

Aviation Frontiers: On-Demand Aircraft

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Throughout the 20th Century, NASA has defined the forefront of aeronautical technology, and the aviation industry owes much of its prosperity to this knowledge and technology. In recent decades, centralized aeronautics has become a mature discipline, which raises questions concerning the future aviation innovation frontiers. Three transformational aviation capabilities, bounded together by the development of a ‘Free Flight’ airspace management system, have the potential to transform 21st Century society as profoundly as civil aviation transformed the 20th Century. These mobility breakthroughs will re-establish environmental sustainable centralized aviation, while opening up latent markets for civil distributed sensing and on-demand rural and regional transportation. Of these three transformations, on-demand aviation has the potential to have the largest market and productivity improvement to society. The information system revolution over the past 20 years shows that ‘vehicles’ lead, and the interconnecting infrastructure to make them more effective follows; that is, unless on-demand aircraft are pioneered, a distributed Air Traffic Control system will likely never be established. There is no single technology long-pole that will enable on-demand vehicle solutions. However, fully digital aircraft that include electric propulsion has the potential to be a multi-disciplinary initiator of ‘solid state’ technologies that can provide order of magnitude improvements in the ease of use, safety/reliability, community and environmental friendliness, and affordability.

Nomenclature

<i>CBM</i>	=	Condition Based Maintenance
<i>IVHM</i>	=	Integrated Vehicle Health Monitoring
<i>UAV</i>	=	Unmanned Aerial Vehicle
<i>VTOL</i>	=	Vertical Takeoff and Landing aircraft

I. Introduction

Aviation has experienced one hundred years of vibrant growth to establish itself as a core driver of economic vitality. However, the current growth is on the decelerating backside of the product innovation S-curve², with vehicle capability improvements becoming smaller with time. While the first fifty years involved disruptive technologies that facilitated rapid vehicle improvement, the second fifty years focused on sustaining technologies with an evolutionary path of decreasing costs and increasing safety in a Hub & Spoke infrastructure dominated by commercial transports. Yet the end result is a transportation system that has a customer satisfaction ranking of 63 out of 100³, 2 points lower than customer satisfaction at the IRS! While aviation provides great long distance and Hub to Hub transportation, the majority of trips are shorter with centralized solutions presenting large time and inconvenience penalties. Aviation is not currently capable of meeting the needs of mid-range regional travel in distributed markets⁴. Only 19% of all trips over 100 miles are captured by aviation⁴, with automobiles being used for almost all the rest due to their freedom from prescheduled service. However, automobiles only achieve an average speed of less than 33 mph⁵. Hub & Spoke airline travel achieves a far higher average speed, but once the

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² The Innovators Dilemma, Clayton Christensen, Harper Business Press, 1997.

³ The American Customer Satisfaction Index, University of Michigan, <http://www.theacsi.org>, 2007.

⁴ Airline Hubs: Fair Competition or Predatory Pricing, Hearing before the Subcommittee on Anti-Trust, Business Rights and Competition, U.S. Senate, April 1, 1998.

⁵ The American Travel Survey, Department of Transportation, 1995.

true door to door travel time is considered, the advantage decreases significantly and is often less important than the flexibility provided by automobiles.

Looking into aviation's future, three vehicle technology transformations are at the heart of enabling faster technology accelerations along new market capability S-curves. Commercial transports could be transformed into

vastly superior environmentally responsible products as carbon and other emissions are actively designed into aircraft systems as objective functions; remote sensing through aerial robotic vehicles could provide widespread observation and data sampling across highly diverse civil missions; and Rural & Regional vehicle solutions could provide on-demand transportation in scale-free networks. Along with these vehicle technology transformations, is the need for a new Airspace Traffic Management system that can accommodate explosive growth across the quantity, type, and missions these air vehicles will perform. Implementation of aerial robotics (UAVs) in the airspace is a natural lead-in to on-demand aviation, as many of the vehicle technologies are similar, and UAVs will facilitate society's acceptance of 'optionally' piloted vehicles. Figure 1 depicts a time history of existing and new markets that could be enabled by transformative vehicle capabilities that take advantage of new technologies.

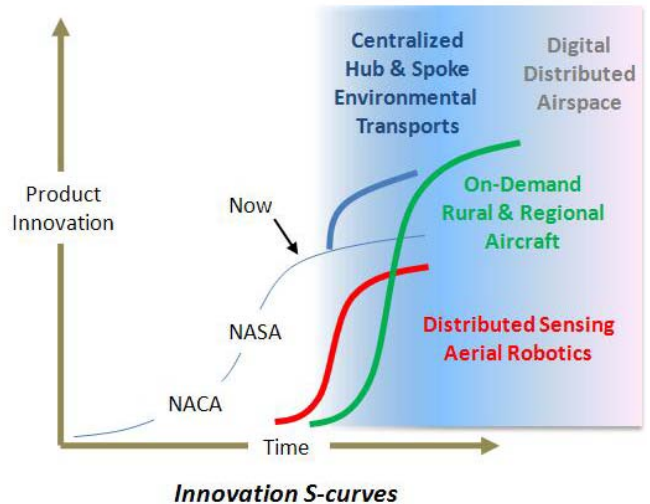


Figure 1. Existing and potential future aviation innovation market S-curves, and the vehicle technology transformations that could result.

The next 30 years provide significant challenges for aviation, and these challenges provide the opportunity to embrace transformative changes. Key challenges include the need for US energy independence, cost of energy, global warming concerns, terrorism threats, congestion/capacity limitations of both highways and airport hubs, as well as the overall resilience of centralized aviation to disturbances. Over the past years, disturbances to the Hub & Spoke system have resulted in decreasing service to smaller Hubs⁶, with the centralized system compressing down to only the most profitable high density Hubs when the system is stressed. Centralized systems, while highly optimized for a single objective function, tend to be quite fragile – 9/11 showed the impact of shutting this system down over a single event. Centralized systems provide relatively easy and enticing targets of opportunity due to the large unprotected areas surrounding airports that are within reach of the traffic patterns of large, vulnerable aircraft. Sophisticated weapons would not be required to attack highly vulnerable centralized targets⁷. While Hub & Spoke is a vital resource, aviation should also enable other transportation choices, capable of providing greater distribution and robustness. Even without singular high profile disturbances, highway and hub system forecasts indicate a dramatic slow down as congestion reaches exponentially increasing delay.⁸

How can aviation provide high speed mobility, while also satisfying the distributed and on-demand travel needs of most travel, especially when most Americans live hours away from Hub airports?

Can future aviation provide new mobility alternatives, so that the choice is not merely between the extremes of slow automobiles that can get you where you want to go, and fast airliners that can't?

Key to the challenges, and opportunities, of the next generation in aviation is the realization that the early NACA and NASA years were vibrant periods of discovery. Not because of larger budgets, smarter engineers, or better facilities, but because they were active defining a new frontier. NASA has the opportunity once again to lead in aggressive discovery on these new aviation frontiers, through the study of how new technologies can lead to

⁶ Commercial Aviation – Programs and Options for Providing Air Service to Small Communities, GAO, Testimony before the Subcommittee on Aviation, April 25, 2007.

⁷ Shoulder Launched Missiles – The Ominous Threat to Commercial Aviation, USAF Counter proliferation Paper Series, James Whitmire, Dec 2006, and The Threat to Civil Aviation, Advanced Security Integration, 2005.

⁸ Two Billion Cars: Driving Towards Sustainability, Daniel Sperling, 2009.

successful emerging aviation markets. Many major organizations in the past have failed to re-discover frontiers as they become entrenched in merely addressing current customer incremental needs. This has been described as “existing customers holding hostage organizations”¹ which prevents them from providing dramatic technical breakthroughs, even when new technology opportunities arise. The past 30 years have provided a technology foundation for an aviation system that can embrace requirements and desires that align much closer to those defined by the traveling public: that is, fast mobility for people and goods that is accessible, scalable, robust, flexible, secure, safe, convenient, efficient, and affordable – while providing the lowest possible emission and noise footprint to the environment. Metrics in each of these areas, from door to door block speed, to mean distance between access portals, to departure time flexibility, to weather delay time, to passenger satisfaction index indicate that the current system is designed more for the benefit of the commercial airliner than for the travelling public. On-demand aircraft most fully embrace the distant vision of aviation being designed around the needs of the travelling public, is the least understood and established in the aviation community, and is the only emergent market area where NASA is currently not investing. For these reasons, this paper will focus on the On-Demand aviation market, and the technologies that enable this new societal capability.

II. The On-Demand Aviation Market

Over the past 20 years, technology has shown the ability to democratize information services that were previously entrenched in centralized, legacy solutions. Cell phones, PDA's, laptops, and PC's are the ‘vehicles’ that transformed our ability to achieve on-demand information and communications; resulting in economic, productivity, and quality of life improvements which we now could not imagine living without. The internet demonstrates the integral nature of the overall system enabling ‘vehicles’ and was critical towards accomplishing this change (just as a free flight aviation system would enable on-demand vehicles). But the information transformation was brought about by new ‘vehicles’ that pushed for the ability to work cooperatively among each other. On-demand accessibility could extend beyond merely digital information, and provide objects with mass (people and goods) the same freedom and choice to travel whenever, wherever, and however they choose at speeds that only aviation can provide across distributed areas. Just as automobiles replaced the horse, and commercial transports replaced the train, increasing mobility *reach* through on-demand aviation will empower a new generation with the catalyst for growth and optimum resource management in our expansive nation. However, the system innovation can't occur without the platform innovations occurring first; this is the reason why investment in aviation vehicle ‘platform’ technologies is required as a pioneering initial step, before attempting to settle new airspace ‘territories’.

How can the high risk pioneering ‘Lewis and Clark’ breakthroughs be developed to establish new aviation market territories?

If there is a clear public benefit for On-Demand aviation, what are the gaps that are preventing this new market from emerging?

Developing a transformative mobility age for society would provide a similar economic productivity impact as the information age. Key to achieving this impact is enabling aviation to no longer be limited to incredibly expensive products made at very low production volumes (both in terms of the actual vehicle products, and the trained operators). Just as with computer markets, distributing products to lower performance mass production provided tremendous investment and acceleration of technology capabilities. ‘Leapfrogging’ current auto and airport hub based travel would facilitate overcoming natural travel barriers that otherwise would require additional expensive bridges, roads, and highways (e.g. ~\$20 million per mile), and commercial airports (e.g. \$1 billion per



Figure 2. High capacity heliport design to enable close proximity ultra quiet VTOL aircraft operations to business parks.

major commercial runway). As fully autonomous systems are achieved over the years, on-demand vehicles will enable more travelers to experience enhanced mobility (the elderly, handicapped, etc). Missions will include transportation of both people and goods, with vehicles of many sizes; courier and package delivery vehicles (sized only to carry a payload much smaller than an on-board pilot), single person gridlock commuters, fractionally owned and rental air vehicle fleets, or as taxi's and delivery vans. Larger vehicles could utilize the distributed infrastructure of the approximately public and private airfields that already exist, with operations at over 18,000 airfields reported by the FAA this past year. These smaller airfields would attract businesses as portals for higher traffic volumes. Smaller vehicles that could achieve a low enough acoustic signature and require limited or no runways would utilize new high capacity heliports or 'pocket airport' infrastructure, as shown in Figure 2, to enable much closer proximity aviation operations to neighborhoods and businesses. Annual auto sales are \$500 to \$1,000 billion in the U.S. alone; therefore projections of an on-demand aviation market could provide annual sales on the order of \$100 billion, with the vehicles providing greater productivity than cars to offset their higher acquisition costs. Such an economic impact prediction could be dwarfed as subsequent global generations fully embrace their newfound mobility, just as the capabilities and uses of today's smart phones could not have been imagined.

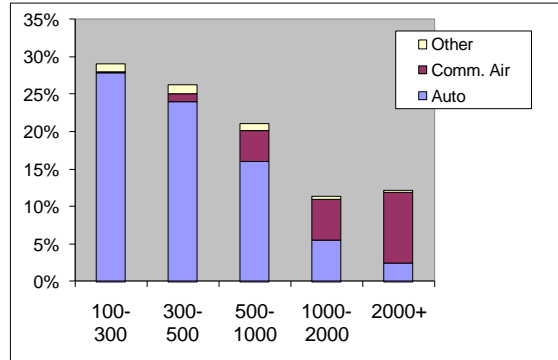


Figure 3. Distribution of trip distance (miles) and the mode of travel taken, for all trips over 100 miles in the U.S.

Most travel requires on-demand operations that are in close proximity to communities and businesses; necessitating easy to use, incredibly safe, environmentally friendly, efficient, and affordable vehicles. The distribution of trip distances (for all trips over 100 miles)⁴ is shown in Figure 3, which shows that automobiles capture the vast majority of trips, with airlines only matching automobiles at distances greater than 1000 miles. On-demand vehicles must be free from large infrastructure requirements to enable the vehicle to be used in a distributed fashion for optimal doorstep to destination travel, with minimal intermodal delay. Providing an improvement in trip speed provides a non-linear improvement in mobility reach (the regional area that can be accessed for daily use). Current ground travel provides average trip speeds of less than 33 mph, with a daily reach of about 2500 square miles (based upon an average radius travel time allocation of 1.25 hours)⁹. On-demand aviation could provide 4x auto speeds, with 16x the daily mobility reach. The mobility impact is shown in Figure 4 for the Hampton Roads, Virginia region, with on-demand aviation providing a mobility reach from Charlotte to Washington DC, with a vast increase in accessibility across the regional area. Building more highways and hubs can't achieve this order of magnitude improvement in mobility, instead new vehicle solutions are required to fill the huge gap between the current transportation options.

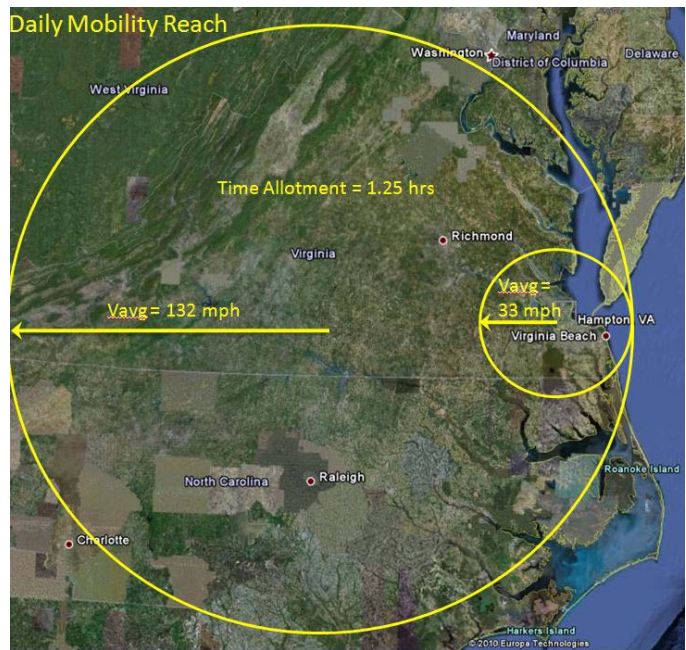


Figure 4. Mobility Reach in the Hampton Roads, Virginia Region. The yellow circles show the daily mobility reach for automobile-based and on-demand aviation-based travel.

⁹ Transportation Beyond 2050, World Passenger Travel through 2050, Dr. Andreas Schafer, MIT, Sept 26-27, 2000.

On-demand air vehicles would require accomplishing the following top level goals in order for these new aircraft to achieve similar levels of utility as existing on-demand transportation (automobiles).

Ease of Use: As easy to fly as driving a car (with an electronic chauffeur whenever needed).

Safety/Reliable: As safe and reliable as commercial airlines.

Community Friendly: Meet local noise restrictions without excessive infrastructure.

Environmentally Friendly: Energy use and emissions that are sustainable indefinitely.

Affordable: Provide a competitive cost to performance as other modes of travel.

These goals are not merely an evolutionary step, but a revolution – which is clear from the order of magnitude required improvement in each goal area compared to the current state of the art in small aircraft. These goals must be achieved simultaneously in order to provide the desired societal capability. Frontiers offer such opportunities for dramatic improvements. None of these goals are unrealistic, as similar characteristics have been achieved in other vehicles, but not in small aircraft. Especially novel to this vision challenge (at least to the aerospace community) is the practical constraint that technologies must be capable of taking advantage of economies of scale to achieve cost effectiveness. Some aspects of these on-demand vision goals will initially develop very rapidly, as technology that has been developed for military and commercial transports is applied to smaller, general aviation-sized aircraft in a cost effective manner. Small aircraft and rotorcraft have been left behind in many technical areas, because of the lack of a vibrant market that could justify research and development expense – leaving many small aircraft characteristics lagging behind other aerospace industries.

III. On-Demand Aviation Technologies

Accomplishing the goals for this On-Demand Aviation Market requires technical breakthroughs in the disciplines of Integrated Vehicle Health Management (IVHM), autonomous control at vehicle level, aeroacoustics, powered-lift aerodynamics, materials and structures, and advanced concept system integration. One of the core technology breakthroughs that will provide cross-cutting benefits across all the vision goals is the implementation of electric propulsion. It is as transformational as the turbine engine was to the reciprocating engine during the 1940's, with an equal degree of controversy as to whether such propulsion systems could ever be practical for aircraft. It is only now within reach that digital controller technology can couple with high specific power electric motors to match turbine engine performance. Every characteristic associated with electric propulsion is superior to small reciprocating or turbine engines, except for one. The cost, reliability, emissions, noise, efficiency, scaling, thermal/cooling considerations, maintenance, rpm variability, ability to make redundant, air breathing independence, and freedom of integration are all superior for electric propulsion. Only the battery energy density of the energy source lags, by a large factor – which is the core of the controversy over whether electric propulsion can be practical. However, battery technology (along with high specific power electric motors) is already a vibrant technology investment area – as private industry is currently investing billions of dollars per year due to electric automotive and consumer electronic needs. Hybrid electric solutions also provide a method of still taking advantage of the scale-free nature of electric propulsion, while only requiring relatively small amounts of battery energy. Understanding how to integrate electric technologies synergistically into aircraft is the key, in order to take advantage of the current high technology acceleration rates (and influence the direction of these technologies). An all electric aircraft provides the opportunity for a dramatic cross-cutting impact across every goal area. It is also a unifying technology strategy among all the disciplines, permitting mechanical systems to be replaced with digital and optical solid state solutions at component scales not much larger than the Remote Control (RC) market. Instead of aerospace technology merely pushing down from military and commercial transports, low cost RC products could push up to provide disruptive technology change to On-Demand aircraft. Figure 5 shows a comparison of gyroscopes going from mechanical-based to solid-state technology solutions, with a resulting improvement across all metrics to yield devices that are commonly used in RC products, at the cost of only pennies per unit.



Figure 5. Solid state versus mechanical gyro comparison. *Solid state components offer drastically lower cost and size, while offering dramatically improved reliability and accuracy.*

The order of magnitude goal improvements translate into several critical technical approaches that don't require order of magnitude technology improvements. Instead, these approaches require fundamentally different implementation and technology development strategies than the current disciplinary focus.

Electric Propulsion Powered-Lift Integration: Explore the design freedom that new electric motor/controller systems provide for powered-lift vehicle solutions; along with battery and hybrid energy storage technologies that are emerging within the auto industry. Develop ‘solid state’ airframes capable of highly coupled aero-propulsive-control design while integrating collaborative multi-disciplinary strategies.

Autonomous Systems Capable of Off-Nominal Conditions: Develop sophisticated autonomous vehicle management system that can safely and efficiently deliver a passenger point-to-point without requiring human intervention. Provide adaptive autonomy that can intelligently react to a rapidly changing environment or changing instructions while maintaining safe operations in a digital airspace system.

Advanced Sensors and IVHM Systems: Develop a highly integrated vehicle health management (IVHM) system where a network of sensors are an integral part of the vehicle’s structure and propulsion system, with the data from these sensors utilized by the onboard control computers to make intelligent decisions about the control, performance and flight envelope of the vehicle.

Aeroacoustically Constrained Lift and Propulsion: Investigate acoustically driven designs for propulsion/airframe systems that meet vertical or near vertical takeoff and approach operations. Incorporate new absorption, reflection and interference cancellation technologies in combination with system level design.

Lightweight Integrated Structures: Achieve highly efficient minimum gage structures that incorporate new low density materials into multi-functional structures that interact with other disciplines to facilitate combinatory goal approaches.

High Volume Production Aerospace Design: Application of automotive lean design principles to reduce touch labor from 2000 hours per small aircraft, to the automotive standard of less than 100 hours per automobile; while exploring new materials capable of near-net shape fabrication strategies.



Figure 6. Examples of recently developed advanced concepts that utilize primary electric propulsion. *The Puffin concept on the right is a single person tail-sitter VTOL aircraft, while the Samarai on the right is a two person stopped multi mono- rotor aircraft.*

The key to the success of these collective goals and approaches is the ability to engage in disruptive technology research that can explore highly coupled multi-disciplinary breakthroughs, through completely new types of integration concepts. Such breakthroughs will leverage digital and electric systems that could not have even been considered merely a decade ago. Many of these technologies may not even be practical at larger vehicles scales, and

thus have been neglected in prior NASA research, which focused only on larger scale aviation solutions (buses instead of cars). These vehicle configurations will provide VTOL operations that are non-intrusive enough to operate in a highly distributed fashion, as integral transportation devices for our daily lives. Such vehicles will not simply be an extrapolation of helicopters, which come closest to meeting this goal today; they will be new configurations that have completely different features, as shown in the exploratory examples of Figure 6 that take advantage of the new degrees of freedom that all electric configurations provide.

IV. Detailed Discussion of On-Demand Goals and Technologies

Autonomy Goal

An essential element of achieving the safety goal is incorporation of high levels of autonomy, and the on-demand need to transform towards ‘optionally piloted’ vehicle. This necessity is based on approximately 65% of current small aircraft accidents relating to pilot error. Even if the vehicle were completely failsafe, there would be no way to accomplish sufficient safety, especially in higher density operation environments. High levels of autonomy is key for the safety and affordability goals to come together into vehicles that can be used by far less experienced operators, with almost any individual being empowered with this new aerial mobility. Current small aircraft have a high workload environment, with all aspects of the vehicle control being regulated by the pilot; therefore the magnitude of difference of ease of use is vastly more than an order of magnitude. Research into autonomous vehicles has grown over the past couple of decades, just as the number of definitions of measures/metrics for autonomy. The definition proposed for autonomy is the degree of tasks for which the pilot is responsible. As autonomy is applied to on-demand vehicles, they will naturally become like Unmanned Aerial Vehicles (UAVs). The current state-of-the-art for a UAV is the ability to take off, fly to a preselected area of operation, identify or confirm the intended target, execute the mission relative to the target, take evasive actions if under hostile threat and return home to the designated location. These actions come from a selection of preprogrammed actions. Minimal mission replanning can be accomplished on board, such as new path generation for a different set of targets (at least not in real-time). Evasive action is an automatic maneuver, equivalent to current TCAS instructions, for collision avoidance and is a preprogrammed set of options for threats further out. UAVs are unable to deal with close proximity pop-up threats, precisely because they don’t have the capability for real-time trajectory generation with constraints. Unless a new mission has been preprogrammed, dynamic mission replanning cannot be done without active intervention of the human supervisor. The state-of-the-art for piloted vehicles essentially amounts to execution of pilot assigned tasks in an automated manner. Though these automated systems can perform relatively complicated maneuvers, for example landing, these maneuvers are executed using detailed surveys of geographic features and very specific instruction sets. Furthermore, these automatic features operate exclusively in nominal conditions while off nominal atmospheric conditions, traffic, or other anomalous events revert control back to the pilot. Essentially, the current state-of-the-art autonomous aircraft systems make no independent high-level decisions – this would need to change for future on-demand aircraft.

Autonomy Breakthroughs

In order to achieve the required level of autonomy for safe and efficient on-demand operations in a future airspace system, the vehicle management system must have full autonomy and a “pilot optional” function. By full autonomy, the vehicle receives goals from the human operator and translates that into tasks which it does without needing human intervention. The vehicle has authority to make all necessary decisions, which immediately necessitates a very robust validation and verification of decision-making systems. Full automation requires highly reliable fault handling capabilities and the ability to detect and deal effectively with a potentially large number of anomalous situations. In addition to requiring the technical capability to deal with all types of foreseeable errors, full automation without human monitoring also assumes the ability to safely handle unforeseen faults and events. This requirement vastly surpasses the state of the art for fault-management systems. All of this must happen in real-time or very close to real-time. This particular requirement, adds tremendous level of difficulty to the required capabilities. Furthermore, to be acceptable for civil applications requiring certification, the operational envelope of such a system must be reliably predicted and quantified. Again, this vastly exceeds the current state of the art.

Full automation is the ultimate level of autonomy; however, “pilot optional” implies that the level of autonomy can be varied based on the desire and skill of the human operator. What constitutes an appropriate level of “pilot options” and associated interfaces and how these relate to required minimum skills is an open research topic. The required capabilities of an autonomous vehicle must include, but are not limited to, near-all weather flight,

autonomous navigation, guidance and trajectory generation in near real-time, ground obstacle avoidance, peer-to-peer de-conflicting and non-cooperative vehicle sense and avoid, multi-spectral sensing and data fusion to provide information to the vehicle management system all in order to accommodate a potentially quickly changing operating environment. The human-machine interface is equally important as a progression of autonomous capability is developed, and an intuitive display and control system is applied to permit operators to focus on strategic intent, instead of lower level command functions. The vehicle control system should be departure resilient which implies that the vehicle should be unable to enter flight regimes from which safety of flight cannot be restored and the safety of vehicle occupants and persons and property on the ground sufficiently assured. The design of vehicle configuration itself will play a role in this safety feature. Furthermore, this level of resilience may require integration of reversionary capabilities such as an active parachute recovery system providing fail-safe protection against otherwise catastrophic failures.

Safety and Reliability Goal

Enabling on-demand aircraft to achieve the safety and reliability goal of commercial transport levels of safety and reliability is an order of magnitude improvement over small aircraft in use today. Such a vehicle will require an IVHM system, due to inexperienced operators that are incapable of the same skill levels of highly proficient commercial pilots. State of the art for small aircraft involves little to no IVHM systems, except within engines due to their relatively poor reliability in comparison to the rest of the vehicle. On-demand vehicles would require a network of sensors that are an integral part of the vehicle's structure and propulsion system. The data from these sensors would be utilized by the onboard control computers to make intelligent decisions about the control, performance, flight envelope and maintenance of the aircraft. Much of the current state of the art in health management for commercial aircraft consists of a few discrete sensors that measure environmental conditions (i.e. temperature, pressure and load). Data from these sensors are processed, with out-of-nominal conditions reported to the pilot. The pilot must then decide what mitigating action should be taken. In many cases today IVHM information is used solely as a trigger for Condition Based Maintenance (CBM). In this scenario, the mitigating action of the pilot would be to refer the aircraft to a maintenance facility, where the data produced by the IVHM system would then be used by the maintenance technician as a starting point for diagnosis and repair. This typical use of IVHM is analogous to what is done in the automotive industry. That is, when an out-of-nominal condition occurs, the check engine light in the vehicle illuminates indicating that the vehicle should be serviced. The mechanic would then connect the car to a computer and download the error code that would indicate what component(s) needed further diagnosis. Currently, IVHM software and health management technology is in the infancy stage. In most cases the IVHM system, if it exists, is a standalone system that is totally independent of other systems on the vehicle. On-demand aircraft will require advancement in software health management capabilities to accurately interpret sensor data to support autonomous decision making for handling both hardware and software integrity failures, whether previously anticipated or not, at the vehicle-level. Safety of flight is a broad inter-disciplinary problem that couples the IVHM system with the flight control system as well as the degree of autopilot authority. Currently these methods of coupling require proficient pilots with anomalies detected by either monitoring system or the pilot and mitigated at an incident, not accident, level. With relatively untrained pilots, or optionally piloted vehicles, the diagnosis and reparation would be nearly completely allocated to the vehicle having a survival instinct, with intelligence and sensory perception equivalent to simple life forms. Along with avoiding accidents, the vehicle must also be more capable of achieving crash survivability, with on-demand vehicles needing to duplicate the dramatic improvements in crash safety that the automotive industry has achieved over the past decades. This goal area requires more than just extrapolation of the existing aerospace perspectives, instead requiring a cross-pollination across aerospace, auto, and sensory robotics industries.

IVHM Breakthroughs

One of the most important challenges facing aviation safety for on-demand aircraft is safeguarding against system/component failures and malfunctions. This is because hardware faults and failures are very difficult to detect, diagnose, and mitigate in-flight with existing technologies. Consequently, when these problems occur they can lead to catastrophic accidents. To meet this challenge a number of developments in IVHM are needed. Sensory materials and structures must be developed. Today many discrete sensors exist that can aid in determining the health of a vehicle, but for effective IVHM, materials that can both provide structural strength and data related to the state of the structure are needed. Additionally, these sensory materials must provide more information than just the current environmental conditions that the structure is experiencing, but they must provide data as to actual structural conditions (the presence of defects or damage, the loss of strength, etc.).

Nanostructured structural materials offer the possibility of incorporating sensors intrinsic to the structure. For instance graphene sheets have excellent electrical and mechanical properties and can be integrated into structural members. The graphene provides lightweight structural reinforcement and potential for wireless sensing. Functionalized graphene sheets are already available commercially. Partnership with the supplier and some academic investigators can advance the concept of wireless sensing with the signal being broadcast from the multifunctional structure. Multifunctionality can include structural materials with sensors intrinsic to the structure. One approach is taking advantage of multifunctionality offered by nanotubes to impart sensing, actuating and acoustic damping to structures. Another approach is tailored structures where lightweighting is achieved through innovative design of unconventional stiffeners such as curvilinear stiffeners to provide load bearing as well as acoustic dampening. Incorporation of new materials processing techniques enables fabrication of structures with material properties tailored to specific areas within the structure. Just as structures can be analyzed with finite elements, advances in materials processing techniques are enabling fabrication of structures where the material properties can be controlled and changed, either actively (as is the case with embedded smart elements like piezoelectric ceramic particles or shape memory wires) or passively (through controlled chemistry and microstructure at various locations in the structure).

In order to properly utilize the increased data from the sensory materials, significant advances in sensor networking, architecture, computational capabilities and software are essential. For example, more is required from IVHM software than an error or failure indication. Software that is capable of providing decisions, not just data, is needed. These decisions would involve the mitigating action that needs to be taken to prevent a failure of the vehicle, and these decisions need to be closely tied into the vehicle control system. The IVHM system could also be utilized as part of the mitigating action. For example, the same sensory materials that are used to detect damage to a structure could be used to provide energy that would activate self-healing components of the material. The IVHM system would then need to interrogate the quality of the repair and the effect this will have on the performance and safety of the vehicle. In order to increase the affordability of on-demand aircraft, the IVHM system needs to be capable of providing detailed information regarding the state of the structure and propulsion systems to the vehicle maintainers. This allows true CBM, where maintenance is performed only when needed and maintainers are not required to spend large amounts of time troubleshoot failures that may have occurred, or replacing components at specific time intervals.

Community Friendly Goal

External community and internal cabin noise are persistent and complex problems that continue to impede the acceptance of aircraft within the community. The current quietest rotorcraft achieves certification Sound Pressure Levels (SPL) in the low 80 db's at an equivalent distance of approximately 500 ft. Community noise level standards similar to leaf blowers would require these close proximity aircraft to operate at levels in the low 50 db's, requiring a 30 db reduction. Therefore, a 10x reduction in perceived noise is required to have a reasonable expectation that communities could embrace such vehicles. The propulsion systems of aircraft are the dominant external noise source whether it is an engine or prop-rotor system. The source and character of the noise also is highly dependent on the flight operation. The approach noise of current high bypass engines is dominated by the fan and to a lesser degree jet and airframe noise, while during takeoff exhaust jet and aft fan noise dominate. For propeller or rotor systems the noise is much more directional and it's characterized by its impulsiveness, which results in high community annoyance levels. The most influential design variable to reduce noise is the blade tip speed, which impacts noise to approximately the 4.5 exponent. But even for rotor systems that could utilize low tip speeds, there is still the potential for disturbing levels of Blade Vortex Interaction (BVI) noise during approach descent. Therefore the trajectory, and even the specific local flight routing, must be able to be computed in 3D space while avoiding atmospheric or terrain features that could aggravate the signature. Methods to reduce noise for these propulsion systems have been studied for years and advances have been made for acceptance of aircraft that operate within the Hub & Spoke airports. However for vehicles that would operate within the community performing on-demand missions, the burden of achieving lower noise is far more severe (while still attempting to not degrade performance). This noise goal can only be achieved with new technologies for highly coupled engine and vertical lift systems that would allow for source noise reduction, as well as 'new' low noise flight operations not available or even considered today. In addition to this technical challenge existing noise certification standards won't accurately capture the local community types of noise dominate at these lower levels, with the frequency distributions of these new technologies that may be more or less offensive without being captured in the regulatory standards. Therefore new metrics must be defined to insure acceptable operations in combination with these technologies which are highly configuration dependent.

Aeroacoustics Breakthroughs

Accomplishing ultra-low community noise operations require integrated propulsion-airframe systems that are designed to meet acoustic requirements while maintaining performance, safety and emissions. Research efforts to accomplish this must include a much higher degree of cooperation across the configuration system design and detailed aeroacoustic analysis, with specific engagement in the following approaches. 1) Tip speed variation to optimize the noise and performance state of the prop-rotor throughout the flight envelope. 2) Variable prop-rotor RPM that allows for a variation in rotor tip speed through the drive system, allowing low noise operation to be traded with improved performance and increased thrust capacity at other RPM. 3) Variable prop-rotor diameter provides a means of varying both the tip speed and the disk loading during flight. 4) Adaptive planforms enabling the solidity to be adjusted in flight, for instance increasing lift carrying capability during low noise, low RPM operation and increasing efficiency during high RPM flight. 5) Compliant airfoil designs capable of adjusting camber and/or thickness to trade lift carrying capability with low noise operation, as needed. 6) Active and passive flow control mechanisms capable of reducing both tonal and broadband rotor noise and increasing rotor efficiency. 7) Multifunctional structural members with acoustic damping elements inherent to the structure that reduces the parasitic weight from retrofitting noise damping mechanisms.

An onboard aerodynamic and acoustic flight configuration management system needs to be developed to take full advantage of the highly coupled and adaptable aircraft configurations tailoring the flight state and vehicle configuration to meet the noise requirements for different segments of the flight schedule. The flight configuration management system would have the intelligence to predict acoustic emissions from the vehicle in real-time, and direct it to a quiet acoustic state. Real-time acoustic prediction capability will also enable the automatic selection of flight path guidance in order to reduce noise while retaining sufficient safety and performance margins. The noise heard inside of the cabin may not be related to external noise radiation and does not provide the pilot with sufficient information to fly quietly. This necessitates the development of a suite of in-flight sensors to monitor the flight and vehicle state required for an “accurate” acoustic prediction to be made.

Most critical is the exploration and exploitation of integrated lift systems, using the placement and installation of the rotor and electric drive system to reduce externally radiated noise. Multiple propulsive systems and changes to the aircraft configuration may also be explored to reduce noise. For example, the X-force control concept applies a highly coupled implementation of thrust compounding to change the acoustic state of the rotor and may be used to virtually eliminate BVI noise during approach by keeping the wake away from the prop-rotor during the landing approach.

Affordability Goal

Coupling all these goals and disciplinary technical challenges together, is the need to achieve them at an affordable transportation price to performance. This goal translates to achieving both a low vehicle acquisition cost and low operating costs. Current rotorcraft have both high buy-in and recurring costs, resulting from complex systems that require high maintenance. High operating costs are compounded by poor efficiencies (L/D's of 4-5) that result in high fuel costs, as well as poor safety records that result in high insurance costs. Current acquisition cost for a light helicopter is approximately \$400,000 to \$600,000 (for a 4 passenger vehicle, without full IFR flight capability). The burdened cost for the least expensive current solution totals approximately \$4.25 per mile (\$2 ownership, \$1 insurance, \$.75 maintenance, and \$.50 fuel), with a 2 person rotorcraft costing about 65% of the 4 person. This represents the lowest cost entry point for a certified helicopter, with faster and more capable helicopters being far more expensive. Automobile fully burdened operating costs are currently \$.54 per mile (AAA average), with a 4x difference between the average speed of helicopters and automobiles. Therefore, based on a direct cost per mile comparison, helicopters are on the order of 8x more expensive as a minimum. As autonomy and the vehicle goals are implemented on the vehicle, at least a full order of magnitude will be present. So while safety and reliability directly map into the insurance and maintenance costs, efficiency is also important to counter high fuel costs. Volume production is the main factor for decreasing acquisition cost, along with drastic reduction in the amount of touch labor required for assembly of small aircraft. Labor hours required are 10 to 100 times greater than automobiles due to the lack of lean design principles and advanced tooling being applied to small aviation vehicles.

Currently certification and liability are blamed as major impediments to low cost products relating to aerospace and small aircraft in particular. This is entirely true, because of the low production volumes that exist for the current products and manufacturers. With production volumes of less than 500 aircraft per year, the cost burden to certify,

or recertify due to design improvements, is prohibitive simply because this cost is not amortized over a large number of units. Liability likewise encumbers manufacturers with large liability reserves. Many factors impact the liability cost, including the lack of FAA certification standards to provide a shield for lawsuits, small aircraft having relatively poor reliability and safety statistics that are easy to attack in court, and public perception that flying is a high risk activity for the rich (and that the companies providing these expensive products have deep pockets). By promoting and achieving mass markets for these products with large production volumes, both the certification and liability concerns are dramatically diminished. This is accomplished by amortizing certification costs and risk over a much larger number of vehicles, as well as ancillary factors that typically accompany large production volume products. These high production volume benefits include consensus-based standards such as ASTM standards that hold up well against liability litigation, automated production that eliminates touch labor mistakes that reduce reliability, and public acceptance that the market is not a novelty but instead a normal part of society with acceptable risks.

Structures & Materials Breakthroughs

Near-net shape fabrication methods in combination with manufacturing automation can be implemented to significantly reduce the touch labor time. An ancillary benefit to near-net shape fabrication methods is significant reduction in material scrap, which has the economic benefit of reduced cost and reduced environmental impact by eliminating scrap material and cooling fluids used to remove (machine away) unwanted material. There are a variety of different near-net shape fabrication methods available today, depending on the type of material and geometry of the components to be fabricated. For metals, these would include processes like freeform fabrication or direct manufacturing, superplastic forming, die forging, precision casting, shear forming, etc. For composites and polymeric materials these would include processes like stereolithography, direct manufacturing, die forming, fiber tow placement, stitching, vacuum-assisted resin transfer molding, out-of-autoclave processing, etc.

V. Conclusion

Investment in three frontiers would provide a balanced technology portfolio across completely different infrastructure and market solutions, and provide healthy investment in a wide range of technology areas that are critical towards global competition in the aviation, automobile, and robotics markets. Transforming commercial airlines to embrace new environmental restrictions will provide a sustaining technology portfolio that supports the entrenched aerospace companies, while investing in frontier environmental technologies where industry can not afford due to high risk. Transforming aviation to enable the Remote Sensing and On-Demand markets will provide disruptive investments that create whole new industries, and societal capabilities that don't currently exist.

Achieving the on-demand vision goals in concert will take an orchestration of inter-disciplinary cooperation, and is unlikely to occur without government leadership, especially with the high risk, and long-term payoff of this new market. NASA is the natural facilitator of this vision, while engaging corporations, universities, and other government agencies such as the FAA/DOT as collaborating partners. NASA Langley has been a pioneer in this research area through the efforts of the Advanced General Aviation Technology Experiments (AGATE) program, the General Aviation Propulsion (GAP) program, the Small Aircraft Transportation System (SATS) program, and the Vehicle Systems Program Personal Air Vehicle (PAV) Sector. Research that requires investment catalysts are the most appropriate for government R&D efforts; especially in fields that implicitly involve public good, new standards, integration of highly complex systems, and inherent government regulations (which abound in transportation at both local and federal levels). Clearly aviation could not transition to support such an aggressive on-demand aviation vision, without government involvement to spur activity along this new frontier.

*“In terms of risk management, the main advantage that the government has is its power to compel, including its power to tax. This allows it to spread risks extremely broadly (even, in some cases, onto generations that have yet to be born) and to overcome a broad range of failures in the private marketplace. This is why, in my view, government truly is the ultimate risk manager.”*¹⁰

Other government investments help to strengthen the appropriateness of a near-term on-demand research effort. Specifically DARPA TTO has just initiated the Transformer project, which will establish compact VTOL platforms that utilize hybrid-electric propulsion systems for military HUMVEE-like troop carrying missions. While most military UAV funding is focused on developmental projects, research efforts into Aerial Robotics will also spur

¹⁰ When All Else Fails, Laura Linard, Harvard Business Press, 2002.

investment in similar technology areas – as these two markets share many technology paths – but diverge into very different missions and vehicle concepts.

Based upon a review of the On-Demand aviation vision, and the technology needs to achieve those goals, there is the appearance that such vehicles are feasible, and entirely possible with focused technology research. The question of whether the vehicles would be affordable to achieve the required mass markets to make them integrally important to society, and not just a rich man’s toy, is a legitimate concern. But this same concern was present in many markets that shared such compelling societal benefits, as well as such significant hurdles. The automobile and the personal computer are the two closest analogies, with both being considered entirely impractical at the outset of their technology development to ever achieve mass markets, and highly affordable and useful products. Often a single event can provide a catalyst for changing the perceived barriers, and create an epiphany capable of altering public perception. The Orteig prize was such a catalyst for the initial aviation industry, which helped to transform aviation from hobbyist inventors to rapid investment towards a new industry when Charles Lindbergh won this \$25,000 prize in 1927. A similar prize is currently being offered by NASA as the Green Flight Challenge, which is a \$1.65 million prize to be awarded in 2011 to the entrant who can achieve the greatest flight efficiency and speed, while surpassing a 200 passenger mile per gallon and 100 mph minimum qualification. It is the author’s hope that such a prize can usher in a change in the perception of the On-Demand aviation market discussed in this paper, and catalyze a similar age of innovation in aeronautics as experienced by NACA in the 1930’s through 1960’s.



Figure 7. Vehicle methods used for on-demand mobility over the past 100 years, as well as potentially the next 100 years.

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