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Second Annual Transformative Vertical Flight Concepts Workshop

Enabling New Flight Concepts Through Novel Propulsion and Energy Architectures

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This report is available in electronic form at

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Introduction

On August 3rd and 4th, 2015, a workshop was held at the NASA Ames Research Center, located at the Moffett Federal Airfield in California to explore the aviation community's interest in Transformative Vertical Flight (TVF) Concepts. The Workshop was sponsored by the AHS International (AHS), the American Institute of Aeronautics and Astronautics (AIAA), the National Aeronautics and Space Administration (NASA), and hosted by the NASA Aeronautics Research Institute (NARI). This second annual workshop built on the success and enthusiasm generated by the first TVF Workshop held in Washington, DC in August of 2014. The previous Workshop identified the existence of a multi-disciplinary community interested in this topic and established a consensus among the participants that opportunities to establish further collaborations in this area are warranted. The desire to conduct a series of annual workshops augmented by online virtual technical seminars to strengthen the TVF community and continue planning for advocacy and collaboration was a direct outcome of the first Workshop.

The second Workshop organizers focused on four desired action-oriented outcomes. The first was to establish and document common stakeholder needs and areas of potential collaborations. This includes advocacy strategies to encourage the future success of unconventional vertiport capable flight concept solutions that are enabled by emerging technologies. The second was to assemble a community that can collaborate on new conceptual design and analysis tools to permit novel configuration paths with far greater multi-disciplinary coupling (i.e., aero-propulsive-control) to be investigated. The third was to establish a community to develop and deploy regulatory guidelines. This community would have the potential to initiate formation of an American Society for Testing and Materials (ASTM) F44 Committee Subgroup for the development of consensus-based certification standards for General Aviation scale vertiport capable flight systems. These standards need to accommodate novel fixed wing concepts that do not fit within the existing Federal Aviation Administration (FAA) rotorcraft certification framework (Code of Federal Regulations, Title 14, Chapter I, Subchapter C, Part 27). The fourth desired outcome was to launch an information campaign to ensure key U.S. Government agencies understand the potential benefits and industry interest in establishing new vertiport capable flight markets.

This record of the Workshop proceedings documents Workshop activities and products including summaries of the video recorded technical presentations, overviews of three breakouts sessions (Missions/Operational Concepts, Prioritized Technical Challenges, Regulatory Roadmap), and a preliminary draft roadmap framework for TVF.

Objectives

The Workshop's primary objectives were to inform participants from industry, academia, and government agencies about recent developments in vertiport capable flight configuration designs, operational concepts, technology, market opportunities, and regulatory environments. A secondary objective was to engage the group in developing inputs for a preliminary roadmap that will aid in the advocacy and pursuit of emerging technologies and approaches that can potentially transform air transportation (e.g., electric/hybrid power and distributed propulsion). As conventional analytical tools cannot model these new configuration types adequately, they will require new conceptual design tools. They also do not inherently fit into the existing FAA certification frameworks, and regulations able to capture the fundamental differences in approach will

need to be developed. This Workshop brought together interested parties with the diverse backgrounds and experience necessary to establish an intellectual framework that can serve as a foundation for a preliminary roadmap. Roadmaps are useful tools for guiding investment strategies to fill the gaps necessary to achieve successful new aviation products, and this Workshop took a step toward making this type of tool available for TVF systems.

Approach

The Workshop combined the mutual interests of technical organizations, government laboratories, and industry to collaboratively explore and exploit the potential for new vertiport capable flight opportunities. The Workshop focused on achieving participation from all stakeholders, including new and small companies aggressively focused on this topic, as well as mature aerospace companies for whom this could enhance or augment their conventional vertiport capable flight products.

A conscious effort was made to achieve a balance between sharing information in the form of technical presentations and encouraging attendee participation in the dialog necessary to surface diverse perspectives, concerns, and perceived opportunities by engaging them in interactive breakout sessions.

The technical sessions were captured on video recordings and streamed live over the Internet. Abstract summaries of the technical sessions are provided later in this document and links to the video recordings are listed in Appendix A.

To facilitate the breakout sessions, a process was adopted that ensured manageable group sizes and still permitted all of the participants to engage in each of the three breakout focus areas, “Missions/Operational Concepts,” “Technical Challenges,” and “Regulatory Frameworks.” The process was to divide all of the attendees randomly into three groups, with each group spending 25 minutes discussing each topic, then all groups simultaneously rotating to the next topic. After two rotations all of the attendees were able to discuss and contribute to all three focus areas. Each focus area had an assigned discussion lead responsible for capturing participant comments and summarizing the inputs contributed by all three groups for presentation to the attendees later in the Workshop. Summaries of the breakout focus areas are also provided in this document and the inputs contributed by the participants are being used as a starting point for development of the preliminary roadmap.

Workshop Content Outline, First Day

Welcome & Introductions

The NASA Ames Center Deputy Director, Dr. Thomas Edwards, opened the Workshop with a Welcoming Address (video recording available). The welcome included a brief history of the NASA Ames Research Center and its contributions to novel rotary wing and powered lift vertical flight configurations, including the F-35B Lightning II, V-22 Osprey, AV-8B Harrier, and Sikorsky Advancing Blade Concept.

Following the welcome, the Workshop Administrative Chair, Michael Dudley, provided an introduction that covered the Workshop objectives, format, processes, and outcome expectations to help prepare the attendees for how best to participate in the Workshop.

Technical Presentations

Advanced Vertiport Capable Flight Concepts Panel Discussion

Moderated by Michael Duffy, Workshop Technical Chair
(video recording available)
The panel presented and discussed the following five concepts:

1. **Simulation of Electric Aircraft Components**
   - Korbinian Petermaier, Siemens Technology
2. **Analysis and Full Scale Testing of Joby S4 Propulsion System**
   - Alex Stoll, Joby Aviation
3. **Flight Test of NASA GL-10 Distributed Electric Propulsion UAV**
   - Bill Fredericks, NASA Langley
4. **Full-Scale Test of LEAPTech Wing**
   - Andy Gibson, ES Aero
5. **LIFT! – Modular, Electric Vertical Lift**
   - Michael Duffy, The Boeing Company

Advanced Batteries Progress, Invited Presentation

Presented by Aron Newman, Advanced Research Projects Agency - Energy (ARPA-E)
(video recording available)

Business and Market Opportunities Panel Discussion

Moderated by Mark Moore, NASA Langley
(video recording available)
The panel presented and discussed the following three opportunities:

1. **Existing VTOL Operators Needs Perspective**
   - Mark Moore, NASA Langley

2. **Market Drivers for Civil Vertical Lift**
   - Rich Ouellette, The Boeing Company

3. **Silicon Valley Early Adopter CONOPS and Market Study**
   - Kevin Antcliff, NASA Langley

The Workshop Technical Chair Michael Duffy concluded the first day's presentations and panel discussions with a wrap up of the activities.

Workshop Content Outline, Second Day

Welcome

Mike Hirschberg, (AHS) International Executive Director, launched the second day of the Workshop with a welcome and acknowledgement to participants, supporters and organizers, followed by some observations and reflections on vertical flight. His comments focused on the unique opportunity the workshop participants have to contribute to the identification of barriers to transformative vertical flight, and to help begin to chart a roadmap that will enable the transformation. He emphasized the importance of paying attention to the employment of evolving technologies like automation and fly-by-wire to ensure levels of safety comparable to other transportation systems are achieved. He also reminded the participants to take advantage of networking with the technical experts at the meeting, and encouraged involvement in AHS activities, as well as taking advantage of the online vertical flight technical resources.

Technical Presentations

Electric Propulsion and Electric Energy Storage Technologies Panel Discussion

Moderated by JoeBen Bevirt, Founder of Joby Aviation
(video recording available)

JoeBen Bevirt introduced the panel members and shared his perspectives on how we are on the eve of a transportation breakthrough. He noted that just as the automobile transformed cities in the last century, the creation of vehicles that are as nimble as a helicopter, fast as an airplane, and practical as an automobile would create a new transportation paradigm with the potential to transform the cities and societies of this century. Electric Vertical Take Off and Landing (VTOL) systems are one of the most promising approaches to achieve this capability. However a viable system needs to be safe, quiet, and efficient to gain public acceptance. This will require additional research to suppress acoustic signatures, improve vertical flight safety risks from what now is close to a motorcycle down to those of a road vehicle and achieve higher performance for electric propulsion and energy storage systems. This panel's presentations and discussions focused on the third of these challenges, Electric Propulsion & Electric Energy Storage Technologies in the following six presentations:

1. **Advanced High Energy Density Lithium Batteries**
   - Michael Sinkula, Envia Systems

2. **Solid State Batteries**
   - Josh Buettner-Garrett, Solid Power

3. **Launchpoint 1 kW and 40 kW Hybrid Electric Range Extender**
   - Mike Ricci, LaunchPoint Technologies

4. **Metis 30 kW Turbine-Alternator Hybrid Electric Range Extender**
   - Rory Keogh, Metis Design

5. **Swiss Turbine 7 kW and 75 kW Hybrid Electric Turbine-Alternator Range Extender**
   - Tim Moser, Swiss Turbines

6. **Heavy-Fuel SOFC Fuel Cell**
   - Nick Borer, NASA Langley

Invited Presentations

Advances in Distributed Propulsor Acoustic Modeling

Steve Rizzi, NASA Langley
(video recording available)

- NASA perspective on how noise constraints are expected to be a significant consideration for transformative vertical flight.

Road Mapping Example For On-Demand Mobility

Ken Goodrich, NASA Langley
(video recording available)

- Preparation for the afternoon breakout sessions designed to gather inputs from the participants that could be used to develop a roadmap.

GoFlyUp HeroX $2 Million Personal VTOL Prize

Gwen Lighter, The Lighter Group
(video recording available)

- Lunchtime presentation outlining the rules and objectives for a prize challenge to create a compact piloted or remotely piloted personal air vehicle.

Breakout Sessions

The afternoon of the second day was dedicated to participatory breakout sessions that provided the Workshop attendees an opportunity to share their perspectives in three focus areas that will be critical to developing a TVF roadmap, namely "Missions/Operational Concepts," "Technical Challenges," and Regulatory Frameworks." The breakout session process described in the "Approach" section on page 2 allowed the discussion leads in each area to develop a consensus view of the Workshop attendee's perspectives in each area. The discussion leads for the three focus areas were Mark Moore for "Mission/Operational Concepts," Brian German from Georgia Tech, and Ken Goodrich from NASA Langley for "Prioritized Technical Challenges," and Tom Gunnarson from Zee.Aero for "Regulatory Roadmap." They were given one hour to

organize the information collected during the breakout sessions and prepare a summary to present back to the Workshop participants during a closing panel session.

The summaries provided by the discussion leads in the closing panel session were a snapshot of the dialog generated in the breakout sessions and provided material to stimulate questions and general discussion amongst the entire body of attendees. The limited time available to organize the information did not permit a thorough compilation or deliberate discussion; it did permit all in attendance to get an initial appreciation of the material. After the Workshop the discussion leads continued to organize the material from their breakout session and an expanded version of their reports are presented later in this document.

At the conclusion of the Workshop the Technical Chair, Michael Duffy, led a general discussion of the group's common vision and how to move forward.

Technical & Invited Presentation Abstracts

Advanced Vertiport Capable Flight Concepts

Simulation of Electric Aircraft Components

Korbinian Petermaier, Siemens Technology

Siemens works on electric propulsion systems for aircraft to reduce fuel consumption, pollution, and operational costs enable better aerodynamic efficiency of aircraft by silent distributed propulsion.

Siemens has developed a direct drive electric motor for aircraft that was tested with 261 kW of continuous power. This gives a power density of more than 5 kW/kg at 95% efficiency. It produces high torque deploying a Halbach array and flat wire windings. Its high performance cooling concept permits a high current density at a coolant temperature level of 90°C, which enables small and lightweight heat exchangers. Also the structure has been optimized to meet aircraft load requirements with reduced weight. The motor has an integrated propeller bearing and can be coupled with a hybrid electric drive train that includes a combustion engine, integrated generator, inverters, and batteries. The topology provides two redundant power paths to increase safety. The mid-term focus is to scale up the hybrid electric drivetrain for regional airliners with 50 to 100 seats.

Analysis and Full Scale Testing of Joby S4 Propulsion System

Alex Stoll, Joby Aviation

Joby Aviation is developing the electric S4 four-seat Vertical TakeOff and Landing (VTOL) tilt-rotor aircraft. The S4 uses six rotors. Four rotors are only used in VTOL and fold up against their respective nacelles in cruise. This design compares very favorably to conventional small four-seat VTOL aircraft, such as the Robinson R44, in operating costs, cruise speed, noise, and payload, without significantly sacrificing range despite being powered entirely with batteries. Regional air taxi transportation models using the S4 predict fare prices comparable to conventional on-demand ground transportation. The rotor development considered critical design constraints, including power and torque requirements in different flight phases, noise, resilience to bird strikes, and impact on nacelle weight and drag. Acoustic predictions were informed by the construction of multiple full-scale propeller models, which were tested at hover conditions. The bird strike structural analysis was validated by construction of a bird strike test stand, utilizing an industrial-grade chicken cannon.

Flight Test of NASA GL-10 Distributed Electric Propulsion UAV

Bill Fredericks, NASA Langley

Greased Lightning (GL-10) is an aircraft configuration that combines the characteristics of a cruise efficient airplane with the ability to perform Vertical TakeOffs and Landings (VTOL). This presentation summarized the results of the flight test experiments. Two key technologies have been utilized in this aircraft design. Namely, 1) distributed electric propulsion and 2) closed loop control laws capable of flying an inherently unstable aircraft. For many decades the aviation industry has been attempting to build a vehicle that can combine the speed and efficiency of an airplane with the

vertical takeoff and landing of a rotorcraft. Overall it has been determined through flight test that a design that leverages these new technologies can yield useful VTOL cruise efficient aircraft.

Full-Scale Test of LEAPTech Wing

Andy Gibson, ES Aero

The Leading Edge Asynchronous Propeller Technology (LEAPTech) Wing development project is a collaboration of ESAero, Joby Aviation, the NASA Armstrong Flight Research Center (AFRC), and the NASA Langley Research Center (LaRC). Its objective is to further the development of distributed electric propulsion technology. This research explored the aerodynamic and acoustic advantages of distributing propulsor fans along the leading edge of a large-scale wing model operated at takeoff and landing speeds. The LEAPTech experimental investigations discussed in this presentation utilized the Hybrid Electric Integrated System Testbed (HEIST), also developed by this team, to simulate flight conditions. HEIST is a mobile platform (truck) that supports and transports the model and its power and instrumentation systems. The HEIST was operated with the LEAPTech wing attached on the Edwards Air Force Base Rogers Dry Lakebed to collect aerodynamic pressure and force data, and electric motor and controller data. The presentation highlights the history, challenges, and progress achieved in understanding how to pursue the novel and promising technology of electric aircraft propulsion. The team worked together to develop the research systems hardware and test plans. Joby Aviation led the wing and HEIST development and fabrication, ESAero led the instrumentation integration and verification, AFRC executed the research testing, and LaRC provided the wing aero design, analysis, and acoustic evaluation. An overview of some lessons learned and planned follow-on research phases expected to lead to a flight test were also provided.

LIFT! – Modular, Electric Vertical Lift

Michael Duffy, The Boeing Company

The LIFT! Project explored scaling of all-electric multi-rotor propulsion, ground powered tether technologies for large multi-rotor aircraft, and methods of cooperation between multiple VTOL aircraft. Multi-rotor aircraft have become pervasive throughout the hobby industry, research institutions, etc. due—in part—to very powerful, inexpensive lightweight inertial measurement devices and increased energy density of Li-Ion batteries driven by the mobile phone industry. Although the energy density of Li-Ion batteries has enabled all-electric flight, the currently available Li-Ion battery energy density severely limits flight times and useful load capabilities of all electric aircraft. The LIFT! Project's objective was to leverage emerging electric aircraft architectures to demonstrate modular lifting units for short distance missions. The all-electric propulsion architecture developed for the LIFT! Project allows for ground power delivery capabilities via a high-voltage tethering system, which enables greatly increased flight time and increased useful load capabilities. This presentation outlined the LIFT! Project's powered tether implementation that demonstrates the effectiveness, modularity, and scalability of electric multi-rotor technologies for large, electric, unmanned multi-rotor aircraft. This research offers new insights on the feasibility of large electric VTOL aircraft, empirical trends, ground powered operations, and future research necessary for the commercial viability of electric VTOL aircraft for potential unconventional markets such as mobile crane industrial lift applications.

Invited Presentation

Advanced Batteries Progress

Aron Newman, ARPA-E

In 2007 Congress established the Advanced Research Projects Agency – Energy (ARPA-E) to ensure domestic economic and energy security by enhancing American technology competitiveness. ARPA-E was patterned after the Defense Advanced Research Projects Agency (DARPA) but with a focus on high-risk/high-payoff energy technologies. In 2009 ARPA-E received $400M inaugural funding with a sustaining annual budget between $250M and $300M. ARPA-E has grown to 30 programs and has awarded funding to over 450 $1-3M energy research projects.

The Agency's primary mission is to launch energy research efforts that improve energy efficiency to reduce emissions and U.S. dependence on energy imports. Their approach to mature technologies at an accelerated pace is to promote revolutionary advances in applied sciences that have a steeper learning curve. Projects funded by ARPA-E have a maximum lifecycle of three years and poor performing research projects are subject to early termination.

The research products resulting from ARPA-E support shows promise that electric propulsion can be a viable competitor to the internal combustion engines used today for personal ground and air transportation. While much of the Agency's efforts are directed at improving energy storage densities, they recognize a systems approach is needed to reach the factor of three program goals for vehicle cost at a given range. An integrated vehicle systems design approach that utilizes ceramic chemistries, multi-functional designs, and robust system architectures has the potential to reduce a vehicle's containment/structural weight required for safety and relaxes some of the demand for extreme energy densities. Coupled with the projected energy density increase from today's roughly 150 Wh/Kg to 250 Wh/Kg sometime in the early 2020s, program goals are realistic. The current research portfolio is consistent with this philosophy and covers a range of diverse technologies that include solid ceramic membranes, new solvent additives, high energy density sulfur carbon nanotube batteries, porous solid state material to control charging-cycle volumetric changes, impact resistant batteries, battery alternatives like fuel cells, and motor magnets that do not use rare-earth materials.

Business and Market Opportunities

Existing VTOL Operators Needs Perspective

Mark Moore, NASA Langley

There are currently few examples of commercial successful Vertical Take Off and Landing (VTOL) regional transportation enterprises. HeliJet is one exception. It provides service between Victoria and Vancouver, Canada, across the Salish Sea. The company employs Sikorsky S-76 helicopters traveling an indirect 65-mile route over water to minimize community noise. The 26 scheduled trips a day take less than an hour and a ticket cost $275. The primary reason this market exists is the car/ferry alternate mode of transportation takes 3 hours and 20 minutes. While S-76 operations can be profitable in this situation, the vehicle performance is not a good match for the mission requirements. Civil VTOL commuter flights generally require less than 30 seconds of hover time for takeoff and landing. The S-76, like most helicopters is

optimized to permit the longer duration hover times that are needed to satisfy a variety of military and certain civil operations. This results in performance tradeoffs in other areas, namely range, speed, payload, noise, and affordability.

The HeliJet business model demonstrates that geographic constraints limiting the convenience and productivity associated with other transportation modes can make VTOL flight a viable alternative. In extreme cases, like HeliJet's transit of the Salish Sea, helicopter operation at over $4/passenger mile can still be profitable. However vehicles optimized for VTOL regional transportation that can operate for less than $1/passenger mile will have the potential to open new markets in less extreme geographically constrained regions. By providing a faster, cost effective, and convenient alternative to existing transportation modes, a VTOL transit system can expand and diffuse population centers while increasing societal productivity and the quality of life.

Future Urbanization and Mega-Regions

Rich Ouellette, The Boeing Company

The world's population continues to grow doubling every 40-years. With that growth is an expanding appetite for transportation services, with a majority of the growth occurring the emerging economies of Brazil, India, and China. Over the past 20-years North American (NA) and European (EU) Revenue Passenger Kilometers (RPK) has tripled, outpacing the general growth in population, and accounts for 50% of the world's total RPK. However the rest of the world has increased by a factor of almost nine during that period, and over the next 20-years is expected to account for 62% of the RPK.

At the same time the world is becoming more urbanized. Already the NA, EU, and Brazilian populations are over 80% urban and projected to reach 90% in the next three decades. China and India are trailing at 55% and 35%, but these are significant levels and trending upward. As the world's populations become more urban, it will necessitate new transportation systems and generate new market opportunities. As the number of megacities (population > 10M) and mega regions (population >20M) continues to grow it will create new self-contained transportation markets a few hundred miles in scale.

Our current air and ground transportation infrastructure based on the hub-and-spoke architecture is already beginning to show signs of chokepoints and gridlock. Considering over 23% of flights are under 300 miles and 50% of fuel burn is consumed on trips under 500 miles, it suggests a new paradigm that shifts from a static hub-and-spoke model to a dynamic dispersed point-to-point model might be more effective. A starting point could be for the TVF Workshop participants to explore new market opportunities and develop advocates and advocacies. A challenge to individuals possessing an entrepreneurial spirit is to simultaneously investigate enabling technologies and public acceptance of a system that allows access to inaccessible transportation nodes, increases productivity, and is environmentally responsible, safe, secure, quiet, and flexible.

Silicon Valley Early Adopter CONOPS and Market Study

Kevin Antcliff, NASA Langley

The question that inspired this study is: Could a cost effective, electric powered, Vertical Take Off and Landing (VTOL), highly distributed public/private regional

transportation infrastructure provide travel time savings and convenience that would compel early adopters to create such a system in a specific region? For this study the Silicon Valley (Santa Clara Valley, California) was selected. The topics explored were understanding the issues and constraints related to helipad site selection and distribution, the concepts of operations (CONOPS) necessary for an effective and robust transportation system, and a first look at some of the vehicle performance requirements.

The demographics of Silicon Valley make it a strong candidate for the early deployment of a regional VTOL transportation system. The region has a high-income population, 25% of the commutes take over 1.5 hours (each way), and the residents have a reputation for being early adopters. The excessive commute times are driven by several factors: the high population densities, a 117-mile average suburban travel distance, geographic barriers (mountains and water) that increase point-to-point distances by 20–30%, and average suburban rush-hour travel times of 209 minutes.

The VTOL transportation system concept proposed in this study assumes hundreds of highly distributed helipads spaced closer than one per square mile. To attain this density the CONOPS envisions helipads located in the center of freeway cloverleaves and building rooftops. A preliminary conclusion of the study is that in order to comply with FAA height and community noise restrictions over private property, operations will require a near vertical takeoff and landing flight path up to 385 feet. This in turn will drive vehicle performance requirements. Preliminary mission analysis indicates this system could significantly reduce travel time, in most cases by more than a factor of 2.5.

Electric Propulsion & Electric Energy Storage Technologies

Advanced High Energy Density Lithium Batteries

Michael Sinkula, Envia Systems

There is increasing demand for unmanned aerial vehicles (UAVs) using electric propulsion for both commercial and military applications. The ultimate performance capability of these applications is determined largely by the weight of the vehicle, of which the battery is a very large contributor. Therefore, reducing the weight of the battery is of tremendous value. Envia Systems has developed a lithium battery with an energy density of 350 Wh/kg for UAVs and is very rate capable. This technology utilizes silicon based anodes and high capacity cathodes. This cell, which is commercially available, already offers higher energy density than the performance hoped for future technologies.

Solid State Batteries

Josh Buettner-Garrett, Solid Power

Solid Power is in the process of developing a next generation solid-state battery with higher energy and power densities than current technology liquid electrolyte lithium batteries. By replacing liquid electrolytes with non-flammable solid components, it is possible to achieve greater stability at higher temperatures. The solid-state architecture has the potential to employ new or enhanced conventional cathode materials not possible with liquid electrolytes. The elimination of liquid electrolytes is a prerequisite for lithium metal anodes with long calendar and cycle life. The Solid Power battery design employs a conventional bulk manufacturing process that does not suffer the scalability and costly deposition procedures associated with thin-film solid-state batteries. Solid

Power is targeting energy densities in the 300–500 Wh/kg range with cycle and calendar life equal or greater than currently available batteries.

Launchpoint 1 kW and 40 kW Hybrid Electric Range Extender

Mike Ricci, LaunchPoint Technologies

LaunchPoint Technologies is presently developing reciprocating engine based gen-sets as part of their "Propulsion By Wire" technology that will enable long endurance highly reliable electric flight. Hybrid-electric propulsion systems can achieve significant endurance improvements over battery electric systems while retaining the key performance and design flexibilities of electric propulsion. The gen-sets being developed range from 1.5 kW to 40 kW and utilize LaunchPoint's high specific power dual Halbach array electrical machines to achieve exceptional performance. LaunchPoint is also developing dual Halbach array machine for motor applications and is developing custom power and control electronics to interface the motor and alternators with a DC bus in a hybrid electric vehicle.

Metis 30 kW Turbine-Alternator Hybrid Electric Range Extender

Rory Keogh, Metis Design Corp.

Metis Design Corp. is developing a lightweight, compact gas turbine generator that draws on recent innovations in the fields of permanent magnet generators and turbomachinery to achieve a target power density of over twice the state-of-the-art and the potential to scale to 100s of kW. The proposed turbine engine uses a lightweight, two-spool configuration that eliminates the need for the heavy reduction gearbox required by state-of-the-art systems. Gas turbines are lightweight, very reliable, low maintenance, low noise, and can operate on heavy fuels. At large scale, gas turbine engines are almost exclusively used for the conversion of liquid fuels to thrust, shaft power, or electricity. At smaller scales (100s of kW) gas turbines are typically only used for weight critical applications such as aircraft and rotorcraft power plants. Small-scale non-aviation gas turbines will commonly use a waste heat recovery system (recuperator) to improve fuel efficiency. Small recuperated gas turbines (microturbines) have the added advantage of being very quiet as the recuperator attenuates much of the noise generated by the turbomachinery and combustor.

Swiss Turbine 7 kW and 75 kW Hybrid Electric Turbine-Alternator Range Extender

Tim Moser, Swiss Turbines AG

Swiss Turbines AG, a Swiss based joint venture company between AeroDesignWorks GmbH and Creative Technologies GmbH, has developed a family of small-scale shaft power engines for lightweight aircraft and UAV applications. The power of its engines ranges from a 7kW electric power turbo generator (SP7e) to a two-shaft 75kW gas turbine engine (SP75) providing an excellent power to weight ratio of about 3 with a specific fuel consumption (SFC) of about 0.4 kg/kWh. The mid-range power output of about 35 kW will be covered in the near future by the two-shaft SP35 turbo shaft engine. Both the SP35 and the SP75 can be adapted to the customer application as shaft power or as electrical power output variant. Whereas SP35 will be developed on the basis of the existing and in-service 25 kW uArriel shaft power engine, the SP75 was developed from scratch with highly efficient 3D-optimized turbo components, including a

three stage axial-axial-diagonal compressor with a pressure ratio 6.25 for an optimal fuel burn efficiency. Due to the modular engine design, a 125 kW variant of the SP75 could provide an excellent solution for helicopter and advanced VTOL applications up to about 700kg maximum takeoff weight. Swiss Turbines provides top-level expert knowledge in the field of the aero-thermal design of the engine and turbo components, flight regulation, and control, as well as electrical components engineering.

Heavy-Fuel SOFC Fuel Cell

Nick Borer, NASA Langley

Electrically powered aircraft can enable dramatic increases in efficiency and reliability, reduced emissions, and reduced noise as compared to today's combustion-powered aircraft. This presentation described a novel flight demonstration concept that will enable the benefits of electric propulsion while keeping the extraordinary convenience and utility of common fuels available at today's airports. This addresses a critical gap in airborne electric propulsion research by accommodating adoption at the integrated aircraft-airport systems level, using a confluence of innovative but proven concepts and technologies in power generation and electricity storage that need to reside only on the airframe. Technical discriminators of this demonstrator concept include (1) a novel, high-efficiency power system that utilizes advanced solid oxide fuel cells originally developed for ultra-long-endurance aircraft; coupled with (2) a high-efficiency, high-power electric propulsion system selected from mature products to reduce technical risk, assembled into (3) a modern, high-performance demonstration platform to provide useful and compelling data, both for the targeted early adopters and the eventual commercial market.

Invited Presentations

Advances in Distributed Propulsor Acoustic Modeling

Steve A. Rizzi, NASA Langley

This presentation first recaps the 2014 finding that metrics like average source power are not sufficient to reflect annoyance. It further demonstrates that simple noise simulation approaches, which neglect unsteadiness of the source, are not suitable for use in human annoyance studies that are intended to lead to low noise design strategies. This is because such simulations do not accurately represent time-varying characteristics affecting annoyance. This conclusion is drawn from two demonstration problems. In the first, the effect of motor control and atmospheric turbulence is shown to significantly reduce the modulation strength of the simulated noise of a LEAPTech concept employing a spread frequency strategy. In the second, the effect of body and rotor drag, atmospheric turbulence, and imbalance is shown to give rise to the annoying beehive sound characteristic of quadcopter noise.

Road Mapping Example for On-Demand Mobility

Ken Goodrich, NASA Langley

This presentation outlined the development of a technical strategy and roadmap to enable significantly improved ease of use and safety for small aircraft. In addition to

formulating operational goals and technical requirements and strategies, the roadmapping process involves identifying and engaging a community of stakeholders from research, industry, and regulatory organizations in aviation and related transportation and technical sectors. The presentation described safety and ease of use barriers that limit broader use of small aircraft transportation and hypothesized safety and training performance targets required to effectively overcome these barriers. Next, the current and emerging future capabilities of candidate technologies were assessed relative to the performance targets. Recognizing that a purely technical system is likely to have significant disadvantages compared to a human-machine system, the complementary strengths and limitations of human and automation agents was briefly described. Finally, an evolutionary technical progression of development and operational feedback from three design epochs or generations is described and served as the basis for a proposed developmental roadmap.

GoFlyUp HeroX $2 Million Personal VTOL Prize

Gwen Lighter, The Lighter Group

The goal of the GoFly Prize is to foster the development of a safe, human-ratable, quiet, ultra-compact, near VTOL personal flying device capable of carrying a 200-pound person twenty miles without refueling or recharging.

The time is now to make the impossible, possible. Recent advances in propulsion, energy, lightweight materials, and control and stability systems have combined to produce a moment of achievable innovation. The GoFly Prize will catalyze the invention of an “everyone” personal flying device. GoFly’s vision is to foster the creation of the twenty-first century “Model T” of personal flight, capable of being used by anyone, anywhere. GoFly welcomes revolutionary design, and while all devices must be human-ratable, innovators have the option to use a mannequin to simulate the user for this competition, operating the device as a remotely piloted or autonomous UAV. The device should function safely in both crowded cities and rural areas, it should be lightweight enough and maneuverable enough so that anyone can move it around, and it should be quiet not only for the user, but also for the general public. GoFly is propulsion agnostic, but like all great inventions the device should be user-friendly, almost an extension of the user’s body, and provide the thrill of flight.

The GoFly Prize operates under an incubator framework to ensure the success of proven teams by supporting them with panels of expert advisors and providing incremental prizes to propel the innovation.

The GoFly Prize will be held in three stages over a period of two-years, and will have a $2.0M prize purse. The three stages will be 1) definition of the entrant’s technical specification, 2) a VTOL prototype, and 3) a Final Fly Off. The contest’s fundamental design constraints are that the vehicle must fit in the space encompassed by a six-foot diameter sphere, have 20-minutes of flight endurance, a 30-nautical mile per hour minimum cruise speed, takeoff within a 30-foot diameter area, be quieter than 87 dB-A within 50-feet, and traverse a 6-nautical mile speed-run course. The contest winner will meet all of the rule thresholds and have the best combined score for vehicle size, speed and noise. The official GoFly Prize launch announcement is expected in 2016.

Breakout Session Summaries

Mission/Operational Concepts

Session Lead: Mark Moore, NASA Langley Research Center

Introduction

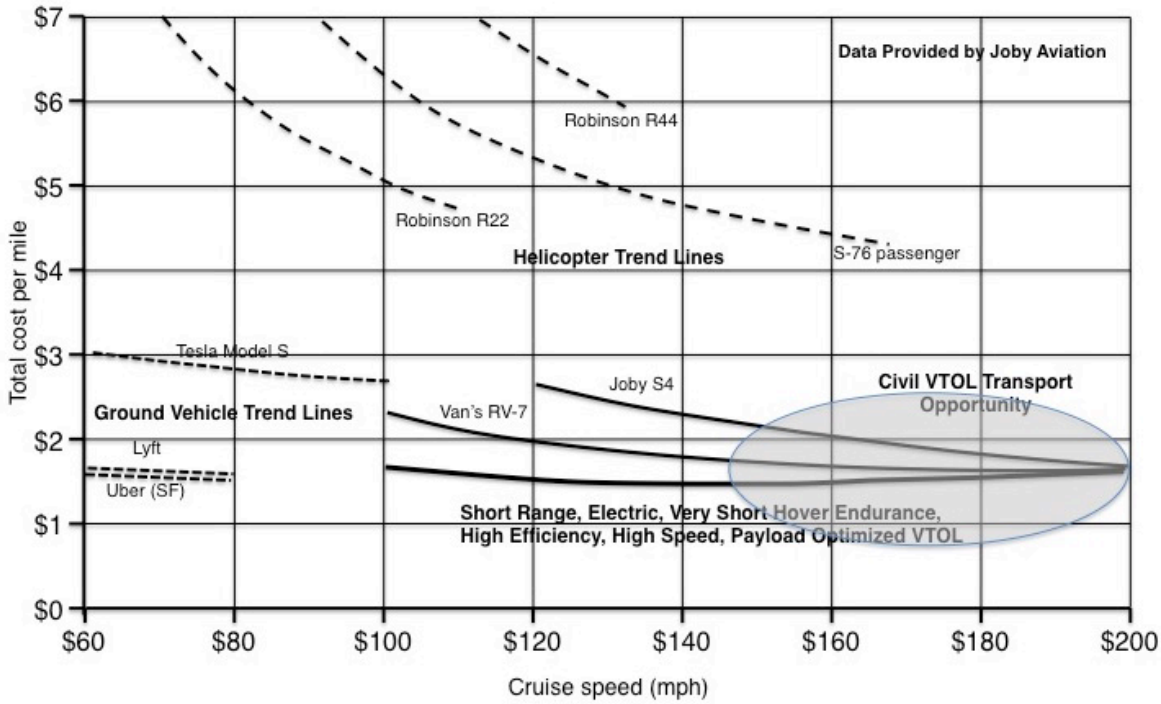
The business case and market feasibility that relates to Transformative VTOL aircraft products must consider a combination of perspectives across technology trends, market needs, operations, user, and market constraints. Moreover the development of strategies that can expand the existing helicopter markets into high growth emerging VTOL aviation markets must take into account the convergence of opportunities that exists in each of this market factors. A breakout session was held in the workshop to discuss all the contributing factors relating to the development of success criteria, as well as strategies to promote the evolution of successful markets relating to transformative VTOL products. During these discussions, poster boards were available for all participants to contribute ideas. There was a consensus recognized by the participants that the VTOL industry is positioned at a unique time of potential convergence across the contributing market feasibility conditions. Proof of this statement exists in the many small companies that have sprung up over the past five years to attempt development of transformative VTOL products, including Airbus Ventures, Zee.Aero, Joby Aviation, E-Volo, etc. Yet the established vertical flight community, Sikorsky, Bell, MD Helicopters, Robinson, etc., has not yet embraced investment in technologies to apply to these latent markets that are as of yet unproven. The question this breakout session looked to answer include the following:

- *What is different that justifies investment in transformative VTOL products?*
- *How can we better understand whether technology is leading to real market opportunities?*
- *Are emerging technologies aligning with user and market needs?*
- *How can we decompose the complexities of the opportunity space to better predict the market evolution and therefore successful market strategies?*

Technology Trend Perspective

While the specifics of the technologies relating to transformative VTOL products was covered by one of the other breakout sessions, it is critical to at least mention the perspective that technology trends are playing as one of the prime factors relating to what is different. While there are approximately 20,000 vertical lift products flying around the world it is reasonable to ask if this is the true demand, or whether their success is curtailed by the current capabilities they achieve. Likely the best approach to answering this question is to attempt comparison to other aviation markets. The General Aviation fixed wing market currently has approximately 200,000 aircraft in operation, in just the U.S. One of the obvious factors relating to this more than an order of magnitude difference in market size is cost associated with vertical lift. This topic was introduced in the TVF workshop presentation by Moore (Figure 1) showing that the total operating cost relating to current vertical lift products are 2–3x greater than fixed wing aircraft of the same passenger size and considerably slower. In addition this figure shows where current Joby and NASA transformative vertical lift concepts are targeting in terms of total operating cost; that is the goal to be able to have similar costs as achieved by

companies such as Uber and Lyft, yet at speeds 2–4x faster. This goal could reasonably be called ridiculous, unless new technologies are enabling major vehicle changes. The key enabling technology trend that drives the Joby and NASA concepts to claim such improvements is the application of electric propulsion to VTOL aircraft. The application of this scale-free technology permits highly distributed and redundant propulsion integration with a resulting propulsive efficiency ~3x greater (propulsion efficiency of 90% versus 30%), as well as aerodynamic efficiencies ~3x greater (Lift/Drag ratio of 15 versus 5), that result in aircraft efficiencies ~9x greater.



Vehicle Operating Cost/Mile vs. Cruise Speed Across Various Transportation Options
Figure 1

Such claims seem grandiose, however they are linked to sub-scale demonstrators such as the NASA GL-10 that have successfully transitioned and have achieved these characteristics in comparison to similar scale rotorcraft. Accounting for the difference in energy cost between AvGas and electricity cost (electric rates vary between $.07 and $.14/kW*hr. depending on volume use while AvGas has a cost of ~$.18/kW*hr., yielding another 1.6x factor), the basis for the difference in energy/fuel cost is ~14x, due to the application of electric propulsion. Consulting current total operating costs for the Robinson R-44 (Table 1), fuel cost comprises 35%, with the opportunity to drop this down to ~2% in energy costs and ~5% accounting for battery amortization. Another noticeable contribution is that 86% of the total operating cost relates to maintenance costs and maintenance reserves, which are once again about 2–3x worse than fixed wing aircraft. Distributed electric propulsion technology not only enables fixed wing vertical lift configurations that eliminate much of articulated rotor maintenance and high vibration that decreases airframe Time Between Overhaul (TBO) to 2200 hours, but also permits motors that have only a single moving part (bearings) and enables motor TBO to increase from 2200 hours to greater than 10,000 hours. Combine these cost attributes of electric propulsion to the cruise speed increasing from 132 mph to 200 mph (while maintaining high efficiency), which results in more productive vehicles that amortize

costs per mile at a rate ~1.5x more effectively. Such fundamental cost changes are the basis for describing this emergent class of vertical lift products as transformative. Electric propulsion is a clear technology trend that is already creating disruptive change to the automobile world, with companies such as Tesla able to create a new market sector and surpass products from established auto companies in only a few years.

Price of R44 Raven II with optional Garmin GTN 625 GPS	$	473,400
FIXED ANNUAL COSTS		
Depreciation (Negligible, freshly overhauled R44s typically sell for more than original costs)	$	N/A
Insurance based on a pilot with 200 hours logged helicopter time, including 40 PIC hours in an R44, with a good safety record and RHC Safety Course Certificate		
Liability Insurance		2,560
Hull Insurance		9,235
FIXED COST PER YEAR	$	11,795
RESERVE FOR OVERHAUL		
2200 Hour Engine Overhaul ($52,000 RHC exchange)	$	23.64
2200 Hour Aircraft Overhaul Parts Kit ($137,000) (Includes new bearings, seals, belts, etc., and life-limited components with less than 2200 hours remaining.)		62.27
Labor (240 Manhours @ $95 per hour)		10.36
RESERVE PER HOUR	$	96.27
DIRECT OPERATING COST		
Fuel @ $5.50 per gallon and 14.0 gph for average use	$	77.00
Oil		1.10
Periodic Inspections, Labor @ $95 per hour		15.20
Unscheduled Maintenance, Parts and Labor @ $95 per hour		10.26
DIRECT OPERATING COST PER HOUR	$	103.56
TOTAL OPERATING COST		
Fixed Cost per Flight Hour Based on 500 Hours per Year	$	23.59
Overhaul Reserve Per Hour		96.27
Direct Cost per Flight Hour		103.56
TOTAL OPERATING COST PER HOUR	$	223.42

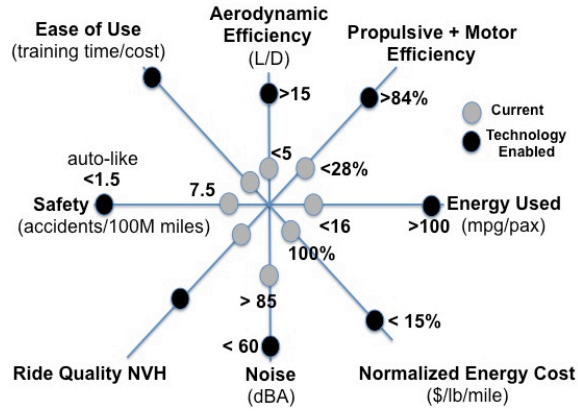
Robinson R44 Light Helicopter Operating Costs
Table 1

But electric propulsion is only one of several major technology changes emerging in the transportation sector. Another major technology frontier is autonomy, which is also just at the beginning of creating disruptive changes to the automobile world through the application of self-driving cars. This technology is likely even more impactful than electric propulsion because it has the potential to fundamentally change the user base of vertical flight products. While there are ~600,000 pilots in the U.S., only ~40,000 of these are certified to fly vertical flight aircraft. As long as the same training requirements (time and cost) exist, even if transformative VTOL aircraft can decrease their costs by a factor of 2–3, the total market side will be severely limited. Autonomy technologies have the potential to increase the user base by 3–4 orders of magnitude, which is clearly a transformative change to the market feasibility conditions. However, autonomy

technologies are more than a one dimensional change in feasibility, with another major impact being the ability to decrease the accident fatality rate, which is currently ~6 times higher than automobiles (on a per mile basis).

Applying just these two technology trends, VTOL aircraft capability has the potential to be radically improved, which is represented by the Spider Chart to the right (Figure 2) that was also shared by Moore in the TVF workshop. Other technology opportunities also exist that offer significant improvements. Robotic composite manufacturing has permitted BMW to build an all-carbon composite car (the i3) while maintaining a $42,000 price.

The ability of these machines to be programmed to produce multiple parts and be highly productive even with low unit volumes offers the potential to dramatically reduce aircraft acquisition costs.



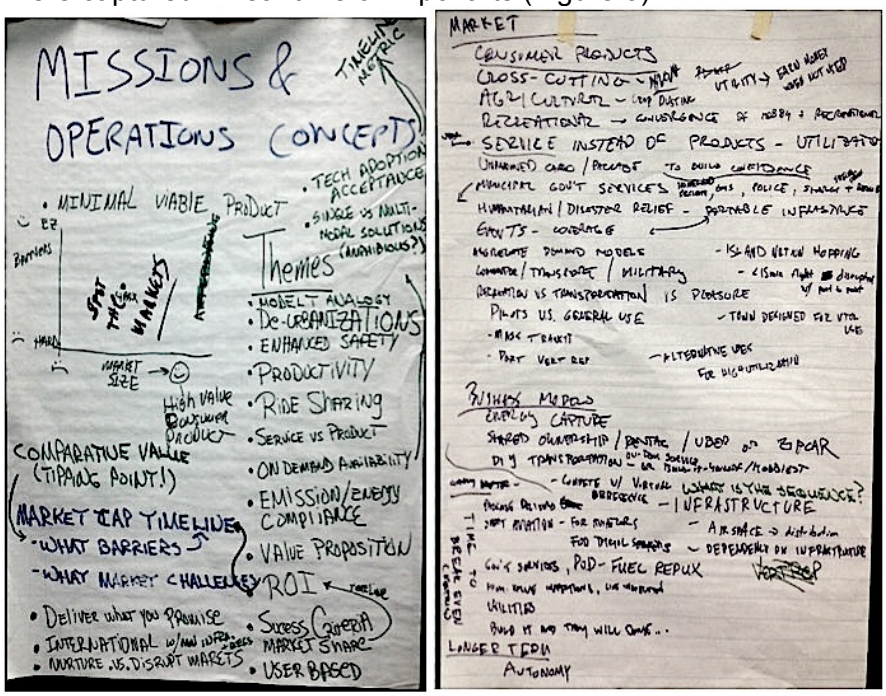
Opportunity Improvement Dimensions Spider Chart

Figure 2

New designs for Ballistic Recovery Systems (BRS) offer the potential to achieve nearly zero velocity and zero altitude recoveries, and combined with fixed wing VTOL configurations, offers the potential to further reduce the fatal accident rate. Advanced sensors and health monitoring systems also offer the potential to promote higher operational safety. These near-term technology trends offer tremendous potential to develop vertical flight systems, which can offer the marketplace transformative change.

Market Needs Perspective

During the breakout discussions, overall market needs and themes were discussed and ideas were captured in real-time on flipcharts (Figure 3).



Breakout Session Flipcharts Raw Data

Figure 3

Market trends of de-urbanization and urban sprawl and the need to develop low carbon solutions that can help the U.S. transition to renewable energy solutions were showcased in Workshop presentations and discussed in this breakout session. The New York University Super-Commuter and U.S. Census Mega-Commuter studies document the rise of long distance commuting and focus on trends across all industries to move toward the optimal consumer experience models of on-demand services (i.e., communications, manufacturing, computing, etc.). This poses the question of being able to provide on-demand mobility and transportation services through aviation, particularly in the shorter regional markets that do not currently offer many alternatives. Ground transportation congestion trends were highlighted with discussion of the highly non-linear relationship of congestion to delay times, with current metropolitan areas such as the Silicon Valley and Los Angeles already experiencing average highways speeds of less than 30 mph during peak commuting times. This is significant as the value of time continues to increase. Individuals with the top 20% of income are able to afford more expensive travel solutions that could provide time saving.

One of the most intriguing market trends that aligns synergistically with transformative vertical flight markets is the trend towards internet-based ride-sharing solutions that can rapidly provide a mechanism to achieve high utilization rates and avoid expensive private ownership. Uber is a highly successful example of this, as an app-based company only coming into existence five years ago and already has a value of greater than $50 billion. Uber has already experimented with the use of helicopters for specific sporting and other events, and has signed a deal with Airbus Ventures to explore using Airbus helicopters as urban VTOL air taxies. This unique capability of being able to instantly match user demand and capacity with minimal capital investment creates new mechanisms to achieve high load factors and equipment utilization. These factors are two of the most sensitive economic parameters for determining profitable operations. There is no question that transportation markets are evolving rapidly and that private ownership models will be challenged in the near future. This trend in the market is a perfect fit for the higher productivity vehicles that result from higher speed and load factor operations, and that can offset their more expensive operating cost with higher utilization to effectively amortize expenses for a cost effective transportation system. It is clear that transformative VTOL aircraft will likely leverage this trend and not be dependent on expensive private ownership models.

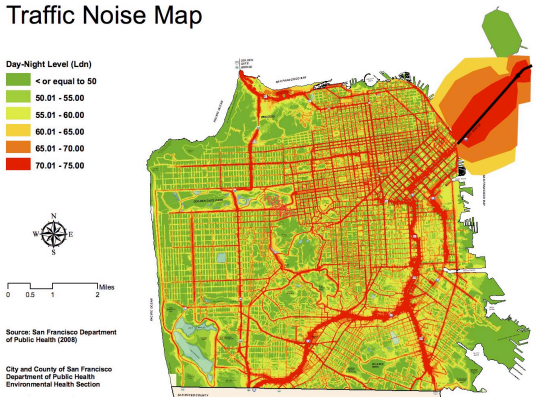
Operations Perspective

From an operations perspective, the key difference relating to these new VTOL products is that they will be expected to operate in much closer proximity than existing helicopters, and with much higher trip volumes exposure to communities. In particular as technologies such as electric propulsion are utilized, the match-up between technology capability and market opportunity is in the relatively short distance urban VTOL air-taxi mission. These trip distances range between 10 and 50 miles, which provide an excellent match to near-term advanced batteries that are capable of 100 to 200 mile range. Another key difference relating to this mission is that lack of need for a sustained hover, since the basis for the vehicle design is to perform transportation, and not to maximize the flexibility of operations such as helicopters, which includes search and rescue, landing at unprepared locations, and other missions that are more related to military needs. However, from an operations perspective the largest factor relating to the transformative VTOL market is the need for these close proximity takeoff and landings to be conducted with a dramatically lower community noise signature. San Francisco was identified as a specific example of the severe operational limits the communities pose on current helicopters, with only one helipad existing in all of San

Francisco (at a hospital) and significant curtailment of even that one location. These limitations are almost purely related to the current noise levels of helicopters, with many helicopters being near their maximum allowable Sound Exposure Level of 85 dB for a 500 ft. altitude flyover at a ~4000 lb. gross weight.

Figure 4 on the right shows a representative current SFO city-wide noise map, and while these amounts are shown with an A-weighted SPL, this map clearly shows that ~85 dB signatures would result in significant comparative disturbance levels. Since community noise is an overwhelming constraint upon the transformative VTOL market feasibility, discussions of what noise levels would likely be permitted were entertained. Without detailed studies, an acceptable benchmark was proposed that a ~65 dB level at the nearest private property would be a goal for future transformative VTOL aircraft.

Traffic Noise Map



San Francisco Traffic Street Level Noise Map
Figure 4

User Acceptance Perspective

Another critical perspective discussed to achieve feasible transformative VTOL markets is user acceptance. While ride quality and comfort, high completion rate, and trip reliability are important factors, the overwhelming consideration was agreed to be combine true and perceived safety of the vehicle. Discussions also focused on the need to achieve simplified vehicle operation and ease of use for private-use models, but this capability was of lessor importance for an urban air-taxi fleet operated by highly proficient pilots. (Professional pilot costs can be effectively amortized by high vehicles productivity and utilization.) The tie-in relating to achieving reduced fatality rates and the emerging technologies has already been mentioned. However, several aspects relating to user acceptance and perceived safety were highlighted in discussions. The ability to design transformative VTOL aircraft that have no single point failure modes (i.e., lack of dependence on a single engine or a single part of a helicopter hub to prevent loss of control) was considered a large advantage. It is also likely that a full vehicle parachute capability such as a Ballistic Recovery System (BRS), especially with a near zero-zero deployment capability, would provide users greater perceived safety.

Market Constraints Perspective

Other perspectives also discussed included the importance of existing FAA regulations acting as a barrier for adoption of many of the new technologies and resulting in very large certification costs for new products (or revision of existing products to achieve improved capabilities). However, these discussions were deferred to the Regulatory breakout session. Additional constraints on the market feasibility were mentioned, including limitations of the available helipad infrastructure. With helipad approval being determined through local zoning issues, this infrastructure concern pointed back to the operations discussions and the importance of transformative VTOLs to achieve ultra-low community noise levels. Another recurring constraint and market barrier that was repeatedly mentioned was the current product expense and unacceptable total operating costs of helicopters. This issue was accepted as the number one factor limiting a robust VTOL market feasibility, which directly plugs back into the technology discussions already mentioned.

Convergence of Perspectives

Coming away from all of the groups that rotated through the Business and Market Feasibility breakout session, a consensus opinion was established that all of the perspectives play an important part. A major take-away was that in order to maximize the probability of success for the transformative VTOL market, companies pursuing this goal needed to develop a clear understanding of the convergence between technology trends, market needs, operations, users, and the fundamental bounding constraints. Because of this, it was agreed to coalesce the expressed opinions into these different perspective groupings to better define the problem space.

Business Case Feasibility

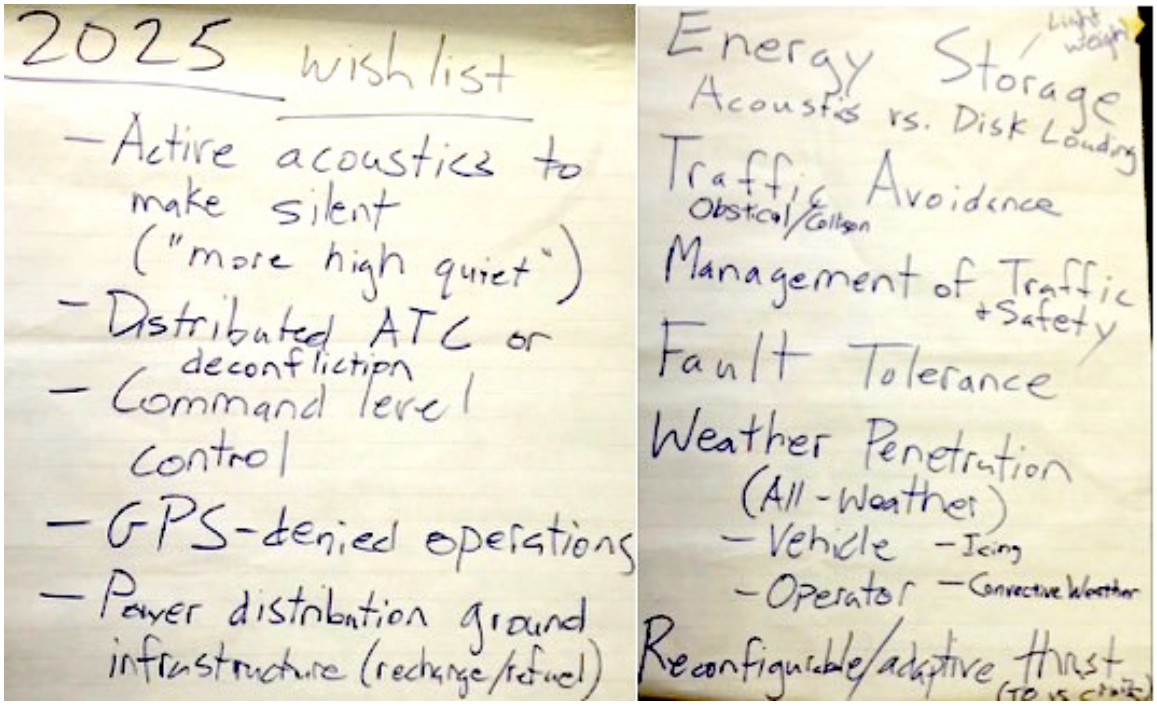
The last part of the discussions focused on the different market and mission opportunities, with an attempt to classify the markets into near-term and farther-term potential. An attempt was made to have individuals share a 5-, 10-, and 20-year timeline of market opportunities to predict how early adoption could be achieved, while pursuing a tipping point that could move transformative VTOL aircraft into mainstream aviation markets. This was a difficult undertaking for a short breakout time period, with discussions focusing on any first application incurring high expense due to certification barriers relating to new technologies. For this reason it was felt that leveraging military missions and funding would be an important avenue to pursue. However, it was also pointed out that it is likely that these transformative VTOL aircraft may be of little interest to the military because of a mismatch in desired capabilities, with significantly longer range and larger payloads being better matched to military needs. One military mission that did appear to have good alignment is Special Forces interest in ultra-low noise signatures for insertion missions. Another evolutionary market strategy discussed was to leverage established helicopter operations, such as HeliJet in Vancouver, daily commuting in Brazil by the rich to avoid congestion and kidnapping risk (Robinson has sold more helicopters to Brazil than any other country), emergency medical and police services, as well as oil rig transport. However, consensus was not achieved on whether the best strategy for transformative VTOL products was to leverage these existing markets and offer aircraft that are less flexible, or focus attention on creating new markets that are best suited to the characteristics of transformative VTOL; that is, far lower operating costs, and far lower noise, with increased perceived and real safety for short range urban trips.

Technology

Session Leads: Brian German, Georgia Institute of Technology and Ken H. Goodrich, NASA Langley Research Center

Introduction

Enabling the transformative VTOL markets, operations, and vehicles discussed in the AHS/AIAA/NASA Transformative VTOL concepts workshop will require a broad range of technological advances. The technology breakout group was chartered with brainstorming, discussing, and prioritizing the technologies that would be required. The goal of the activity was to provide initial guidance for the formulation of a technology development roadmap for the VTOL community that can be used to inform public and private research and development investment priorities. A representative example of some of the discussion topics that were captured real-time on flipcharts is shown in Figure 5 below.



Technical Breakout Session Flipcharts Raw Data

Figure 5

In initial discussions, the breakout group briefly reviewed relevant vehicle sizes, payload-range capabilities, and concepts of operations (CONOPS) to provide a sound basis for determining which technologies are most important relative to envisioned system capabilities. Because another breakout group focused on CONOPS details, the consensus from this discussion was to avoid CONOPS-specific technologies and simply envision vehicles and operations generally representative of the missions discussed in the workshop: 20–300 mile range capability, 4–9 passengers, large numbers of operations in congested airspace, all-weather capability, and simplified vehicle operation.

The group then began a free-form brainstorming session to identify the needed technologies and related engineering knowledge. It was later recognized that the resulting technologies could be grouped into four thematic areas:

(1) Fundamental science and modeling tools
(2) Standards and design rules
(3) Vehicle technologies
(4) Operations and controls technologies

In certain cases, the technologies categorized in one area have significant overlap with technologies identified in other areas. The group made no special effort to achieve a mutually exclusive categorization.

Fundamental science and modeling tools

The area of fundamental science and modeling tools comprises the knowledge base and analysis methods that are required for modeling and designing aircraft with electric propulsion, including both distributed electric and hybrid electric architectures. The specific topics identified within this area were as follows:

- Modeling and designing high-power aircraft electrical systems.
- Interactional aerodynamics of distributed propeller/rotor propulsion, accounting for couplings between propellers/rotors and lifting surfaces.
- Acoustics of distributed propeller/rotor propulsion.
- "Science of Hybridization"—approaches for optimal, robust, reliable, and safe allocation of propulsive power and energy from multiple sources (e.g., batteries, gas turbines, range extenders) across the flight envelope and for specific flight trajectories. Understand relevance of both vehicle design and flight control.
- "Science of Distribution"—approaches for achieving optimal, robust, reliable, and safe operation of distributed propulsors across the flight envelope and for specific flight trajectories. The flight control problem with distributed propulsion is highly underdetermined with respect to aircraft trim. The remaining degrees of freedom could potentially be allocated to optimize acoustic directivity patterns, achieve greater safety in the event of motor failures, and/or to control structural response and cabin noise.

Standards and design rules

The breakout group also identified the need for design and operational standards and representative design reference data. Industry participants, and government research and regulatory agencies through venues such as the ASTM committees F39 and F44 and the relevant Radio Technical Commission for Aeronautics (RTCA) committees would ideally develop these standards as a pre-competitive activity. The specific topics within this area were as follows:

- Power transfer/distribution standards.
- Fault-tolerant data protocol standards.
- Component and system reliability standards and assessment tools.
- Component and system safety standards and assessment tools.
- Footprint and ground operations standards.
- Ground equipment expectations.
- Design handbook data, e.g., wind tunnel databases for reference configurations and empirical design rules.

Vehicle technologies

The vehicle technologies area comprises technologies that are envisioned to overcome gaps in the flight performance capabilities of envisioned transformative VTOL aircraft. Specific technologies that were identified include:

- Energy storage technologies to advance the specific energy of battery and fuel cell systems.
- Power transmission and conversion technologies to reduce the weight (and/or improve the specific power) of power electronics and motors.
- Adaptive thrust technologies to reduce the penalties of VTOL capability for cruise-efficient flight.
- Acoustics technologies to overcome the challenges of noise at high disk loadings and high propeller/rotor tip speeds.
- "Plan B" safety technologies for primary propulsion failure, e.g., autorotation, parachutes.

- Cabin pressurization and other accommodations for high-altitude flight, reflecting the understanding that environmental control systems are energetically challenging for battery-electric systems.
- Technologies to enable all-weather capabilities, e.g., icing and flight into convective weather.
- Fault tolerance, fault accommodation, and contingency management for primary propulsion.
- Vehicle health monitoring (situational awareness, prognostics) for electrical and avionics systems.

Operations and controls technologies

The operations and controls area comprised technologies that were envisioned to overcome gaps in vehicle piloting and flight control. Specific technologies that were identified include:

- Digital communications connections to air traffic control for information interchange.
- Full envelope protection.
- Technologies to automate deterministic functions to achieve simplified vehicle operations.
- “Virtual airways” technologies.
- Software validation, verification, and certification technologies.
- Cybersecurity technologies.
- Approaches for appropriate function allocation and allocation of decision authority between air traffic control, pilot, and autonomy.
- Traffic and obstacle detection and avoidance technologies.
- Brownout mitigation technologies.

Wish list technologies

The breakout group also identified a “wish-list” of technological developments that could be achieved in the near-term, i.e., within approximately five years. These technologies were as follows:

- Digital communications connections to air traffic control for information interchange.
- Full envelope protection.
- Fully automated procedure-based instrument flight rules flight.
- Understanding of electromagnetic interference for high-power aircraft electrical systems for flight propulsion and the corresponding design guidelines.
- Lightning protection approaches for high-power aircraft electrical systems.
- Standard fault-tolerant data protocols.
- Methods to accurately predict battery discharge behavior.

Regulatory Roadmap

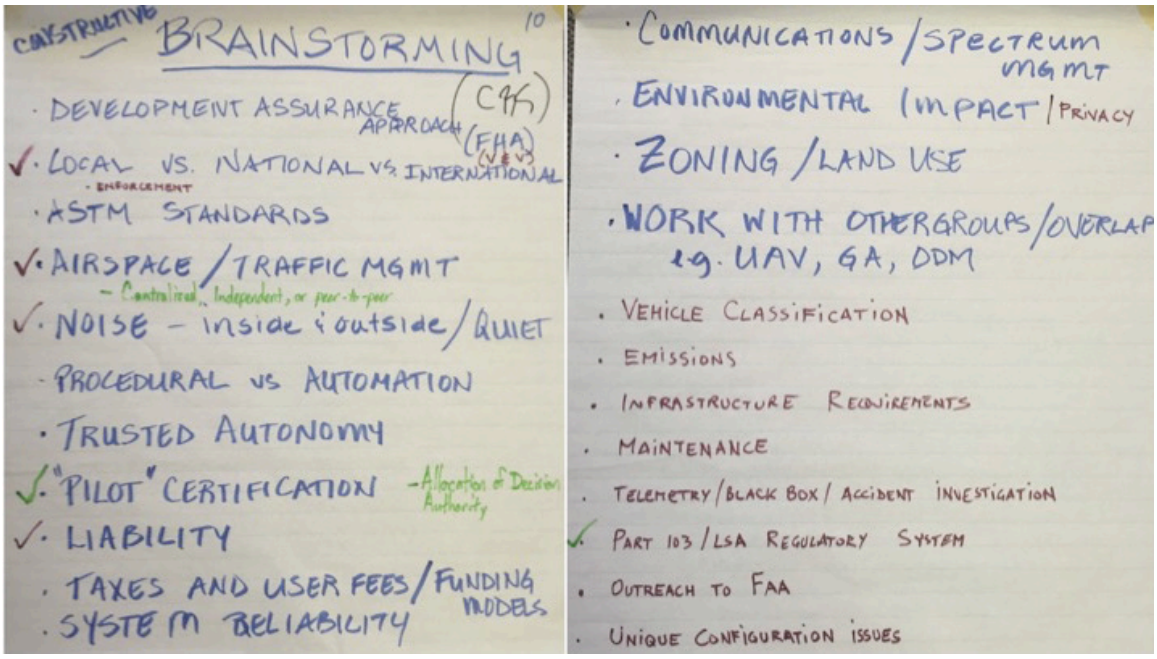
Session Lead: Tom Gunnarson, Zee.Aero

Introduction

Technical innovation that leads to opportunities for exploiting new transportation options often brings with it the need to amend older regulations that may not appropriately cover the scope or impact of new methods, materials, and operations. Many of the transformative vertical flight concepts presented during the workshop, if realized, would expose numerous gaps in current FAA regulations. This creates a significant barrier to certification of new products that could otherwise take advantage of the technology to provide safer, more efficient, and environmentally friendly transportation solutions.

Identifying technologies that are nearing commercialization and looking at how they may be used in the National Airspace System lays the foundation for prioritizing areas of concentration in a regulatory roadmap. The roadmap will help industry determine where to put resources to promote enabling policy and rule change.

This breakout session was broken down into four steps building from 1) Brainstorming to 2) Areas of Major Focus to 3) Timeline to 4) Priorities. In the brainstorming session, 22 topics were binned into six general areas of interest: Aircraft, Pilot, Operations, Environmental, Regulatory System/Government and Airspace. Those were distilled into four areas of major focus: Aircraft Safety Requirements, Pilot/Operator Training, Environmental Impact and Airspace/Traffic Management. A representative example of some of the discussion topics that were captured real-time on flipcharts is shown in Figure 6 below.



Regulatory Breakout Session Flipcharts Raw Data

Figure 6

Next, the group considered what technology appeared to be the closest to commercialization or what operational aspect needed immediate attention. Energy storage was felt to be close with power density up to 400 kW/Kg. At that level, current electric motors were seen to be efficient enough to provide adequate flight times. Full aircraft envelope protection with a fly-by-wire electronic flight control system was considered imminent as state-of-the-art avionics, autopilot systems, and sensors were demonstrating more and more capabilities to provide augmented control input in all conditions.

Proposed hybrid and unconventional aircraft designs will warrant training and education for operations and systems that are different than what is offered today. At the same time, with the goal of reaching a broader audience, most designers and developers are building aircraft systems to significantly reduce cockpit workload and drive down the complexity and cost of qualification to fly future aircraft. Therefore, early industry coordination with FAA on new technology vehicle operation and its impact on pilot training and qualification is considered paramount. User interface standards need to be developed to help both government and industry agree on metrics that will serve a new generation of pilots who are more comfortable with smart phones and social media.

The result of the breakout session was the recommendation to focus on two areas for the regulatory roadmap. The first was non-deterministic certification. New aircraft designs will use non-deterministic software that will be able to modify its behavior in response to the external environment. This would require collaborative human-machine system integration to allow real time flight management with augmented or autonomous course deviations for aircraft separation, airspace limitations, and weather avoidance. Certification of such software would be very difficult today.

The second was simplified operator certification. The advent of electric propulsion, electronic flight control systems, and other intelligent systems in modern small aircraft design do not fit the century-old paradigm of manual control of an aircraft. Like we are seeing today in the automotive industry, future aircraft will be capable of augmenting or performing many of the tasks associated with normal operation and use. This should relieve a substantial burden from the pilot and reduce training complexity, time and cost. Early industry engagement with FAA to share ideas and information will help determine a roadmap to implementation.

In summary, a number of good topics and ideas were shared in a very short time. Some were captured for immediate consideration while others had value and should be brought up again for further discussion. Thanks to the three scribes for legibly documenting the discussion on the paper flipchart pads. Table 2 below summarizes the information captured in the Regulatory Roadmap Breakout Session.

Tabular Summary of Regulatory Roadmap Information Captured

Constructive Brain Storming (CBS)	***Areas of Major Focus (AMF)***	***Realistic/Optimistic Timeline (ROT)***	***Prioritized List of Useful Suggestions (PLUS)***
AIRCRAFT - *Level of Safety (FHA, V&V)* - *ASTM Standards* - *Maintenance* - *Telemetry/Black box* - *Unique Configurations*	*AIRCRAFT SAFETY REQUIREMENTS* - *Safety Level (FHA, V&V)*	*Energy Storage - Propulsion* - *Ready now 400 kW/Kg* *Full Vehicle Protection* - *Fly by Wire*	*Non-Deterministic Certification*

PILOT - *Certification* - *Allocation of Decision Authority*	*PILOT/OPERTOR TRAINING* - *Every aircraft has a Type Rating*	*Industry Coordination with FAA for New Technology/Vehicle Design* - *Operator Certification* - *User Interface Standards*	*Simplified Operator Certification*
OPERATIONS - *Communications/ Spectrum Management* - *Zoning/Land Use* - *Infrastructure*			
ENVIRONMENTAL - *Noise/Quiet* - *Privacy* - *Emissions*	*ENVIRONMENTAL IMPACT* - *Acoustics* - *Land Use*		
REGULATORY SYSTEM/GOVERNMENT - *Local vs. National vs. International* - *Trusted Autonomy: Procedural vs. Automation* - *Taxes, User fees, Funding Models* - *Vehicle Classification* - *CFR Part 103 and LSA Regulatory Systems* - *Regulation Adoption Process* - *Outreach to FAA* - *Work with Other Groups – UAS, GA, ODM, Automotive*			
AIRSPACE - *Traffic Management*	*AIRSPACE/TRAFFIC MANAGEMENT* *Segmentation*		

Information Captured in Regulatory Roadmap Breakout Session

Table 2

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Appendix A: Internet URL Links

Sponsoring Organizations:

AHS	http://vtol.org/
AIAA	https://www.aiaa.org/
NASA	https://www.nasa.gov/
NARI	http://nari.arc.nasa.gov/
FAA	http://www.faa.gov/

Presenter's Affiliation:

NASA Ames
http://www.nasa.gov/centers/ames/home/index.html
The Boeing Company
http://www.boeing.com/
AHS International
http://vtol.org/
NASA Langley
http://www.nasa.gov/centers/langley/home/index.html
Georgia Tech
http://www.gatech.edu/
Zee.Aero
http://zee.aero/
Siemens Technology
http://www.siemens.com/
Joby Aviation
http://www.jobyaviation.com/
ES Aero
http://www.esaero.com/
ARPA-E
http://arpa-e.energy.gov/
Envia Systems
http://www.enviasystems.com/
Solid Power
http://www.solidpowerbattery.com/
LaunchPoint Technologies
http://www.launchpnt.com/portfolio/aerospace/propulsion-by-wire-technology/
Metis Design
http://www.metisdesign.com/
Swiss Turbines
http://www.swissturbines.ch/

Presentation Video Recordings:

Welcoming Address
https://ac.arc.nasa.gov/p7sqntp8ojp/
Advanced Vertiport Capable Flight Concepts
https://ac.arc.nasa.gov/p7xpbc3rwu3/
Advanced Batteries Progress
https://ac.arc.nasa.gov/p5loz1exuzi/
Business and Market Opportunities
https://ac.arc.nasa.gov/p6v2dfe2v0k/
Electric Propulsion & Electric Energy Storage Technologies
https://ac.arc.nasa.gov/p6nme5sazcg/
Advances in Distributed Propulsor Acoustic Modeling
https://ac.arc.nasa.gov/p9i2axek5rh/
Road Mapping Example for On-Demand Mobility
https://ac.arc.nasa.gov/p6eelxbmdpq/
GoFlyUp HeroX $2 Million Personal VTOL Prize
https://ac.arc.nasa.gov/p64u2aoqulz/

Appendix B: Transformative Vertical Flight Workshop Survey Q&A

Did you access the online Adobe Connect broadcast? If yes, what did you like about it? What didn't you like about it?

- A great tool to share with co-workers and adds great value to the workshop.
- Yes - good layout and streaming. Would be nice to have the presentation slides (pdf format would be fine), but I know that need is being worked.
- Yes. Liked seeing presenter and charts.
- Yes - very fast and easy to navigate (I accessed it after the workshop was over). One of my colleagues watched in real time and was very pleased with the performance.

What suggestions do you have to improve the workshop for next year? What didn't you like about it?

- Next year discuss unmanned technologies and R&D of flight vehicles feeding into this field. Delivery drones have been covered nationally ad-naseum, but discussions of how to do that practically and safely feed into this workshop where the discussion is about manned flight. Case studies of current vehicles would be helpful (e-volo, Spyder, eFan) - what are they lacking, what needs to improve, what works now and what are future performance goals, and so on. Community should carefully consider areas of biggest impact and goals that can be achieved now or in the near term, and build on those things.
- For Pete's sake, set up the projectors & screens so people can see them. There's no excuse for the botched video.
- Please have a monitor for the presenter to view as he or she presents (preferably showing PowerPoint's Presenter View).
- I thought this was well done. Material was appropriate for the workshop and ideas/concept of operations development.
- Might be nice to have presenter view and pointer at podium so presenter can remain facing audience.
- None, look forward to working with your team next year.
- The workshop was too narrowly focused on electric propulsion for personal air vehicles, not Transformative Vertical Flight configurations. If another TVF workshop is held, either change the content to include TVF topics or change the workshop title to DEP Flight. The breakout sessions were a waste of time. Need a more focused topic if you want useful feedback. In the session I attended, a list was made of the services and functions (EMS, SAR, line inspections, oil rig platform service, etc.) performed currently by helicopters. Presumably, DEP vehicles will perform these services better/cheaper/cleaner?
- -It's NASA, need at least some technical content for intelligent discussion. Most of the content were high-school level gizmo talk with no engineering charts, designs, or studies presented.
- I would have liked to know who was there at the beginning of the conference so I could network with the attendees appropriately. I just now got the contact list and realized there were some people there that I have been wanting to meet for quite some time! What a bummer.
- Focus on current/next steps. Vision is good, but we need to solve/resolve the "now" part of the equation.

- Include perspectives other than the engineers and entrepreneurs seeking to provide solutions. Good enough and only be defined by the users and neighbors.
- It would be good to get more vehicle design content.

What do you think worked well about the workshop? What did you like?

- The workshop was very well done in terms of space, video, staff support, etc. Would like to see a strong connection with technology suppliers, technology needs, would like to stay in close contact with some suppliers, such as battery suppliers and see what their progress is, how can we use this technology in our applications, etc.
- The ability to have in-person discussions with so many people was one of the most valuable aspects of the workshop.
- Most presentation topics were limited to about the right amount of time - 20 to 30 minutes. Speakers hit the critical points without dwelling on details.
- Liked sharing of ideas, then application to breakouts
- This was one of the most intriguing and thought-provoking conferences I've ever attended. I will attend again.
- Interesting to hear progress on battery technology.
- I would shoot for a 50% reduction of introduction.
- The industry discussion on what is available now and near future (battery storage, motor capability).
- Representation from a wide range of organizations (though only technical).
- Check in and lunches and dinner.

Overall, what were your impressions and thoughts about the event?

- Very helpful and inspiring set of presentations.
- Maybe useful for someone else, but too much fantasizing for me.
- I thought it was well executed and look forward to continuing the progress, as well as the session next year.
- Improved from WS #1.
- Well-organized, high-quality (serious) attendees.
- The event content was not what I expected. The breakout sessions were a waste of time.
- It was useful to know some of the battery/electric motor players. Technically it was a useless conference.
- Can't wait for next year. The more industry participation the better.
- I think this workshop is pivotal in getting TVF "off the ground". It brings the RIGHT people together and allows us to showcase progress.
- A good 2nd round. Need to identify what will change going into the third one, as if more of the same it will lose interest of the community as a place to get things done (other than talking).

Advanced Vertiport Capable Flight Concepts Panel

- 3 of the 5 talks were focused on very similar configurations of DEP. Was expecting a broader range of configurations to be captured in this panel.

Business and Market Opportunities Panel

- Much of the discussion was not new information. The SV CONOPS talk in particular didn't address previous NARI work that looked at a Bay Area commuter flight system.
- The data provided by Ken Ouellette was very useful!!

- I would like to see this "gap" addressed again in future workshops.
- It was clear that Engineers were presenting what Engineers see..need real market analysts to weight in.

Advanced Batteries Progress Talk

- Most relevant part of workshop however still not to a level expected in NASA. High-school level content.
- Needed input from the potential users and neighbors ...the Engineers should not discuss the criteria for success.

Breakout Sessions

- These were useful and productive. I'd like facilitators to take more active role (i.e. eliciting ideas, clarifying, and holding off critical comments until needed). A bit too much critiquing/judging/debating of ideas prematurely.
- The scope of the "roadmap" was too large for anything useful to be accomplished in 25min with 15 people. The topic of the breakout sessions should have been "How to enable a DEP personal air vehicle commuter system" since this was clearly the slant of the breakout sessions.
- These sessions went better than I was expecting. Overall, I would do them again. But, please expedite the summary overview; it was very painful to get through towards the end. Some of the speakers were very monotonous and dry, just reading through their notes.

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Appendix C: Preliminary Framework for a Transformative Vertical Flight Capability Roadmap

The objective of the Transformative Vertical Flight (TVF) Workshops and follow-on working groups is to develop a TVF community-of-interest and establish a consensus of how best to realize their shared vision of the future. This community comprised of participants from industry, academia, and government agencies embodies a wealth of knowledge and experience related to air transportation.

Capability Maturation Roadmaps are a commonly used tool to communicate a vision for the future. The TVF workshops and working groups provide a means to capture and document the collective experience of this community to create roadmaps and add substance to the vision. As an initial step the output from the Second TVF Workshop has been used to start developing a high level notional roadmap (see figure next page) to be used as a framework for developing a hierarchical structure for more detailed roadmaps.

This Roadmap is characterized by four major themes: Concepts and Operations; Technology Maturation; Regulatory and Customer Interest; and Market and Business Opportunity. These themes are aligned with the fundamental questions that need to be addressed for any new initiative: What, How, Who, and Why. The notional roadmap provided in this document is at an embryonic stage and is intended primarily to stimulate thinking to improve milestone objective descriptions and provide realistic dates for achieving those milestones. The TVF community is expected to participate in future workshops and working groups to continue populating this and lower-level roadmaps with refined, matured, and updated content to provide guidance necessary for an air transportation transformation.

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TVF Roadmap Framework

Concepts and Operations: *What capability is created?*

Address Customer Needs - Defines Tech Requirements – Satisfy Market Demand

- Personal On Demand (OD) VTOL TVF CONOPS
- Manned VTOL urban air-taxi CONOPS
- Autonomous urban air-taxi CONOPS
- Regional OD air-transport networks CONOPS

Technology Maturation: *How do we get there?*

Path to the CONOPS - Establish Market Feasibility - Promote Customer Confidence

- Light aircraft energy & propulsion systems
- Operational single passenger OD-VTOL
- Light transport energy & propulsion systems
- Operational multi-passenger OD-VTOL
- VTOL regional transport
- Operational Hybrid elect. DEP sys.
- Demonstrate autonomous air-taxi

Regulatory & Customer Interest: *Who is impacted?*

Drive CONOPS - Judge Technology Creditability - Create a Market

- Municipal and personal urban air customers needs documented
- Personal urban OD-VTOL ops regulations
- Autonomous VTOL ops regulations
- Secure muni- and business operator commitments
- FAR commercial ops updated

Market & Business Opportunity: *Why do it?*

Satisfy Customer Needs - Set Technology Performance - Justify the CONOPS

- Metro air-taxi business plan launched
- Mega region air-commuter business plan launched
- Single passenger OD-VTOL for sale
- Metro air-taxi launched
- Mega region air-commuter transportation system
- Single passenger OD-E-VTOL for sale
- Multi-passenger OD-VTOL for sale

2016	2017	2018	2019	2020	2021	2022	2023	2024

Version 1.0

What – How – Who – Why

National