

Fresh air, wide-open space

Researchers are developing a new vision of flight,
a future of ever-safer, more efficient
vehicles and system controls.

**By Daniel S. Goldin,
Samuel L. Venneri, and Ahmed K. Noor**

SINCE THE MIDDLE of the last century aerospace technology has become a unique, indispensable part of our world. Commercial aviation has made it possible for more people and cargo to travel faster than at any previous time in history.

But today, we are reaching the capacity limits of the air-space system, yet transportation demand—both passenger and freight—is expected to increase in the long term. In space, our assets have improved weather prediction, provided global communication and navigation facilities to link people and businesses more effectively, and enabled spectral imaging of Earth to enhance our environmental stewardship and land use. Space-based observations are also taking on unprecedented importance in national security strategy. However, the high cost of launching payloads to Earth orbit has impeded progress in the exploration of space, as well as in its commercial use and development.

To keep pace with the projected increase in demand for mobility, a bold integrated vision is needed for future

aerospace transportation systems. The vision for the next century is based on new technologies, and today some revolutionary ideas, many developing under programs at NASA and other government agencies, are emerging.

LEARNING FROM LIVING SYSTEMS

In the past few years, a growing number of engineers have been seeking inspiration from living systems—birds, insects, and other biological models—in an effort to produce breakthroughs in vehicle concepts, reshape our frame of reference, and change the definition of what is possible. Knowledge of the form and function of biological systems is not used as a blueprint, but as an architectural and operational analog. In many cases, we are finding that nature's basic design concepts—and, in some cases, the actual designs—can be applied to aerospace systems.

Over the eons, nature has developed design approaches that make biological systems far more reliable and more efficient than human-made systems. Biological systems evolve, develop, learn, and adapt on their own. The goal is to make our aerospace systems equally adaptive—that is, capable of undergoing modifications according to changing environmental circumstances, thereby enhancing their safety and performance.

Flying birds display remarkable features of maneuverability that to date have no technological parallel. A bird can morph and rotate its wings in three dimensions. It has the ability to control the airflow over its wings by moving the feathers on its wingtips, which are more effi-

Daniel S. Goldin is the outgoing administrator of NASA in Washington, D.C., and Samuel L. Venneri is associate administrator for aerospace technology and chief technologist. Ahmed K. Noor is an Eminent Scholar and professor of aerospace engineering at Old Dominion University in Norfolk, Va.; director of the university's Center for Advanced Engineering Environments at NASA Langley Research Center in Hampton, Va., and adjunct professor of aerospace engineering at the University of Florida in Gainesville.

cient than the flaps and rigid, pivoting tail surface of current aircraft.

A bird also is made from self-sensing and self-healing materials and has a fully integrated aerodynamic and propulsion system. Its skin, muscles, and organs have a nervous system that detects fatigue, injury, or damage, and signals the brain. It is designed to survive.

Insects manage unsteady flow well. In insect flight the flow is always separated. Understanding the mechanism by which insects dynamically manage unstable flow to generate lift could provide insight into the development of micro-air vehicles for a variety of missions. Also, insects have elaborate systems of sense organs. Organs in the cuticle, for example, detect bending strains and enable the insect to control its movements.

The application of biological concepts and principles to the development of technologies for engineering systems has led to the emergence of biomimetics, neuromimetics, and neuromorphic engineering. Biomimetics is the science of developing synthetic materials, devices, and structures that have the hierarchical organization, functionality, and strategies for optimization similar to biological systems. Neuromimetics deals with the application of neuroscience to building intelligent distributed knowledge networks. Neuromorphic engineering aims at the study of neuromechanical interactions, as well as the design and fabrication of systems whose architecture and design principles are based on biological nervous systems.

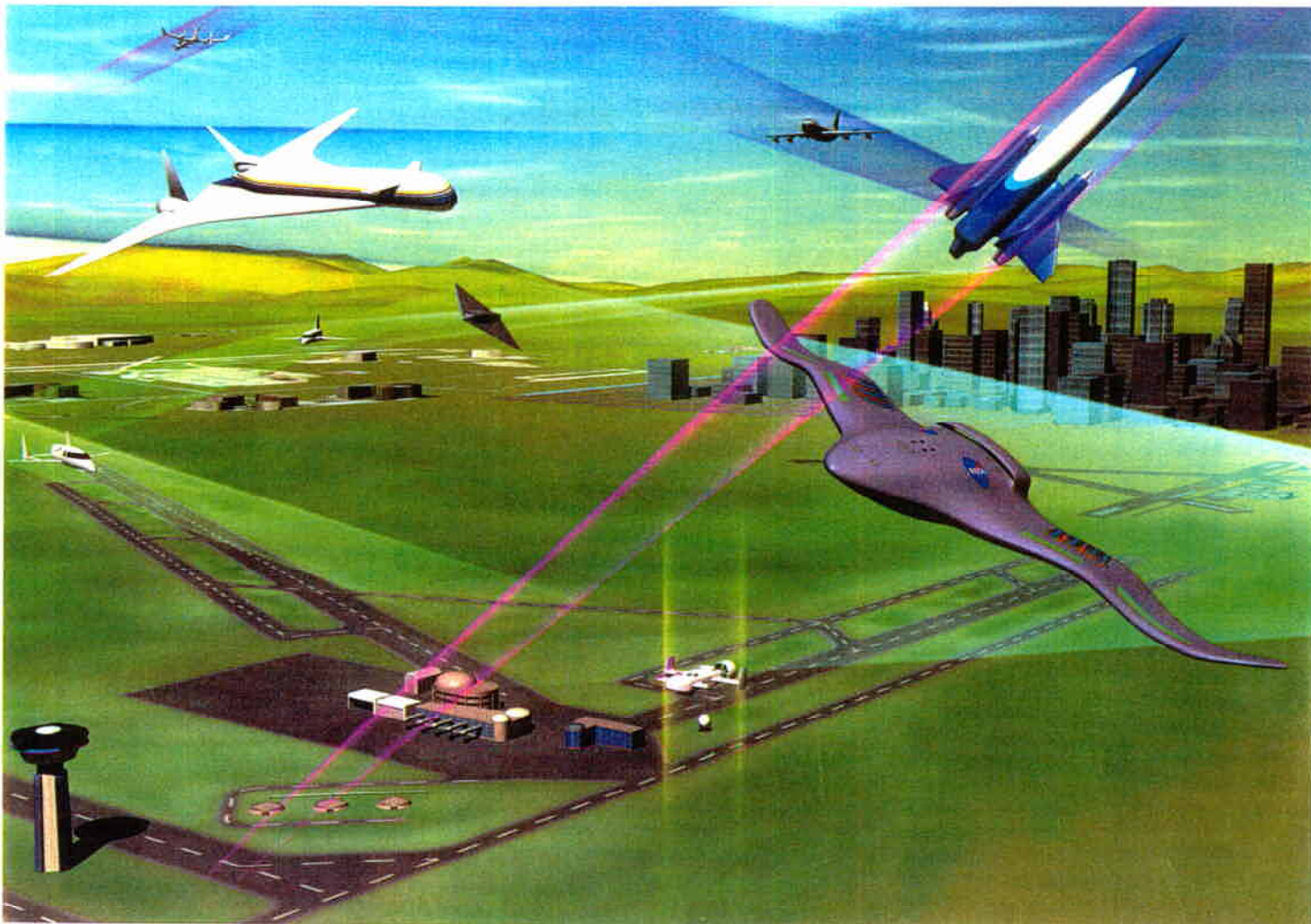
REVOLUTIONARY VEHICLES

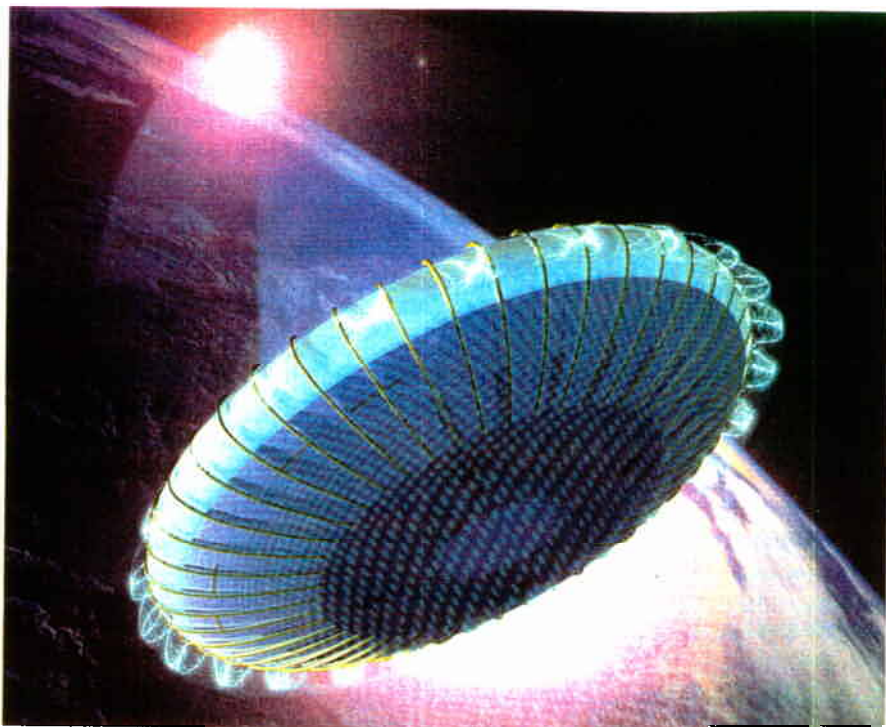
Our national bird, the eagle, can serve as an operational model for a future aircraft. Instead of being built of mechanically connected parts and systems, eagles use fully integrated, embedded smart materials—nerves, sensory receptors, and muscles—that enable exceptional levels of efficiency and control. We are beginning to mimic this capability through the synergistic coupling of bio-, nano-, and infotechnologies.

Molecularly designed materials, or nanomaterials, for example, have the promise to be 100 times stronger than steel and only one-sixth the weight. Their maximum strain can be 10 to 30 percent, much higher than any current structural material. Wings made from such materials could morph and continuously deform for optimal control during takeoff, cruise, and landing. Also, like those of birds, the wings and body will be integrated for exceptional strength and light weight.

The entire surface of the wing will be covered with tiny embedded sensors and actuators. Sensors, like the nerves of a bird, will monitor and analyze temperatures, pressures, and vibrations. In response to sensor data, actuators embedded in the structure will function like a bird's wing muscles. The actuators will smoothly change

Highways in the sky: Sophisticated future technologies that will be able to monitor and, if necessary, take control of aerospace vehicles could one day raise the safety and security of flight to permit unprecedented ease of travel.





Beamed energy propulsion is one of several concepts under study for future space missions; topics of investigation also include laser power and fission propulsion, antimatter, and sails to catch the solar wind.

mini engines, an exoskeletal engine, and pulse detonation engines. Adaptive propulsion system cycles with variable inlets and exhaust nozzles could be configured to mix the flow from the fan and hot exhaust to minimize noise on takeoff and enhance efficiency during cruise.

In the distributed engine concept, the two or three large engines are replaced by many mini or micro engines. The use of several small engines allows thrust modulation to replace the control surfaces in the tail and rudder. Micro engines can be more highly integrated with the vehicle airframe, potentially allowing a form of flow control that could reduce drag.

The exoskeletal engine derives its name from its non-standard design and is ideal for high Mach number applications. The turbomachinery blades are mounted inside a drum, rather than on the outer perimeter of a disc. This drum rotor places the blades in compression, allowing advanced composite and ceramic materials to be used, enabling lighter engines and higher operating temperatures.

the shape of the wing to adapt to flying conditions. The control surfaces will be integrated with the wing, instead of appended to it. And, active flow control effectors will help mitigate adverse aircraft motion in turbulence.

Across the entire vehicle, intelligent systems composed of sensors, actuators, microprocessors, and adaptive controls will provide a full-system, distributed knowledge network—a central nervous system to effect an adaptive physical response. The vehicles will be able to monitor their own performance, their environment, and even their operators. Eventually, vehicles may be able to anticipate and avoid impending failure, crashes, mishaps, and incidents through a distributed self-assessment and repair capability.

The application of high-temperature, molecularly designed materials to aircraft engines will be equally influential. Through successful application of advanced lightweight materials, in combination with intelligent flow control and active cooling, thrust-to-weight ratio increases of up to 50 percent and fuel savings of 25 percent are possible for conventional engines. Further advances in integrating these technologies will result in novel engine concepts that may simplify highly complex rotating turbomachinery.

Among the novel aircraft propulsion concepts considered are adaptive propulsion system cycles, distributed

side a drum, rather than on the outer perimeter of a disc. This drum rotor places the blades in compression, allowing advanced composite and ceramic materials to be used, enabling lighter engines and higher operating temperatures.

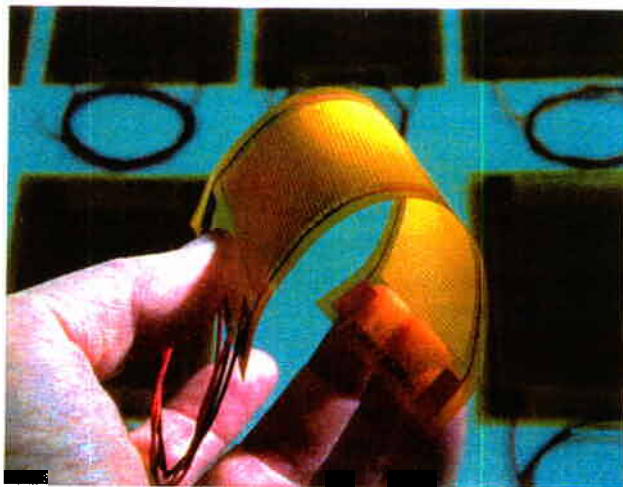
An open-cycle, pulse-detonation wave engine is an air-breathing, intermittent combustion jet engine that uses gas dynamics, instead of turbomachinery, to compress incoming

air. It relies on a traveling detonation wave for the combustion and compression elements of the propulsive cycle. Combined with intelligent engine control capability, such an approach can lead to integrated internal flow management and combustion control. However, the problems associated with noise and the design of a complex set of valves and ducting in this concept need to be addressed.

Carried a step further, all of these concepts have the potential to integrate airflow

over the airframe and through the propulsion systems for unprecedented efficiency, stability, and directional control. This will require new approaches to fully integrated airframe-propulsion design. Integrated propulsion and vehicle technology advancements could enable sustained supersonic flight with minimal impact from sonic booms or other environmental concerns.

In the very long term, comparable advances in electri-



A flexible piezoceramic actuator developed at NASA Langley Research Center can be used to control air- and spacecraft surfaces.

cal energy storage and generation technology, such as fuel cells, could lead to emissionless aircraft propulsion. Future aircraft might be powered entirely electrically. In one concept, thrust may be produced by a fan driven by highly efficient, compact electric motors powered by advanced hydrogen-oxygen fuel cells. However, several significant technological issues, such as efficient generation and storage, and an adequate infrastructure necessary for delivering the fuel to vehicles, must still be resolved in order to use hydrogen as a fuel.

FUTURE SPACE TRANSPORTATION

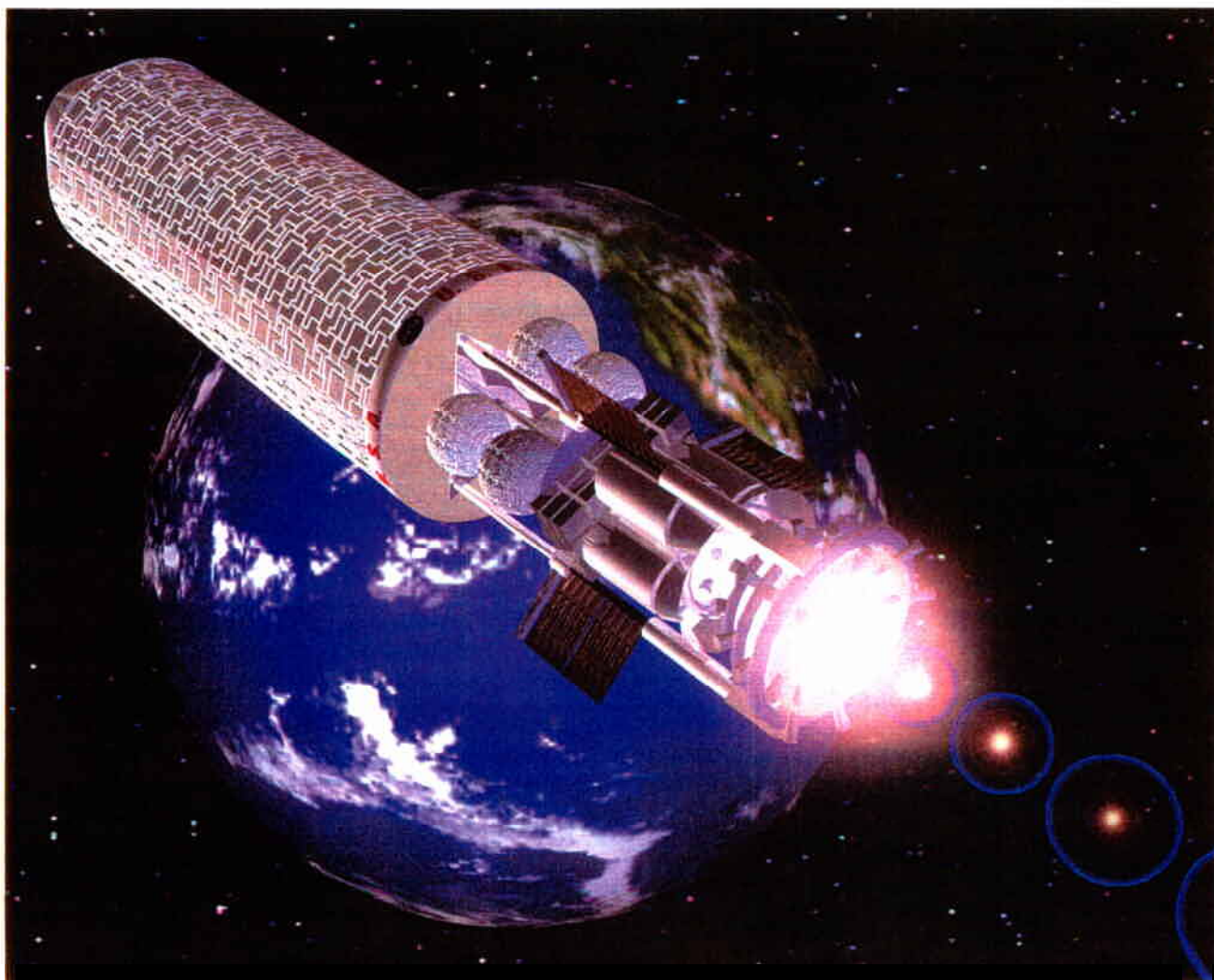
Opening the space frontier to new levels of exploration and commercial endeavor requires a significant reduction in the cost of transportation systems and an increase in their reliability and safety. The long-term goal is to make aerospace vehicles capable of operating from the Earth's surface all the way to orbit, and to eliminate the distinction between a commercial airliner and a commercial launch vehicle.

In the near term, NASA will address crew safety by integrating sensor and information systems into the vehicle for improved health management, and by providing in-flight crew-escape systems. The goal for Earth-

to-orbit systems includes reducing the launch cost to \$1,000 a pound and then to \$100 a pound, while reducing the probability of failure currently from about 1 in 250 to 1 in 1,000 for the loss of the vehicle and 1 in 10,000 for the loss of crew, and eventually to 1 in 1,000,000 for both.

To address these goals, NASA has developed an integrated plan for space transportation, which provides a phased strategy to ensure continued safe access to space. Investment in technical and programmatic risk-reduction activities will support full-scale development of commercially competitive, privately owned and operated Earth-to-orbit reusable launch vehicles, or RLVs. The plan includes developing an integrated architecture with systems that build on evolutionary technologies for Earth-to-orbit launch vehicles; and developing revolutionary technologies for reusable hypersonic vehicles and in-space transportation systems.

Setting the stage for aircraft-like operations for space access and reducing the life cycle cost of Earth-to-orbit vehicles will require advances in a number of technologies, including propulsion, airframes and cryotanks, all-weather thermal protection, avionics and flight control, vehicle health management and monitoring, and au-



Today it's only an idea, but a magnetized target fusion propulsion system may some day enable rapid, affordable access to any point in the solar system.

tomation technology to reduce ground operations costs.

Among the revolutionary propulsion concepts under consideration are supersonic combustion ramjet (scramjet), rocket-based combined cycle (RBCC), turbine-based combined cycle (TBCC), and magnetic launch assist.

The scramjet is a ramjet engine in which the airflow through the whole engine remains supersonic. Unlike rockets, the scramjet requires only onboard fuel, with the oxidizer obtained from the atmosphere. This offers significant weight and volume reductions, while the performance, which varies significantly with Mach number, exceeds that of a rocket over most of the flight trajectory.

The RBCC concept blends the performance of the

rocket, ramjet, and scramjet into one system for seamless ground-to-orbit operation. It uses a rocket engine integrated with a ramjet/scramjet flow path. The rocket engine consumes atmospheric oxygen when flying in the atmosphere. When it leaves the atmosphere, the inlet ducts close and the rocket engine consumes stored liquid oxygen. The concept offers safety, reliability, and cost advantages by making vehicles smaller and more efficient.

The TBCC is similar to the RBCC in that it uses both jet propulsion and rocket propulsion. Initially, inlet ducts provide air to turbojets that have common exhaust ducting with a rocket propulsion system. At low to moderate Mach numbers the turbojets provide thrust. The system

Smart Vehicle, Heal Thyself

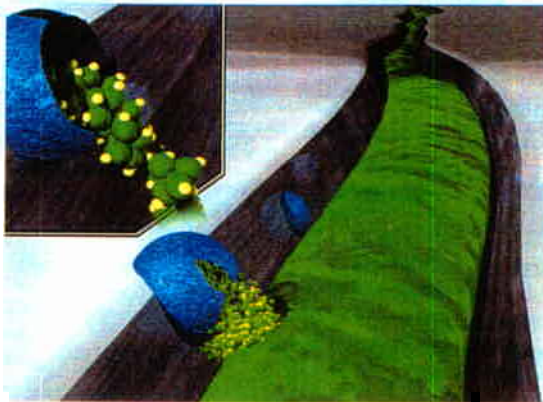
INTENSE WORK IS CURRENTLY being done at NASA, the Department of Defense, and other organizations to raise the bar for component vehicle technologies and to develop a suite of smart technologies and tools, which in combination can lead to revolutionary vehicle concepts and aerospace systems. A smart vehicle can assess a situation, determine if action needs to be taken, and, if so, take it.

"Smartness" can be characterized by self-adaptability, self-sensing, memory, and decision making. Smart vehicles can assess their own health and perform self-repair. They will also know how to fly to a safe haven under emergencies.

Smart vehicle technologies are a blend of smart materials and structures, innovative actuators and sensors, and intelligent flow control strategies—including sonic boom mitigation technologies, revolutionary propulsion ideas, and biologically inspired concepts. The field of smart materials and structures, for example, evolved over the past decades and increased its pace in the 1990s. It has inspired numerous innovative concepts in the United States and abroad.

Major demonstration programs have addressed structural health monitoring, vibration suppression, shape control and multifunctional structural concepts for spacecraft and launch vehicles, aircraft and rotorcraft. The demonstrations have focused on showing potential system-level performance improvements using smart technologies in realistic aerospace systems.

Some recent work related to smart vehicle technology has focused on the development of composite systems with active constituents, of distributed actuation systems, and of fiber optic and compact integrated sensor systems. Current trends aim at the atomic and molecular level to synthesize new materials that are functionally smart. Examples include molecularly imprinted polymers and other materials that contain inherent receptors for information. Other efforts are integrating diverse sensors on a single substrate, and



In a concept developed at the University of Illinois at Urbana-Champaign, micro capsules release a healing agent in a smart material.

working on practical techniques to fabricate them.

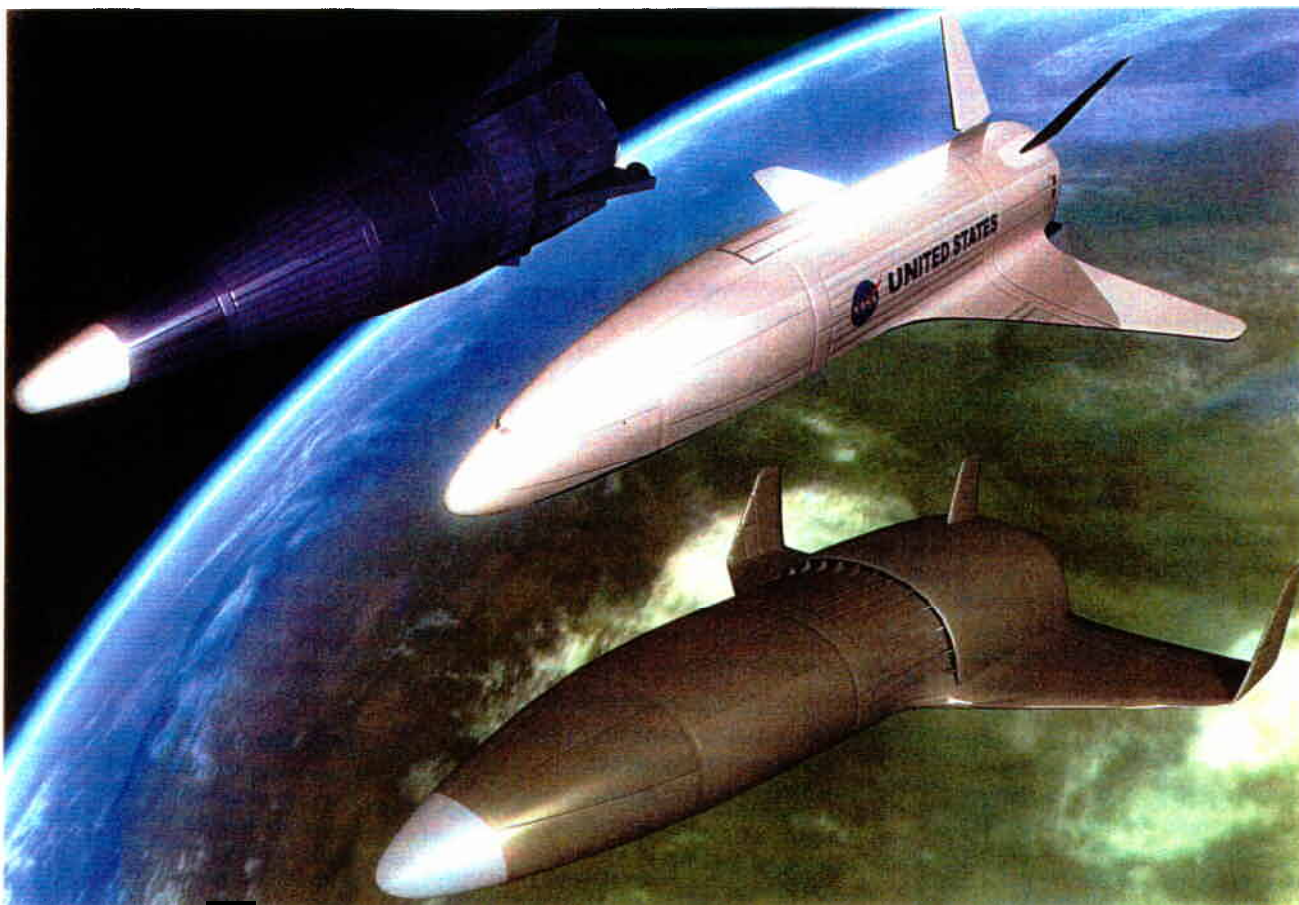
Self-healing material concepts have received increasing attention in recent years. For example, self-healing plastics use material that has the ability to heal cracks when fracture occurs. Shape memory alloys in composites can stop propagating cracks by imposing compressive forces, resulting from stress-induced phase transformation. Current research aims at developing adaptive, self-repairing materials and structures that can arrest dynamic crack propa-

gation, heal cracks, restore structural integrity and stiffness, and reconfigure themselves to serve more functions.

Controlling fundamental mechanisms in fluids has long been the focus of intense effort. Recent applications of air-flow sensing and intelligent control to air vehicles include improving performance by increasing lift or reducing drag generated by a surface and maneuvering through the use of fluidic devices. Current activities aim at understanding the physics associated with the shock wave formation in high-speed flight and developing designer fluid mechanics tools for all types of flow control—flow separation control, vortex control, laminar flow control, turbulent drag reduction, anti-noise, mixing enhancements, combustion control, circulation control, and favorable wave interference.

A suite of high-payoff sonic boom mitigation technologies is being explored for reducing the sonic boom overpressure to an acceptable level to people on the ground (less than 0.3 pounds per square foot). Techniques include air-frame shaping, heat addition, particulate injection, leading-edge plasma generation, temporal and spatial variation of lift distribution, and adaptive flow control.

Indirect reduction of sonic boom amplitudes can also be achieved by decreasing vehicle gross weight, or increasing vehicle lift-to-drag ratio by maintaining supersonic laminar flow. In addition, the use of intelligent propulsion control systems is being explored for efficient, reliable operation of the complex supersonic inlet/engine/nozzle system.



Possible space transportation vehicles: The aim is to bring down the cost of reaching orbit, while safety increases more than a thousand-fold.

then closes off inlet flow from the atmosphere, shuts down the turbojets and converts to rocket propulsion.

In magnetic launch, the vehicle is accelerated horizontally along a track, using magnetic levitation to eliminate friction. Instead of the initial liftoff acceleration being provided by the onboard engines, linear electric motors are used to accelerate the launch vehicle to an initial speed of up to 1,000 kilometers per hour. This initial boost can significantly reduce the amount of fuel needed to reach orbit and, thus, potentially increase payload for a given vehicle weight.

A number of other propulsion concepts are being explored for potential use in outer planet and interstellar space missions, including electric propulsion, fission propulsion, laser-powered propulsion, antimatter propulsion, mini-magnetospheric plasma propulsion that couples to the solar wind for thrust, and space sails (both solar and laser driven). Space-based, electrically driven rotating tethers are also being evaluated for use to boost the velocity of near-Earth spacecraft.

FUTURE AIRSPACE SYSTEM

The current U.S. national airspace system is a complex collection of facilities, equipment, procedures, and airports that operate nonstop, 24 hours a day throughout the year. The FAA and NASA are currently making substantial efforts to modernize the equipment and procedures in order to enhance the efficiency of the airspace, and the safety of its operations. These efforts

include development of a suite of decision-support tools to improve gate-to-gate air traffic management. They also include deployment of technologies for transitioning from ground-based navigation and surveillance systems to precise and reliable satellite-based systems, in order to provide broader, more uniform coverage over the entire country for increased safety and expanded capacity.

The air traffic management system must be robust, able to tolerate equipment failures and interferences such as severe weather, and must be automatically adaptable to deal with increases in traffic. One approach for achieving scalability is through linking air traffic management with an automatic flight management system onboard each aircraft.

Such an air traffic management system will be built on global systems, such as GPS and future constellations of communication satellites. This will allow a precise approach to every runway without requiring installation of expensive, ground-based gear, such as instrument landing equipment, at every airport.

The system will enable the air traffic controller to have both regional and global views of the airspace. And, it will have a high degree of automation, both in the air and on the ground, but human oversight will be retained.

Improved methods of weather data collection, processing, and transmission will be integrated into the airspace system. A significant challenge upon which the new ar-

chitecture depends is the robustness of the global communication, navigation, and surveillance systems. The new system must allow graceful degradation—that is, be able to tolerate multiple failures and still be safe. Robustness in the system needs functional redundancy of communication, navigation, and surveillance systems, for example. This includes the ability to transition automatically and seamlessly from a space-based system to a ground-based system, such as LORAN.

With a robust global system maintaining precise knowledge of position and trajectory for every aircraft, it will no longer be necessary to restrict flying to predetermined corridors. Optimal flight paths will be deter-



NASA 507, a certified Lancair Columbia 300 general aviation aircraft, has state-of-the-art avionics, color moving map/GPS, and side-arm control stick.

mined in advance and adjusted along the way for changes in weather and aircraft traffic.

Each aircraft will become capable of avoiding traffic. It will have an advanced flight management system that provides full knowledge of all aircraft in its area and enables it to coordinate, through an airborne internet, with other planes. The pilot will be able to look at his flight path at different

scales—from a strategic view of the entire route, showing other aircraft and weather systems, to a tactical view showing the immediate surroundings and flight path over the next few minutes.

Other technologies for improving safety and situational awareness may use advanced sensors, digital terrain

Working for More Secure Airspace

THE TRAGIC EVENTS OF Sept. 11, 2001, have made a tremendous impact on civil aviation. A number of technologies can be deployed, adapted, or developed to significantly enhance aviation security and restore public confidence in the system. These technologies can be grouped into three categories, ranging from direct aircraft protections to general security improvements.

Various overrides of the flight control system can prevent even a determined pilot from crashing an aircraft into a specific ground target. The technologies already in development for aviation safety purposes can be adopted for security applications as well.

Technology can be refined to create a "refuse-to-crash aircraft." An automatic ground collision avoidance system, now an active project of the automobile industry, combined with aircraft control, can be applied to commercial airplanes for unusual attitude recovery and ground collision avoidance. The national and worldwide terrain/obstacle database, already under development by a number of organizations, can be extended to identify protective shells, or prohibited airspace, around selected areas such as specific high-risk facilities. The algorithms in the collision avoidance system could interpret these protected areas as hard terrain and force the aircraft to avoid them.

Advanced autopilot, similar to the controls currently used in unmanned surveillance aircraft, can serve as a security backup. In the event of an emergency, or unauthorized deviation, manual flight controls could be disabled by a signal from the pilot or from ground controllers and allow automated safe flight to the nearest secure airport.

An aircraft damaged by a terrorist attack or system failure could, in many cases, be landed safely through the use of reconfigurable flight controls, a technology that has been demonstrated and is based on work by NASA, DOD, FAA, and the aerospace industry, to com-

pensate for damaged or failed systems.

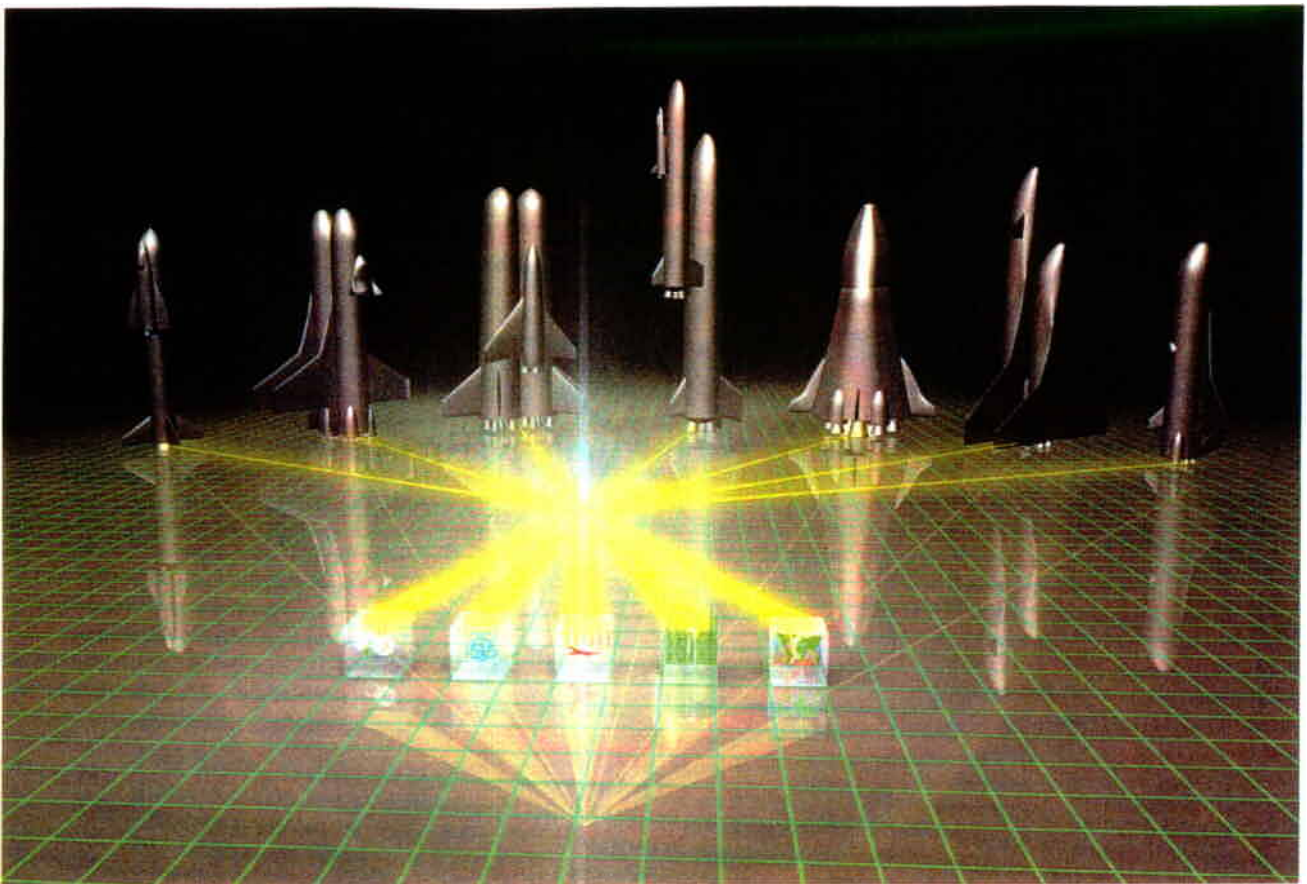
Potentially threatening deviations from the flight paths can be automatically brought to the attention of ground controllers. Such anomaly detection requires the use of an advanced alerting system, capable of assessing the probability that an aircraft is under malign control or the probability of a collision with some object or place. The system would build on existing efforts to develop airspace flow control automation, visualize air traffic patterns, and quantify aviation safety risk by monitoring and modeling air traffic patterns.

Linking passenger cabins and flight stations with ground communication networks into an integrated information environment can enable safety—or potential security—issues to be uncovered during a flight.

The use of biometric technologies (including fingerprint sensors, retinal scans, and facial recognition systems) for verification and identification can ensure that flight controls are used only by authorized pilots.

Enhanced airport and aircraft security can be achieved by using a multilayered suite of trace-detection and active imaging technologies. Examples of instruments using these technologies are compact trace gas analyzers, biosensors, high-tech systems to detect molecular-level evidence of explosives and firearms, and high-speed, low-cost 3-D imaging technologies integrated with better information technology databases and decision support systems, such as automated pattern recognition devices.

These instruments could enable the implementation of a central security screening at a check-in location, and a distributed, roving security detection system that encompasses the total airport environment and individual aircraft. Linkage of various distributed information databases could enable near real-time identification of potential passenger threats.



NASA is pursuing a variety of concepts using various forms of propulsion for reusable launch vehicles, to lower the cost of space exploration.

databases, accurate geo-positioning, and digital processing to provide three-dimensional moving displays showing aircraft, landing and approach patterns, runway surfaces, fixed and moving objects on the ground, and other relevant information.

In the long term, full situational awareness will be achieved through interactive technologies (including voice recognition, eye tracking, and physiological monitoring). Cognitive neuroscience may allow observers to assess pilots' state of alertness, to let them know when they are showing signs of fatigue and to give them warning before they make mistakes.

NEEDED: INTELLECTUAL INFRASTRUCTURE

Although aerospace technologies made significant advances in the last century, they have not reached a plateau. Technology advances in this century will be driven as much by the need for enhanced security, safety, and environmental compatibility as by the desire for improved efficiency, performance, and reduced operating costs. Combining biological, nanoscale, information, and other technologies can lead to the revolutionary vehicle concepts and airspace management. Realizing the vision requires the creation of knowledge organizations, linking diverse interdisciplinary teams from NASA, other government agencies, universities, aerospace industry, and technology providers into hierarchical research and learning networks, configured as neural networks.

The learning networks will stimulate critical thinking

and intellectual growth and promote intermingling among critical fields such as biological nanoscience, information science, and engineering disciplines. They will create a new generation of skilled scientists and engineers who can work across traditional disciplines and perform in rapidly changing environments. The research networks will link diverse, geographically dispersed teams and facilities.

The infrastructure enables collective intelligence, innovation, and creativity, through networking, to bear on the increasing complexity of future systems. Since a high percentage of experienced engineers in the aerospace industry will be eligible for retirement in a few years, the infrastructure could also offset the diminishing design team experience base in industry.

The airspace system can be integrated with the other two sets of transportation services—land and water—to form a comprehensive intermodal transportation system, functioning as one seamless whole, maximizing passengers' and shippers' options for convenience, efficiency, and reduced cost. It is a complex system of highly interconnected subsystems with multiple interfaces, shared information and infrastructure elements, and collaborative air-ground decision-making.

System integrity is absolutely essential to achieving this kind of far-reaching vision. A systems-engineering approach must be used to define requirements, reinvent processes, formulate operational concepts, evaluate them, and then launch goal-oriented technology activities to transform the concepts into realities. ■