Plenty of room in the air

Researchers seek to design a flexible aviation system accessible to all.

By Samuel L. Venneri and Ahmed K. Noor

R ESEARCH IS CURRENTLY UNDER WAY ON A SPECTRUM OF REVOLUTIONARY CONCEPTS AND TECHNOLOGIES, FOR CIVILIAN AND MILITARY AIR VEHICLES AND THE AIRSPACE SYSTEM, THAT WILL ENABLE A BOLD NEW ERA OF AVIATION AND MOBILITY.

The long-range vision includes major changes in personal transportation and significant increases in air travel capacity and safety. On-demand and scheduled air mobility will enable people to travel where they want, when they want, faster, safer, and with fewer delays. Air vehicles will be quiet with no emissions of objectionable gases into the atmosphere.

Aviation is an integral part of America's life. It has played an important role, and is expected to play an increasing one, in the national and world economies. It is also the backbone of our national defense. Aviation generates more than $1 trillion worth of economic activity in the United States every year. It is estimated that, by 2020, commercial air travel could exceed the volume of all auto travel in 1990.

However, aviation is facing a number of key challenges, including limits to capacity; issues concerning the environment, security, and safety; and a diminishing skilled workforce. Aviation is approaching gridlock, and the existing airspace management system is incapable of accommodating projected growth. Emissions and noise concerns are increasing sources of constraints on the air transportation system. If not resolved, they can result in a major shortfall in capacity and a serious degradation in the accessibility of flight.

Safety and security are paramount concerns for all travelers, and are likely to be challenged in unforeseen ways that will require constant vigilance.

Today, more than 54 percent of the current science and technology aerospace workforce is over 45 and nearing

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retirement. The number of science and engineering graduates at U.S. colleges and universities has continued to decline since 1992.

Despite these challenges, a bold new era of aviation is possible that focuses on improvement of the overall quality of life, personal mobility, security, and environmental compatibility. NASA, in collaboration with the Department of Defense, the Federal Aviation Administration, the Department of Transportation, private industry, and a number of universities, has developed a long-term technology vision to address the critical challenges for the next era of aviation.

The vision is included in the NASA Aeronautics Blueprint, published earlier this year. It includes advanced concepts for the airspace system as a complex, highly integrated system of systems. It also outlines a new model for aviation safety and security, revolutionary aerospace vehicles with significantly greater performance, and assured development of a competent aerospace workforce.

A range of technologies needs to be developed as part of this vision. Each technology will provide a different set of challenges, and each will mature at a different pace. All will contribute to the realization of the vision.

HOW THE FUTURE WILL FLY

New air vehicle types with advanced capabilities, both subsonic and supersonic, can enable a new future of aviation and mobility. The vehicles include large, long-haul, and long-duration transports; new vertical lift and short-takeoff aircraft offering doorstep-to-destination mobility; and a new generation of autonomous uninhabited aircraft operating at altitudes above 80,000 feet. They will lead to more personal air travel, reduce environmental impacts, and enhance our national defense.

Future aircraft include personal air vehicles, uninhabited air vehicles, and a visionary autonomous vehicle concept.

The air vehicles of today bear little resemblance to those of the time of the Wright brothers. Similarly, future air vehicles will bear little resemblance to those of today. Future vehicles will emulate intelligent and thinking systems that can adapt, evolve, and generally deal with changes and unanticipated problems. The vehicles will optimize their performance, perform complex maneuvers in complete safety, and repair themselves when they are damaged. They will have dramatically reduced mass and power, as well as increased reliability. The increasing demands on performance and system reliability, and the associated complexity of future air vehicles are providing the motivation for an autonomous vehicle, a smart craft that is easy to operate. The vehicle is modeled on self-regulating, self-administering biological systems.

A useful biological metaphor is found in the autonomic nervous system of the human body. It tells the heart how many times to beat, monitors the body temperature, and adjusts the blood flow. Most significantly, however, it does all of this without any conscious recognition or effort on the part of the person—hence the name "autonomic vehicle" was coined.

The autonomic vehicle concept is similar to the autonomic computing paradigm initiated by IBM to make future computing systems self-managing and self-optimizing, to eliminate the expensive management services needed today. The computing systems considered in that activity consist of large collections of computing engines, storage devices, visualization facilities, operating systems, middleware, and application software.

An autonomic air vehicle can be piloted or uninhabited, and will exhibit a number of advanced characteris-
tics. The vehicle will be self-defining, in that it will have detailed knowledge of its components, current status, internal constraints, ultimate performance, and its relation to other vehicles and to the airspace system. It will be able to reconfigure itself under varying and unpredictable conditions. For example, it will reconfigure wing and airframe geometry to satisfy requirements for a wide range of flight speeds and maneuvers.

The vehicle will look for ways to optimize its performance across the entire flight regime. It will monitor subsystems, components, and metrics by using advanced feedback control mechanisms and will make changes to achieve predetermined performance goals. Flexible, highly adaptive structures and active sensing materials will enable it to adapt for optimum performance. The aircraft will be able to recover gracefully from routine and extraordinary events that might cause some components to malfunction or take damage.

Self-learning concepts will be incorporated into flight-control software to discover problems and to reconfigure the system to keep functioning smoothly. The vehicle will collect, analyze, and share information about itself and its local environment with other craft in the air and with supervisors on the ground to enable a coordinated and optimized airspace system.

The realization of the autonomic vehicle concept requires a paradigm shift in some technologies. For example, current, flutter-free designs based on the idea of aeroelastic avoidance result in stiff and heavy vehicles. That idea must be replaced by aeroelastic exploitation—a controlled, flexible, and continuously self-adapting configuration—that will enable an expanded operational envelope. Passive materials that have limited properties will be replaced by active multifunctional materials that can adapt their properties to the changing environments and significantly enhance structural performance.

Discrete joined structural components from assembled elements require labor-intensive processing and assembly, resulting in high cost and weight. They will give way to unitized, or jointless, adaptive multifunctional structures made in free-form fabrication processes.

Instead of externally applied sensors used for periodic inspection, full-coverage, reconfigurable networked sensor nervous systems will continuously monitor the vehicle during its operational life. Autonomous human decision-making in the cockpit of piloted aircraft will yield to an integrated team of human and machine agents in a seamless partnership for monitoring and controlling the vehicle. A number of NASA/DOD programs are addressing various characteristics of autonomic vehicles and are likely to produce prototype vehicles with some of these characteristics in the coming decades.

The concept of autonomic vehicles can be extended to hierarchical autonomic transportation systems, with the autonomic vehicle being the first level. The second level is the airspace system—a complex collection of networked subsystems, including facilities, vehicles, and ground support. The third level in the hierarchy is an integrated intermodal system, covering space, air, land, and water transportation. It will function as one seamless whole, maximizing options for convenience, efficiency, and reduced cost.

**PERSONAL AIR VEHICLES**

NASA and the Defense Advanced Research Projects Agency are investigating the feasibility of creating personal air vehicles that could replace or, at the very least, augment personal ground and air transportation schemes. Such vehicles can have many useful civilian and military applications.

They will benefit from vertical or short takeoff and landing capability, and operate at block speeds markedly faster than current combinations of land and air transportation, particularly in critical market areas. Their cost will compare to current high-end luxury cars and small general aviation aircraft.

The development of such vehicles requires improvement in propulsion, avionics, and control systems. The use of advanced composites, coupled with modern high thrust-to-weight turbine engines, can reduce vehicle weight and improve reliability and maintainability in the field.

NASA's activities in personal air vehicles are primarily focused on a pioneering integrated design effort for affordable vehicles, with low noise and emissions, and improved safety. A matrix of missions, concepts, and technologies has been developed to explore the potential for small aircraft to better satisfy personal travel needs. This includes door-to-door personal transportation—the
blending of ground and air transportation. Since propulsion is currently the most expensive subsystem, and in many ways drives the cost of the entire vehicle, attempts have been made to leverage automotive engines to achieve economies of scale. Achieving dramatic improvements in affordability requires acceptance that the automotive engine, once integrated into an airframe, won't perform as well as an aircraft engine optimized for aircraft operations, particularly in terms of time between overhauls and specific power. However, the cost per engine-hour can be significantly better than for current aircraft engines.

One of the advanced engine concepts considered is a nearly constant rpm reciprocating engine with a variable expansion ratio. It also uses hydraulically actuated electromagnetic valves and a high pressure ratio turbocharger.

Wing weight reduction is attempted through the use of circulation control and new low-density composite materials. Circulation control blowing from a pressurized air plenum at the trailing edge of the wing can provide a high lift system with no external moving parts, thereby reducing both drag and weight.

Hollow-core composites provide a method of achieving weight reduction in minimum gauge structures, where conventional composites are limited by stiffness, hangar rash, and the damage that comes from normal wear and tear.

Among the concepts being evaluated for reducing noise is a tail-fan concept, which incorporates ducted fan propulsion and exhaust noise suppression devices.

The features that can be incorporated into the design to enhance safety and reduce the number of failures include simple, reliable, redundant systems, and possibly adaptive flight controls that learn in real time. Monitoring systems will alert the pilot to potential problems, and subsystems will be able to fail with graceful degradation in performance, and without catastrophic failure. A key example today is the engine in a Cadillac, which gives you the ability to “limp home” with approximately 50 percent power even after complete coolant loss, instead of losing the engine and, perhaps, the entire vehicle.

High-technology additions to safety that can be developed and incorporated include global positioning satellite precision landing aids, collision avoidance, and interlocked electronic checklists. Currently in small aircraft, a significant amount of time and experience is required to perform a vehicle preflight check. As more of the population uses air vehicles for enhanced mobility, the ability to perform these system checks automatically, through distributed sensor systems that can communicate with a central computer system, becomes essential.

Also, a number of crash survivability features can be built into the design. These include a structure that can withstand an acceleration or deceleration of magnitude 20 g, fire suppression, imbedded flotation, airbags, ballistic parachutes, and low landing speeds. In the long term, personal air vehicles will incorporate the characteristics of autonomous vehicles.

Uninhabited aerial vehicles, or UAVs, have been a feature of aviation for much of its history, though in a limited secondary role. Samuel Langley, for example, built steam-powered, pilotless aircraft in the late 19th century. The successes of UAVs in providing intelligence, surveillance, and reconnaissance data in combat operations and the recent successful flight demonstration of the DARPA/Air Force unmanned combat air vehicle X-45A will result in significantly expanded roles for uninhabited aircraft.

Current operational UAVs are not fully autonomous (that is, they cannot function independently), and are used primarily as remote-controlled traveling sensors. A recently initiated DARPA program, the unmanned combat armed rotorcraft, combines advanced command and control technologies with the advantages of vertical takeoff and landing.

NASA, DOD, and industry have identified a number of.

Mesicopters, such as the one shown here in prototype, may one day be able to test dangerous environments before troops or rescue workers go in.

UAV growth applications, including Earth imaging and sensing, high-bandwidth telecommunications, and testing of unusual vehicle configurations, the high-risk, revolutionary departures from traditional design. The telecommunications operations of UAVs can be complementary and, in some cases, low-cost alternatives, to satellite and terrestrial systems. Surveillance operations include using sensor suites to detect toxic and biological contaminants. Future military UAVs will provide advanced airpower with increased tactical deterrence at a fraction of the size, weight, and cost of current piloted systems.

UAV operation and control is a collaborative venture between onboard, or autonomous, intelligent flight control and remotely located human agents who have monitoring and supervisory control responsibilities. To achieve levels of operational reliability and safety comparable to those of piloted aircraft, real-time vehicle control will have to shift dynamically between the remote human agent and the onboard autonomous control according to the dynamic aspects of the environment (for example, flight phase, vehicle condition, and the presence of environmental hazards).
The optimal blend of onboard and supervisory control is determined by the operating environments and the quality of perceptual information provided to the operator. Technologies under development include photonic vehicle management systems, intelligent reconfigurable control, prognostic health management, and automatic air collision avoidance.

DARPA supported the development of uninhabited micro air vehicles, or MAVs, capable of hovering and vertical flight for up to two hours, with a range of six miles, dimensions less than 6 inches, and weight less than 0.31 lb. That is 9.7 km, dimensions less than 0.1524 meter and mass less than 140 grams.

The small size and mass of micro air vehicles pose significant challenges regarding their structure, aerodynamics, and control. But, the most challenging design problem for MAVs is propulsion—in particular, energy requirements.

A microturbine concept for an electrical power source was developed by researchers at Massachusetts Institute of Technology. This is a button-size gas turbine built on silicon chips measuring 2 cm on a side and about 3 mm thick. It contains only one moving part, a rotating disk 8 mm in diameter and about 1 mm thick that spins at 1.2 million rpm.

Miniaturization is being attempted in a number of projects, including the Smart Dust Project of the University of California at Berkeley and the mesicopter concept of Stanford University. Smart Dust aims at creating massively distributed sensor networks. The networks consist of hundreds (or thousands) of nodes—tiny, fully autonomous silicon sensors with onboard communication, computation, and power—light enough to remain suspended in air for hours at a time. They can be deployed over a region for detecting toxic chemicals in the environment, for monitoring weather patterns around the globe, and for military applications.

The mesicopter is a few-centimeter-size, four-rotor electric helicopter (each rotor as small as 1.5 cm) designed to stay airborne while carrying its own power supply. It could be produced cheaply in large volume. Swarms of mesicopters can be used for planetary exploration, to fly into the heart of a tornado, or to scan a battlefield for chemical or biological agents.

Future UAVs will be autonomous, fast, and quiet. These robotic vehicles will be able to function and navigate under optimum or degraded conditions, and will incorporate adaptive flight controls and other characteristics of autonomous vehicles. They will be equipped with multivehicle coordination and control capabilities, enabling them to operate effectively in groups that may contain piloted vehicles.

By adding facilities for both reactive processing (such as sensory perception) and reflective processing (such as planning), the UAVs could be designed to emulate rudimentary forms of human emotions—curiosity, anxiety, or self-preservation. UAV systems that exhibit these characteristics could play the role of partners to humans in the airspace system and enhance their safety by alerting pilots or traffic controllers to mistakes before they are made.

The realization of future air vehicles, particularly autonomous vehicles, requires the synergistic coupling of a number of revolutionary and leading-edge technologies, as well as novel engineering tools and manufacturing techniques.

The complexity of increased flight operations requires automated systems that will facilitate interactions in real time among the human decision-makers in the triad of flight deck, airspace operations center, and air traffic control. Interactions with today's cockpit automation are complex, with many different modes that can create conflicts between the intent of the pilot and the goals of automated systems. Higher levels of system autonomy could increase the gap between human situational awareness and system intent.

Future autonomous flight systems must be designed to provide information to the human operators and support seamless monitoring and high-level supervisory control. Human information processing strengths and limitations must be accounted for in flight deck design.

NASA is developing a number of flight deck technologies for enhancing aircraft safety and airspace security. They include synthetic vision for providing all-weather visibility, enhanced visualization of local traffic and weather conditions, and “refuse-to-crash” flight control with digital terrain technology, which can correct pilot error and prevent sabotage. These technologies, in addi-
tion to providing situational awareness information, enable conflict avoidance and flight path replanning that realize economic and safety gains while decreasing separation between aircraft on approach and landing.

New promising developments like the Small Aircraft Transportation System, which will significantly enhance safety and enable a carlike, easy-to-use aircraft, will require novel approaches to interaction so people may harness the high complexity of the underlying automation through an easy-to-handle interface. The use of signals from the human nervous system for performing some flight control tasks is being explored. High-density sensing techniques can be used to convey the intent of human operators to highly automated flight control systems. These techniques range from eye tracking, language and gesture recognition, and flight control activity monitoring to bioelectric and neural control systems. These sensing techniques will operate with other manual controls, thereby increasing human interaction with the system.

To date, biocontrol systems have used electroencephalogram and electromyogram signals. The EEG signals measure the brain’s electrical activity. The EMG signals are representative of the electrical energy present during muscle activation. The signals can be sensed non-invasively by placing sensors on the skin to form a low-impedance electrical connection with the tissue.

Multimode high-density sensing technologies, such as neural or brain-based interaction technologies, will allow the system to detect and respond to pilots’ changing physical states and situational awareness, and let them know when they are showing signs of fatigue or workload before they become aware of it themselves. These sensing technologies will depend on model-based reasoning about dynamic task requirements and human information-processing capabilities to make accurate interpretations in real time from sparse data.

Detailed computational models of human-system interaction will be used to provide timely and accurate decision support by anticipating the information requirements of human operators. Such engineering models can also be used to emulate human behavior during simulation-based design and for intelligent training systems tailored to the knowledge gaps of the individual.

Propulsion innovations have been a fundamental driver of progress in air transportation. Novel concepts will enable high-performance, high-efficiency, and environmentally

A Brain Trust for the Future

THE REALIZATION OF NASA’S AMBITIOUS GOALS will require a diverse, technically skilled workforce—a new generation of scientists and engineers who can work across traditional disciplines and perform in a rapidly changing environment. Today, NASA employs more than 10,600 scientists and engineers. Ninety-two percent of them are experienced and in senior positions, and 24 percent—approximately one-quarter of NASA’s core expertise—will be eligible to retire within the next four years.

In addition, the agency faces skill gaps in a number of revolutionary technology fields, which are needed for the realization of future systems and missions. The situation is similar in the U.S. aerospace industry, with over 50 percent of its current science and technology workforce nearing retirement. During the same time that NASA and the aerospace industry expect to lose a significant number of their technologists, U.S. colleges and universities are experiencing a decrease in the number of undergraduate and graduate students in technical fields.

NASA has developed a number of new initiatives for assured workforce development. They include University Research, Engineering, and Technology Institutes (URETIs), the National Institute of Aerospace (NIA), and the Hierarchical Research and Learning Network (HRLN). The overall goal of these activities is to strengthen NASA’s ties to the academic community through long-term sustained investment in areas of innovative and long-range technology critical to future aerospace systems and missions.

At the same time, the three activities will enhance and broaden the capability of the nation’s universities to meet the needs of NASA’s science and technology programs. Seven multi-university URETIs have been selected this year in a number of areas, including aeropropulsion and power, reusable launch vehicles, nanoelectronics, and bionanotechnology materials and structures. The NIA will perform cutting-edge aerospace and atmospheric research, develop new technologies, and help inspire the next generation of the aerospace workforce. The HRLN aims at the creation of a knowledge organization linking diverse interdisciplinary teams from NASA and other government agencies with universities, industry, technology providers, and professional societies.

It is a network of networks, being developed by seven university teams, led by Old Dominion University’s Center for Advanced Engineering Environments. The component networks will link the diverse teams in revolutionary areas, such as bionanotechnology and smart vehicle technologies. The networks provide adaptive learning environments and facilities, obtained by synergistic coupling of advanced instruction, communication, knowledge management, and assessment technologies.

The activities of the HRLN project include development of learning modules and virtual classrooms in revolutionary technology areas, simulators of unique test facilities at NASA, and a telescience system—an online multisite lab that allows real-time exchange of information and remote operation of instrumentation by geographically distributed teams. HRLN will support the lifelong learning needs of aerospace professionals, keeping them abreast of technological and scientific advances on a global scale.

It will create a new generation of skilled engineers and scientists who can work across disciplines and perform in a rapidly changing environment. It will also enable collective intelligence, innovation, and creativity to bear on the increasing complexity of future aerospace systems.
compatible propulsion systems for a wide variety of air vehicles. For instance, hydrogen-based and electric propulsion research aims to eliminate CO₂ emissions from civil transport aircraft by converting their combustion systems to carbonless fuel or by introducing new energy conversion technologies. An intelligent engine, on the other hand, will use a synergistic combination of technologies, including micro-flow management, acoustic masking, innovative combustion strategy, and adaptive engine cycles.

A distributed propulsion concept, meanwhile, is based on replacing the conventional one to four engines by a large number of small (100 to 1,000 lbs. of thrust), mini (10 to 100 lbs.), or micro (less than 10 lbs.) engines. This concept has the potential to result in safer, quieter, and lower-cost aircraft.

The combination of smaller engine size, dispersed signature of engines, and potential shielding effects due to embedded engine installation has the potential of decreasing perceived noise level to that of ground transportation. Distributed propulsion concepts will also enable lighter aircraft, and enhance air vehicle safety by making an engine-out a non-critical event.

Besides distributed engine power plants, "distributed propulsion" also covers distributed exhaust and distributed fans or propulsors. The first idea encompasses a central engine power plant with ducted nozzles for strategic deployment of thrust on the aircraft. The second entails the set of remote fans for propulsion thrust powered by a central power plant or energy source. The lower propulsive and thermal efficiencies produced by distributed propulsion can be mitigated by using innovative technologies that can be realized in the small scale (for example, flow/circulation control through microturbines and foil air bearings).

The exoskeletal engine concept, in which the shafts and discs are eliminated and are replaced by rotating casings that support the blades in spanwise compression, enables higher thermal efficiency through higher operating temperatures. Hybrid propulsion systems that combine pulse detonation with turbo machinery have the potential for substantially increased performance over conventional gas turbine engines. Fuel cells provide an ideal approach for distributed and clean generation of power. Solid-state power devices provide new capabilities for the control and protection of power systems.

**INTELLIGENCE STARTS SMALL**

The integration of intelligence and multifunctionality into the varied airframe and propulsion components of aerospace vehicles requires the development of revolutionary materials, structures, and subsystems. They can be achieved through the fusion of nanotechnology, biotechnology, and information technology into a new discipline—nanobiologies—that is the foundation for biologically inspired materials and structures.

Technologies based on that new discipline can provide transformation functionality—morphing, autonomy, aerodynamic shaping, and novel propulsion. Specifically, nanobiologies addresses the development of:

- Synthetic nanostructured organic/inorganic materials, which allow a range of functions to be coupled to different levels and scales of the structure, and have high strength-to-weight ratios and self-healing mechanisms.
- Embedded sensing and information transmission artifacts in the material through the use of muscle-like actuators and miniaturized nervous-system-like sensors, including sensors for reconfiguration and healing control.
- Distributed collaborative self-assessment and repair—integrating sensing, computation, actuation, and adaptive control in a fine-grained way to provide an effective control nervous system for stimulating the vehicle to effect an adaptive physical response.
- Multifunctional hierarchical structural supercapacitors that carry structural loads, store electrical energy, provide electrical power, provide protection against low- and high-velocity impact, and assist in thermal management.
- Autonomous intelligent adaptive control architecture with highly reconfigurable integrated distributed sensing and actuation.
- Novel power generation and communication components using unique device physics at the molecular scale.

NASA, in collaboration with other government agencies, industry, and academia, is embarking on major technological and cultural changes for the 21st century. The synergistic coupling of a number of revolutionary and leading-edge technologies offers the potential of creating robust, environmentally friendly air vehicles with unprecedented levels of performance and capability, as well as an integrated intermodal transportation system, covering space, air, land, and water transportation as subsystems.

The integrated system combines safety, security, and mobility, and also enhances the quality of our lives. The realization of this vision requires new levels of collaboration among diverse multidisciplinary teams and the creation of knowledge organizations consisting of technically competent workforces, not only from NASA, but from other government agencies, industry, technology providers, and academia.