Propulsion Configuration Design and Analysis for an eVTOL Passenger Air Shuttle

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***Abstract* - This paper describes design maturation of an electric vertical take-off and landing (eVTOL) aircraft for urban air mobility. This work aims to build upon previous work on the propulsion design to ensure the vehicle is stable and airworthy . The design aspects considered for this study are wing position, planform dimensions, number of propulsors and their spanwise position, propeller design, and powertrain configuration. Stability, power requirements, and aerodynamic efficiency of various propulsion configurations will be evaluated and the final design presented.**

I. Introduction

This paper describes the maturation of the aerodynamic and electrical systems design of the Illini Air Shuttle (IAS). It expands upon previous work that attempted to maximize the payload by trading wing aspect ratio, number of propulsors, and propulsive span [1]. While this study suggested an optimal number of propulsors and span for the distribution of propulsors by analyzing the effective power and wing loading, wing design and stability analysis has yet to be conducted. Thus, wing design and flight characteristics analysis are the obvious next steps to mature the design. The aerodynamic analysis is especially important due to the unconventional configuration. While the tandem wing design is desirable for distributing the propulsors for vertical flight, the wing interaction effects should be analyzed to ensure the airworthiness of the design. The wing interaction effects also compound with the propeller-wing interaction (modeling of which is still an active research area).

In addition to aerodynamic analysis, the design of the powertrain is a necessary step to complete the conceptual vehicle design. The total mass, volume, and heat rejected from the powertrain components are important components to understand for system integration. Relevant tasks include topology selection and sizing of the machines, selection and sizing of the energy storage technology, control system design, and dynamic simulation to quantify the efficiency and stability of the power system. The goal is to determine the high-level specifications of the power system at a level of depth and confidence appropriate for conceptual aircraft design.

The motivation of developing the IAS concept is primarily to add to the publicly available body of design work on electric aircraft. While there has been no shortage of vehicle concepts generated in recent years by both startups and established airframers, detailed specifications of matured designs are typically not made freely available. One notable exception is a set of reference vehicles developed by NASA [2]. The availability of such information supports the development of relevant component technologies and ancillary systems by allowing researchers to understand the qualities of electric aircraft designs that are most likely to enter service. Additionally, meta-research on published designs may help identify and track required improvements in contemporary technology needed to realize practical electric flight; this would be especially useful for energy storage and power electronic equipment. In short, publicly available design data on a large set of electric aircraft is valuable for researchers working on related technology and can provide perspective on the state of design techniques.

II. Background

A concept for a vectored thrust eVTOL aircraft has been developed for transportation between cities separated by a distance between 200 km and 300 km, and was presented in Xiao et. al [1]. The aircraft will address limitations of existing methods of public transportation such as unreliable railroad systems and slow buses/shuttles. The aircraft will carry ten people and follow the mission profile shown in Figure 1.

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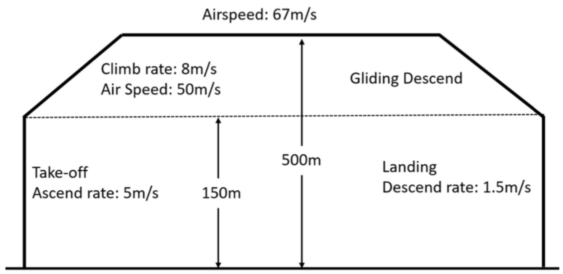


Figure 1 Mission Profile

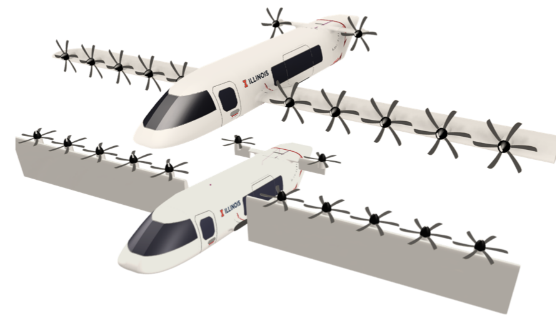


Figure 2 Notional IAS design in cruise (top) and takeoff/landing (bottom) configuration

Due to its high speed and ability to take-off and land in a metropolitan area, an eVTOL aircraft is a desired alternative to current methods of transportation. Traveling by eVTOL also drastically reduces emissions and transit time. The vectored thrust technology has been selected for its high efficiency and endurance compared to other eVTOL aircraft technologies.

Existing designs of manned eVTOL aircraft fall into the following categories: the multi-rotor configuration, the lift-and-cruise configuration, and the tilt-rotor configuration. This design utilizes the tilt-rotor configuration in which the wings and propellers tilt to allow for easy take-off, landing, and cruising.

The proposed eVTOL aircraft shown in Figure 2 details a 12-propeller tilted rotor-wing design with a distributed propulsion system. This concept has been optimized iteratively to provide a high-level representation of the trade-offs between range and payload. Vehicle parameters such as wing aspect ratio, number of propulsors, and propulsive span were varied using a genetic algorithm based optimization tool, GOSET in attempts to maximize the payload. Increasing electric motor specific power was also studied to determine its effects on aircraft performance. However, results indicated that increasing the specific power did not largely affect payload capacity. The resulting aircraft's specifications are given in Table 1.

Table 1 Proposed Design Specifications

Item	Value
Transit Time [min]	64
Total Mass [kg]	3575
Aspect Ratio	13.7
Wing Area [m^2]	26.12
Number of Propellers	12
Radius of Propeller [m]	0.75
Payload [kg]	1000
Wing Loading [kg/m^2]	126.9
Total Energy [kWh]	537
Motor Specific Power [kW/kg]	10
Motor Mass [kg]	95.4
Power Overload Factor	1.28

The first phase of flight indicated in the vehicle's mission profile is vertical take-off from a parking lot or other open area and climb to a minimum building clearance of 150 meters at a rate of 5 m/s. In the second phase, the wings and propellers tilt forward to transition the aircraft into a horizontal climb at a vertical velocity of 8 m/s and an airspeed of 50 m/s. Once the aircraft reaches an altitude of 500 m, the vehicle initiates the third phase and levels off to cruise at 67

Table 2 Mission Profile Parameters

Phase	Duration (s)	Thrust Required (N)
1	30	35034
2	44	6428
3	2875	1752
4	105	0
5	100	35034

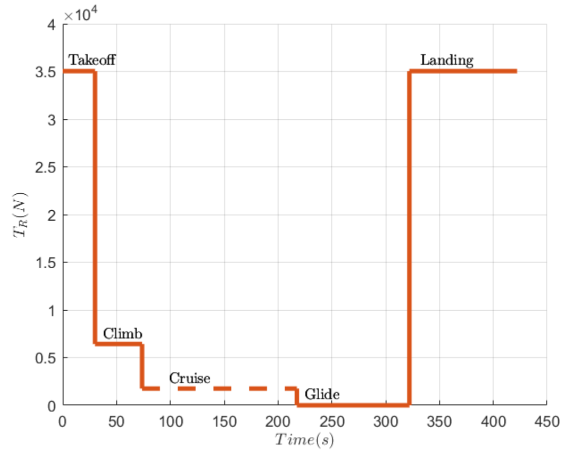


Figure 3 Vehicle thrust over time for each phase of the mission

m/s towards its final destination. Upon nearing the destination, the fourth phase is initiated and the aircraft glides to an altitude of 150 m. In the fifth and final phase, the wings and propellers of the air shuttle tilt upwards consistent with a vertical landing configuration and descends at a rate of 1.5 m/s. The expected mission profile parameters of each phase are listed in Table 2 with the thrust requirements displayed graphically in Figure 3. Please note that the cruise section of the mission profile is much longer than the other portions and was scaled down in Figure 3 for presentation purposes.

III. Proposed Work

The work needed to mature the Air Shuttle design falls into both the aeronautical and electrical domains. The tasks within each domain are given separate treatment here.

A. Vehicle Aerodynamics

In order to mature the design presented in [1] we will use optimization techniques to determine a distribution of wing area and wing position that provides acceptable flight performance within acceptable stress. We may expect that, given the proximity of the tandem wings and their relative size, that the wing performance may significantly deviate from the isolated case. Examination of biplane aerodynamics shows that modification of the flowfield changes the pressure distribution around both wings, leading to a decrement in lift production from both the upper and lower wing. The magnitude of this effect is dependent on the wing gap and stagger [3]. Additionally, there are concerns regarding the effects downwash and wake from the fore wing on the aft wing. While some tandem wing arrangements display favorable behavior in avoiding stall, the performance of the rear wing through the entire flight regime should be well understood to ensure the stability and overall airworthiness of the design [4] [5].

Furthermore, the propulsion configuration of the Air Shuttle effectively creates a blown wing arrangement and further modifies the flow field. Not only will each propulsor interact with adjacent propulsors and the wing to which it is mounted, but different performance should be expected between the upstream and downstream set of propellers. Primarily, it has been shown that the vorticity in the propeller wake can be expected to decrement the thrust of any downstream propellers caught in the wake [6].

This paper will address efforts in modeling the expected delta in performance of the wings and propellers from the isolated to the integrated case, and the subsequent influence of the results on the design of the Air Shuttle. The challenge in maturing the design lies in capturing the overlap of modeling multiple lifting surfaces, blown wings, and propulsor interaction. Lacking a robust, low-fidelity method to address both the wing-wing interaction and prop-wing interaction effects simultaneously, these effects will be modeled separately with the assumption that linear superposition of the effects represents the performance of the integrated system. The software package of choice for aerodynamic modeling will be the VSPAERO inviscid solver packaged with OpenVSP. While empirical verification is beyond the scope of this paper, testing the validity of the linear superposition assumption experimentally is planned as future work.

This problem will be approached by application of a genetic algorithm. GOSET is a MATLAB-based, general-purpose genetic algorithm published through Purdue University, which has previously been applied to solve electric motor design problems [7]. Each configuration will be defined by the dimensions and positions of each wing, with the propulsor count and propulsive span known from prior work. The OpenVSP API will permit use of scripting to generate the geometry and run analysis on powered and unpowered cases. The maximum average aerodynamic efficiency and minimum total weight of both wings, will be used as targets for the duel-optimization. Simple-beam in bending analysis will be used to eliminate designs that do not achieve standard factor-of-safety (FOS) for the main spar. The methodology is illustrated graphically in Figure 4.

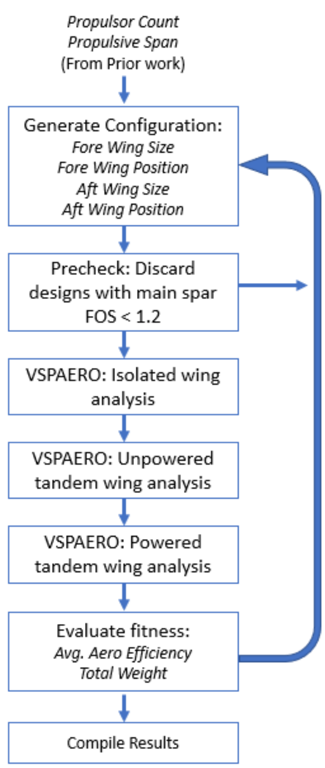


Figure 4 Genetic optimization process flowchart

When the optimization is complete, the wing and propulsion configuration will be manually refined and the results presented here. Additionally, a plan for empirical validation of the vehicle performance will be detailed.

B. Power System Development

Once we are confident that the aerodynamic design of the aircraft is sound and the number of motors required is validated, the power system will be assessed. A power architecture will be chosen based on simulated model performance in Simulink. The simulation will include: motors, a gearbox, inverter, power sources, buses, and transmission lines. Steady state and dynamic analysis will be conducted to show that our components are properly sized to deliver the required power over the entire mission.

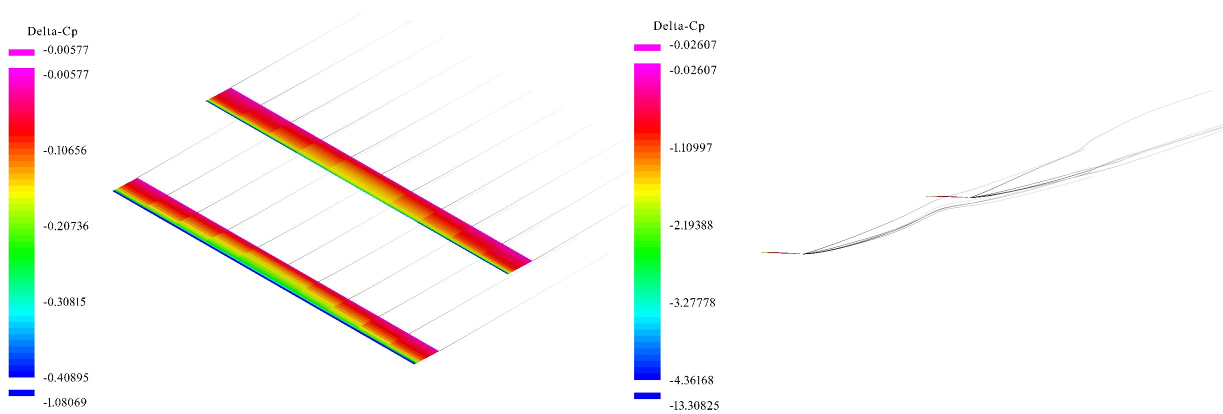
Of particular interest is the battery, as the battery mass needs to be considered in the overall weight budget. An ideal battery for an eVTOL application is one with high capacity, energy density, and power density. The selected battery for this application is lithium polymer because of its outstanding specific energy and potential for technological advancement. Current, market-available lithium polymer batteries exhibit specific energies of around 180 Wh/kg with developments in lithium polymer technology trending towards even greater specific energies as well as specific densities [8]. Using the results from the simulation, the power required for the system will then be used to determine the mass and volume of the selected battery.

A case study conducted in [1] concluded that the selected motor would need a specific power of 10 kW/kg for the 12-propulsor configuration. The full list of design specifications for the 12-propulsor design is given in Table 1. Of note, maximum necessary power is 537 kWh and total motor weight is 95.4 kg, or 7.95 kg per motor [1]. Potential commercial motor options that have the required specific power at approximately an 8 kg scale include permanent magnet synchronous motors (PMSM) and axial flux motors. Motors will be modeled within a fixed volume using Simulink and analyzed for specific power and maximum power output. Results from the overall power simulation and motor choice will then consequently dictate the transmission architecture, components, and control algorithms.

In terms of motor control algorithms, it is necessary to implement one that maximizes torque controllability to account for flight disturbances such as unexpected wind gusts and consequently improves aircraft stability. In a tandem tilt-wing aircraft, stability about its principle axes is controlled by the trust differential between left-right wings as well as forward/aft wings. Yaw stability in the vertical take-off portion of flight is controlled by the differential in propeller torque [9]. A proper motor controls algorithm also minimizes harmonic losses and torque ripple to ensure stability. Different control algorithms will be evaluated in the Simulink model to determine their suitability.

IV. Preliminary Results

An initial investigation of the aerodynamic performance of the tandem wing was conducted using the Vortex-Lattice Method (VLM) solver packaged in VSPAERO. After sizing the wings and locating the roots such that a slight negative pitching moment was achieved, a simple alpha sweep was conducted to view the downwash profile of the trailing wake and the pressure distribution around the wings. Some of the results are shown in Figure 5.



(a) Wing C_p distribution at 0° AOA **(b) Wing Downwash at 20° AOA**

Figure 5 Preliminary wing interaction results

Note in Figure 5a, the low pressure region around the leading edge and root of the fore wing is larger that the aft wing. Figure 5b demonstrates clear interaction between the wake of the fore wing and the flowfield around the aft wing at 20° angle of attack, though the entrainment becomes evident around 12°. We may conclude that the wing interaction effects can at least be partially captured by low-fidelity analysis methods.

V. Expected Results

The expected result of this study is a complete conceptual design for a passenger eVTOL aircraft with accompanying aerodynamic and electrical system analysis. Specifically, we will describe a methodology for modeling wing and propeller interaction effects at a conceptual design level, and the resulting wing design influenced by the results. The wing design will be conducted considering not only the complex flow interactions expected from the vehicle configuration, but also structural rigidity and flight stability. Furthermore, the design of the powertrain and critical integration parameters will be generated and published with dynamic simulation results. Ultimately, maturing the IAS design and disseminating the specifications contributes to elevating the technology readiness of on-demand eVTOL aircraft.

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