, as well as to impose a limit on the maximum current allowed to the motors (constrained to be less than twice the hover current). To evaluate whether current limits are violated, 'maximum' inputs for each axis are defined: a step with magnitude of $w = -3$ m/s ($\approx$ 600 ft/min climb) for heave, $\phi/\theta = 30°$ for roll/pitch, and $r = 20°$/s for yaw.

After meeting standard handling qualities metrics, design margin optimization (DMO) is performed by incrementally increasing the requirements in order to produce a family of Pareto-optimal controllers that provide improved maneuverability with minimal increase in actuator activity. This is done by moving the effective Level 1/2 boundary into the Level 1 region by a percentage (Design Margin) of the width of the Level 2 region. For each axis, the design margin is applied to the piloted bandwidth, crossover frequency, and disturbance

Table 3: CONDUIT® Hover Constraints

Specification	Axes
Hard Constraints	
Eigenvalues	All
Stability Margins	All
Nichols Margin	All
Soft Constraints	
Bandwidth	Roll/Pitch/Yaw
Phase Delay	Roll/Pitch/Yaw
Crossover Frequency	All
DRB	All
DRP	All
Damping	All
Heave Mode	Heave
Heave Delay	Heave
Model Following Cost	All
OLOP (Pilot Input)	All
OLOP (Disturbance)	All
Summed Objectives	
Actuator RMS (Pilot)	All
Actuator RMS (Disturbance)	All
Crossover Frequency	All
Motor Current Minimization	All

rejection bandwidth. Design margin is increased until actuator rate (OLOP or maximum current) or position (maximum blade pitch) limits are reached. The margin is then reduced to 70% of the maximum value, as recommended by Ref. 12.

RESULTS

Hover Control Design & Design Margin Optimization

To establish a baseline against which to compare the hybrid controller, hover controllers are designed with either (but not both) RPM or pitch control inputs. As explained in Ref. 6, the hybrid control cases will use the same gains as pure pitch control because the controllers are designed based on specifications for the short-term response of the aircraft. Further, due to the symmetry of the aircraft, the same gains are used for roll and pitch. As described in Ref. 6, pitch control provides no benefit for torque-driven maneuvers, so RPM-control is always used for the yaw axis.

As in Ref. 6 and with trim parameters listed in Table 4, three hover trim points are considered: labeled Eco, Standard, and Sport mode based on their relative trim power and available pitch actuator control authority for maneuvers. With lower trim rotor speed and higher collective pitch, Eco mode will have the lowest power, but also the lowest pitch actuator margin and reduced maneuverability. On the other hand, Sport mode will have high trim power, but will have greater control authority with pitch inputs, and greater maneuverability.

Table 4: Hover Trim Points

	Eco	Standard	Sport
Rotor Speed (RPM)	1050	1200	1350
Collective Blade Pitch (deg)	22.5	18.7	16.2
Total Hover Power (kW)	83	90	98

The final design margins for each axis and control strategy are listed in Table 5. Eco mode with pitch control is not able to achieve any design margin for the heave, roll and pitch axes due to pitch actuator saturation. Greater design margin is achieved for the thrust-driven axes (heave, roll and pitch) with pitch control as the pitch actuator margin increases, and are instead limited by OLOP requirements (actuator rate saturation). The opposite trend is true with RPM control inputs, due to decreased sensitivity of thrust to changes in rotor speed at higher trim rotor speeds (Ref. 6), though RPM control is generally not able to achieve as high design margins as pitch control.

Though RPM-control is always used for the yaw axis, the design margin differs depending on whether RPM or pitch control is used for the other axes. This is due to phase margin requirements of the roll and pitch axis. When using RPM-control for roll/pitch, the motor time constant tends to be optimized to a lower value, requiring the motors to respond relatively quickly and producing higher peaks in current at the beginning of maneuvers. When RPM-control is only used for the yaw-axis, the motor response time can be reduced somewhat, as voltage inputs directly affect the yaw response, rather than being reliant on changes in rotor thrust. Thanks to the increased pitch actuator margin, a slightly higher design margin is achieved when only the yaw axis is being controlled with RPM.

Table 5: Design Margins (%) and Limiting Factors

		Heave		Roll/Pitch		Yaw	
		DM	Limiting Spec	DM	Limiting Spec	DM	Limiting Spec
Eco	Pitch	0	Max Pitch	0	Max Pitch	35	Max Current
	RPM	56	Max Current	38	Max Current	28	Max Current
Standard	Pitch	115	OLOP (disturbance)	91	OLOP (pilot)	32	Max Current
	RPM	42	Max Current	31	Max Current	21	Max Current
Sport	Pitch	217	OLOP (disturbance)	113	OLOP (pilot)	29	Max Current
	RPM	24	Max Current	15	Max Current	11	Max Current

Trim in Forward Flight

In hover, the trim space was defined by a trade-off between collective rotor speed (Ω_0) and collective blade pitch (Θ_0) (discussed in Ref. 6). Though the heave input was the only nonzero input in hover, in forward flight the pitch input will also be nonzero. Therefore in forward flight, the trim space is two dimensional, with trade-offs in the heave axis (between Ω_0 and Θ_0) being joined by a trade-off in the pitch axis (between Ω_{1c} and Θ_{1c}).

At a forward flight speed of 15 m/s (Fig. 5), the trim space is bounded by pitch actuator saturation (limited to 24°) and tip speed limits (Mach 0.6). At larger values of Ω_0, either the front or rear rotor will reach the tip speed limitation, depending on the sign of Ω_{1c}, while at low Ω_0, the limiting factor is typically the pitch on the slower of the two rotor pairs. The color gradient in the figure represents the power consumption of the vehicle, which is much more sensitive to Ω_0 than Ω_{1c}, indicating that the power benefits of hybrid control are likely dominated by the heave axis.

Though the upper limit of 24° collective pitch is appropriate in hover, the stall boundary can be thought of as a function of aircraft pitch attitude and advance ratio μ. Considering a single, isolated rotor in hover at a fixed rotor speed of 110 rad/s, the thrust coefficient for increasing root pitch is shown in Fig. 6. The peak of this curve represents a maximum thrust coefficient, which is treated as the stall limit of this rotor in forward flight.

For any given combination of advance ratio μ and pitch attitude θ, a maximum collective pitch can be defined by the previously defined stall limit. The maximum collective pitch is plotted in Fig. 7, where the color gradient represents the collective. The data shown in Fig. 7 completely encompasses the trim data, represented by the black dots. The allowable pitch setting generally increases with higher aircraft attitude due to increased flow perpendicular to the rotor plane. At higher pitch settings, increasing advance ratio (either by increase in flight speed or reduction in rotor speed) also causes small increase in the maximum pitch setting as the free stream velocity becomes higher relative to the tip speed, generally reducing the effective angle of attack of the blade. At lower aircraft pitch attitudes (around 5 to 10 degrees), increasing advance ratio has the opposite effect and reduces the allowable pitch setting, likely due to regions of blade stall forming on the advancing side of the rotor.

Assuming only variation of collective rotor speed ($\Omega_1 = \Omega_2 = \Omega_3 = \Omega_4$) and a maximum blade pitch limit imposed based on Fig. 7, the trim space for the aircraft in forward flight can be defined in terms of given forward flight speed and chosen collective pitch setting (Θ_0), shown in Fig. 8. Shown in Fig. 8a, a limit on maximum single rotor trim power of 48 kW is imposed in order to define the maximum achievable flight speed for any collective pitch setting. Minimum power is achieved at around 15 m/s with maximum collective root pitch (minimum collective rotor speed). The lower bound of the trim space (minimum collective pitch setting) is defined by a maximum trim rotor speed, corresponding to a tip speed of Mach 0.65 (Fig. 8b).

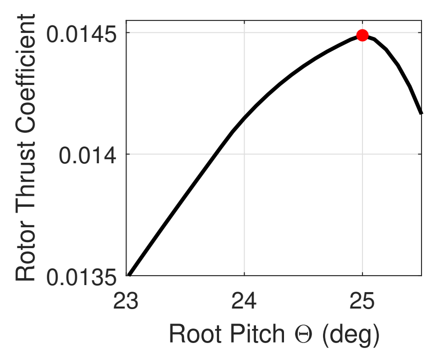


Figure 6: Non-Dimensional Thrust of a Single Rotor in Hover

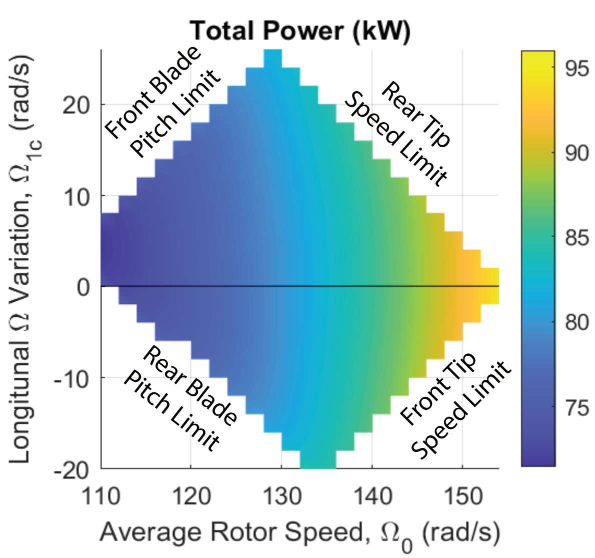


Figure 5: Forward Flight Trim Space at 15 m/s

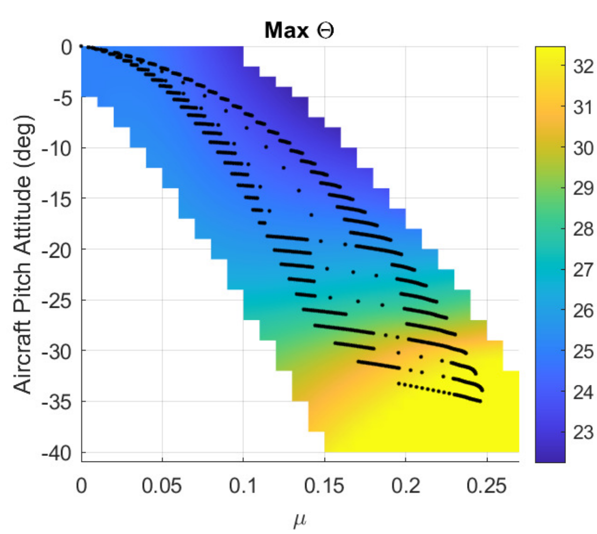
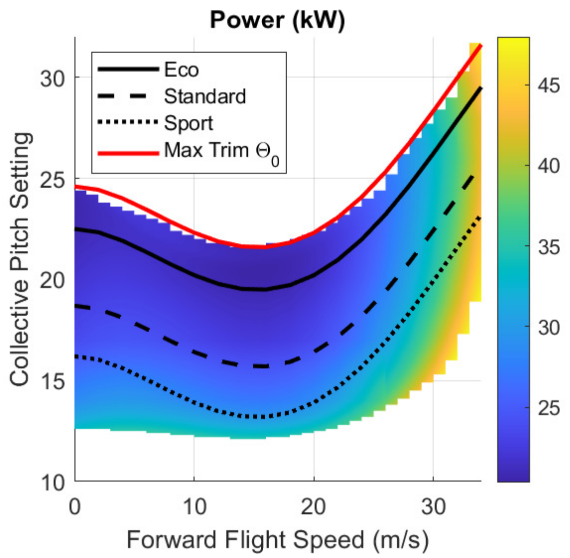
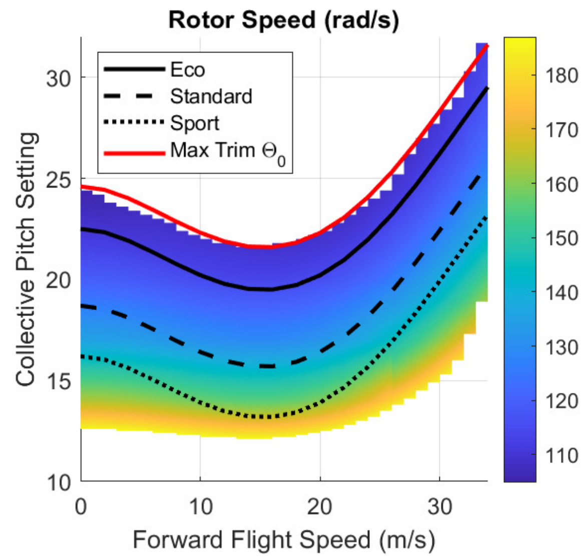


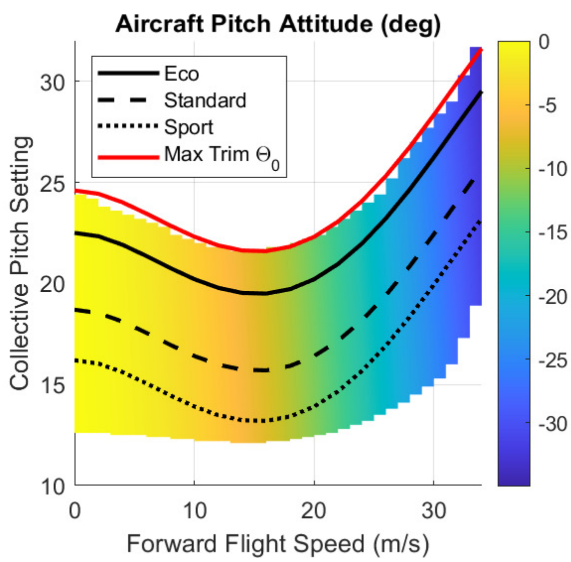
Figure 7: Estimated Root Pitch at Stall



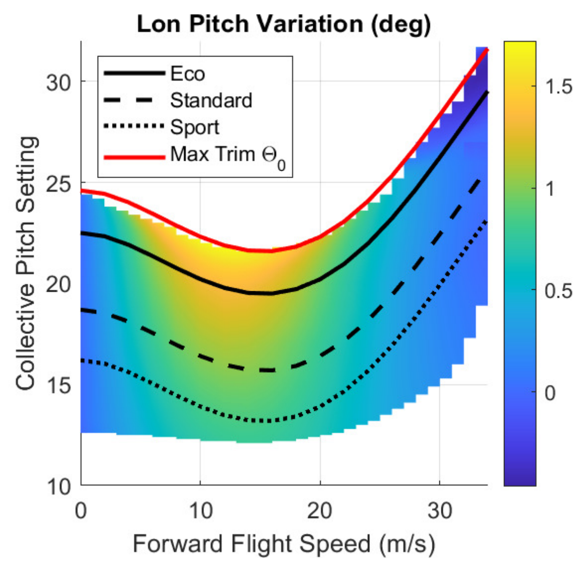
(a) Single Rotor Trim Power in Forward Flight



(b) Trim Rotor Speed in Forward Flight



(c) Aircraft Pitch Attitude in Forward Flight



(d) Longitudinal Root Pitch Variation (Θ_{1c}) in Forward Flight

Figure 8: Forward Flight Trim Space with No Longitudinal Rotor Speed Variation $\Omega_{1c} = 0$

The upper limit of the trim space is defined by the maximum root pitch from Fig. 7, approximated as a spline by the red line. Aircraft pitch attitude and longitudinal pitch variation (Θ_{1c}) are shown for the trim space in Figs. 8c and 8d, respectively, as these influence the maximum collective pitch setting before stall. Aircraft pitch attitude is invariant with the choice of trim point, instead varying with the drag associated with increasing flight speed. Higher aircraft pitch attitude is generally associated with higher allowable collective pitch (Fig. 7), however there is a reduction in allowable collective pitch setting at moderate speed flight. This is primarily due to the longitudinal pitch variation needed to trim, which increases the blade pitch on the rear rotors.

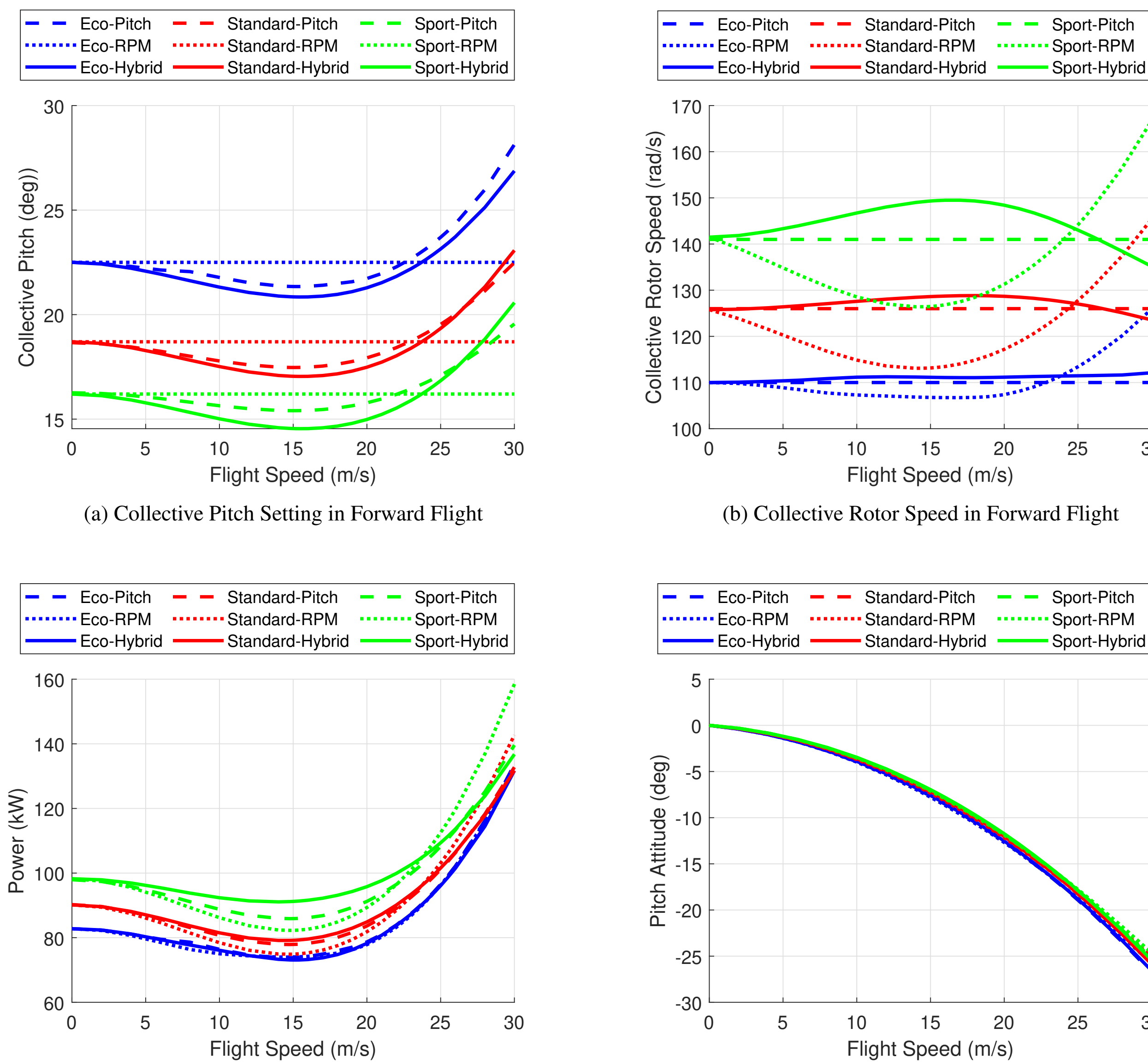
In a similar fashion to Ref. 6, Eco, Standard, and Sport mode trim points are defined in forward flight with hybrid control. These trim modes are defined by an offset from the maximum collective pitch setting (red line, Fig. 8), and will vary both collective rotor speed and collective pitch setting to trim in forward flight. By maintaining constant offset from the stall boundary, the hybrid trim strategy will maintain the pitch actuator margin available for maneuvers. Like in hover, Eco mode in forward flight will have the lowest power and the least pitch margin, while Sport mode will have higher trim power, but more pitch actuator margin for maneuver. Pure pitch or RPM can also be used to trim in forward flight, following either the contour of collective rotor speed in Fig. 8b or a horizontal line across the trim space, respectively.

Hybrid Trim Control in Forward Flight

Three trim points (Eco, Standard and Sport) with three trim control strategies (pitch-control, RPM-control, and hybrid-control), for a total of nine cases, are compared in forward flight (Fig. 9). In Fig. 9, the three trim modes are indicated by line color and the trim control strategy by line style. The collective rotor speed and root pitch for each of the trim modes are shown in Figs. 9b and 9a, respectively. RPM trim control (dotted lines) fixes the collective pitch setting on all rotors to the hover value, using Ω_0 and Ω_{1c} to trim, while pitch trim control (dashed lines) maintains the trim rotor speed on all rotors, using Θ_0 and Θ_{1c} to trim.

Eco mode with RPM trim control (blue dotted line in Fig. 9b) does not follow the same trend in rotor speed as seen with the other modes for moderate flight speeds. The relatively high collective rotor speed is likely due to the increased advance ratio on the front rotors, causing regions of the advancing side of the rotor to have regions of blade stall (dark blue region of Fig. 7). This suggests Eco mode with RPM trim control may not be feasible, as the front rotors operate close to stall.

Trim power in forward flight is shown in Fig. 9c. As explained in (Ref. 7), RPM trim control requires the lowest power for low-to-moderate flight speeds, as seen for Standard and Sport mode (red and green lines, respectively). Eco mode with RPM trim control does not follow the same trends, due to an increase in power associated with stall. Hybrid trim control generally requires the highest power as it increases the collective trim rotor speed in order to maintain the stall margin on the pitch actuator. Though pitch trim control generally has lower power than hybrid trim control, it does not maintain the



(a) Collective Pitch Setting in Forward Flight

(b) Collective Rotor Speed in Forward Flight

(c) Total Aircraft Trim Power in Forward Flight

(d) Aircraft Attitude in Forward Flight

Figure 9: Trim in Forward Flight with Various Strategies

pitch actuator margin from stall, reducing the pitch actuator margin available for maneuvers.

The best range flight speed and corresponding power are determined from Fig. 9c and listed in Table 5. Efficiency is also calculated based on these values. Eco mode has the highest efficiency in forward flight due to its lower rotor speed. The best range velocity is generally highest for Sport mode, but it is the least efficient in terms of energy consumption. The best range velocity is around 24 m/s (46 kts) for all cases, and this is chosen as the cruise speed of the aircraft.

Table 5: Best Range Velocity and Power

		Velocity (m/s)	Power (kW)	Efficiency (m/kWh)
Eco	Pitch	22.9	87.1	15.8
	RPM	22.7	85.7	15.9
	Hybrid	23.0	87.3	15.8
Standard	Pitch	23.6	94.9	14.9
	RPM	22.1	88.9	14.9
	Hybrid	24.0	97.2	14.8
Sport	Pitch	24.3	105.1	13.8
	RPM	22.2	97.3	13.7
	Hybrid	25.7	112.3	13.7

Handling Qualities in Forward Flight

The optimized hover control laws are tested at 24 m/s forward flight, based on the approximate best range speed from Table 5. With the robustness provided by the design margin optimization, several of the hover controllers are still able to meet all standard Level 1 requirements for forward flight. Others have some degraded handling qualities metrics in the Level 2 region, listed in Table 6 with the equivalent negative design margin for each metric. The degradation is quantified in terms of a negative design margin, with this value representing how deep into the Level 2 region the design is (with 100% being on the Level 2/3 boundary). The amount of degradation trends with lower hover design margins, as these controllers were designed with the handling qualities metrics closer to the Level 1/2 boundary in hover.

Though pitch control and hybrid control use the same gains and generally have the same handling quantities metrics, they vary in forward flight due to the different trim control strategies (Fig. 9) because they have different trim points. Eco mode with pitch control sees the most severe degradation in handling qualities due to its zero hover design margin. Eco mode with hybrid control performs better as a result of the hybrid trim control strategy reducing the collective pitch setting, which is generally associated with greater authority of the pitch actuators (Ref. 6).

Since the forward flight handling qualities metrics are predicted based on simulation alone and typically have less than 25% degradation, these degraded metrics do not warrant redesign of the control laws for trim in forward flight, though the designs are not optimal.

MTE Simulation: Lateral Reposition

Mission Task Elements are maneuvers designed to test the handling qualities of rotorcraft. Typically, pilots attempt to perform the maneuvers either in a simulator or physical aircraft and then review their satisfaction with the agility and maneuverability of the aircraft. Here, the lateral reposition maneuver from the ADS-33E-PRF (Ref. 1) is chosen in order to evaluate the lateral performance of the aircraft. Though no pilot is present, the aircraft can be tested in pilot-less simulation in order to predict the performance with a pilot and evaluate whether satisfactory inner loop handling qualities metrics are a fair indicator of MTE performance for this aircraft.

During the lateral reposition maneuver, the aircraft initiates lateral movement by rolling, accelerating to a lateral velocity of around 18 m/s (35 kts), and decelerating to a stabilized hover 122 m (400 ft) down the course. Stable hover is defined as a velocity less than 0.26 m/s (0.5 kts), and must be achieved within 3 m (10 ft) of the end point. The task must be completed within a given time, with desired (Level 1) and adequate (Level 2) requirements listed in Table 7.

The lateral reposition MTE is simulated using EMF control to represent the pilot. During the maneuver, the pilot will initially attempt to accelerate laterally as quickly as possible while maintaining heading and altitude. While approaching the end point, the pilot will begin to slow the aircraft in order

Table 6: Level 2 Forward Flight Handling Qualities with Hover Control Laws

		Degraded Metrics (Design Margin % Reduction)
Eco	Pitch	Roll Bandwidth (25), Pitch DRP (7), Heave Mode (29), Heave/Roll/Pitch Crossover Freq (45/19/16)
	RPM	-
	Hybrid	Roll Bandwidth (11), Heave Crossover Frequency (23)
Standard	Pitch	-
	RPM	Roll Bandwidth (7)
	Hybrid	-
Sport	Pitch	Pitch DRP (11)
	RPM	Roll Bandwidth (13), Heave Crossover Frequency (8)
	Hybrid	Pitch DRP (4)

Table 7: Lateral Reposition Requirements

	Desired	Adequate
Longitudinal Variation (m)	3	6
Altitude Variation (m)	3	4.5
Heading Variation (deg)	10	15
Time to Complete (s)	18	22

to decelerate and stop at the end position. Towards the end of the maneuver, the pilot's focus shifts to controlling the position of the aircraft and coming to a stable hover, rather than accelerating as quickly as possible. These two goals, initially accelerating quickly from hover and finally coming precisely to a stable hover at the end point, constitute a challenge with designing a linear controller, as designing the controller for aggressive acceleration to better represent the beginning of the maneuver will tend to induce more overshoot and oscillation around the end point position and more poorly represent the end of the maneuver.

As a compromise, two additional control loops are included around the architecture shown in Fig. 2. A lateral Translational Rate Command (TRC) controller determines the attitude input based on an EMF control loop with PI feedback, with an additional lead-lag filter centered around the crossover frequency of the velocity loop. A lateral position control loop with proportional control is utilized around the TRC control loop such that lateral position can be commanded for the maneuver. The maneuver is then represented by a ramp input on aircraft position, with the slope of the ramp corresponding to 18 m/s lateral flight. Several CONDUIT® specifications are used to design this controller, including stability margin, crossover frequency, and disturbance rejection requirements. Lateral position and velocity requirements are designed to minimize overshooting the end point during the MTE, while performing the maneuver as quickly as possible. The velocity time constant is fixed based on the roll bandwidth from the inner loop control design.

The execution of the MTE with each trim mode with either hybrid or RPM control is shown in Fig. 10. Pitch control is not shown, as the response is identical to hybrid control because the maneuver is too brief for the low-frequency RPM control to be utilized. The initial acceleration of the aircraft trends with the roll bandwidth in hover, determined by the roll design margin in Table 5. However, the speed at which the aircraft approaches the end point varies more with the inner loop damping ratio (Table 8). Cases with reduced roll damping must approach the end point more slowly in order to avoid overshooting and oscillating near the end point. The lateral velocity during the lateral reposition maneuver is plotted in Fig. 10b, with the bounds of "stable hover" indicated by the black dotted line. The maneuver is considered complete when both the position and velocity are within the target values and stable hover has been achieved at the end point (indicated by the gray shading in Fig. 10), with times to complete the maneuver for each case listed in Table 9.

First, consider the cases with hybrid control (solid lines in Fig. 10). With the highest design margin, Sport mode with hybrid control performs the maneuver quickest (11.6 s), while Eco mode with zero design margin is slowest (29.4 s) and Standard mode serves as an intermediate point between the two. Eco mode with hybrid control is unable to reach as high of a lateral velocity as the other control cases as a result of its limited pitch actuator margin, while Sport mode is able to achieve the highest roll attitude (Fig. 10c) and hold 18 m/s lateral velocity during the maneuver for several seconds. Despite being the fastest to perform the maneuver, Sport mode does not come close to using the available pitch actuator margin, while Eco mode nearly saturates. Fig. 10d shows this, presenting the change in root pitch on rotor 3 as a percent of the maximum deflection. This suggests that both Standard and Sport mode could be capable of accelerating in to the maneuver faster, but are instead limited in this simulation by their reduced inner loop damping ratio (0.35 compared to Eco mode's 0.56). The Standard and Sport mode controllers must instead be designed to perform the maneuver less aggressively to avoid oscillating around the end point with the linear, EMF control architecture.

Next, consider the trim modes with pure RPM control. Despite the fact that Eco mode with RPM control achieved the highest roll design margin in hover, it has the slowest response. Although the initial acceleration still trends with the roll bandwidth, higher inner loop damping (Table 8) for Standard and Sport mode allows the aircraft to come to a stable hover more quickly without oscillating about the end point. Eco mode must approach the end point much more slowly to avoid over-shooting due to its reduced roll damping (0.4 compared to Sport mode's 0.5). This difference in aggressiveness can also be seen in the change in rotor 3 speed during the maneuver, shown in Fig. 10e.

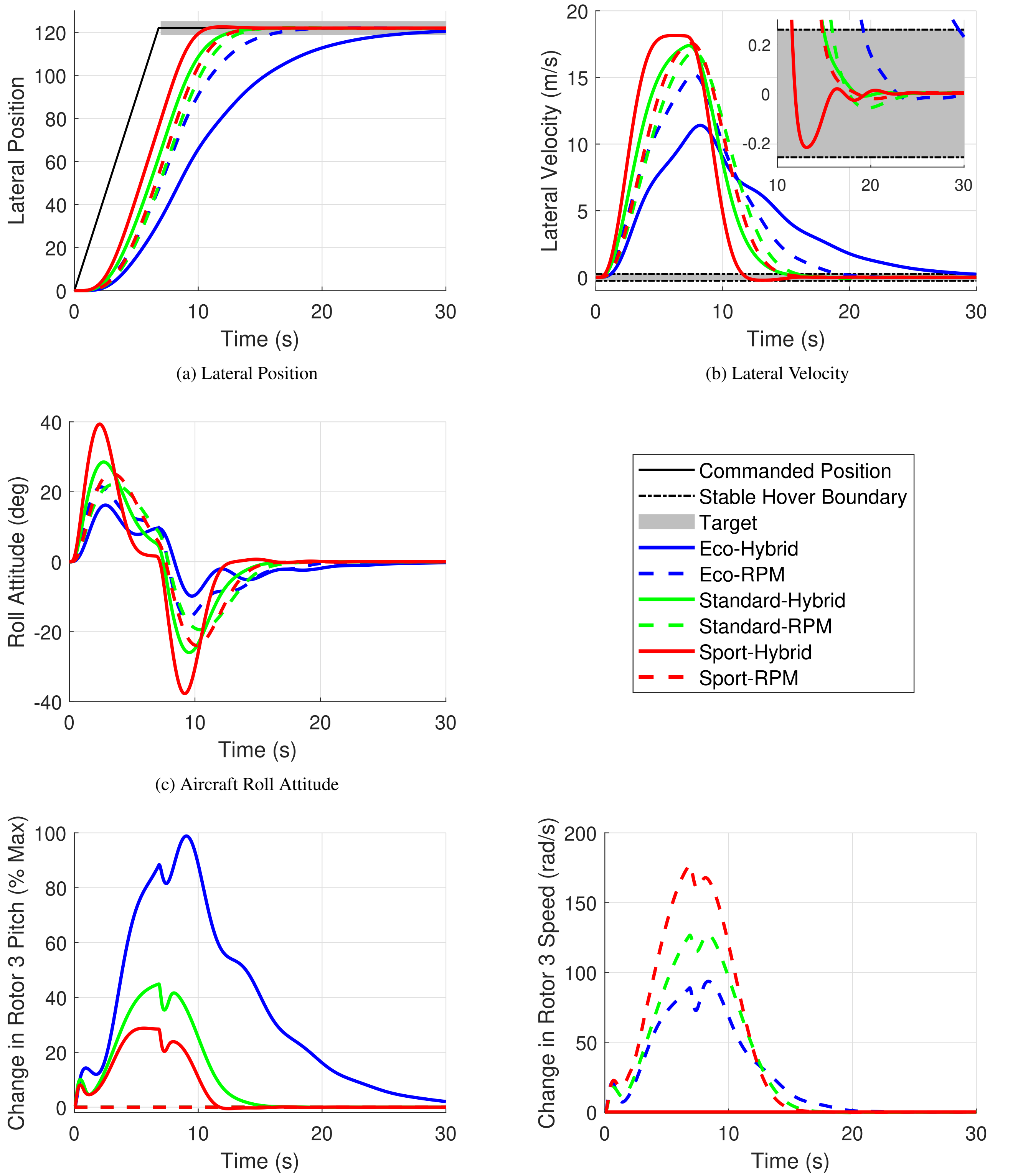
Table 8: Select Inner Loop Roll Handling Qualities Metrics Affecting Lateral Reposition Performance

		Roll Bandwidth (rad/s)	Damping Ratio
Eco	Hybrid	2.5	0.56
	RPM	2.6	0.4
Standard	Hybrid	3.3	0.35
	RPM	2.5	0.43
Sport	Hybrid	3.6	0.35
	RPM	2.5	0.48

Table 9: Lateral Reposition Results

		Time (s)	Level
Eco	Hybrid	29.4	3
	RPM	19.2	2
Standard	Hybrid	14.9	1
	RPM	15.9	1
Sport	Hybrid	11.6	1
	RPM	14.9	1

Finally, the hybrid control cases are able to outperform the RPM control cases for this maneuver, except for Eco mode which suffers from limited pitch actuator margin with hybrid control. Though Eco mode performs better with RPM control than hybrid control, it still fails to meet Level 1 requirements as a result of decreased inner loop damping (Table 9). Standard and Sport mode see reduced performance with RPM control compared to hybrid control as a result of the lower



(a) Lateral Position

(b) Lateral Velocity

(c) Aircraft Roll Attitude

(d) Change in Rotor 3 Blade Pitch as Percent of Maximum

(e) Change in Rotor 3 Speed

Figure 10: Lateral Reposition Simulation Results

roll bandwidth achieved during design margin optimization, though Standard and Sport mode are able to meet Level 1 requirements with either control type.

DISCUSSION & CONCLUSIONS

Expanding from the hover analysis presented in Ref. 6, a UAM-scale quadcopter with both RPM control and blade pitch actuation was considered in forward flight. The trim space is defined by two trade-offs: collective RPM/pitch and longitudinal RPM/pitch variation. Like in hover, increased power was traded for increased pitch actuator margin by increasing trim rotor speed. Variation of longitudinal rotor speed had minimal effect on trim power, and therefore was fixed to zero for the hybrid control cases. This was done to simplify the trim space by removing the longitudinal RPM variation as a trim variable, but could also be potentially beneficial to the aircraft acoustics or vibrations by allowing for controlled rotor phasing.

Rotor stall was considered in forward flight conditions in order to define a stall boundary and limit the blade pitch based on the trim condition. Based on a maximum achievable rotor thrust coefficient, stall blade pitch was defined as a function of attitude and advance ratio. This was then used to determine the upper bound of collective pitch setting for the aircraft trimmed in forward flight, as well as define a limit on pitch actuator deflection.

Three trim control strategies were considered in forward flight: pure RPM control, pure pitch control, or a hybrid combination of both. Trimming with RPM alone generally provided the lowest power in forward flight conditions. However, due to the changing stall margin, the pitch actuator margin before stall was also reduced if trimming with RPM alone in forward flight. Hybrid control mitigates this by increasing the rotor speed (and power) to maintain the pitch actuator margin. Trim with pitch control alone was also considered, but provided no benefit as it required higher power than RPM trim control, but also consumed stall margin.

As was done in hover, three hybrid trim modes were defined in forward flight based on an offset from the maximum trim collective rotor speed. Eco mode offered reduced trim power at the sacrifice of reduced maneuverability due to decreased pitch actuator margin, while Sport mode required higher power but has been shown to be more agile and generally have better handling qualities. Standard mode was presented as an intermediate point between Eco and Sport mode.

EMF controllers with design margin optimization were designed in hover. These controllers differ from those in Ref. 6 as a result of updated sensor models that better represent the accumulation of delays expected on senor readings for real aircraft. This generally reduced the design margin achieved by the aircraft as a result of the additional delay in the feedback loop.

Though the yaw axis was always RPM-controlled, the yaw design margin varied depending on whether RPM or pitch control was used on the other axes. More aggressive yaw controllers were viable when only the yaw axis was RPM control. This was due to faster motor response time being required when RPM control is used for roll/pitch. With only yaw being RPM-controlled, the motor time constant could be relaxed, increasing the achievable design margin before current limitations became restrictive.

Forward flight handling qualities metrics were evaluated with the hover controllers. Though some metrics were degraded into Level 2, the hover controllers are expected to provide adequate handling in forward flight around the the cruise speed of 24 m/s.

The lateral maneuverability of the different trim modes and control types were tested through simulation of a lateral reposition maneuver. As the aircraft dynamics are roughly symmetric, this maneuver can be thought of as a test of longitudinal maneuverability as well. The pilot was simulated as an outer loop EMF controller with a ramp input on aircraft position to simulate the maneuver. Unlike a pilot, the controller's parameters had to be fixed throughout the maneuver, leading to a need for balance between designing the controllers for aggressive acceleration and precision of stopping on target. Thus, outer loop controllers were designed to minimize overshoot and oscillation at the end point, while accelerating as aggressively as possible. The lateral reposition performance was influenced by both inner loop bandwidth and damping ratio, with higher bandwidth generally allowing greater acceleration and higher damping ratio leading to reduced oscillation.

Eco mode with hybrid control lacked the pitch actuator margin to adequately respond to the command and took nearly 30 seconds to complete the maneuver. Though it performed better than hybrid control, Eco mode with RPM control was also unable to complete the maneuver in the required 18 second time frame due to reduced damping, requiring the aircraft to approach the end point more slowly than the other cases to avoid overshooting. Standard and Sport mode with any control type were able to perform the lateral reposition maneuver within the desired time to meet Level 1 requirements. Based on this simulation, pilots flying in these modes are predicted to report Level 1 handling qualities requirements for lateral and longitudinal maneuvers as well. Sport mode with hybrid control was able to complete the lateral reposition maneuver the fastest with minimal oscillation around the end point, significantly surpassing the 18 seconds requirement and coming to a stable hover in 11.6 seconds.

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