

A Summary of the NASA Design Environment for Novel Vertical Lift Vehicles (DELIVER) Project

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The number of new markets and use cases being developed for vertical take-off and landing vehicles continues to explode, including the highly publicized urban air taxi and package deliver applications. There is an equally exploding variety of novel vehicle configurations and sizes that are being proposed to fill these new market applications. The challenge for vehicle designers is that there is currently no easy and consistent way to go from a compelling mission or use case to a vehicle that is best configured and sized for the particular mission. This is because the availability of accurate and validated conceptual design tools for these novel types and sizes have not kept pace with the new markets and vehicles themselves. The Design Environment for Novel Vertical Lift Vehicles (DELIVER) project was formulated to address this vehicle design challenge by demonstrating the use of current conceptual design tools, that have been used for decades to design conventional rotorcraft, applied to these novel vehicle types, configurations and sizes. In addition to demonstrating the applicability of current design and sizing tools to novel vehicle configurations, DELIVER also demonstrated the addition of key transformational technologies of noise, autonomy, and hybrid-electric and all-electric propulsion into the vehicle conceptual design process. Noise is key for community acceptance, autonomy and the need to operate autonomously are key for efficient, reliable and safe operations, and electrification of the propulsion system is a key enabler for these novel vehicles. This paper provides a summary of the DELIVER project and shows the applicability of current conceptual design and sizing tools novel vehicle configurations and sizes that are being proposed for urban air taxi and package delivery type applications.

INTRODUCTION

Aviation is at the cusp of transformation that will bring new levels of economic growth and create new transportation opportunities. Some of these new transportation opportunities will be realized using small-Unmanned Aerial Systems (sUAS), such as package deliver as proposed by Amazon, Google, and others, as well as many other commercial markets including powerline and pipeline inspection, surveillance, crop management, filming, and hundreds of others. Science mission would include surveying and monitoring terrain and environmental conditions, wildlife tracking and management, and exploration of other planets. And public service missions such as monitoring wildfires, search and rescue, disaster relief, law enforcement and border patrol, etc. Entrepreneurs are also proposing the new markets for urban passenger transportation, personal air vehicles, and aerial taxis providing on-demand mobility for the masses, including Uber with their Uber Elevate (Ref. 1) activity and A³ by Airbus with the Voom (Ref. 2) on-demand helicopter service demonstration in Sao Paulo, Brazil. The most compelling of these new markets will be realized with a new generation of Vertical Take-Off and Landing (VTOL) vehicles that include sUAS as well as passenger carrying size vehicles.

The vehicles that are being proposed for these new applications are as varied in size and configuration as the markets and missions themselves. Figure 1 shows some examples of these types of vehicles, but there are many others with new ones being proposed almost every day. The vertical axis of Figure 1 shows the vehicle configuration from convention VTOL configurations, such as single main rotor helicopters, co-axials, tiltrotors and tamdems to increasingly alternative configurations like multi-rotors and distributed electric vehicle concepts. The horizontal axis shows the size, going from 2-4 passenger vehicles on the left that are being proposed and developed for urban air taxi and passenger operations, down to small vehicles and multi-copters that are being used for sUAS missions including surveillance, filming and ultimately package delivery. In this paper, this vehicle concept space is terms the Urban Air Mobility (UAM) concept space that is inclusive of urban air taxi and package delivery sUAS type vehicles.

With the wide range of vehicle configurations and sizes (shown in Figure 1), the challenge for vehicle developers is to design and size a vehicle that is best suited for the intended mission or use case. For many of these companies and vehicle developers,

particularly those that do not have a strong VTOL aircraft design background, there is no way to systematically assess the benefits, limitations and trade-offs of the various designs in order to choose the best vehicle configuration for the particular application, and then size it appropriately to meet the mission requirements. Many of these companies and vehicle design efforts will ultimately fail because of the difficulty in designing and building a vehicle that will beset meet market demands.

The Design Environment for Novel Vertical Lift Vehicles (DELIVER) project was formulated to address this vehicle design challenge by demonstrating the use of current conceptual design tools that have been used for decades to design and size conventional VTOL vehicles, applied to new vehicle types and configurations that are being proposed for UAM type applications, including urban air taxi and package delivery. Vehicle design tools that incorporate all of our aeronautics knowledge and history would allow vehicle developers to easily determine which vehicle designs make sense for a particular mission and which are misguided, and size the vehicles appropriately for the mission. The ultimate vision is for a design environment that would not require expert knowledge or someone trained in aeronautics, but could be used by almost anyone with a desire to open new markets with a new generation of VTOL vehicles. Providing such a design environment would be truly game changing since a capability such as this does not currently exist.

The main goal of DELIVER is to demonstrate the use of current conceptual design and sizing tools for the modeling, design and analysis of vehicles in this UAM concept space, and to understand where the tools work and where there are gaps. In addition to demonstrating the applicability current design and sizing tools to the UAM concept space, DELIVER also demonstrated the addition of key transformational technologies into the design process for vehicle acceptance, operability and utility. These key transformative technologies addressed in DELIVER include: noise, which is key for community acceptance; autonomy and the need for autonomous operations is key for efficient, reliable and safe operations; and hybrid-electric and all-electric propulsion systems that are key enablers for these vehicle types and sizes. The infusion of these transformative technologies into the vehicle conceptual design process would create a revolutionary design capability that does not currently exist, and would be a game changer for vehicle designers. Noise is probably the largest limiting factor for currently helicopter operations in and around urban areas, and it is anticipated that UAM type vehicles will have the same limitations in urban areas. Autonomy is a key enabler to most of the operations that are being proposed for UAM vehicles, and enabling the efficient design of the autonomy system in the early design phase, as well as accounting for the required on-board equipment in the design and sizing of the vehicle is required to ensure safe and efficient operations. Finally, it can be argued that all of the vehicles shown in Figure 1, require some form of electric propulsion to even be feasibility let alone operate efficiently. DELIVER considered these technologies of noise, autonomy and hybrid-electric propulsion as part of the vehicle design process, and examples of work performed in each technical area is described in this paper.

In order to demonstrate the use of current design tools for this new concept space, a number of vehicles were examined. Figure 1 highlights the vehicles that were the focus on DELIVER, and includes some small UAS - the DJI Phantom vehicles (Ref. 3) and the Straight Up Imaging (SUI) Endurance quad-copter (Ref. 4), the NASA developed distributed electric concept demonstrator Greased Lightning (GL-10, Ref. 5), the Elytron 2S (Ref. 6) and 4S UAV (Ref. 7) box-wing configuration vehicles and the Joby S2 (Ref. 8) urban air taxi concept. An overview of how these vehicles were used in the DELIVER project is described in this paper.

This paper provides a summary of the DELIVER project, which executed for 3-years (October 2014 until September 2017) in the NASA Aeronautics Research Mission Directorate. The paper describes the conceptual design process that was the target of DELIVER, and the specific tools that were examined. This is followed by examples of the tools being applied to the design of vehicles described in the UAM vehicle concept space, and shows the work performed for the vehicles examined in DELIVER. Next, the key transformative technologies of noise, autonomy and hybrid-electric propulsion are described and examples of the work performed in including these technologies as part of the vehicle design process are presented. Finally, some concluding remarks are presented along with an assessment of the next steps in making out current design tools more conducive to the design of these next generation vehicles.

DELIVER VEHICLE DESIGN PROCESS AND TOOLS

DELIVER is primarily focused on the conceptual design and sizing phase of vehicle development, where the vehicle configuration is determined by analyzing the performance and mission suitability of various alternatives, and the vehicle is sized for the particular mission or use case. An illustration of the conceptual design process is shown in Figure 2. The missions or use cases are defined in terms of required performance and mission parameters, and operational environment. Examples include: speed, altitude, range, endurance, payload, day/night operations, level of autonomy, operational concepts, etc. A trade-space of vehicles and propulsion systems is defined, and the vehicle configurations and missions are run through the design environment.

The results of this process are vehicles that are optimized and sized for the particular mission, if the vehicle configuration closes for the particular mission. In addition to the vehicle size, the design process produces sensitivities of the vehicle design and size to the mission and operational requirements, and to the vehicle configuration and technologies. These sensitivities allow mission and technology trade-studies to be performed that allow the designer to further optimize the mission and operational parameters, and the vehicle design to produce the optimum vehicle.

For conventional vertical lift vehicles, like single main rotor helicopters, tilt-rotors, tandems, and co-axials, in the 2-4 passenger size range and above (lower left corner of Figure 1), conceptual design and sizing tools are available that are well developed and have been validated over decades of development and use. These tools include empirical data from many existing vehicle sizes and configurations and allow designers to perform vehicle conceptual design and sizing, mission synthesis and technology trade-studies with accuracy. The output of these current tools allows designers to move quickly and confidently from conceptual design and sizing to preliminary and detailed design phases of vehicle development.

For alternative vehicles, that are being proposed for urban air taxi operations like those from Joby (Ref. 8), Zee.Aero (Ref. 9), etc. shown on the left side of Figure 1, calibrated and validated design tools currently do not exist, and vehicle development makes extensive use of expert knowledge. If conceptual design tools are used, custom tools are often developed for the specific configuration being investigated, and these tools are calibrated with experimental data from both wind tunnel and flight testing, and supplemented with analytical data. The vehicle design process typically starts with sub-scale demonstrators to prove the concept, subsequent design iterations increase the size to the full-scale vehicle. This results in a very slow and time-consuming process of build, test, and iterate to get to the final design, with no real confidence that the technologies will scale-up to full-size, or that the final vehicle will meet the mission requirements.

For small UAS, like those shown on the right side of Figure 1 for package deliver applications, the process is typically to start directly with a full-scale vehicle because of the smaller size and lower costs, and use a sketch, build, fly, and iterate process without the need to make extensive use of design tools. While this approach can get a vehicle flying quickly, there are no guarantees that the vehicle concept will work for the particular mission, and there is no systematic way of performing technology and mission trade-studies beyond building and testing.

The DELIVER project seeks to show an alternative approach by demonstrating the utility of current conceptual design and sizing tools for use with urban air mobility type vehicles. The design environment that is examined in DELIVER consists of a number of different tools that work together as part of the vehicle design process. The specific tool sets that are examined in DELIVER are listed in Figure 2, where the core tool is NDARC (NASA Design and Analysis of Rotorcraft, Ref. 10), which is conceptual design and sizing code developed by NASA. In the vehicle design process, NDARC uses a combination of: simplified analysis models (eg. rotors, engines, etc.), look-up tables and curve fits based on empirical data, surrogate models based on high-fidelity calculations, historical vehicle design and configuration data, and includes technology factors to account for advanced future technologies. Various other discipline specific tools are used in the conceptual design process to provide data to NDARC, and the specific disciplines and tools investigated in DELIVER include:

- **Aeromechanics Tools:** CAMRAD II (Ref. 11) is a rotorcraft comprehensive analysis tool that is typically used to estimate rotor performance and accounts for rotor wake and elastic blade properties for NDARC. Propeller Analysis System (PAS) is a part of the ANOPP (Aircraft Noise Prediction Program, Ref. 12) code and provides a lower fidelity prediction of hovering, low speed and axial flight rotor performance, and blade loads that are used in noise predictions.
- **Aerodynamics Tools:** OVERFLOW (Ref. 13-14) is a high-fidelity CFD (Computations Fluid Dynamics) code that is used to predict full vehicle performance and perform design trade-studies. RotCFD (Ref. 15) is mid-fidelity CFD code that is also used to predict full vehicle performance. FUN3D (Ref. 16) and Xfoil (Ref. 17) are used to calculate airfoil section aerodynamic tables. And the Lattice-Boltzmann Method (Ref. 18) is a potentially high-speed CFD method for predicting propeller and vehicle performance.
- **Acoustics Tools:** PSU-WOPWOP (Ref. 19) is used to predict harmonic noise from blade and vehicle pressure loading calculated from aeromechanics or CFD tools. BARC (Broadband Acoustic Rotor Codes (Ref. 20) predicts mid- and high-frequency broadband noise from blade-wake interactions and self-noise.
- **Propulsion System Tools:** NPSS (Numerical Propulsion System Simulation, Ref. 21) is used to calculate propulsion system performance for baseline conventional propulsion systems. NDARC propulsion system models (Ref. 22) are used for all-electric and hybrid-electric propulsion system modeling.

One notable exception from this list of design and analysis tools is that there are no tools currently available to account for autonomy, and the need for the vehicle to operate autonomously, as part of the vehicle design process. The DELIVER project demonstrated a prototype system to design and optimize the autonomy system to meet the mission requirements, and this prototype system is discussed later in this paper.

CONCEPTUAL DESIGN OF EMERGING VERTICAL LIFT VEHICLES

The challenge of applying current conceptual design and sizing tools, such as those shown in Figure 2, to vehicles in the UAM concept space is that the tools typically have not been used for these alternative and small vehicles, and therefore have not been validated for these configurations and sizes. For instance, NDARC has been extensively calibrated and validated with conventional rotorcraft in the 2-4 passenger size range and above, and while alternative and small vehicles can be physically modeled in NDARC, the accuracy of the results has yet to be determined. One reason for this is that the look-up tables, curve fits, empirical data, historical trends, etc. used within NDARC have not been extended to cover small and alternative vehicle configurations, and may not produce accurate results for these vehicles. Another challenge is that while there are an ever-increasing number of vehicles in the UAM concept space, there is very limited detailed data available for these vehicles in terms of vehicle weight statements, lists of components, and full vehicle and component performance measurements and predictions, etc.

The approach to addressing these challenges in DELIVER was to survey some of the vehicles in the UAM concept space to build the look-up tables and curve fits that are needed to perform vehicle conceptual design and sizing within NDARC. DELIVER set up some key partnerships with companies that are developing UAM type vehicles to model their designs and validate the models with actual vehicle and component test data. The data received from partners was supplemented with in-house component and full-vehicle testing to characterize the performance. The vehicles that were the focus of DELIVER are highlighted in Figure 1 with the green boxes, and cover as broadly as possible the concept space that is of interest to DELIVER.

A significant amount of testing was performed to support the DELIVER activity, including isolated propeller testing to measure performance and efficiency; full-vehicle wind tunnel testing to characterize the body aerodynamics and propulsion system performance; indoor flight testing to measure propeller speeds and flight endurance as a function of vehicle weight; and outdoor flight testing to measure vehicle performance and trim conditions as a function of speed. Ref. 23 describes a wind tunnel test that was performed to characterize the multi-copter aerodynamic (with and without the propellers) and propulsion system performance, for a number of different multi-copters. The multi-copters tested during this wind tunnel entry include: the DJI Phantom 3 (Ref. 3), 3D Robotics SOLO, 3D Robotics Iris+, Straight Up Imaging Endurance (Ref. 4), and the Drone America DAX8 octocopter. For the wind tunnel test, the vehicles were mounted on a 6-axis load cell to measure the resultant forces and moments on the vehicle. Vehicles were tested with and without propellers to obtain bare-airframe aerodynamics as well as full-vehicle performance. The test matrix included variations in: wind tunnel flow speed, model angles of attack and sideslip, and individual propeller speeds. A data report is currently being prepared that includes all of the data collected during the wind tunnel test, and will likely represent the first comprehensive data-set on multi-copter aerodynamics and performance. A second wind tunnel entry was performed in January-February 2017 that included the Straight Up Imaging Endurance and the Elytron 4S UAV (Ref. 7).

The comprehensive set of data collected during the wind tunnel entries was used to develop and validate analysis and design models of the vehicles tested. Ref. 24 describes the estimation of sUAS rotor performance in hover using the CAMRAD II comprehensive analysis software (Ref. 11) using different levels of fidelity of the rotor wake and elastic blade properties for the T-Motor Carbon Fiber 15x5 propeller used on the SUI Endurance. The propeller performance maps calculated in CAMRAD II were validated with the wind tunnel and hover test data, and used as the rotor performance model used in NDARC for the SUI Endurance. This process is described in Ref. 25 along with the development of NDARC conceptual design models of the SUI Endurance and trade-studies showing the effects of parametric design variations on vehicle performance and scale. A conclusion of this work is that the full-scale rotorcraft scaling models that are currently included in NDARC are not appropriate for sUAS design, and new scaling models need to be developed using surveys of data from current sUAS vehicles.

The DJI Phantom series (Ref. 3) of vehicles were also examined in DELIVER since they are the most common sUAS for both hobby and commercial purposes, and vehicles were already available at NASA Ames and Langley Research Centers where the majority of the vehicle testing in DELIVER was performed. They are also relatively cheap with many aftermarket parts available commercially. Testing of the DJI Phantom 2 and 3 vehicles include: isolated propeller testing to measure performance and efficiency; full-vehicle wind tunnel testing to characterize the body aerodynamics and propulsion system performance; indoor

flight testing to characterize prop RMSs in hover and flight endurance, and outdoor flight testing to measure the vehicle performance and trim conditions as a function of speed. As with the SUI Endurance, the test data for the DJI Phantom was used to build and calibrate design models in NDARC, CAMRAD II and other tools, and to validate the predictions from the tools.

Another vehicle that was considered in DELIVER was the Greased Lightning GL-10 that was developed at NASA Langley Research Center as a distributed electric tilt-wing demonstrator aircraft. Flight demonstrates of GL-10 started in October 2015 with hover and envelope expansion, and full-transition was achieved in April 2016. Ref. 5 describes the initial flight test campaign for the GL-10 vehicle. Later in 2016 the aircraft was re-built based on lessons learned from the initial flight test campaign. Many internal components and wiring were upgraded, including an upgraded power distribution bus, upgraded tail servo to increase tail pitch range, install additional shielding on the power distribution wiring of the main wing, and upgraded flight control software to use the increased pitch range of the moving tail. A data acquisition system was also developed, built and integrated onto the vehicle including a significant amount of new instrumentation and wiring, and added telemetry for safety of flight monitoring. Ref. 26 includes details of the vehicle upgrades to support research data collection requirements for DELIVER. Flight testing was conducted on the re-built version of the GL-10 in June 2017 to measure the aerodynamic performance in free-flight. The flight testing campaign consisted of a total of 22 flights, including 18 data collection flight, with 12 of these flights including full transition to airplane mode and back to VTOL mode. Figure 3 shows some images from the flight test campaign. Figure 4 shows one of the key results and compares the experimental unpowered aerodynamic performance between flight (Ref. 26), and a sub-scale wind tunnel test (Ref. 27). The aerodynamic data collected during the DELIVER flight tests indicates the GL-10 flight model has an L/D_{max} of about 7.2 which is achieved at an angle of attack of 5° at a speed of 45 knots. The wind tunnel data has a slightly lower L/D_{max} of about 6.5, also at an angle of attack of 5° . The data collected during the GL-10 flight test campaign is available for vehicle modeling and validation, however this data was collected too late in the DELIVER project for this modeling to be performed.

Computational Fluid Dynamic (CFD) modeling and analysis is typically not an integral part of the conceptual design process, but it can provide detailed analysis that is not available with any other design and analysis tools. Examples of analysis data that can be calculated using CFD include: high-fidelity propeller performance predictions, propeller and airframe aerodynamic interactions, propeller and body pressure distribution for acoustics calculations, etc. A number of different CFD tools were used in DELIVER to demonstrate their application to UAM type vehicles. Ref. 6 describes the use of the RotCFD mid-fidelity CFD tool (Ref. 15) to perform an aerodynamic analysis of the Elytron 2S prototype aircraft concept. This aircraft has a unique box wing design with a centrally mounted tilt-wing supporting two rotors. Figure 5 shows the Elytron 2S prototype demonstrator on the left, and graphics of the box wing design in VTOL and cruise mode configurations on the right. The key challenge for this vehicle is the aerodynamic interaction between the wakes from the propellers and wing in cruise mode, in particular the high mounted aft wing that is impacted by the wake of the propeller. Figure 6 shows an example RotCFD calculation from Ref. 6 illustrating this interaction in a low speed cruise flight condition. The aerodynamic interaction between the prop wake and the rear wing has a significant influence on the aerodynamic pitching moments of the aircraft, and is particularly sensitive to the vehicle angle of attack and the center wing tilt angle. Analysis with CFD tools can help to quantify the effects of the aerodynamic interference and define the transition corridor for vehicles such as the Elytron 2S. Elytron also developed a smaller box wing vehicle that is termed the Elytron 4S UAV that has a 5.5-foot wing span. Ref. 28 provides results of an aerodynamic analysis of this particular vehicle with the high-fidelity OVERFLOW tool.

High-fidelity CFD was also examined in DELIVER using the OVERFLOW tool applied to a number of different vehicles in the UAM concept space. Figure 7 shows an OVERFLOW simulation of the SUI Endurance and highlights some of the challenges in modeling sUAS with high-fidelity CFD. First, as with most multi-copter vehicles, the props are mounted very close to the body, and in close proximity to each other, resulting in significant prop-to-body and prop-to-prop aerodynamic interactions, which requires care with CFD calculations to ensure solution convergence. Second, the propellers in these vehicles are controlled independently so they are always out of phase, and it is important to capture this phase offset between the propellers in the CFD simulation. Third, for multi-copters in forward flight, the rear props spin faster than the forward props, and this speed difference depends on the forward speed. For the case shown in Figure 7 for the SUI Endurance, the rear props are spinning about 30% faster than the forward props, which creates issues when considering periodicity of the solution. Additional details of the challenges, capabilities and results of modeling small multi-copter vehicles with OVERFLOW can be found in Refs. 29-32.

One example of using high-fidelity CFD in the vehicle design process is an examination of a trade-off between over-mount and under-mount props in terms of vehicle performance. Figure 8 shows OVERFLOW CFD calculation of a DJI Phantom-like vehicle in 3 different configurations, first with the props mounted above the arms (offset is 10% of prop radius), second with the props mounted the same distance under the arms, and third with the props mounted 25% of the prop radius below the arms. Table

1 lists the thrust and fuselage download results for the 3 cases considered. Note that the thrust and download numbers have been normalized by 4 times the isolated single prop thrust, so a value of 1 would be the same thrust as 4 isolated props. For the over-mount (or baseline) case, the prop thrust is about 2.5% amplified by proximity of the body creating by a pseudo ground effect, and the download on the body is about 7.6% of the normalized total thrust. The resulting total thrust is about 5.1% loss in thrust compared with isolated props due to prop-prop and prop-body interactions. For the under-mount configurations, the prop thrust is lower and the fuselage download is higher than the over-mount case, resulting also in less total thrust and indicating that under-mounting the props reduces the performance. Finally, the off-body under-mount case is with the props mounted 25% of the prop radius below the arms. This configuration produces the lowest prop and total thrust, indicating that there is significant penalty by having the props so close together. Additional details of these results are shown in Ref. 31. These results illustrate how high-fidelity CFD can be used in the vehicle conceptual design process to help to refine the vehicle configuration.

Table 1: OVERFLOW thrust and download predictions for DJI Phantom-like vehicle with various prop mounting locations (Ref. 31). OVERFLOW simulation results shown in Figure 8.

Configuration	Rotor Thrust	Fuselage Download	Total Thrust
Over-mount	1.025	-0.076	0.949
Under-mount	1.016	-0.080	0.936
Off-body Under-mount	0.954	-0.038	0.916

Note: Forces have been normalized by 4x isolated single rotor thrust

KEY TRANSFORMATIVE TECHNOLOGIES

The key transformative technologies examined in DELIVER are noise, autonomy, and hybrid-electric and all-electric propulsion. Each of these technologies are discussed in this section, including vehicle conceptual design trade-studies with the technologies included.

Acoustics

As previously mentioned, noise is the largest limiting factor for helicopter operations in urban areas, and it will likely be one of the key drivers for community acceptance for both air taxi and sUAS operations in urban areas. There is currently limited ability to account for noise as part of the vehicle design process, and the only real option is to limit the tip speeds of the props / rotors. While this approach can potentially limit the noise produced by a vehicle, it does not account for noise factors other than tip speed, and will not allow designers specify a noise or annoyance target. The focus on the noise work in DELIVER is on sUAS noise and annoyance. For sUAS, the perception is that because the vehicles are small and typically use all-electric propulsion they will be quiet. However, the reality is that the vehicles will operate much closer to the public than current aerial vehicles, and there will potentially be greater numbers of them in the urban skies, so noise and annoyance will be a factor.

In order to address sUAS noise, and ultimately vehicle design for low noise, the DELIVER project developed four main goals:

1. Characterize and understand the noise of sUAS through experimental testing of both isolated props full-vehicles.
2. Assess the ability of current acoustics tools (listed in Figure 2) to predict both component and full-vehicle noise.
3. Characterize the level of annoyance produced by current sUAS through human subject psychoacoustics testing.
4. Demonstrate the ability to perform design trade-studies that take noise into account as part of the vehicle design process.

Each of these areas is described in detail below, along with some key example results. Additional details of the sUAS noise work performed in DELIVER can be found in Ref. 33.

In order to characterize and measure the noise, experimental testing was performed for both components and full-vehicles in free-flight, and acoustics chambers and wind tunnels. Figure 9 shows an example of free-flight testing performed to characterize the noise of a number of different vehicles (Ref. 34). This figure shows a portable 3-microphone system that was developed specifically for these tests, details in Ref. 34. A low-cost, light-weight and highly accurate positional flight data acquisition system was also developed (Ref. 35) that provide vehicle position relative to the microphone system. This system was key to synchronizing the vehicle position data with the microphone data. Figure 10 shows the free-flight noise characterization of a DJI Phantom fly-over at 6 m/s in the form of a spectrogram with the frequency behavior varying with time (Ref. 34). This figure illustrates the nature of the noise that is typically of multi-copters where control of the vehicle is achieved entirely through prop speed changes. For this quad-copter, the blade passage frequencies can be clearly seen for the 4 props as the lower frequencies shown on the figure. It should be noted that the DJI Phantom props have 2-blades, so the blade passage frequencies are 2 times

the prop rotational speeds. Figure 10 illustrates that the rear props are spinning faster than the forward props, and that all of the props are spinning at different speeds. This data also shows that the prop speeds are constantly varying due to turbulence and the control inputs that are required to keep the vehicle on the specific straight and level flight path. The conditions for the flight tests were relatively calm, and it is expected that this unsteadiness would increase significantly with more turbulent conditions and during maneuvering flight. Figure 10 also shows that the noise from multi-copter vehicles is a complex addition of noise from each of the individual props and is very sensitive to the flight atmospheric environment and vehicle flight condition and speed.

In terms of noise prediction, a number of tools were investigated at various levels of fidelity (Ref. 36). Figure 11 shows an example noise prediction for an isolated DJI Phantom 2 aftermarket carbon fiber prop, and compares the predicted noise with that measured for an isolated prop on a hover test stand in an anechoic chamber. This figure shows the sound pressure level as a function of frequency with the experimental data in black. The solid green line is the noise prediction using OVERFLOW to calculate the blade pressure distributions and PSU-WOPWOP to calculate the resulting noise harmonics. The dashed red line is the motor noise that was measured from an isolated motor test in the same anechoic chamber. The measured motor noise was used since a prediction of electric motor noise was not available. The dashed blue line shows the broadband noise calculated using the BARC code. The solid magenta line is the total prediction and includes the harmonic and broadband predictions, and the measured motor noise. The comparison indicates that fairly accurate predictions of the lower-frequency harmonics and higher-frequency broadband noise (with the addition of measured motor noise). One key factor in the noise generated by multi-copters is rotor-airframe interactional noise, which is discussed in detail in Ref. 37, which shows experimental characterization of the effect of airframe proximity to props on noise, and demonstrates the ability to predict this interactional noise with OVERFLOW and PSU-WOPWOP. An extension of this to full-vehicle noise prediction is shown later in this section.

Previous results have shown noise characterization and the ability to predict noise for multi-copters. The next goal explored in DELIVER was to assess the level of annoyance generated by these types of sUAS multi-copter vehicles. A key to performing human subject testing such as the development of an auralization simulation of multi-copter noise that is representative of noise measured from the free-flight vehicle tests. Ref. 38 describes the development of the sUAS auralization that is based on CFD noise predictions, and Ref. 39 describes the development of a simulation of quad-copter flight dynamics that includes the aeromechanical factors pertinent to auralization fidelity. Once this sUAS auralization development was complete, a human subject test was conducted in the Exterior Effects Room at NASA Langley Research Center to produce an initial characterization of the psychoacoustic properties of sUAS noise (Ref. 40). The key objective of the experiment described in Ref. 40 was to evaluate the level of annoyance of multi-copter noise compared to typical ground vehicles that would be present in urban areas, such as cars and delivery trucks. Figure 12 shows a key result from the human subject testing, as presented in Ref. 40, that shows the Mean Annoyance Rating versus sound pressure level for each of the data points recorded. The solid circles and the solid red curve-fit line show the assessed annoyance for the various sUAS and the blue triangles and dashed red curve-fit line show the annoyance for the ground vehicles. The key result is that the multi-copters were consistently rated as more annoying than ground vehicles at the same sound pressure level. The implication is that a commonly held belief that ‘as long as sUAS are no louder than delivery trucks, operators won’t have to worry about noise for package delivery’ may not hold true, and that noise may be indeed be a more important factor in vehicle design and operations than is currently thought.

It has been established that annoyance is an important factor in vehicle operations in urban areas, and it is therefore important to consider noise in the vehicle design process, either to design a vehicle to minimize the noise, or design to a particular noise/annoyance threshold. One example that was examined in DELIVER is the trade-off between over-mount and under-mount props that have been explored by some sUAS manufacturers, who have suggested that under-mount props would produce lower noise than over-mount props. This premise was explored using the design and analysis tools examined in DELIVER. It was shown in Table 1, using OVERFLOW CFD simulations (shown in Figure 8), that under-mount props on a DJI Phantom-like vehicle produce less thrust at the same RPM than over-mount props. In order to examine the impact of prop mounting on noise, the OVERFLOW simulation time histories of the surface pressure distributions on the props and body were processed through PSU-WOPWOP to calculate the noise harmonics. Figure 13 shows results of the predicted sound pressure level versus blade passage frequency harmonics for the two different prop configurations, with the predictions for the over-mount props in blue and the under-mount prop predictions in red. These results clearly indicate that the under-mount configuration generates significantly more noise than the over-mount configuration, and provides an illustration of how noise can be incorporated in the design process. Additional details can be found in Ref. 33.

Autonomy

Autonomy is a key enabler for most of the operations that will be performed by UAM type vehicles for both sUAS operations including package delivery, and urban air taxi where removing the pilot increases the number of paying passengers that can be accommodated, and reduces the cost without the need to pay for a pilot. For the purposes of vehicle design, the on-board equipment that enables autonomous operations has weight and volume, and requires power, and it is important to take these constraints into account during the early design phase to ensure that the need to carry these systems does not reduce the payload capability if the weight and volume of the autonomy systems are underestimated. The equipment and operational factors that are considered in the autonomy system can be loosely binned in the following categories:

1. **Mission Systems:** Defined as the on-board equipment that allows the vehicle to perform the intended mission. This equipment includes, on-board sensors, computer processors and storage, payload or sensor stabilization, communication equipment, etc. For instance, if the mission required the delivery of a package, this would include all of the sensors and processing required to detect the landing point and navigate to the landing spot while avoiding obstacles in the landing zone.
2. **Concept of Operations:** Defined as the equipment needed to fly within environment specified for the mission. This includes: day / night operations (and fog, wind, rain, snow, etc.); on- vs. off-board decision making and processing; integrating with and coordinating with other vehicles. For instance, different sensors may be required for day and night operations if these were a part of the mission.
3. **Regulatory Requirements:** Defined as the equipment that is needed on-board to enable the vehicle operations, and could include: UTM/FAA required systems, communications equipment, redundant systems, ADS-B, see and avoid technologies, contingency management, and lost link capabilities.

The conceptual design and sizing tool, NDARC, has the ability to account for these autonomy systems as an ‘equipment’ input that is reliant on the user to define the weight, power, volume and location of all components as part of the vehicle design. The challenge for the vehicle designer is to determine what equipment is needed as a part of an autonomy system to enable a particular mission or use case, and include this as a design constraint. An additional challenge is how to model and optimize this autonomy system as part of vehicle design and mission synthesis and this challenge was the focus on the autonomy effort in DELIVER. Once the autonomy system is defined, its characteristics can be used as a constraint in the vehicle conceptual design and sizing process.

An Application-Based Conceptual Design (ABCD) framework was developed to help define the autonomy hardware that would be appropriate for a particular mission or use case. Initially the mission would be broken down into a set of requirements for the autonomy system and the vehicle platform itself. For instance, if the mission involved flying within a building, there would be constraints on the size of vehicle that could be used, which also sets constraints on the sensors and processing capabilities that could be carried on-board the vehicle. Another example is if the mission required specific sensors (such as for detecting gas leaks), then the sensors required to perform this mission would be needed to be included in the autonomy system. A further example is if the mission required the vehicle to navigate without GPS, then the autonomy system must include sensors and processing to provide a localization and mapping capability. These requirements derived from the mission then impose constraints on the vehicle, and also reduce the size of the design space in terms of autonomy components that are available to the designer.

The next step is to perform trade-studies to find the optimal autonomy system for the particular application. A prototype autonomy trades modeling system was developed in DELIVER to allow the designer to perform these autonomy system trade-studies (Ref. 41). Figure 14 shows a screen shot of this system that includes the simulation of all key parameters, including: mission requirements, sensor characteristics, processing capacity, algorithms, visual and operating environment, vehicle dynamics limits, etc. The screen shot in Figure 14 shows an example of the prototype system for an optical flow algorithm that includes all of the parameters that can be tuned for this particular algorithm. Other tabs at the top of the window can be selected to represent different sensors, on-board processing capacity, and vehicle dynamics. This system allows the designer to select and compare different algorithms, and optimize each the algorithm for a particular scenario. The visuals can include a photo-realistic modeling and simulation environment (Ref. 42) that is connected to the prototype system, or real video collected with actual sensors. By populating the prototype system with various sensor and algorithm combinations, the designer can perform trade-studies to determine which sensors and algorithms have adequate performance to do the mission, and select the optimal combination to get best mission performance. The prototype system developed in DELIVER is unique, and no such capability current exists for performing interactive trade-studies to efficiently design and optimize an autonomy system.

In order to validate the results of the autonomy trades modeling systems, a case study was selected, namely ‘Search and Rescue Under the Tree Canopy’. In this scenario, a sUAS (or fleet of sUAS) would enter a forest and search for a lost hiker. The vehicle

would define a search plan based on how fast a hiker could travel, and where they are likely to go. The vehicle would periodically share a map of the forest whenever it has communications with a base station or other vehicles. The vehicle would find and track the lost hiker, deliver emergency supplies, and guide rescuers. The key requirements of the autonomy system for this particular mission include:

- Function independently and minimize operator workload (out of the range of ground controllers)
- Fly reliably through forested areas, avoiding obstacles (GPS non-reliable under the tree canopy)
- Execute a search algorithm, adapt to local conditions, and coordinate search with other vehicles
- Generate on-board maps during flight and merging maps with multiple vehicles
- Detect a human with on-board sensors and algorithms and track if moving
- Return to launch point and provide location and map data to rescuers

Refs. 43-47 provide details of the work performed in developing autonomy solutions under this challenging scenario.

Hybrid-Electric Propulsion

Hybrid-electric or all-electric propulsion is a key enabler for all of the vehicles considered in the UAM concept space for both urban air taxi with distributed propulsion systems, and multi-copters proposed for package deliver applications. For most of these vehicle configurations, conventional propulsion systems would be difficult, if not impossible to implement, and would most likely increase the vehicle weight, complexity and cost. For instance, with multi-copters, conventional propulsion would need belts or shafts running from a single motor to each of the propellers, or multiple engines would be required. Most current multi-copters have fixed-pitch propellers and use independent propeller speed changes to achieve vehicle control. With conventional propulsion, each of the propellers would require variable blade pitch to achieve the same level of control as an electric system, which significantly increases the mechanical complexity, and likely the weight and cost of the system. The same is true for urban air taxi and passenger carrying distributed electric vehicles where the need to drive and control multiple props making electric propulsion systems the most viable option.

The DELIVER work in hybrid-electric propulsion focused on two main objectives. The first was to explore the capabilities of current conceptual design and sizing tools to design and optimize urban air mobility type vehicles, shown in Figure 1, that use hybrid-electric propulsion systems. The second objective was to explore cryogenically-cooled hybrid-electric power system options and assess the potential benefits as compared with conventionally-cooled hybrid-electric systems.

Cryogenically-cooled power systems use a cryogen as a fuel source, as well as to cool the power electronic components of the vehicle propulsion system in order to increase their performance. Cryo-cooled power systems offer a number of potential benefits over conventionally-cooled power systems in terms of improved propulsion system efficiency and performance, superior thermal management capabilities, reduced environmental impact compared to traditional fuels, improved safety over traditional fuels, and reduced drag without the need to use airflow for cooling. An initial trade-study of available cryo-fuels identified Liquid Natural Gas (LNG) as the most viable option since it has an established heritage in ground transportation, is currently produced in large quantities, and is readily available in most large urban areas. LNG is probably most suitable for high utilization missions and urban environments. An assessment of cryo-cooled power system components was performed for application for urban air taxi operations (Ref. 48). In order to perform the trade-studies, the DELIVER team identified the key performance parameters needed to accurately model the performance of cryo-cooled power systems. Some of these parameters were extracted from literature or calculation, but some required experimental data to be collected. Hardware was designed, built and tested in DELIVER to collect this key data, including the design and calibration of a custom torque cell to operate at cryogenic temperatures (Ref. 49). Details of the development of a combined thermal, fluid, electrical and mechanical simulation model for the design and sizing of hybrid-electric power systems, including cryogenically-cooled power systems, are provided in Ref. 50.

The hybrid-electric propulsion system trade-studies performed in DELIVER focused on demonstrating the capabilities of the current design tools listed in Figure 2 to a retro-fit of a single main rotor helicopter with various hybrid-electric propulsion architectures, and a Joby S2-like distributed electric propulsion concept, which will be termed the DEP concept for this paper. Refs. 51-52 provide details of trade-study performed for a retro-fit of the Schweizer S300 and Joby S2-like vehicle with various hybrid-electric propulsion options. For the DEP concept vehicle, the baseline vehicle was sized for all-electric operations for a mission requiring a range of 150 NMI (nautical miles). The mission consisted of 5-minutes of idle on the ground, 2-minutes of hover out of ground effect, climb at maximum power to 2000-ft altitude (climb credited in the total range), cruise at the vehicle best range speed, and a 2-minute out of ground effect hover and landing with 10% energy reserve at the conclusion of the flight. Figure 15 shows a schematic of this mission and the power required at each of the mission phases. For this particular mission, the power required for hover out of ground effect is about 480 HP (horsepower), and the power required to cruise at best range

speed is about 170 HP. Design excursions were performed with conventionally-cooled and cryo-cooled hybrid-electric propulsion systems with different sized generators, namely 150, 175 and 200 HP. The vehicle maximum gross weight was held constant at the all-electric baseline for each of these design excursions.

Table 2 shows the results of these vehicle trade-studies in terms of the maximum range that the vehicles can achieve, and the number of 50-mile urban air mobility-type missions that can be performed between re-fueling/re-charging. Here the baseline all-electric vehicle has a range of 150 NMI, which was the design range. The hybrid propulsion system significantly increased the range that can be achieved, with the maximum range achieved with the 200-HP generator with a cryo-cooled power system. It should be noted that the range with 150-HP and 175-HP generators is limited by the battery energy since there is not sufficient generator capacity to change the batteries during the cruise phase of the mission. With respect to number of UAM missions, the baseline all-electric aircraft can perform 2 such missions before the batteries need to be recharged. With a hybrid-electric propulsion system, the number of UAM missions that can be performed is more than doubled in each case, with the maximum number being achieved with the 200-HP generator with a cryo-cooled power system that can perform 7 such mission between re-fueling. For the operations considered here, the hold time is the ground time required with the generator running and the batteries being fully-recharged. Additional details of these trade-studies are presented in Refs. 51-52.

Table 2: Vehicle and mission performance of Joby S2-like distributed electric propulsion vehicle with various hybrid-electric propulsion options. The baseline vehicle is all-electric, and sized for a 150 NMI range mission.

Vehicle→	Baseline	Conventionally-cooled hybrid			Cryogenically cooled hybrid		
Genset Size		150 hp	175 hp	200 hp	150 hp	175 hp	200 hp
Maximum vehicle range mission							
Max Range, nmi	150	298*	460*	496	378*	530*	580
Multiple UAM missions							
Number of 50 nmi missions (28 min.)	2	4	4.6	4.9	5.3	5.6	7
Hold time, minutes †	-	36	22	15	31	19	12

* Battery energy limited range

† Time on ground between UAM missions to self-recharge battery to full

The goals of the DELIVER project in hybrid-electric propulsion were to assess the abilities to model urban air mobility type vehicles with all-electric and hybrid-electric propulsion systems. Additional work is required in modeling of the thermal management of these types of systems.

SUMMARY

This paper provides a summary of the DELIVER project. The DELIVER project was formulated to demonstrate the use of current conceptual design and sizing tools, that have been used for decades to design and size conventional rotorcraft, applied to novel vehicle types, configurations and sizes, such as those that are being proposed for urban air taxi and package deliver applications. This demonstration focused on a number of vehicles that covered the urban air mobility concept space, namely some small UAS - the DJI Phantom vehicles and the Straight Up Imaging (SUI) Endurance quad-copter, the NASA developed distributed electric concept demonstrator Greased Lightning (GL-10), the Elytron 2S and 4S UAV joined wing configuration vehicles and the Joby S2. In addition to demonstrating the applicability of current design and sizing tools to novel vehicle configurations and sizes, DELIVER also demonstrated the addition of key transformational technologies of noise, autonomy, and hybrid-electric and all-electric propulsion into the vehicle conceptual design process. Noise is key for community acceptance, autonomy and the need to operate autonomously are key for efficient, reliable and safe operations, and electrification of the propulsion system is a key enabler for these new vehicle types and sizes.

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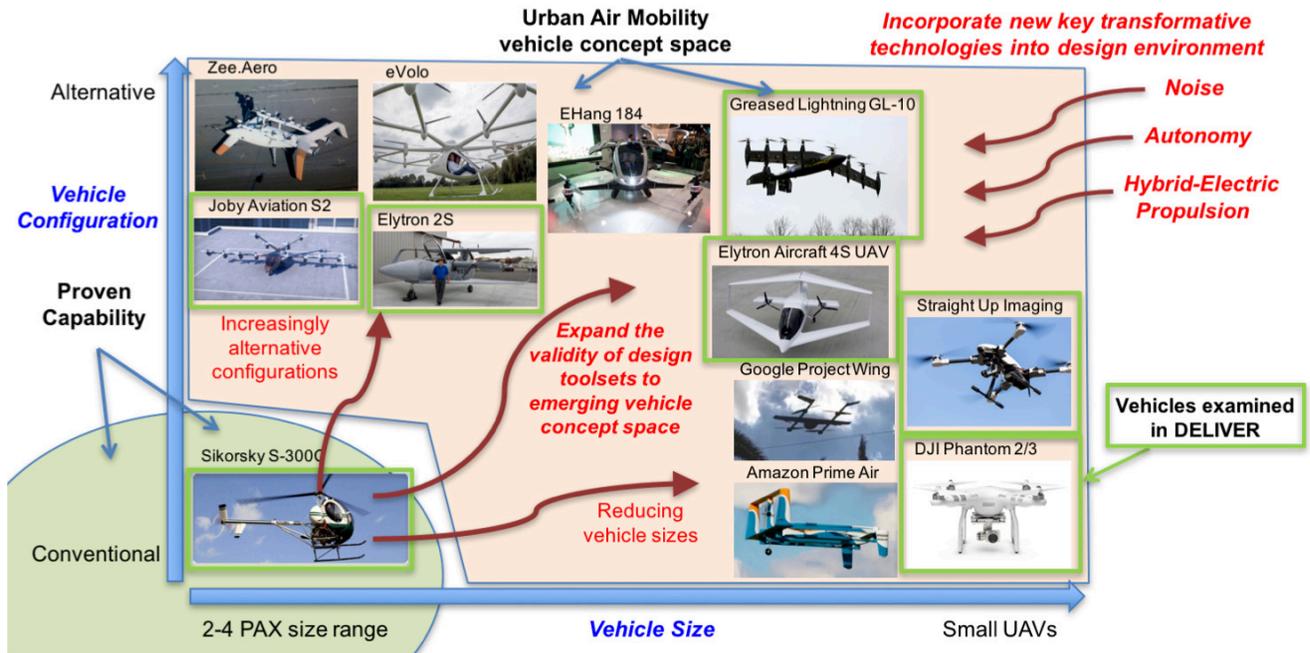


Figure 1. Urban Air Mobility (inclusive of urban air taxi and package deliver type vehicles). Vehicle examined in the DELIVER project are highlighted with green boxes.

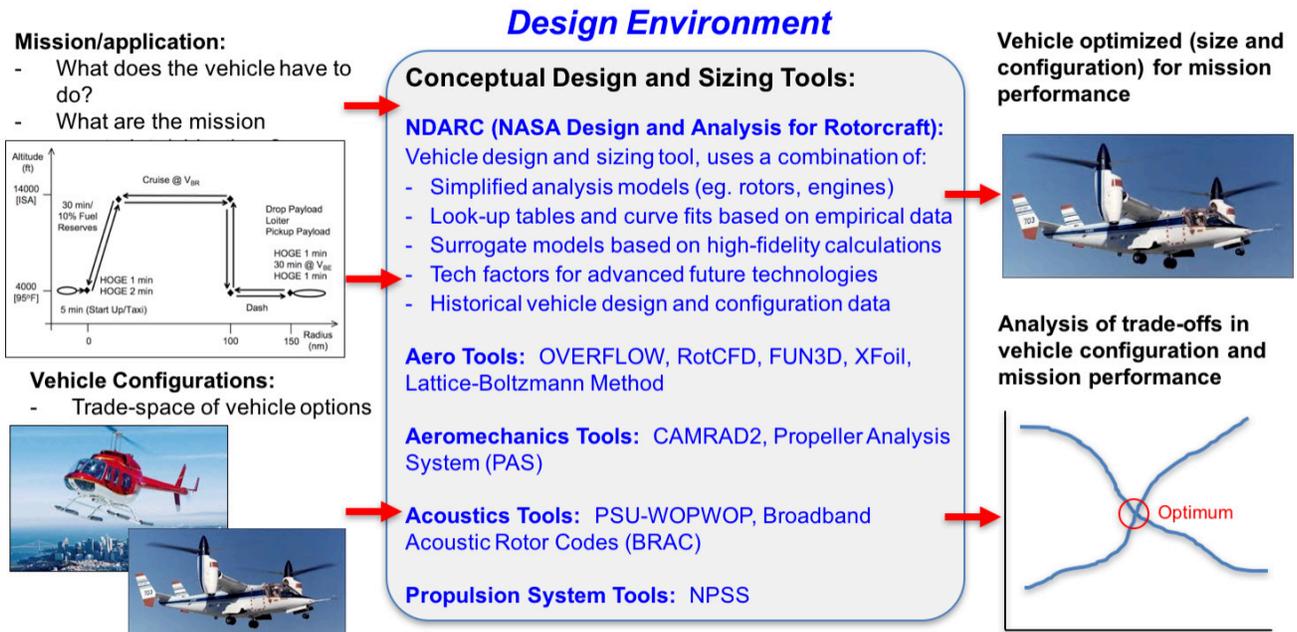


Figure 2. Vehicle design process, environment and tools considered in DELIVER.



Figure 3. Images from GL-10 research flight test campaign in June 2017 (Ref. 26).

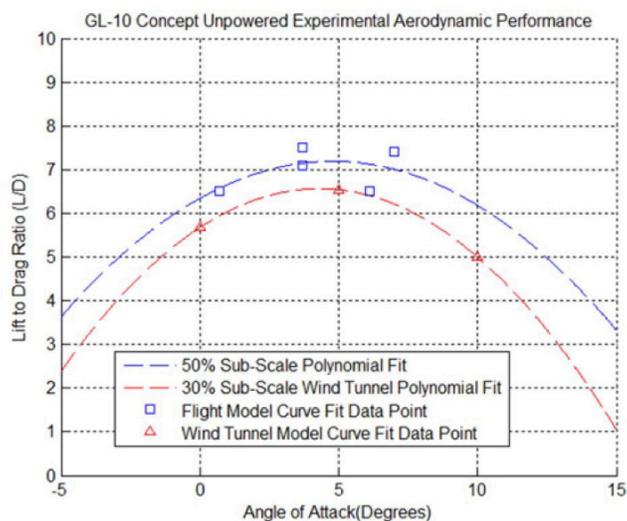


Figure 4. GL-10 experimental unpowered aerodynamic performance comparison. The data for the blue symbols were measured from the GL-10 flight test campaign in June 2017 (Ref. 26). The data for the red symbols were measured during a sub-scale wind tunnel test in September 2013 (Ref. 27).

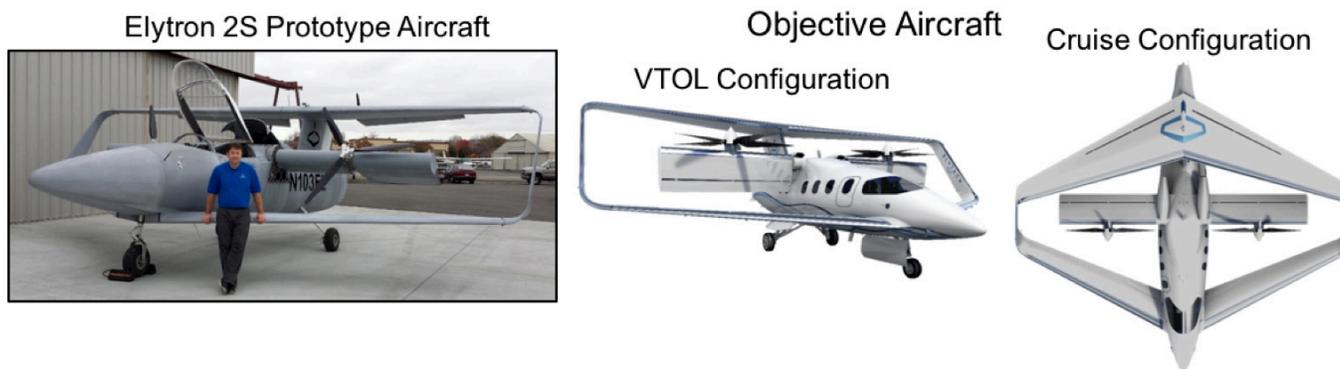


Figure 5. (left) Photo of the Elytron 2S prototype aircraft. (right) Box wing aircraft concept in VTOL and cruise configurations (Ref. 6).

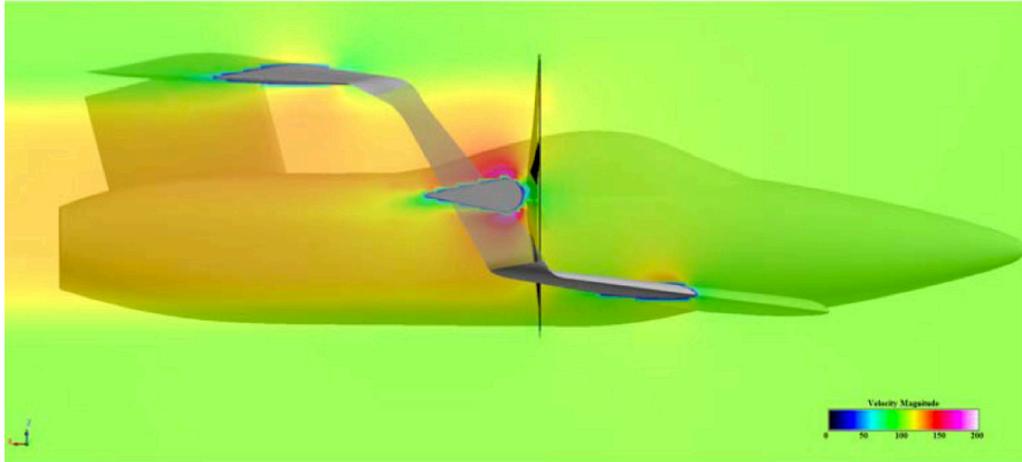


Figure 6. RotCFD simulation of Elytron 2S in low speed cruise at 57 knots illustrating rotor / wing flow interactions (Ref. 6).

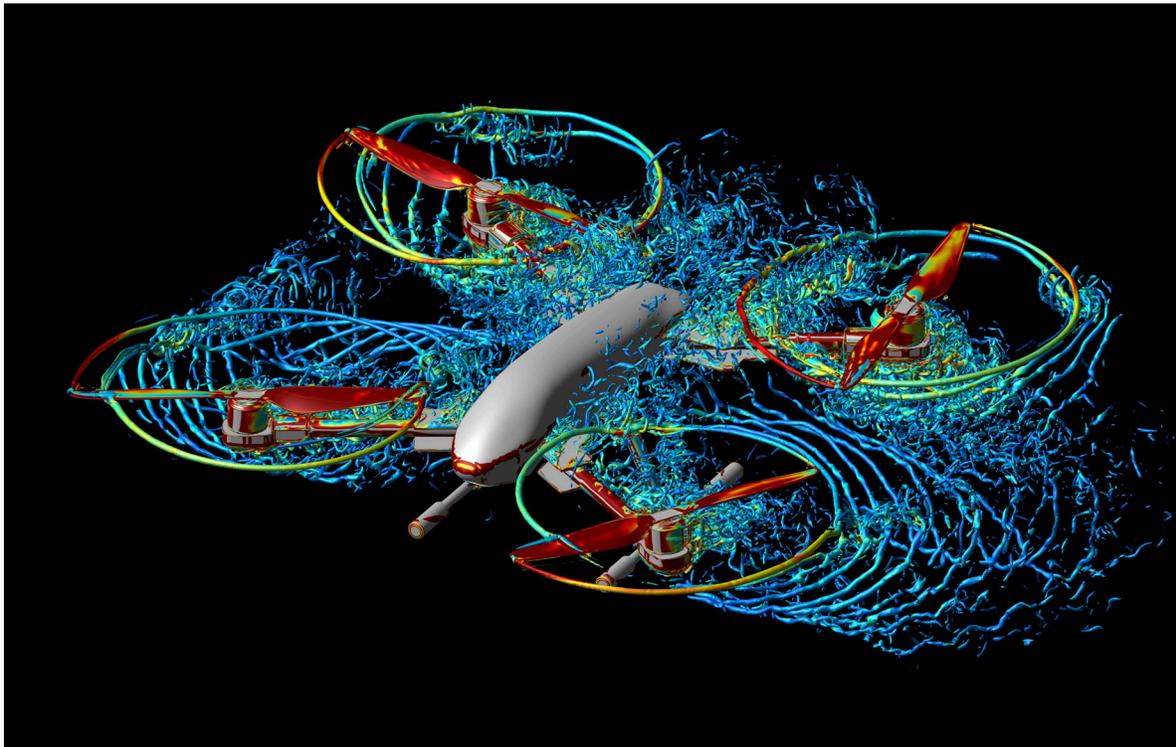


Figure 7. OVERFLOW simulation of the SUI Endurance showing the pressure distributions on the props and body, and the wakes from the props.

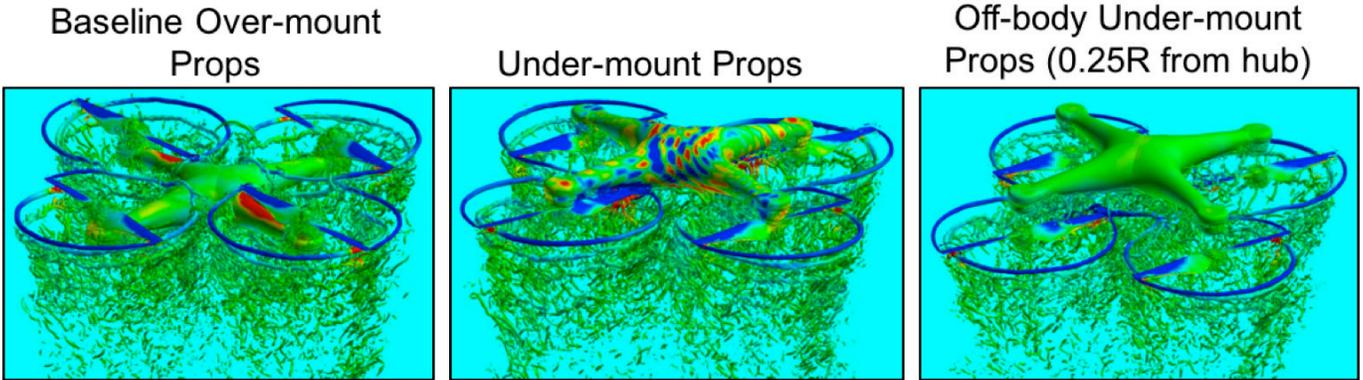


Figure 8. OVERFLOW simulations of DJI Phantom-like vehicle with 3 different prop locations (Ref. 31).

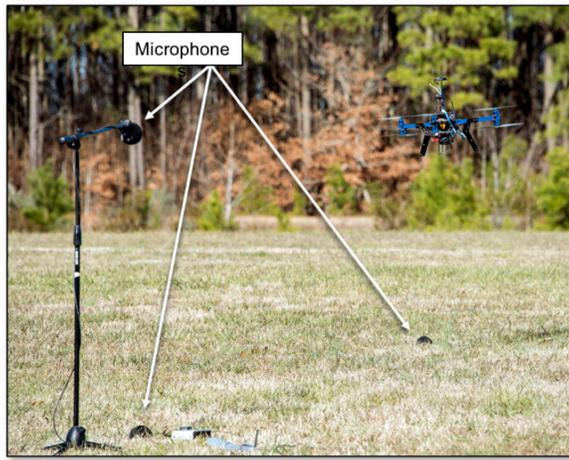


Figure 9. Free-flight multi-copter flight testing, with a 3-microphone array to characterize the noise.

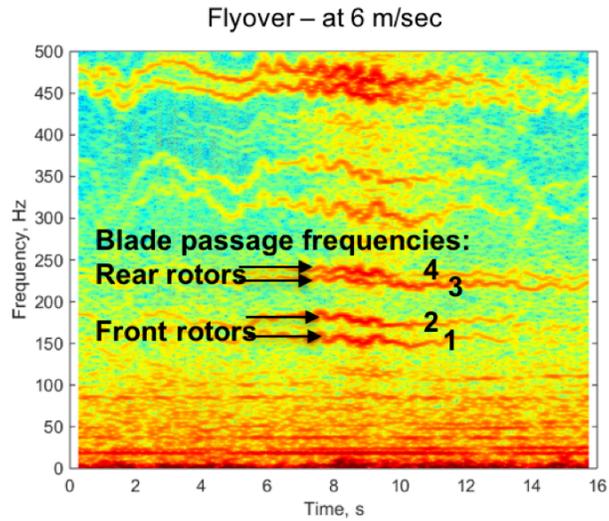


Figure 10. Spectrogram of a DJI Phantom flyover at 6 m/s and 6m above ground level (Ref. 34).

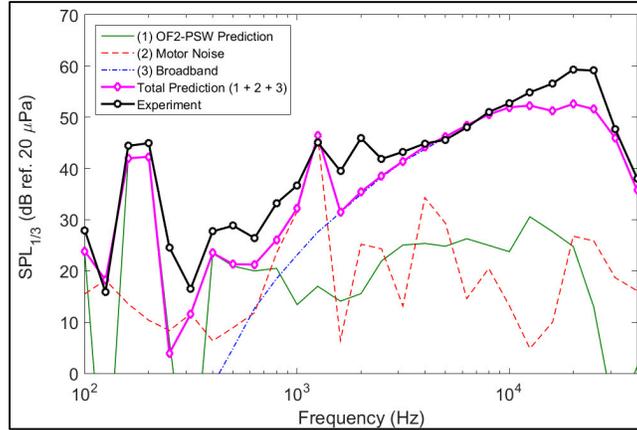


Figure 11. Comparison between noise prediction and experimental measurement for an DJI Phantom aftermarket carbon fiber prop in hover.

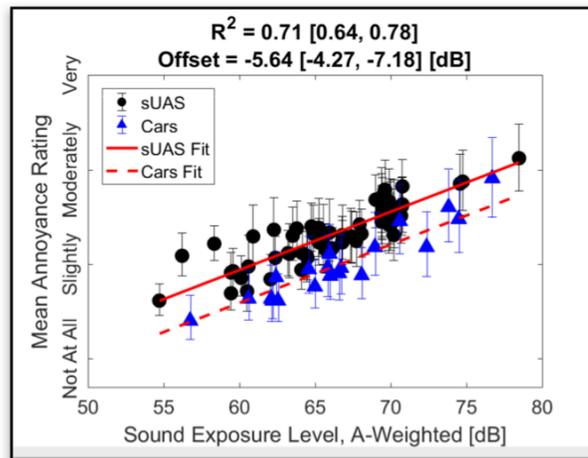


Figure 12. Mean subject annoyance ratings for sUAS and ground vehicles (cars) as a function of sound exposure level (Ref. 40).

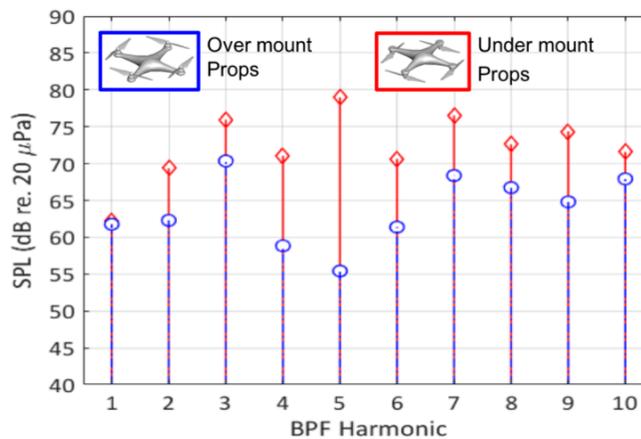


Figure 13. Sound pressure level for blade passage frequency harmonics for over mount and under mount propellers on a DJI Phantom-like sUAS (Ref. 33).

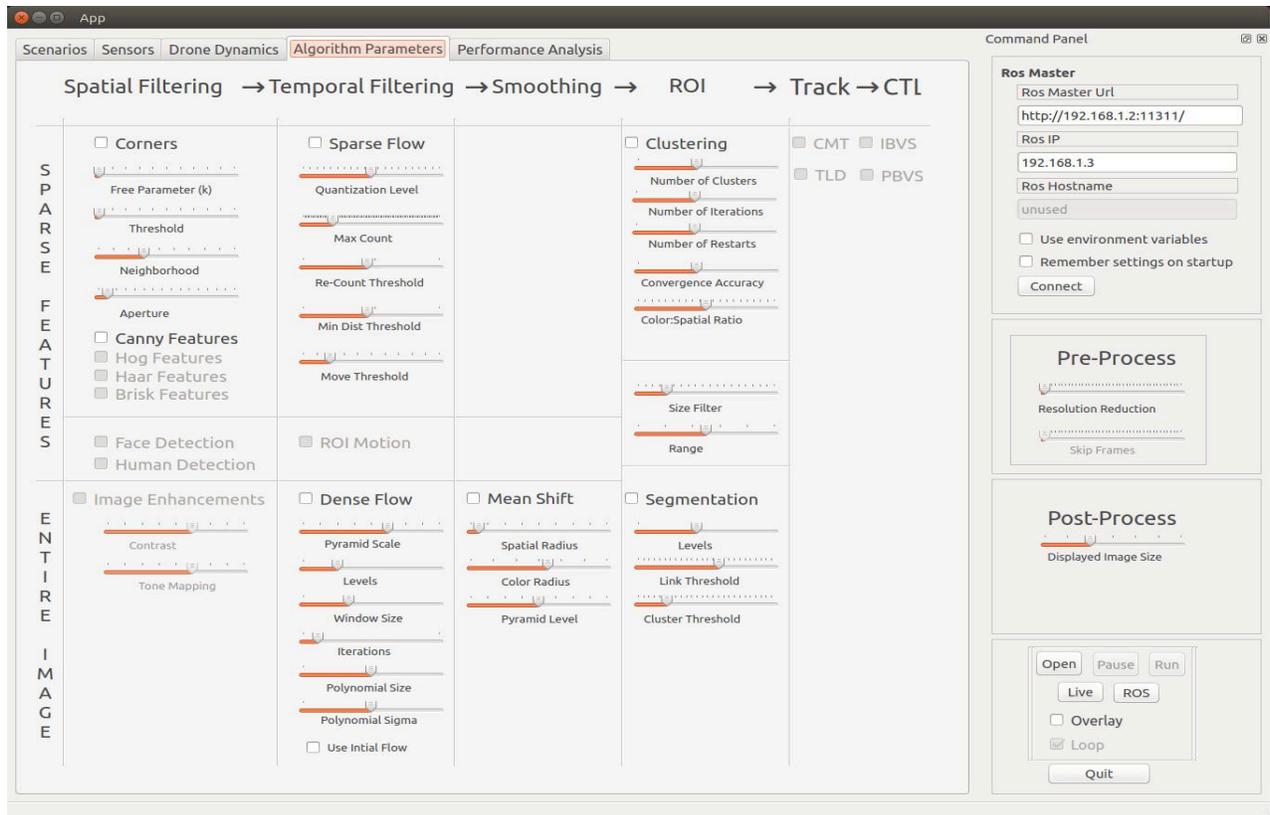


Figure 14. Screenshot from prototype autonomy trades modeling system.

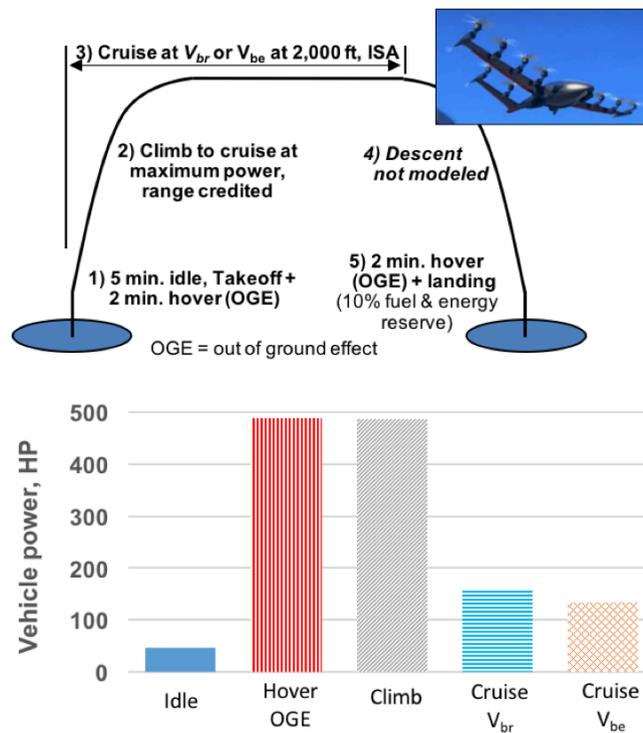


Figure 15. Urban Air Mobility mission for Joby S2-like distributed electric propulsion vehicle, and vehicle power required during various phases of the mission.