Designing a Coaxial Quadrotor for Urban Air Mobility

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ABSTRACT

The NASA Revolutionary Vertical Lift Technology Project has created several Urban Air Mobility reference design vehicles to aid the burgeoning UAM industry. With over 700 conceptual designs already proposed, much interest has been generated across many unique configurations to bring vertical flight to the masses. The quadrotor configuration is one of the NASA reference vehicles, and does have some conceptual designs proposed in the industry. This study looks at the conceptual design of a coaxial quadrotor vehicle as an extension of the NASA RVLT quadrotor concept vehicle. The coaxial quadrotor has a similar layout to the quadrotor, but with a coaxial rotor at each of the four corners of the vehicle. Trade studies carried out using the NASA Design and Analysis of Rotorcraft (NDARC) tool analyzed the vehicle sizing, design gross weight, and performance for four design variants. The variants all use the baseline coaxial quadrotor layout, but analyze the effects of two major design choices: 1) variable pitch vs variable speed rotor control, and 2) motor to rotor power transmission via a gearbox vs direct-drive. The results indicate one design variant may have more benefits on some of the design objectives while another configuration may better satisfy the others.

NOTATION

A	Rotor Disk Area [m^2]
C_T	Thrust Coefficient = $T/(\rho A \Omega^2 R^2)$
C_Q	Torque Coefficient = $Q/(\rho A \Omega^2 R^3)$
D	Rotor Diameter [m]
P	Rotor Power [W]
Q	Rotor Torque [N-m]
R	Rotor Blade Radius [m]
r	Radial Location [m]
T	Rotor Thrust [N]
Ω	Rotor Speed, [Rad/s]
AAM	Advanced Air Mobility
DD	Direct-Drive
DGW	Design Gross Weight
ESC	Electronic Speed Control
eVTOL	Electric Vertical Take-Off and Landing
G	Gearbox
RPM	Revolutions per Minute
RVLT	Revolutionary Vertical Lift Technology
VP	Variable-Pitch
VS	Variable-Speed
UAM	Urban Air Mobility

INTRODUCTION

Advanced air mobility (AAM) has come to include a new set of vehicle concepts for commercial missions such as cargo delivery and passenger-carrying air taxi services. AAM was derived from a recent push for electric Vertical Take-off and Landing (eVTOL) aircraft. This push started with the advent of Urban Air Mobility (UAM) about a decade ago with only a handful of conceptual designs. That number has since exploded to more than 700 electric vehicle concepts for a variety of missions, some of which already exist, and some of which are windows into a futuristic vertical flight landscape around major population hubs across the world, Ref. 1.

The NASA Revolutionary Vertical Lift Technology (RVLT) project develops critical technologies and infrastructure to aid the design and analysis of these UAM vehicles. The RVLT project has developed a toolchain that aims to enhance the capability within industry, government, and academia to analyze and design novel vehicle concepts. In addition to developing this toolchain, the RVLT project has also created several UAM reference vehicles to provide generic versions of common configurations to be used in various trade studies exercising new VTOL technologies, Ref. 2.

This paper documents the conceptual design of a new configuration following the NASA UAM reference vehicle process and using part of the RVLT toolchain. The design of a coaxial quadrotor will be presented and discussed. This vehicle will be designed for the same UAM mission profile used in previous design studies, and parallels will be drawn to similar configurations such as the NASA quadrotor reference vehicle. Two major design choices for this vehicle, which are applicable to UAM in general, will also be explored: 1) variable speed vs variable pitch rotor control and 2) a direct-drive vs a gearbox approach to connect each motor to

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each rotor. All vehicles assume fully electric power systems with distributed electric propulsion, i.e. eight electric motors and eight rotors.

Various configurations of UAM platforms are constantly being proposed, and most of them are based on a multirotor system consisting of single or coaxial rotors. The performance of multirotor systems has been studied since the early works by Gessow, Harrington, and Dingeldein that characterized effects of rotor geometry on performance, Refs. 3-5. Several works have also summarized the experimental and computational findings of the last several decades related to multirotor systems, Refs. 6-8. More recently, work has progressed to analyze and test novel multicopter configurations relevant to the burgeoning UAM field, Refs. 9-14.

Many conceptual design studies have also been documented that used parts of the RVLT toolchain and a summary of these studies was presented by Johnson and Silva, Ref. 2. Figure 1 shows examples of the NASA UAM reference vehicles. Work by Radotich has begun to explain in more detail the process of using RVLT tools for this conceptual design process, Ref. 15.

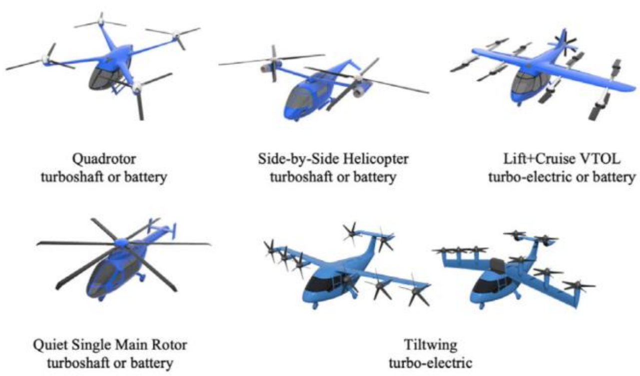

Figure 1. NASA UAM aircraft designs: six occupants (1,200 lb), 75 nm range, Ref. 2

This effort is an extension from the existing quadrotor UAM reference vehicle into a similar configuration of the coaxial quadrotor. This configuration offers potential benefits such as a reduction of induced power for the same vehicle footprint, additional redundancy against motor out conditions, and improved performance in some areas. One part of the RVLT toolchain, the NASA Design and Analysis of Rotorcraft (NDARC) tool, is used for the conceptual design of this configuration, Ref. 16. This effort aims to further build understanding of the trades in redundancy, complexity, and performance going from the quadrotor layout to the coaxial quadrotor configuration. Additionally, results from the design trades of rotor control approach and power transmission method will be compared. An example coaxial quadrotor UAM vehicle is displayed in Figure 2, Ref. 17.

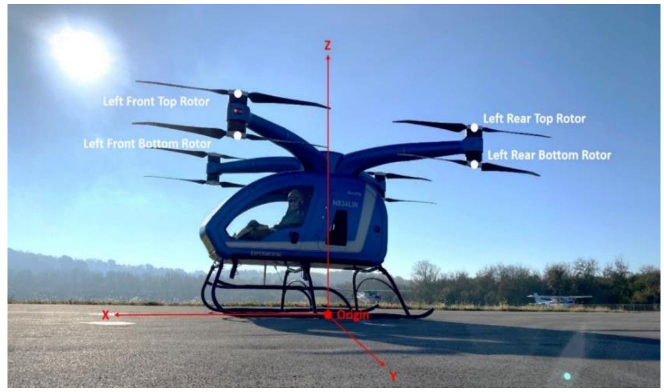

Figure 2. Example Coaxial Quadrotor Vehicle, Ref. 17

The objectives of this paper are to:

1. Document the creation of a baseline NDARC model for the coaxial quadrotor configuration.
2. Split the vehicle trade space into a 2x2 matrix including a) variable pitch vs variable speed and b) gearbox vs direct-drive.
3. Optimize each configuration to compare effectiveness of the different major design choices.

QUADROTOR VS COAXIAL QUADROTOR

This work aims to develop an optimized conceptual design for the coaxial quadrotor configuration. To maintain continuity and tractability with existing NASA UAM reference vehicles, the NASA RVLT quadrotor concept vehicle was used as the starting point for the aircraft design. An image of the quadrotor concept vehicle is included in Figure 3. Two variants of the vehicle were sized including both turboshaft and electric powered versions. A summary of the basic design parameters for those two variants are in Table 1, Ref. 2.

Figure 3. Quadrotor Concept Vehicle, Ref. 2

Table 1. Characteristics of RVLT Quadrotor Variants

Design Parameter	Turboshaft Quadrotor	Electric Quadrotor
Payload [lb]	1200	1200
Range [nm]	75	75
Rotor Radius [ft]	9.2	13.1
Disk Loading [lb/ft^2]	3.5	3.0
L/D_e	4.9	5.8
Power [hp]	2x305	4x168
DGW [lb]	3,735	6,480
Empty Weight [lb]	2,345	5,270
Structure [lb]	1,101	1,641
Propulsion [lb]	554	1,100
Battery [lb]	NA	1,561

The quadrotor is one of the more typical concept designs in the unmanned aerial vehicle world given its propensity for distributed electric propulsion with one rotor and motor located at each corner of the vehicle. Some concept designs have considered it for UAM operations due to the hypothesized benefits including ease of manufacturing with the distributed electric propulsion approach and potentially less complex rotor systems with the individual rotor actuation providing vehicle control. One major drawback of the configuration, however, is its lack of redundancy to a single motor or single rotor failure that leads to catastrophic loss of the entire aircraft. It is possible to mitigate this issue with interconnect shafts on a pitch-controlled vehicle with constant rotor speed, but this design variant is more complex than the distributed electric propulsion approach.

The coaxial quadrotor aims to implement additional redundancy by placing two motors and rotors at each corner of the vehicle. This in theory allows for a more robust distributed electric propulsion architecture without increasing the vehicle footprint. The addition of coaxial rotors also typically reduces the total induced power for the same projected area, resulting in a lower total vehicle power and potentially lower vehicle gross weight. Trades are required to identify how the additional weight from more motors, blades, etc., compares to the reduction in power requirement.

Given the above assumptions on desired use of distributed electric propulsion, this work will focus solely on electric variants of the coaxial quadrotor. The results will be compared with the electric variant of the NASA UAM quadrotor concept vehicle, which has a design gross weight (DGW) of approximately 6,500 lb. Within the electric coaxial quadrotor configuration, two major design trades will be explored. Table 2 breaks the trade-space into four distinct design variants that will be studied in this work.

Table 2. Coaxial Quadrotor Design Variants

Design Variant	Gearbox (G)	Direct-Drive (DD)
Variable-Pitch (VP)	1	2
Variable-Speed (VS)	3	4

The goal is to identify the sensitivity of the vehicle design to such decisions as the rotor control approach and the motor to rotor connection choice. Creation of the baseline coaxial quadrotor model will first be discussed as an extension from the existing quadrotor. Each design variant will then be presented, sized using NDARC, and discussed.

COAXIAL QUADROTOR BASELINE

This section details some of the specific modifications made to the NASA UAM quadrotor reference vehicle NDARC model to create the baseline coaxial quadrotor model used in this work. Although meant to be a plain language summary, some terminology is specific to the implementation in the NDARC tool. Additional details for the specifics mentioned can be found in the NDARC user manuals, Ref. 16.

The NASA UAM quadrotor concept vehicle is used as the starting point in this work. The NDARC files can be accessed from within the reference vehicles section of the NDARC user website. To build the coaxial quadrotor, several of the major NDARC component subsystems remain the same as for the quadrotor concept vehicle.Figure 1**Error! Reference source not found.** For a more thorough review of what each of the subsystems consists of, how they are put together, and what they represent, the author recommends the recent work by Radotich, Ref. 15.

Parameters Matching the Quadrotor Concept Vehicle

Several systems in the coaxial quadrotor NDARC model are the same as what is used in the quadrotor vehicle to maintain continuity and ensure a fair comparison between the results of this work and the original quadrotor design. As such, the Aircraft, Fuselage, Systems, Landing Gear, and Battery Model are all consistent from the quadrotor concept vehicle.

In subsequent sections, any changes required to transform the quadrotor concept vehicle into the first baseline variant of the electric, variable-pitch with gearbox, coaxial quadrotor will be discussed.

Geometry

The vehicle geometry locations were modified to account for a duplicate set of rotors. The existing layout from the quadrotor model was used with rotors 5-8 added. The vertical location was alternated between the upper and lower rotors, pylons, and engines to physically locate all the components. A hub-to-hub rotor separation of 25% the rotor diameter was used and was selected as a balance between spreading the rotors apart for aerodynamic performance gain, Ref. 18, while keeping them at a reasonable distance from the supporting structure to minimize weight gain.

Figure 4 is a representative sketch of the coaxial quadrotor. Comparing it to Figure 3 highlights the continuity maintained from the original quadrotor reference vehicle to this baseline coaxial quadrotor. The major visible change of course being a coaxial rotor system on each corner of the vehicle.

Figure 4. NDARC Coaxial Quadrotor Model

Propulsion Group

One gearbox assembly and driveshaft were retained in each propulsion group. The gearbox is required by NDARC even in the instances of direct-drive, in which case the gear ratio is specified as one and no gearbox weight is included in the weight estimates. Torque and power were divided among the eight propulsion groups.

Engine Group

The engine group has most features in common with the quadrotor input files. The only changes are that the engine group is where a gear ratio of one can be enforced for the direct-drive variants to eliminate the gearbox between each motor and rotor. An initial guess for the motor size (maximum rated power) is also specified here, which was defined as 100 hp per motor.

Additionally in the engine group, a flag was incorporated to account for weight of a thermal management system. This is a recent addition and provides a more accurate representation of the total electric system weight.

Motor Model

Two different motor models were used in this study. One model pre-packaged in NDARC is the NASA15 motor model, which scales the weight of electric motors as a function of their torque requirement. The model is based on high torque-to-weight motors relevant to the speeds used in a gearbox variant of a UAM vehicle, i.e. a motor operating at several thousand revolutions per minute (RPM).

The above high speed motor model was found to over-predict motor weight for direct-drive applications compared to available data on existing motors recently used in aerospace applications. A low speed, very high-torque motor from Siemens was used to create a new motor model in NDARC. The motor used was the SP200D, which has a specific torque value of roughly 31 Nm/kg, Refs. 19-20. This motor operates in a range similar to the vehicles discussed in this work, so a custom motor model was tuned to attain its specific torque characteristic. The SP200D was used in an airplane, i.e. an axial flow application. Motors for UAM must contend with the hub moments resulting from edgewise flight, which may require larger motor bearings and a heavier overall motor.

Weight for the electronic speed control (ESC) was also added into this section using recent additions in the NDARC capability. This again helps to accurately capture all the resulting weight penalties associated with the implementation of an electric power system. Additional information on the motor and ESC models can be found in the NDARC Theory Manual, Ref. 16.

Fuel Tank

The fuel tank is mostly the same as from the quadrotor electric input files. The only modifications include the addition of thermal management system weight and disabling the option for auxiliary batteries. The same pack level installed energy density of 400 Wh/kg is used, consistent with other studies of the NASA UAM reference vehicles. This energy density assumes the attainment of improved battery technology in the coming years.

Tech Factors

NDARC tech factors are used to calibrate to an existing technology and capture forecasted improvements in rotorcraft technologies that could be implemented in a new design planned several years in the future. The tech factors modify the physical weight of components on the aircraft.

One such example implemented in this work was a tech factor on the motor performance. A peer-reviewed article within the electrical vehicle industry predicts a more than 10% annual improvement in permanent magnet synchronous motor performance for the next several years, Ref. 21. In this work, a more conservative tech factor equivalent to a 5% annual weight reduction over five years was used.

Other tech factors of relevance here are related to the rotor swashplate hydraulic controls and the engine air intake and exhaust, which are all eliminated in the variable-speed design variants. The variable-pitch design variants still include appropriate weights of the rotor control. There are also tech factors for the drivetrain weights, which are used to eliminate the weight of gearboxes and related items for the direct-drive design variants.

Rotor

The rotor model from the quadrotor concept vehicle is used with a few notable variations. The thrust-weighted blade loading, defined at each rotor using one-eighth the vehicle DGW in hover and the resulting thrust-weighted solidity, is used as a tunable parameter. It is increased beyond what has typically been used in past UAM reference design studies. Five degrees of delta3 was also added to the rotor model to allow a bit of additional tip clearance for the collective only flapping rotor model used. The delta3 introduces pitch-flap coupling to reduce the amount of blade flapping in forward flight, which is essential given the proximity of the rotors to the support structure holding them. In this study, a constant rotor separation of half the rotor radius was used, which should work to mostly mitigate this concern.

The rotor model is also a place where one makes the distinction between variable-pitch and variable-speed rotor control. The NDARC theory manual specifies the inputs for each of the different applications. For the RPM controlled models, the built-in rotor pitch was tuned to keep the hover rotor tip speed in proximity to that of the variable-pitch design variants, which is 550 feet per second. The tip speed for these RPM controlled variants will vary based on flight condition and is discussed more in the results section.

The quadrotor concept vehicle rotor performance model generated in CAMRAD-II was used in this study, Ref. 22. The model is used by NDARC to approximate rotor performance in various flight conditions and capture effects such as rotor stall and performance in high advance ratio edgewise flight. Since the rotor layout and size is of similar magnitude to the quadrotor concept vehicle, and the coaxial rotor separation is large, this was accepted as a reasonable starting point. Future studies will iterate the fully optimized NDARC models through CAMRAD-II to tune the rotor performance models as detailed in Ref. 15.

The next section details the procedure used to size and optimize the performance of the NDARC design variants.

NDARC SIZING MISSION AND PERFORMANCE CONDITIONS

The NASA reference vehicles are sized in the NDARC tool using a consistent set of performance requirements from Patterson et al., Ref. 23. These requirements are derived from a sizing mission along with some additional point design operating conditions. The sizing mission is meant to simulate a nominal short-haul UAM mission and may be representative of what these aircraft will eventually be used for. A schematic of the UAM mission used to size the vehicles in NDARC is included in Figure 5.

The sizing mission includes an initial taxi, a vertical takeoff and initial climb, a cruise climb, and a cruise segment followed by the reverse order back to the ground. This flight is conducted twice with each leg being 37.5 nautical miles and totaling 75 nautical miles. The 500 foot per minute cruise climb condition was also used.

Another common constraint applied for the design of the UAM reference vehicles is a low-noise tip speed. Five hundred and fifty (550) feet per second is typically used for the reference vehicles and is applied here as well for the variable-pitch design variants. As previously mentioned, effort was made for the variable-speed design variants to have a hover tip speed close to 550 feet per second. The results will be documented for each variant across the sizing mission flight conditions. Constraining the design space to a lower tip speed generally has a negative impact on performance, but this constraint is put in place to reduce noise impact on the urban environments in which these vehicles will fly.

The four variants were manually optimized using several design variables to try and achieve peak performance of each variant. Design objectives include a best range cruise speed of approximately 100 knots, minimizing design gross weight, and maintaining a small vehicle footprint which is driven by rotor size. Some of these objectives are generally opposing each other, such as the desire for a low gross weight and small rotors. The smaller rotors, however, do increase disk loading which is found to help in attaining higher cruise speeds. One could optimize with the most weight on a low gross weight design, but that will tend to have large rotors and be slower as a result. Although maintenance costs were not tracked in this work, it is hypothesized that reduced flight time results in lower maintenance costs. As such, a high cruise speed with low block time, i.e. the time required to fly the UAM sizing mission, was most important in the conceptual design trade with rotor size second and design gross weight third.

VARIABLE PITCH – GEARBOX

The first design variant uses variable pitch to control the vehicle. Due to the distributed rotors around the vehicle, only collective input is required on a variable pitch rotor to have full vehicle control. One could implement full cyclic and collective rotor controls, but the collective only implementation was used to further reduce weight in the rotor system and flight control system. Table 3 documents the best performing results at each rotor design radius. The maximum speed, V_{max}, is defined for steady level flight with each motor limited to 95% of their maximum continuous power. Trends for the design iterations as a function of rotor radius are also depicted in Figure 6. DGW increases by 6% and disk loading by 58% as rotor radius decreases from 11 ft to 9 ft.

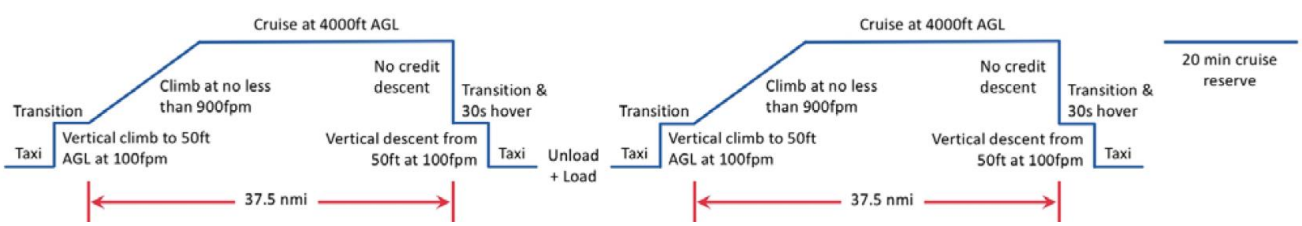

Figure 5. UAM Sizing Mission, Ref. [2]

Table 3. Variable Pitch – Gearbox

Radius [ft]	11	10	9
DL [lb/ft^2]	3.400	4.160	5.360
Solidity	0.020	0.025	0.032
Lock Number	4.670	4.380	4.090
DGW	5,170	5,224	5,463
Rotors [lb]	458.6	423.1	395.2
Motors [lb]	149.6	155.3	173.3
Drive Sys. [lb]	229.9	225.3	236.7
Battery [lb]	1,583	1,658	1,844
V_{br} [kt]	82.70	89.20	96.50
V_{max} [kt]	111.0	116.2	125.4
Time [min]	61.50	57.60	52.00

Most of the component weights were observed to either decrease with decreasing rotor size, or at least be relatively stable around a given value. As the rotor size decreases, the vehicle power requirement increases so the motor and drive system weight remain mostly flat. The battery size, however, is monotonically increasing with smaller rotor size, and this leads the behavior of the total vehicle DGW.

For this specific model, NDARC could not size a vehicle with less than 9 ft radius blades since the power requirement would then become too high. In this electric implementation, a higher power requirement results in a heavier motor and battery, which then again requires an even higher power to fly. This leads to a diverging design loop with no solution.

A single point design from each rotor radius sweep will be chosen to compare with the other design variants. The point will be chosen subjectively with consideration of speed, weight, and size. For this design variant, this was identified as the 9 ft rotor vehicle with a nearly 5,500 lb gross weight. The performance values for this design variant are reported in Figure 7. The vehicle with 9 ft rotors had a best range cruise speed of 96.5 kt and a block time of 52 minutes.

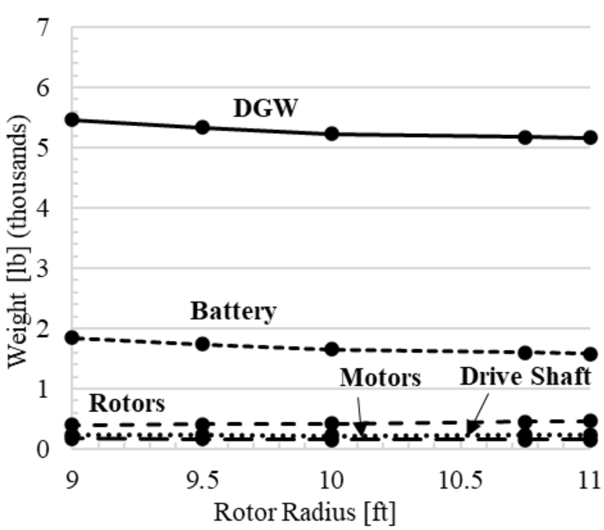

Figure 6. Variable Pitch, Gearbox: Weight

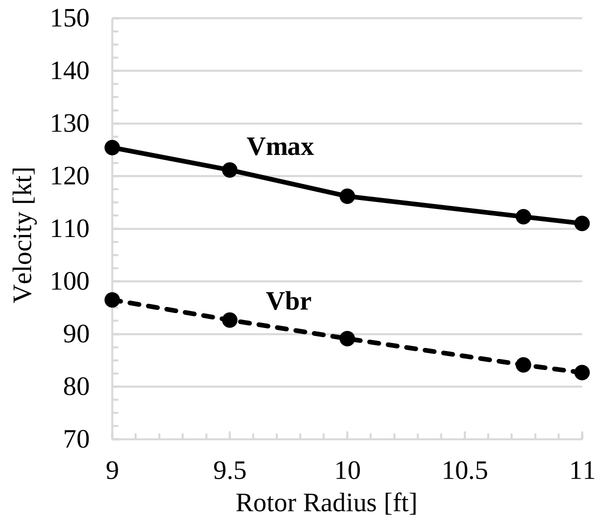

Figure 7. Variable Pitch, Gearbox: Performance

VARIABLE PITCH – DIRECT-DRIVE

The direct-drive variant of the variable pitch coaxial quadrotor vehicle eliminates the gearbox and the associated additional drive shafts and replaces it with a direct connection from the motor to the rotor. This design variant is meant to simplify the vehicle design with the removal of complex and expensive gearbox systems. Conventionally, the combination of a light high-speed motor with a gear reduction system will come out lighter than a direct-drive high-torque motor, but this may change as more time and money is invested in low-speed high torque motors, Ref. 21.

For this design variant, vehicles were sized with rotors from an 11 ft radius down to an 8 ft radius. The results of the sizing trade study are summarized in Table 4. A similar story as with the first design variant using a gearbox is observed. The larger rotor size results in a lower total design gross weight but decreasing the rotor size increases disk loading and allows the vehicle to attain a higher best range speed, maximum level flight speed, and a lower block time per mission.

Table 4. Variable Pitch – Direct-Drive

Radius [ft]	11	10	9	8
DL [lb/ft^2]	3.640	4.420	5.520	8.220
Solidity	0.022	0.026	0.033	0.049
Lock Number	4.670	4.380	4.860	4.500
DGW	5,523	5,558	5,615	6,619
Rotors [lb]	474.5	437.1	377.1	371.9
Motors [lb]	493.4	481.8	480.1	669.0
Drive Sys. [lb]	29.70	29.80	30.00	36.80
Battery [lb]	1,670	1,748	1,861	2,472
V_{br} [kt]	86.40	92.50	101.1	116.8
V_{max} [kt]	124.2	126.2	127.2	140.9
Time [min]	58.90	55.00	50.10	43.50

Weight trends for the variable pitch design variant using direct-drive are included in Figure 8. The performance is reported in Figure 9. Similar trends are observed with several of the component weights remaining mostly flat with changing rotor size. The difference between rotor and motor weight is a bit more pronounced, however, with motor weight largest and rotor weight lowest for the 8 ft rotor radius. Notably, the drive system weight for this direct-drive configuration is very low. It consists only of the linking shaft coming out from the motor and into the center of the rotor. The reduction in drive system weight is one of the hypothesized benefits of the direct-drive implementation, along with reduced mechanical complexity of the power transmission system.

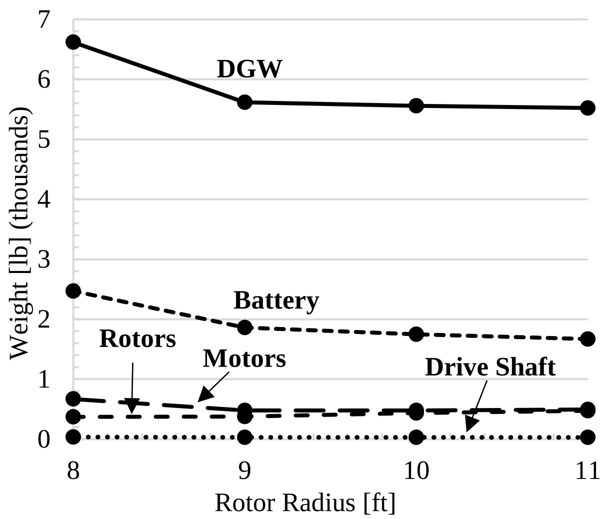

Figure 8. Variable Pitch, Direct-Drive: Weight

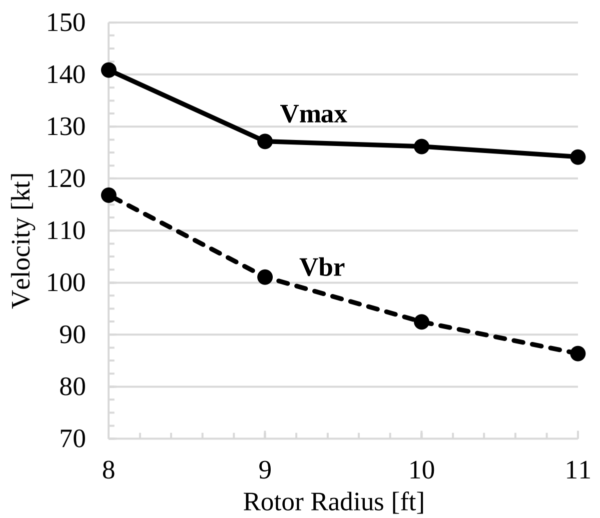

Figure 9. Variable Pitch, Direct-Drive: Performance

Comparing the design solution with 9 ft rotors between the two variable pitch variants suggests that the direct-drive variant does weigh slightly more than the gearbox variant. This is because the gearbox variant has a lighter power transmission system, i.e. the combination of motors and drive system. The 8 ft radius design variant using direct-drive does attain improved performance, but the design gross weight has increased by about 1,000 lb or about 18%, as compared to the 9 ft rotor radius design. For that reason, the 9 ft radius design is again chosen and will be used to compare with the other variants. It has a best range speed of approximately 100 kt and a block time of 50 minutes with a DGW of 5,600 lb.

VARIABLE SPEED – GEARBOX

Design variant three has a speed-reducing gearbox, but with a different control system for the vehicle. The collective actuation of the rotors is removed and replaced with rotor speed control using fixed-pitch rotors. This is another major design consideration currently under debate in the UAM industry. It is less complex to bolt a rotor onto a motor or drive shaft than it is to design and implement a collective controlled rotor with swashplate assembly and actuators. The former has the promise of reduced mechanical complexity, while the latter typically delivers enhanced control response via lower rotor control time constants. The trade is partially captured in NDARC in that the move from variable pitch to variable speed removes the rotating system control actuators that would typically be used to move the swashplate, thus reducing the vehicle weight. On the other hand, however, control of the vehicle becomes more complicated, with each individual rotor RPM having to be trimmed to attain a desired flight condition. Control responsiveness requirements in sizing the motor for variable-speed control are not presently captured in this trade; see Ref. 24.

Introducing variable rotor speed designs into the design matrix creates a slightly mismatched comparison between the design variants since a major consideration of the NASA reference vehicles is a low rotor tip speed to minimize rotor noise. As previously mentioned, the RPM controlled designs will vary up and down from some mean value. In this study, the variable speed designs were manually tuned via the built-in rotor pitch such that the hover condition had a tip speed approaching that of the fixed-speed variants, i.e. 550 feet per second. In practice, the hover tip speeds were slightly higher and certain conditions such as climb see rotor tip speeds on the order of 700 feet per second. As such, the noise impact of variable-speed designs should eventually also be considered in the wholistic performance of each design variant.

The results for the rotor radius sweep of the variable-speed variant with gearbox are summarized in Table 5 with the weight trends in Figure 10 and the performance values in Figure 11. Of special note is that the design gross weight is not a monotonically increasing value with decreasing rotor radius. For this variant, the design gross weight initially decreases to a minimum for 10 ft rotor radius and then begins increasing again as still higher values of disk loading are achieved. For these design iterations with the RPM controlled variant, a few additional variables are added into the design space such as the rotor's default pitch setting. This was set to maintain a low hover tip speed comparable with the pitch-controlled variants to maintain low total vehicle noise. This appears to squeeze some additional performance out of the rotors that mitigates the previously observed weight growth of the other variants with decreasing rotor size. The battery weight minimum corresponds with the DGW minimum, while the performance is monotonically improving with reduced rotor size and thus increased disk loading.

The design study for the variable speed rotor with gearbox has an optimal design at the smaller rotor radii. For an 8.5 ft radius rotor, the vehicle weighed 5097 lb and has a best range speed just above 100 kt. Further iterations attempted to reduce the rotor radius to 8 ft, but a converged solution was not obtained. Further optimization may yield improved performance at reduced rotor size and should be investigated in future work.

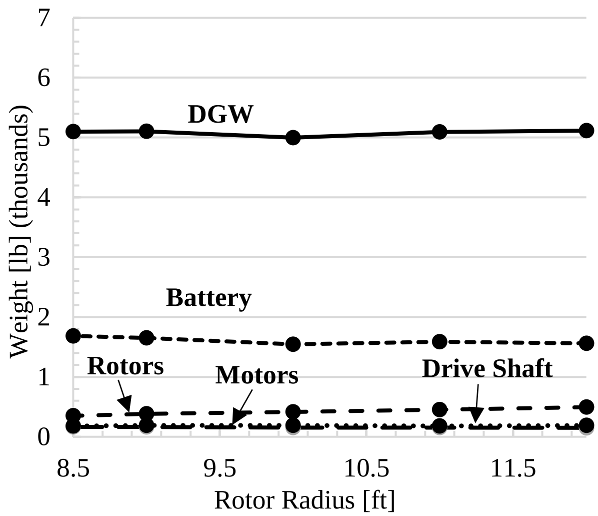

Figure 10. Variable Speed, Gearbox: Weight

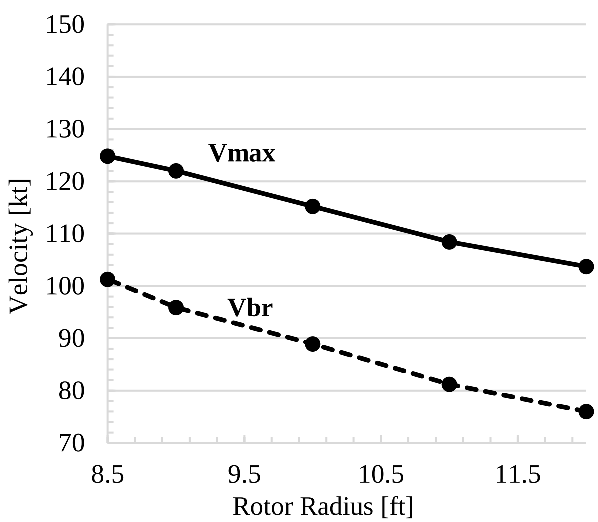

Figure 11. Variable Speed, Gearbox: Performance

The one caveat to the lower design gross weight for the RPM controlled variants is the motor sizing. Studies conducted by Malpica et al., Refs. 24-26, and Gandhi et al., Ref. 27, identify a power margin requirement for control bandwidth of variable speed UAM-sized aircraft. Since the control approach for these vehicles is quickly accelerating and decelerating the individual rotors, the motors must be strong enough to quickly change each rotor's inertia. This is slightly more complex when using a transmission system with gear reductions, but it is in principle a challenge for both gearbox and direct-drive variants using RPM control. For all variants, the cruise climb condition in the UAM mission typically sized the motors, which may indicate steady level cruise type conditions have enough power margin for good controllability. Note again that the power margin needed for adequate RPM control authority was not evaluated in the present work and should be accounted for in the future to verify the conclusions of trade studies involving variable speed control rotors.

Table 5. Variable Speed – Gearbox

Radius [ft]	12	11	10	9	8.5
DL [lb/ft^2]	2.826	3.348	3.978	5.014	5.614
Solidity	0.017	0.020	0.024	0.030	0.031
Lock Num.	4.940	4.670	4.380	4.090	3.940
DGW	5,115	5,091	4,998	5,103	5,097
Rotors [lb]	494.7	455.1	413.5	381.0	349.5
Motors [lb]	149.8	152.4	152.5	161.8	164.0
Drive Sys. [lb]	189.5	180.7	188.0	188.0	181.0
Battery [lb]	1,561	1,587	1,545	1,652	1,685
Vbr [kt]	76.00	81.20	88.90	95.90	101.3
Vmax [kt]	103.7	108.4	115.2	122.0	124.8
Time [min]	67.00	62.60	56.70	52.20	49.90

VARIABLE SPEED – DIRECT-DRIVE

The last design variant analyzed in this work uses a variable speed direct-drive implementation to control the vehicle. This is hypothesized to be the simplest design approach for UAM vehicles using distributed electric propulsion. The method does have several drawbacks, however, such as the need for heavier high-torque motors to meet motor-speed based vehicle flight control margin. Still, this variant offers much potential if these challenges can be overcome.

Results for the trade study on a variable-speed direct-drive controlled aircraft are reported in Table 6 and Figures 12-13. Due to the higher motor weight that comes with direct drive, a slightly different trend is observed as compared to the gearbox equivalent variant. In this case, the minimum design gross weight is observed for a much larger rotor radius of 11 ft Given the objectives to reduce the vehicle size and improve performance, however, the vehicle sweep was still carried out to a minimum rotor radius of 8 ft. The aircraft sized with 8 ft rotor radius has a design gross weight comparable with both variable-pitch variants having 9 ft rotor radius. At the same DGW, the performance of this variant appears superior to the other design variants. The 8 ft rotor solution has a best range speed of 118 kt and the fastest block time of 43 minutes to complete the UAM mission from Figure 5, and will be used to compare to the other design variants.

In this case, the best range speed and maximum level flight speed are observed to rapidly increase with decreasing rotor size. This is due to disk loading's squared relationship with the rotor radius. Further reduction in the rotor size would allow for still higher flight speeds, but at the cost of heavier motors and battery. From Figure 12, it appears as if the DGW is not yet rapidly increasing at an 8 ft rotor radius. A slightly smaller rotor radius could result in a superior concept design depending on which design objective is given the highest priority.

Table 6. Variable Speed – Direct-drive

Radius [ft]	12	11	10	9	8
DL [lb/ft^2]	2.886	3.394	4.168	5.356	6.884
Solidity	0.017	0.020	0.025	0.032	0.034
Lock Num.	4.940	4.670	4.380	4.090	3.780
DGW	5,222	5,162	5,237	5,452	5,536
Rotors [lb]	499.8	458.3	423.6	394.8	324.6
Motors [lb]	403.6	385.3	405.6	447.6	478.9
Drive Sys. [lb]	24.30	23.10	22.50	22.70	24.50
Battery [lb]	1,527	1,540	1,615	1,771	1,883
V_{br} [kt]	78.00	83.10	89.90	99.30	118.1
V_{max} [kt]	103.0	106.4	118.3	124.4	136.9
Time [min]	69.50	60.70	56.20	51.30	43.30

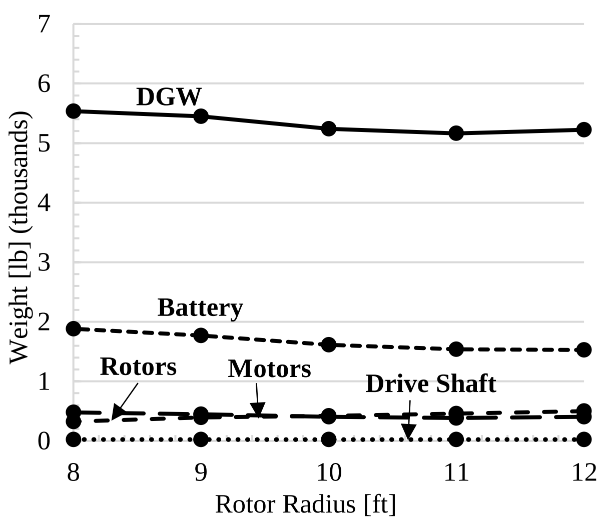

Figure 12. Variable Speed, Direct-Drive: Weight

The design sweep for this variant did continue to smaller rotor sizes as far as a 7 ft radius, but the required power and thus design gross weight did quickly became untenable. The design gross weight using a 7 ft radius rotor was nearly 7,000 lb while only achieving marginal improvement on the block time. Still, a compromise somewhere between 7 ft and 8 ft rotor radii may result in an acceptable DGW with still higher flight speeds than the 8 ft design.

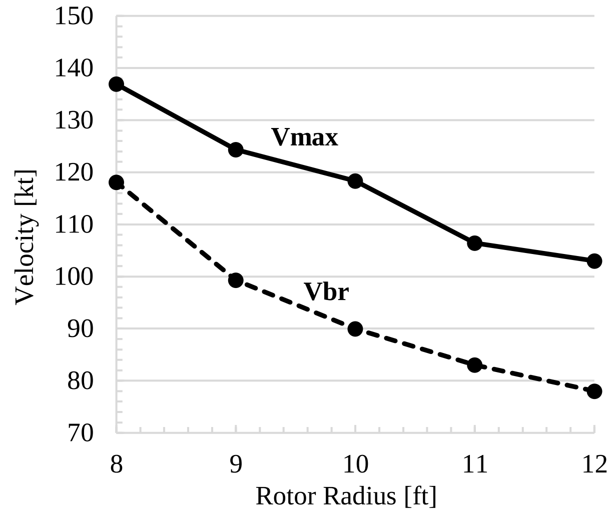

Figure 13. Variable Speed, Direct-Drive: Performance

COMPARING THE DESIGN VARIANTS

With all four design variants having been analyzed, the DGW of each as a function of rotor radius can be compared. This comparison is reported in Figure 14. For the cases that were able to find a converged solution, the direct-drive variable-pitch variant was by far the heaviest. Even more interesting was that the variable-speed rotor with gearbox was consistently the lightest. Confirming this result in future studies could have large implications in confirming the hypotheses that the reduced mechanical complexity of the rotor system leads to an overall lighter vehicle. As mentioned previously, however, future studies should also quantify the control margin and noise levels of variable-speed rotor designs to provide a fair comparison with the variable-pitch counterparts.

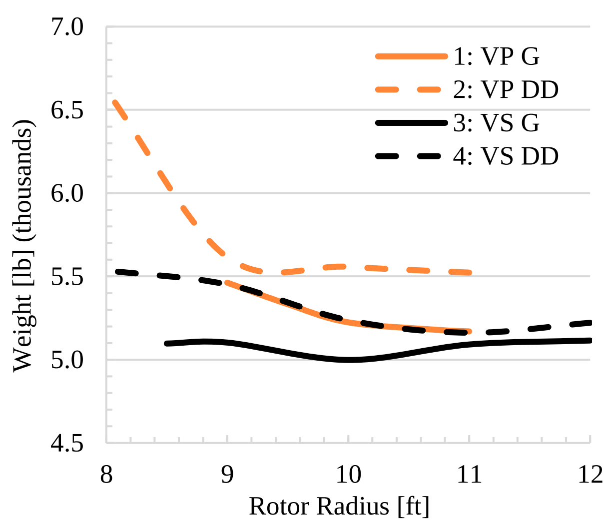

Figure 14. Design Gross Weight: All Variants

The following few charts will compare component weight and performance from the selected point designs of each variant. As a reminder, variants 1 and 2 were selected at the 9 ft rotor radius design points. The 8.5 ft rotor radius design point was selected for variant 3 and the 8 ft rotor radius was selected for variant 4. The four variants are labeled in the charts from one to four, and also using the nomenclature of variable-pitch (VP), variable-speed (VS), gearbox (G), and direct-drive (DD).

A summary comparing the DGW and other component weights of the four selected design points is reported in Figure 15. It should be noted that the gearbox variant for both VP and VS are lighter than their direct-drive equivalents. To more closely analyze why this may be the case, the component weights are reported in Figure 16 with a zoomed in y-axis.

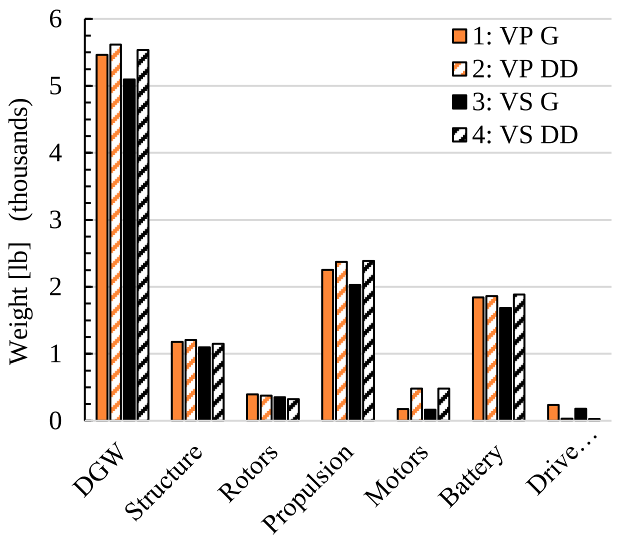

Figure 15. Weight Buildup: All Variants

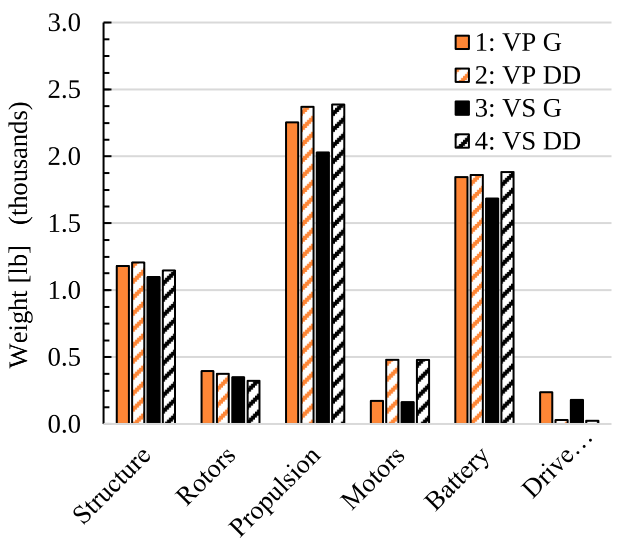

Figure 16. Component Weights: All Variants

Although the drive system weight in the most far-right column for the direct-drive variants is practically negligible, the motor weight for those same variants is much higher than their gearbox counterparts. The battery weight for the DD variants is also slightly higher. The combination of a higher battery weight and motor weight outweighs the reduction in drive system weight. Still, the finding that the direct-drive equivalents are close in weight to the gearbox versions indicates a trade that may be worth the reduced mechanical complexity of using direct-drive.

Some performance metrics are compared across the four variants in Figure 17. Takeoff power, best-range speed, maximum steady level flight speed, and block time required to complete the mission are all compared. Variant four has an obvious advantage across the three performance metrics but also has the highest takeoff power requirement.

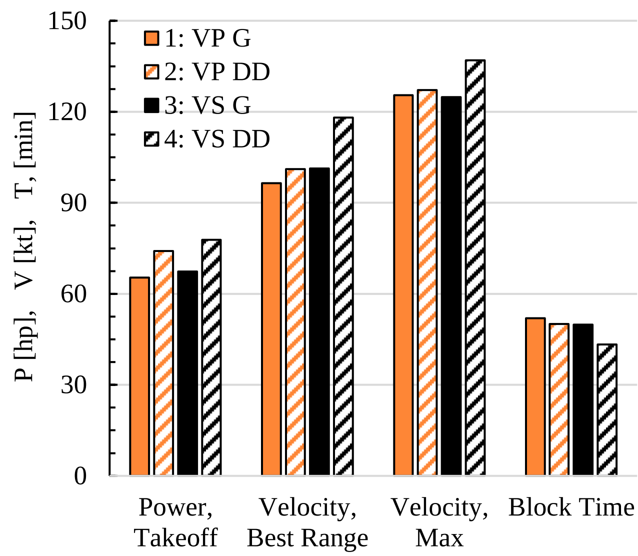

Figure 17. Performance: All Variants

To better understand the operational characteristics of each of the design variants, comparisons must be made across similar flight conditions. Two flight condition sweeps were used to achieve this. The first was a steady and level forward-flight speed sweep. Figure 18 summarizes the tip speed for the four selected design points starting at their hover condition up to approximately their maximum flight speed in increments of 10 kt. Since the variable-pitch variants maintain a constant rotor speed of 550 feet per second and use collective rotor inputs for control, they simply show a horizontal line at 550 feet per second across the entire speed sweep.

The RPM controlled variants, however, show some deviation. They start in hover above 550 feet per second, dip below 550 for some moderate forward flight speed as the rotor induced power is reduced, and then climb again at higher forward flight speeds. At their maximum steady level flight speeds, the RPM controlled variants have an approximate tip speed of 640 feet per second, which is 16% higher than the variable-pitch designs and will have implications on vehicle noise.

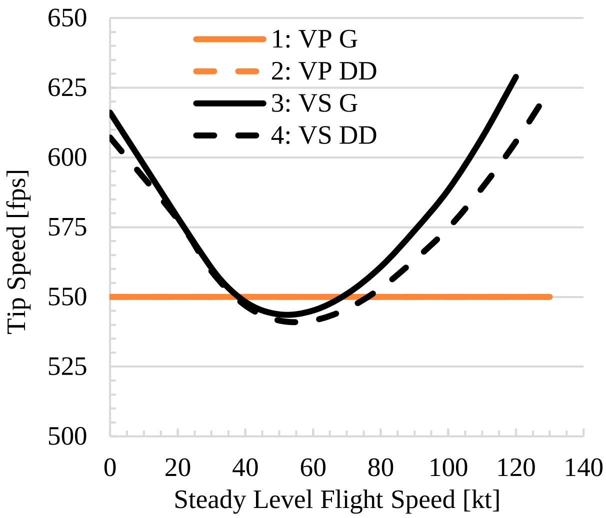

Figure 18. Forward Flight Velocity Sweep, Tip Speed: All Variants

The second set of flight conditions used to compare the design variant performance is the sizing mission from Figure 5. The tip speed of each selected point design of the four design variants is reported in Figure 19 for each segment of the UAM sizing mission. Again, the variable-speed variants are observed to dip above and below 550 feet per second rotor tip speed depending on the given flight condition. Segments 5 and 13, which are the starting cruise-climb to altitude on each leg of the mission, are shown to have the highest tip speed. The descent segments to have a much lower tip speed than the peak cruise-climb condition, which may be advantageous to avoid disruptive blade vortex interaction noise typically encountered in descending flight conditions.

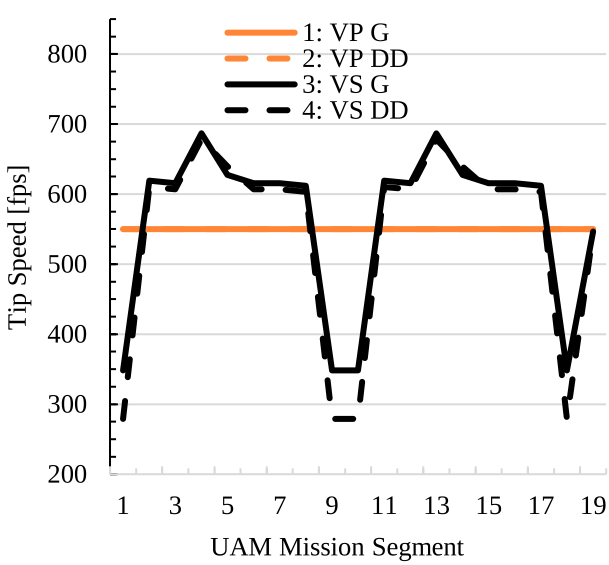

Figure 19. Sizing Mission, Tip Speed: All Variants

To assess the motor performance throughout the UAM sizing mission, the average power usage across all eight motors is reported for each flight segment in Figure 20. Not surprisingly, segments 5 and 13 have the highest power usage and are the conditions that 'size' the overall motor power requirements. The motors are sized such that this cruise-climb condition uses only 95% of the maximum continuous motor power. Somewhat unexpectedly, the motor power usage as a percent is mostly consistent across all four of the design points for each individual mission segment. This is a result of the aggressive cruise-climb being the reference point from which all other flight conditions are then related.

The referenced studies on UAM motor sizing for adequate handling qualities, Refs. 24-27, suggest varying levels of motor power margin required. Unfortunately, the answer is not necessarily consistent for all vehicle designs and must up to this point be assessed for each newly designed vehicle. Still, some general conservative metrics can likely be concluded from the studies. It should again be noted that the variable-speed designs will likely require a much higher power margin to achieve satisfactory control of the vehicle. Future work should be carried out to determine if a low-order approximation, but still improved over the current general rule of thumb, can be implemented to provide rough estimates of the true power margin required for new concept designs. In this case, the variable-speed design variants likely do not have enough power margin for adequate vehicle control. Adding additional power margin will increase the DGW of the vehicles.

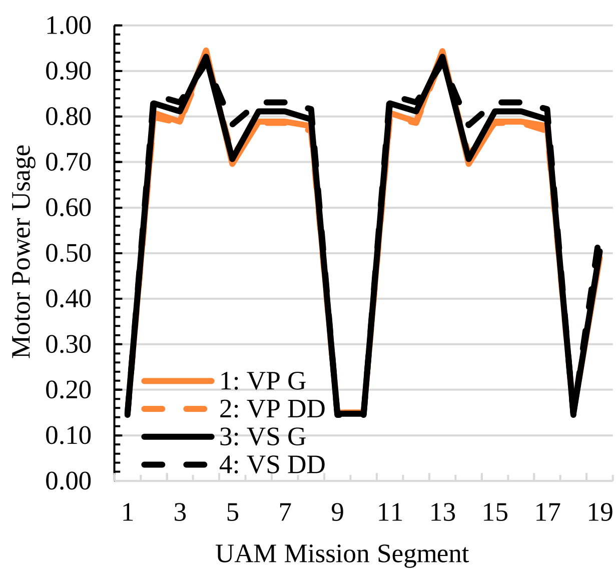

Figure 20. Sizing Mission, Power Usage: All Variants

SUMMARY

This work documented the development and conceptual design trade studies for a coaxial quadrotor configuration relevant to Urban Air Mobility. The vehicles were sized using the NASA Design and Analysis of Rotorcraft tool that uses simplified aerodynamics to calculate trim conditions and empirical relationships to estimate total vehicle weight, installed power, and performance. The approach for sizing the vehicles in NDARC followed the same approach used by the NASA Revolutionary Vertical Lift Technology project to create the publicly available NASA UAM reference vehicles.

The coaxial quadrotor is proposed as an alternative conceptual design to the standard NASA reference quadrotor and provides the potential benefits of additional redundancy and improved performance. With eight individual rotors, this configuration is well suited for distributed electric propulsion, which was used across all the design variants analyzed. Having two individual rotors and motors on each corner of the vehicle enable it to maintain flight even with one motor or rotor inoperable. Performance benefits of the coaxial quadrotor include a reduced induced power requirement and can lead to smaller rotor sizes, hence smaller vehicle footprint, as compared to the quadrotor.

Two major design trades were investigated: 1) variable-pitch vs variable-speed rotor control, and 2) gearbox-driven vs direct-drive power transmission. The conventional rotorcraft approach may suggest using a variable-pitch controlled rotor with a high-speed motor and gearbox reduction system. Many of the existing UAM conceptual designs, however, propose an RPM controlled approach with a motor directly driving the rotor. This eliminates completely the need for a gearbox and transmission system, which reduces vehicle complexity.

The vehicles were sized and iterated with three main design objectives: 1) minimize design gross weight, 2) minimize rotor size and vehicle footprint, 3) maximize vehicle performance with the metric being flight speed. The first two objectives are hypothesized to lead to a lower total vehicle cost and the third reduces the time required to fly a standard UAM mission, which is hypothesized to reduce operational and maintenance costs and more quickly deliver payloads to their destination.

Starting with the first objective to minimize gross weight, the best performing aircraft design was the variable speed rotor variant using a gearbox transmission and 10 ft rotor radius. This design point had a design gross weight just under 5,000 lb. A key finding was that the gearbox variants were consistently lighter than their direct-drive counterparts. This is due to direct-drive high-torque motors being quite heavy. This situation could see improvement in the future, however, if research supports the development and improvement of this specific motor application. Most of the designs were clustered together between five- and six-thousand pounds. As such, the other metrics became larger drivers in determining which variant had the best results.

Considering the designs that sized at a smaller rotor radius, and thus smaller total vehicle footprint, the different configurations had similar attributes. Most notably was that the variable-speed control with gearbox had by far the lowest design gross weight for a given rotor radius. The eight-and-a-half-foot rotor radius design had a gross weight just under 5,100 lb. The variable-speed control design using direct-drive, however, provided by far the best performance. The design with 8 ft rotor radius weighed just over 5,500 lb and has a best range speed of approximately 118 kt and a maximum level flight speed of 137 kt. This was the fastest of all the trade studies and more than 10 kt greater than the next best performing variant at a similar DGW.

Results were compared across one design point from each of the four design variants. As a summary of the results, two configurations stand out after considering them in context of the design objectives put forth in the beginning of this study. For the lowest gross weight design, the variable-speed gearbox implementation appears to outperform the other design variants. The combined gearbox and motor weight was found to be consistently less than the motor weight of the direct-drive variants. For the highest performance, however, the variable-speed direct-drive variant appears to outperform the others with its high disk loading achieved at a reasonable design gross weight.

Rotor tip speed and motor power usage was also compared across the four design variants for the UAM sizing mission that was used to design the vehicles. The variable-pitch (VP) design variants have a set tip speed of 550 feet per second to reduce noise impact on the urban environments in which they would fly. The variable-speed (VS) design variants were observed to have as much as 16% higher tip speeds between hover and the maximum steady level flight speed as compared to the 550 feet per second baseline of the VP cases. They did achieve lower tip speeds, however, for some moderate level forward flight speed.

All four of the design variants were observed to have their motors sized by the aggressive cruise-climb segment of the UAM sizing mission. This resulted in all vehicle design variants having a similar percentage power margin at each segment of the UAM mission. The cruise conditions had between 15-20% margin over the motor’s maximum continuous power. Previous studies suggest a large power margin is required for these VS (RPM controlled) UAM vehicles.

Future work is required to help identify a low-order approach that can be easily used in the design process to determine a realistic and not overly conservative motor power margin for new UAM designs. This is particularly important for RPM controlled variants, since their DGW will be sensitive to the required motor power margin. Still, the reduced complexity of the variable-speed direct-drive variant with no swashplate assemblies or gearboxes has much promise for distributed electric propulsion vehicle design architectures.

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