

Powertrain System Analysis for an Urban Air Mobility Tiltwing Concept Vehicle

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ABSTRACT

In support of research and development for Urban Air Mobility (UAM) operations, the National Aeronautics and Space Administration (NASA) is developing a fleet of Vertical Takeoff and Landing (VTOL) concept vehicles. These vehicles aim to identify key areas for technological growth and provide reference data to the UAM community. A six-passenger Tiltwing concept recently added to the fleet offers new opportunities to explore the UAM design space through trade studies of the power and propulsion systems. In this paper, a turboelectric powertrain is designed and analyzed using the Numerical Propulsion System Simulation (NPSS) tool, the NPSS Power System Library, and a motor drivetrain optimization tool. Direct and geared motor drivetrains are designed and compared across a UAM design mission. Sensitivity of the Tiltwing maximum takeoff weight to powertrain weights and efficiencies is estimated and used to inform optimal motor and gearbox selection. Results indicate that direct-drive and geared-drive configurations are comparable for this vehicle, with slight advantages to direct-drive when the radius of the drivetrain is unconstrained. When the drivetrain radius is constrained, a geared-drive system becomes more optimal.

INTRODUCTION

The rapidly emerging Urban Air Mobility (UAM) market has the potential to disrupt the transportation industry as a whole: offering faster, quieter, and cheaper intracity and regional air travel (Ref. 1). To enable future large-scale UAM operations, multiple research challenges must be addressed. These challenges include but are not limited to: a) defining UAM mission requirements and concepts of operation, b) identifying key enabling technologies, c) exposing vehicle design trades and constraints, d) overcoming airworthiness and certification barriers, and e) developing capable modeling and simulation tools. NASA's Revolutionary Vertical Lift Project (RVLT) under the Advanced Air Vehicles Program (AAVP) is helping to address these challenges by developing a catalog of publicly available conceptual reference vehicles for use in trade studies, tool development, and exploratory research (Refs. 2, 3). While these reference vehicles are not intended to represent or evaluate any specific concepts or vehicles in industry development, they aim to represent a broad spectrum of proposed UAM vehicle configurations.

Explored in this paper is the powertrain for a six-passenger, turboelectric tiltwing concept (hereafter referred to as the Tiltwing) developed by Whiteside et al., Ref. 4. The Tiltwing uses tilting rotor technology, so the rotors can transition between vertical and horizontal orientations. This technology enables tiltwing type vehicles to operate more efficiently and

quietly at cruise than their fixed-rotor counterparts. However, tilting rotor technology has distinct operational challenges: A tiltwing propulsion system must be able to deliver high-power bursts during hover, takeoff, and landing while still performing efficiently during low-power cruise flight, and the system must be capable of mid-air transition between hover, climb, and cruise modes.

In this paper, a system-level design of the Tiltwing's turboelectric powertrain is completed to better quantify the weight and performance of the propulsion system and vehicle. Particular focus is given to assessing whether direct-drive or geared-drive motor drivetrains enable better vehicle performance. Propulsion system designs are completed for both configurations and compared.

A set of design and optimization tools are used to model various powertrain components. The turboshaft engine is modeled using the Numerical Propulsion System Simulation (NPSS) tool (Ref. 5). Power electronics are modeled with the addition of the NPSS Power System Library (Refs. 6, 7). Motors, motor power electronics, generators, and gearboxes are designed using an analytical version of the NASA-developed motor drivetrain sizing tool (Ref. 8) in MATLAB (Ref. 9). This tool is an analytical form of the Finite Element Analysis (FEA) based motor drivetrain design tool developed in Refs. 8, 10, 11, 12, and 13. Engine weight and size is determined using the Weight Analysis of Turbine Engine

(WATE++) tool (Ref. 14), and other weights are determined from their respective modeling tools. The tools and methods applied in this study follow a similar approach to prior work by Thomas et al. (Ref. 15) on the RVLTL Quadrotor concept reference vehicle. This study differs from prior work in the motor drivetrain modeling approaches and the specific design trades examined.

The primary motivation for this study is to raise the fidelity of system-level assessments of propulsion systems for UAM vehicles to inform future vehicle designs. It is intended that these results will help inform design decisions for future electric Vertical Takeoff and Landing (eVTOL) vehicle concepts and highlight key research areas for accelerating the development of the tiltwing category of vehicles.

CONCEPT VEHICLE OVERVIEW

Conceptual design of the baseline Tiltwing vehicle was conducted previously by Whiteside et al. (Ref. 4). Different configurations for the wings and rotors were down selected based on considerations for vehicle stability and power distribution. The NASA Design and Analysis of Rotorcraft (NDARC) tool (Ref. 16) was used to perform vehicle sizing and mission analysis. The published baseline vehicle model, available in Ref. 3, consists of a six-passenger turboprop vehicle with a cruise speed of 155 knots and a maximum gross weight of 6,750 lb. Eight motor-driven propellers, six located on the main rotating wing and two on the fixed horizontal tail, are powered from a centrally located turboshaft engine and battery. Renderings of the Tiltwing in its hover and cruise configurations are shown in Fig. 1. Additional information on the design, iteration, and sizing of the Tiltwing can be found in Ref. 4.

A direct-drive powertrain was selected for the baseline vehicle design, as it was determined to be beyond the scope of the study to conduct an in-depth drivetrain trade study. While modern high specific torque motors can deliver the torque required for the propellers within weight requirements, direct-drive systems tend to drive propeller designs towards lower torque and higher tip speeds. In contrast, a geared-drive architecture would likely have driven the propeller design towards higher-torque, lower speed solutions. This could be beneficial for acoustics but could also require a redesign of the wings if heavier or larger propellers are more optimal. A thorough vehicle analysis of the impact of geared versus ungeared systems on the optimal propeller design would be needed to fully determine the best powertrain configuration. This paper does not make any vehicle or propeller design changes from the baseline vehicle design in its exploration of geared and direct-drive powertrain trades.



Figure 1. Renderings of the Tiltwing reference model in hover (top) and cruise (bottom) configurations (Ref. 5).

Cross shafting was considered but not selected for the baseline vehicle design, as a method to maintain balanced thrust and lift in the event of a motor failure. Cross shafting would reduce the need to oversize the tilt wing motors for motor-out conditions but would have no benefit for the tail motors, since there are only two of them and it would be difficult to couple them to the tilt wing motors using cross shafting. In this study, the powertrains are designed without cross-shafting. It is assumed that in the event of a motor failure, the remaining motors can exceed maximum rated power for short intervals as outlined in Ref. 4.

The baseline Tiltwing was sized using a UAM design mission first defined by Patterson et al. (Ref. 17) and used to size the other RVLTL concept vehicles (Ref. 18). The mission parameters for each mission segment are listed in Table 1. The mission consists of a departure flight (segments 1-9), an identical return flight (segments 10-18), and a 20-minute cruise reserve (segment 19). Each flight has a 37.5 nautical miles (nmi) range into a 10-knot headwind. The mission assumes a ground level of 6,000 ft Above Sea Level (ASL). The cruise altitude is assumed to be 4,000 ft Above Ground Level (AGL) (10,000 ft ASL). Temperatures are assumed to be +18 °R (+10 °K) above the International Standard Atmosphere (ISA) standard day reference (Ref. 19). A diagram of one of the flights is shown in Fig. 2.

In addition to the UAM design mission, a second emergency mission was modeled to size a backup primary battery for the Tiltwing. This mission consists of two minutes at hover out of ground effect (HOGF) power, using only battery power. The sizing assumed that the battery would be fully discharged for this scenario and would require immediate replacement.

Table 1. UAM Design Mission Parameters.

Segment	1	2	3	4	5	6	7	8	9	19
Description	Idle	Lift	HOGF	Climb	Cruise	HOGF	HOGF	Descent	Idle	Reserve
Initial Alt. (ft ASL)	6,000	6,000	6,050	6,050	10,000	6,050	6,050	6,050	6,000	10,000
Final Alt. (ft ASL)	6,000	6,050	6,050	10,000	10,000	6,050	6,050	6,000	6,000	10,000
Time, t (sec)	15	30	10	t_{climb}	t_{cruise}	10	30	30	15	1200
Dist., D (nmi)	-	0	0	D_{climb}	$37.5-D_{climb}$	0	0	0	-	-
Airspeed, V (kts)	-	-	0	V_y	V_{br}	0	0	-	-	V_{br}
Rate of Climb (ft/min)	-	100	0	≥ 900	0	0	0	-100	-	0
Power, P ($\%P_{max}$)	10%	100%	100%	P_{climb}	P_{cruise}	100%	100%	100%	10%	P_{cruise}

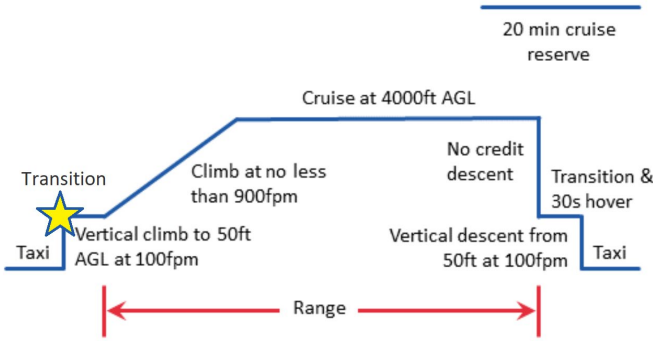


Figure 2. UAM Design Mission Profile (Ref. 17).

In this study, the powertrain design point is selected as the end of vertical lift (segment 2) at 6,050 ft ASL, represented by the yellow star in Fig. 2. This point is chosen because it corresponds with the highest power demand across the UAM mission. It is assumed the turboshaft engine will be flat-rated at this condition, with no excess capability at lower altitudes. The other UAM mission points are modeled to ensure all mission requirements are met by the powertrain system. There are additional conditions which could possibly affect the component sizing and were not considered in this study. These conditions include specific maneuvers such as turning and banking, power electronics failure scenarios, and the transition between the hover and cruise configurations.

POWERTRAIN ARCHITECTURE

A schematic of the general turboprop powertrain design is shown in Fig. 3, representing the direct and geared architectures. The propellers are driven by individual motor drives that connect to the main electrical bus, depicted as red lines in the figure. The motor drive blocks shown in the figure represent the motor, an inverter, and optionally a gearbox. The generator drive block in the figure represents a gearbox, generator, and rectifier that supply power to the main electrical bus. The generator drive is connected to the power turbine shaft of a turboshaft engine. The backup battery is also connected to the main electrical bus.

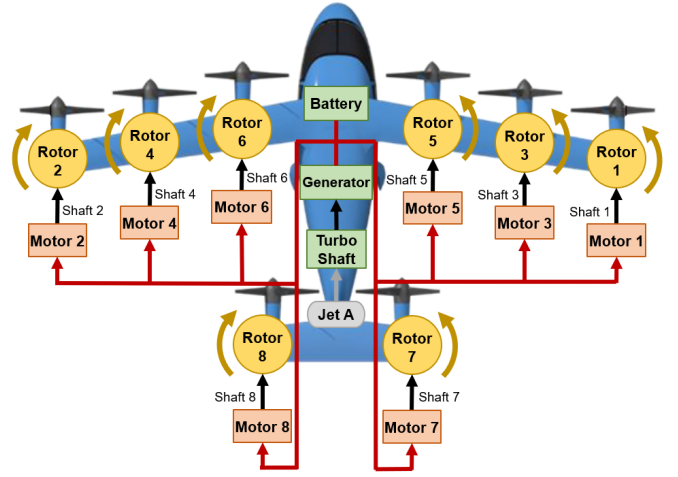


Figure 3. Schematic of the base powertrain design.

A list of the design specifications and assumptions made for the baseline powertrain models is shown in Appendix A. These assumptions are derived from a combination of empirical data, reasonable guesses based on existing electric vehicles, and results from the NDARC vehicle sizing. The assumptions made also represent the technology level of the powertrain and overall vehicle. Most of the baseline components are assumed to be at a currently realized technology level, such as the turboshaft engine, electric machines, and power electronics. The exception is the battery, which assumes a specific energy representative of the technology needed to enable hybrid and all-electric UAM vehicles.

A block diagram of the powertrain assembly including power electronics is shown in Fig. 4. Note that due to the different sizing requirements between the wing and tail motors, two different load assemblies are shown. The generator drive block represents a generator and rectifier. In the case of the direct-drive architecture, the motor drive block represents an inverter and motor. For the geared-drive architecture, the motor drive represents the inverter, motor, and gearbox.

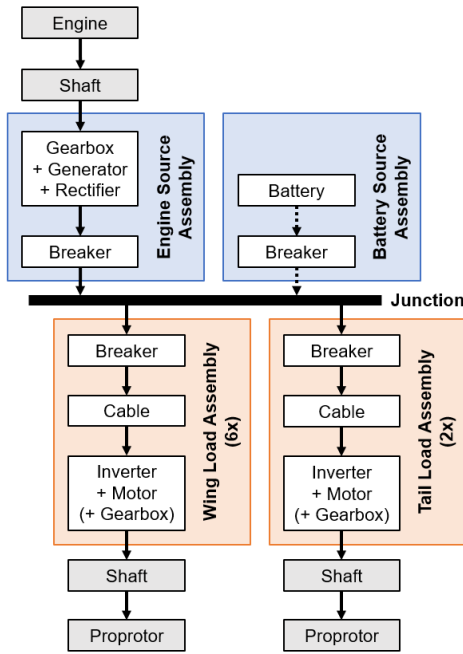


Figure 4. Block diagram of the base powertrain design.

A direct-current (DC) electrical bus was assumed. The DC bus simplifies the connections to the battery component but increases the size of the circuit breaker and individual cables (though less cables are needed). This assumption is deemed acceptable for this type of vehicle based on prior assessments of conceptual turboelectric power systems (Refs. 15, 20).

A single motor is assumed to drive each propulsor. In some cases, it may be beneficial to use two independently operating motors to drive each propulsor, which can reduce the need to oversize motors for a motor failure scenario but requires higher drivetrain complexity.

It is also assumed that the temperature of the motor and inverter cooling loop is maintained by means of a Thermal Management System (TMS). The TMS is not modeled in detail as part of this study, but is approximated by a constant specific power as discussed in the following section.

POWERTRAIN MODELING

Component-level modeling of the powertrain assembly shown in Fig. 4 is accomplished through a combination of NPSS (Ref. 5), the NPSS Power System Library (Refs. 6, 7), WATE++ (Ref. 10), NDARC (Ref. 16), and MATLAB (Ref. 9). The following subsections describe the powertrain components and their assumptions, modeling methods, and tools applied. Design specifications and assumptions for each component can be found in Table A1 of Appendix A.

Turboshaft Engine

NPSS is used to perform the cycle design of the turboshaft engine. The model is derived from a library of turboshaft models created by Chapman et al. (Ref. 21) for the RVL

project, which populates the cycle model using trends from a collection of physical engine data. A block diagram of the NPSS engine model elements is shown in Fig. 5. Some of the key inputs and outputs are shown, including the air flow, altitude, Mach number (MN), temperature deviation from the ISA standard (dT), fuel flow (Wf), and thrust. The generator block is included with the power shaft for continuity.

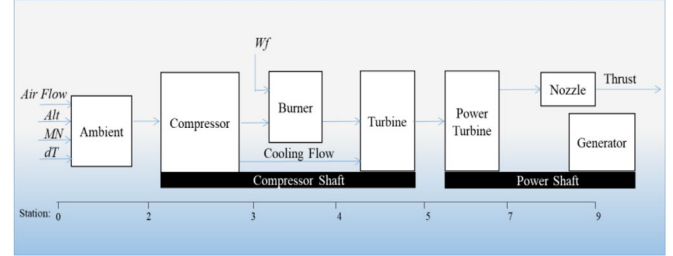


Figure 5. Turboshaft engine block diagram (Ref. 15).

An engine with a similar design power to that of the Tiltwing required power is selected from the turboshaft library, and resized to match the required design power (1512 hp for the direct-drive architecture, and 1559 hp for the geared-drive architecture). The resulting turboshaft model contains a single core spool and a free power turbine. The compressor section consists of two centrifugal stages with pressure ratios of 5.0 and 2.8. The overall pressure ratio of the engine is 14.0. The maximum burner temperature is set at 2860 °R (1589 °K) based on available combustor cooling for a small to mid-size turboshaft engine. A maximum turbine blade temperature of 2160 °R (1200 °K) is used to set engine cooling requirements (Ref. 22). Polytropic efficiencies and other engine assumptions are based on advanced technology trends. The design Power-Specific Fuel Consumption (PSFC) of the engine is 0.437 lbm/(hp-hr) for the direct-drive architecture and 0.436 lbm/(hp-hr) for the geared-drive architecture.

Weight and flow path geometry of the turboshaft component was determined using WATE++. A cross-section of the engine design from the WATE++ analysis is presented in Fig. 6. The high-pressure spool and free power turbine spool can be seen, along with the air flow path. Supporting frame locations are shown in yellow.

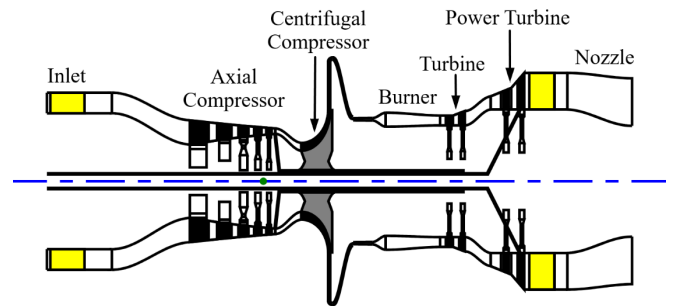


Figure 6. Turboshaft engine cross-section diagram.

Battery

The lithium-ion battery is modeled in NDARC as an equivalent circuit, defined by internal resistance and current. A fixed battery efficiency is used to compute power loss. More information on the equivalent circuit model can be found in the NDARC theory manual (Ref. 23).

The battery is sized to deliver two minutes of HOGE power with a full discharge, roughly equal to a discharge rate of 30C. Weight is determined from a battery cell specific energy assumption of 650 Wh/kg. A 30% mass increase is assumed for the battery pack structure, wiring, and insulation. A maximum useable depth of discharge (DoD) of 80% is assumed. The resulting total battery pack specific energy is 400 Wh/kg, representative of an advanced technology level battery system.

Electric Machine Drivetrains

Motors, inverters, and gearboxes are designed using an analytical equation-based version of the motor drivetrain optimization tool developed by Talerico in Ref. 8. The version of the tool used for this study was developed with MATLAB. The tool completes combined design and sizing of motors, gearboxes, and inverters using the theory described in Ref. 24. The tool requires a large number of material and component assumptions. The assumptions from Ref. 25 were largely maintained for this study, but only the permanent magnet synchronous machine topology with in-slot cooling was considered.

The tool completes design for a set of desired mission points defined by required power, shaft speed, and duration. A genetic optimizer is used to generate a Pareto front of drivetrain designs based on drivetrain mass and mission efficiency (total energy out divided by total energy in over the mission design points). Within the genetic algorithm's fitness evaluation, drivetrain elements are sized subject to loading, life, and operational constraints.

From the Pareto front of drivetrain designs, a single design is selected for each case as described in the Results section of this paper. The tool produces speed and torque-dependent drivetrain efficiency maps for the selected designs. These maps are then added into NPSS Power System Library motor and generator elements, so that the electric machine drivetrains can be modeled with the other powertrain elements at the desired mission points.

The current tool is configured for motor drivetrain design. For generator design, the power flow through the tool is reversed but no additional considerations are made. The input mechanical power from the power turbine is approximated for the generator by taking the known electrical power and assuming a 90% generator drivetrain efficiency. A tool configured for a generator design would improve design fidelity but would not significantly affect the predicted generator drivetrain mass and efficiency.

Power Electronics

Additional power electronics not included in the motor drivetrain are modeled using the NPSS Power System Library. These include circuit breakers and cables. Constant efficiency and specific power are assumed for the breaker components. The cable efficiency is determined at the design point using empirical lookup table data. A sizing routine determines the lightest possible cable assembly that meets current requirements, and determines inductance, resistance, and mass per unit length as a function of the wire gauge. Cable lengths are estimated based on the central location of the generator, the fuselage length, and the wing spans.

The NPSS Power System Library components are defined in the NPSS solver as a set of electrical ports and electrical nodes. Components either contain an electrical node and carry voltage information, or do not contain an electrical node and carry current information. The solver perturbs component voltages and resolves currents by balancing the net current at each electrical node.

Thermal Management

The electric machine drivetrains and power electronics are assumed to be liquid cooled, with all internal thermal management elements included within the components. However, the external cooling loop and air-to-coolant heat exchangers were not explicitly designed as part of this study. To estimate the remainder of the thermal management system (TMS) weight, the rejected power at design for each powertrain component is divided by a constant specific power of 5.1 kW/kg. This value was derived from prior work on the RVL T Quadrotor concept reference vehicle (Ref. 15). It is assumed that the battery does not require thermal management due to its short-time operation.

ARCHITECTURE TRADE RESULTS

From the weight versus mission efficiency Pareto fronts for the drivetrain design solutions, drivetrain designs were selected that minimize the vehicle's Maximum Takeoff Weight (MTOW). MTOW is a good indicator of overall vehicle efficiency as it captures both the weight of the vehicle systems and the fuel required for the desired mission. Because the Tiltwing's two tail motors are higher power than the wing motors, it was necessary to design the tail and wing motor drivetrains separately and then combine their Pareto fronts. Scatter plots were created representing every combination of weight and efficiency for the total vehicle motors. An energy weighted average of efficiencies was used to determine the net mission efficiency for each solution. This resulted in a new Pareto front representing the best motor combinations for the vehicle.

The powertrain models produced in this paper are not currently integrated with the Tiltwing sizing model in NDARC, meaning the vehicle MTOW is not a direct product of the powertrain design. To estimate the effect of different powertrain designs on MTOW, a set of different motor

efficiencies, generator efficiencies, and powertrain weights were run in NDARC. A reasonable constant efficiency was assumed for the generator drivetrain while the motor drivetrain efficiency was adjusted, and vice versa. Due to differences between the NDARC empirical drivetrain models and the motor drivetrain optimization tool, some uncertainty was introduced. The results of this sensitivity study established a design space where the approximate change in MTOW could be interpolated for any drivetrain design solution.

In the drivetrain design, it was found that the maximum allowable motor radius had a significant impact on the achievable performance of the direct-drive motor drivetrain. To capture this sensitivity, a set of solutions for both direct-drive and geared motor drivetrains was run with different drivetrain radius constraints. The Pareto fronts for each of these cases are shown in Fig. 7. The contours shown represent the estimated vehicle MTOW (lbs) for each solution for a given drivetrain weight and mission efficiency. Similar performance for both geared and direct-drive motor drivetrains are achieved with a 500 mm radius constraint. Smaller radius constraints are shown to significantly impact the direct drive drivetrains performance. Geared drivetrains are shown to be relatively insensitive to radius in the range studied, but the gear ratio of the geared drivetrains did increase with reduced radius.

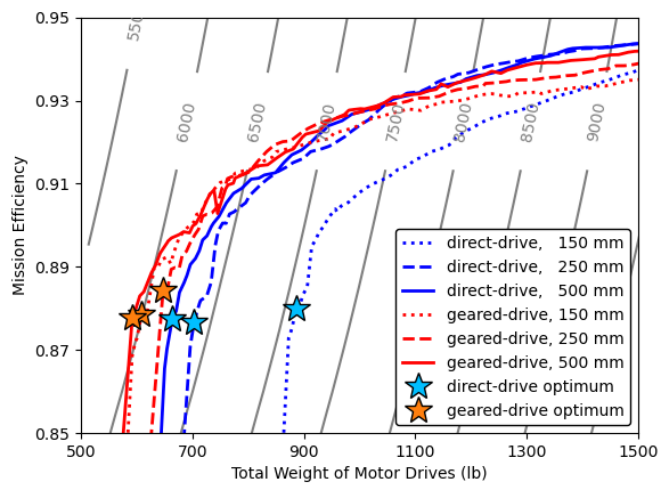


Figure 7. Radius-constrained motor drive solutions against estimated MTOW contours.

The Tiltwing proprotor radius is 7.33 ft (1.12 m). The motor radius in the baseline Tiltwing design is 170 mm (roughly 15% of the total proprotor radius). It is estimated that motor drivetrain radii around 225-335 mm (20-30% of the total proprotor radius) would be acceptable before thrust losses due to blockage become too large. As is shown in Figure 7, adding this constraint would penalize direct drive drivetrains and result in geared drivetrains outperforming them. However, the performance penalty of exceeding this radius constraint is not well quantified for the vehicle and is correspondingly neglected for the following drivetrain comparisons.

The results for the motor drivetrains without radius constrained is shown in Fig. 8. The contours shown represent the estimated vehicle MTOW (lbs) for each solution. Due in part to the number of motors, motor drivetrain weight is shown to have a significant impact on the vehicle MTOW which leads to lightweight, lower efficiency solutions being optimal. Small increases in individual motor weight can lead to large increases to the overall vehicle due to the eight motors on the vehicle. The achievable performance is similar for both geared and direct drive motor drivetrains, but some of the geared-drive solutions offer higher efficiency for equivalent weight.

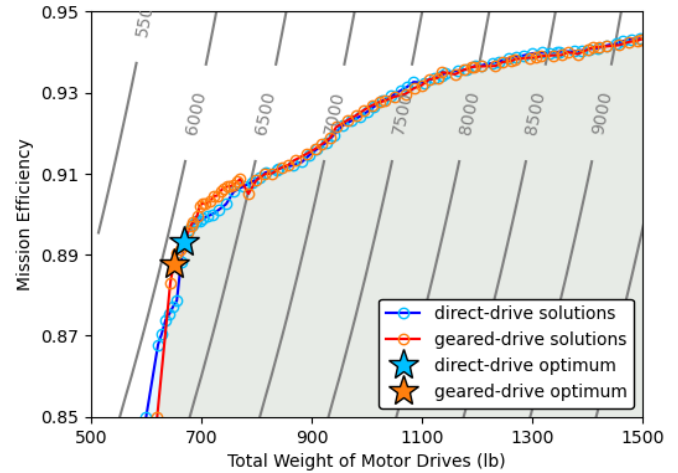


Figure 8. Unconstrained motor drive solutions against estimated MTOW contours.

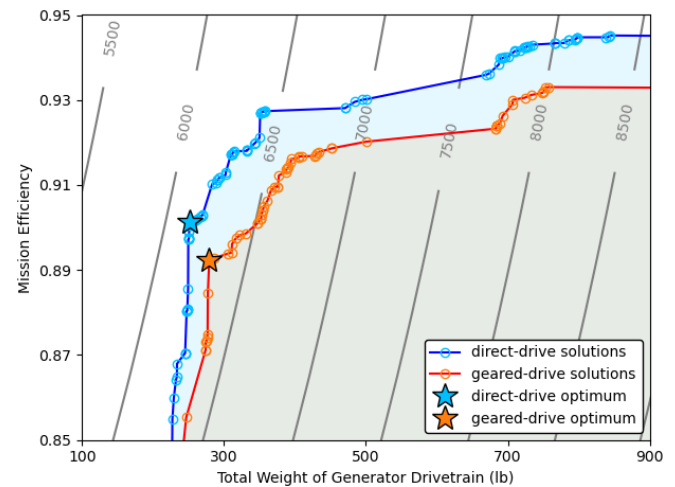


Figure 9. Unconstrained generator drive solutions against estimated MTOW contours.

The optimal direct-drive motor drivetrain solution based on MTOW has a slightly higher efficiency, which results in lower power requirements for the generator and engine. This can be seen in Fig. 9, where greater generator drivetrain efficiency is achieved for the direct-drive architecture at a reduced weight compared to the geared-drive architecture. The selection of a less-efficient geared motor prior to

generator design made a significant contribution to lower performance for the geared drivetrain. Co-optimization of generator and motor drivetrains may lead to more optimal solutions than the results presented here.

Using the optimal solutions for the motors and generators based on the estimated minimum vehicle MTOW, the powertrains are modeled in more detail using NPSS and the NPSS Power System Library. Key weight and performance comparisons for each of the powertrain architectures are shown in Table 2.

Table 2. Architecture Trade Study Results.

Metric	Direct-Drive	Geared-Drive
Weights		
Powertrain Weight (lb)	2088.6	2164.5
Battery Weight (lb)	528.2	542.9
Engine Weight (lb)	453.5	490.9
TMS Weight (lb)	100.1	115.2
Electric Machine	921.0	928.8
Drivetrain Weight (lb)		
Power Electronics	85.8	86.7
Weight (lb)		
Other Parameters		
Turbine Design Power (hp)	1512.3	1559.2
Powertrain Design Losses (hp)	310.5	357.4
Powertrain Hover Eff.	79.47%	77.07%
Powertrain Cruise Eff.	73.51%	72.49%
Engine Hover PSFC (lbm/[hp-hr])	0.437	0.436
Engine Cruise PSFC (lbm/[hp-hr])	0.578	0.580

Next, the net powertrain performance across the UAM mission are compared for the two powertrain architectures. Fig. 10 shows the net efficiency for each segment of the mission. Fig. 11 shows the turboshaft PSFC for each segment of the mission. It can be seen that the net efficiency of the geared-drive architecture is roughly 5% lower across the whole mission. This is due to the optimal motor drivetrain solution based on MTOW being lower efficiency for the geared motor drivetrain, thus requiring a lower efficiency generator to remain competitive with weight. PSFC is very similar between the two cases, with a slight advantage to the geared-drive architecture. While additional power is required from the turboshaft engine for the geared-drive architecture, it operates with equal or better fuel efficiency.

A weight breakdown is shown in Fig. 12 for each powertrain architecture. The powertrains are similar in overall weight, with a direct-drive net weight of 2088.6 lb and a geared-drive net weight of 2164.5 lb.

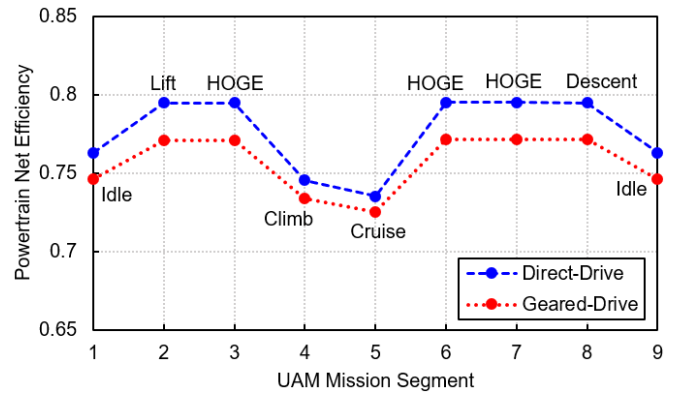


Figure 10. Powertrain net efficiency across the UAM design mission.

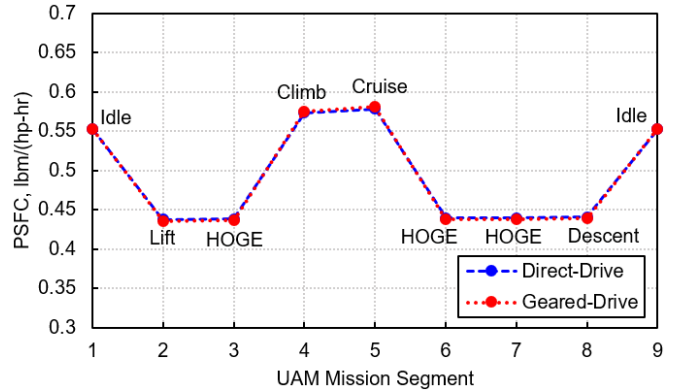


Figure 11. Turboshaft Power-Specific Fuel Consumption across the UAM design mission.

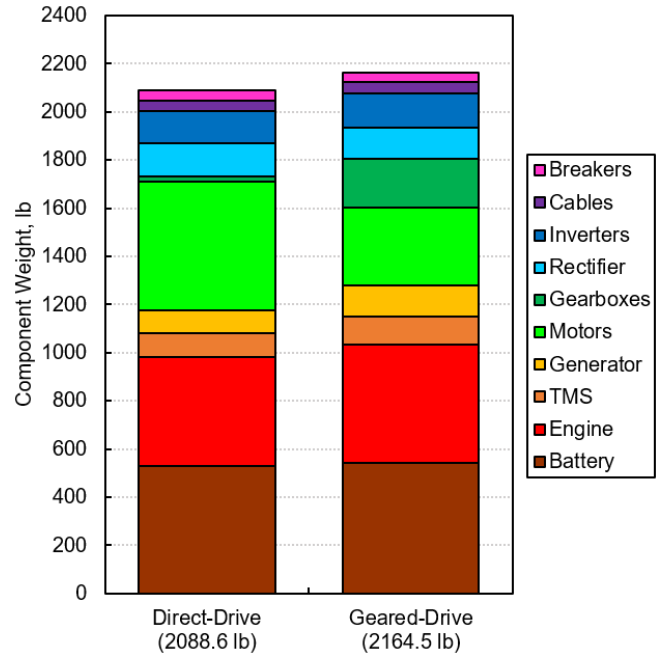


Figure 12. Weight Breakdown Comparison of Powertrain Architectures.

CONCLUSIONS

A turboelectric powertrain was designed and modeled for NASA's new six-passenger Tiltwing conceptual reference vehicle under the RVLT project. The powertrain was modeled using NPSS, the NPSS Power System Library, and supporting tools. This was done with the intent to provide more detailed propulsion system data for UAM vehicles, inform design decisions for future concepts, and highlight key areas for technology development. Direct-drive and geared-drive powertrain architectures were designed and modeled. Sensitivities of the vehicle MTOW were estimated and used to select optimal motor and generator solutions. A trade study was conducted in which the powertrain weights, efficiencies, and PSFC values were compared for each powertrain architecture. It was found that the direct-drive and geared-drive architectures present similar overall vehicle performance, with a small advantage to a direct-drive system for an unconstrained analysis. However, vehicle level requirements such as allowable motor radius, propotor torque, and propotor speed significantly influence the powertrain design. Constraining motor drivetrain radius or reducing rotor speed could lead to a geared-drive system being advantageous.

Opportunities for future work include coupling the powertrain and vehicle sizing models so the powertrain components can be sized dynamically with the vehicle power requirements. A detailed TMS model could improve the fidelity of the system analysis and allow an additional trade comparison to be made. A propotor design study would yield valuable conclusions on the impact of a geared-drive system for the Tiltwing and more conclusively determine the optimal drive type. Finally, comparisons with additional powertrain architectures such as hybrid and all-electric would yield insights on the UAM design space for the Tiltwing.

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APPENDIX A

Table A1. Powertrain design specifications and assumptions.

Specification / Assumption	Value
Atmosphere	
Mach Number	1000
Altitude (ft ASL)	6050
Delta Temperature (°R/°K)	+18 / +10
Turboshaft Engine	
Overall Pressure Ratio	14
Compressor Stage 1 Pressure Ratio	5
Compressor Stage 2 Pressure Ratio	2.8
Cycle Max Temperature (°R/°K)	2860 / 1589
Blade Max Temperature (°R/°K)	2160 / 1200
High Pressure Shaft Speed (rpm)	24466
Power Turbine Shaft Speed (rpm)	8000
Power Turbine Power Output (hp)	1512 ^a / 1559 ^b
Electric Machine Drivetrains	
Electric Machine Type	PMSM
Winding Type	Concentrated
Inverter Type	2-Level SiC
Wing Motor Max Rated Power (hp)	130.4
Tail Motor Max Rated Power (hp)	209.7
Generator Max Rated Power (hp)	1356 ^a / 1387 ^b
Wing Prop Assembly Mass (lb)	27.8
Tail Prop Assembly Mass (lb)	42.3
Hover Motor Speed (rpm)	1384.1
Cruise Motor Speed (rpm)	754.9
Generator Speed (rpm)	15000.0
Max Voltage (V)	1000
Min Voltage (V)	700
Allowable DC Bus Ripple (V)	15
Coolant Thermal Cond. (W/m ² ·K)	0.380
Coolant Specific Heat (J/kg·°K)	3776.5
Coolant Density (kg/m ³)	1000.0
Coolant Viscosity (cP)	1.080
Gearbox Oil Temperature (°C)	65
Gearbox Oil Density (kg/m ³)	956
Battery	
Battery Peak Voltage (V _{dc})	1000
Cell Specific Energy (Wh/kg)	650
Battery Pack Mass Penalty	30%
Useable Depth of Discharge	80%
Discharge Efficiency	98%
Discharge Time (min)	2
Power Electronics	
Electrical Bus Peak Voltage (V _{dc})	1000
Breaker Efficiency	0.995
Breaker Specific Power (kW/kg)	9.0
Avg. Wing Cable Length (ft)	21.2
Avg. Tail Cable Length (ft)	15.2
Thermal Management	
TMS Specific Power (kW/kg)	5.1

^aDirect-drive, ^bGeared-drive

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