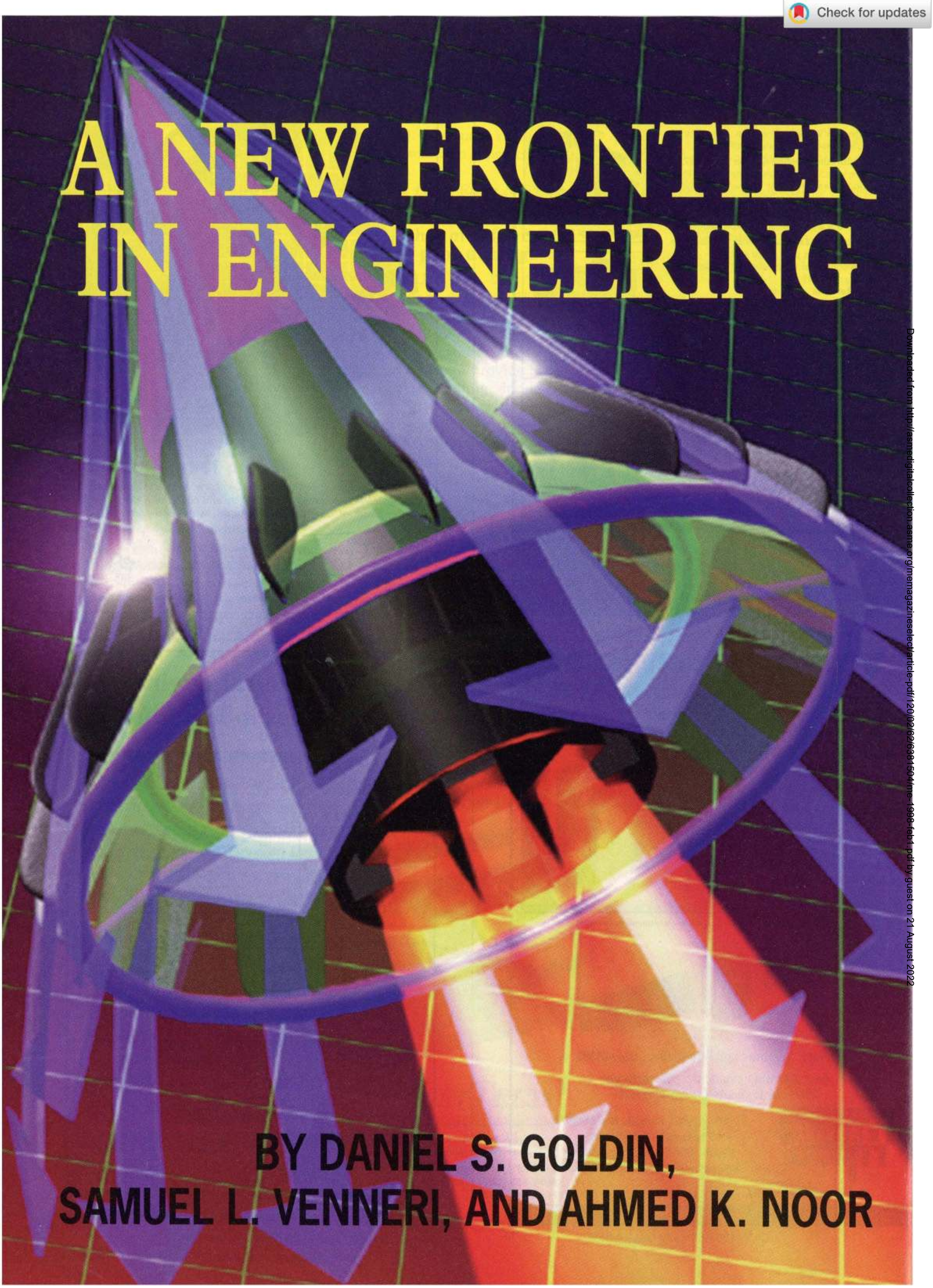
A NEW FRONTIER IN ENGINEERING



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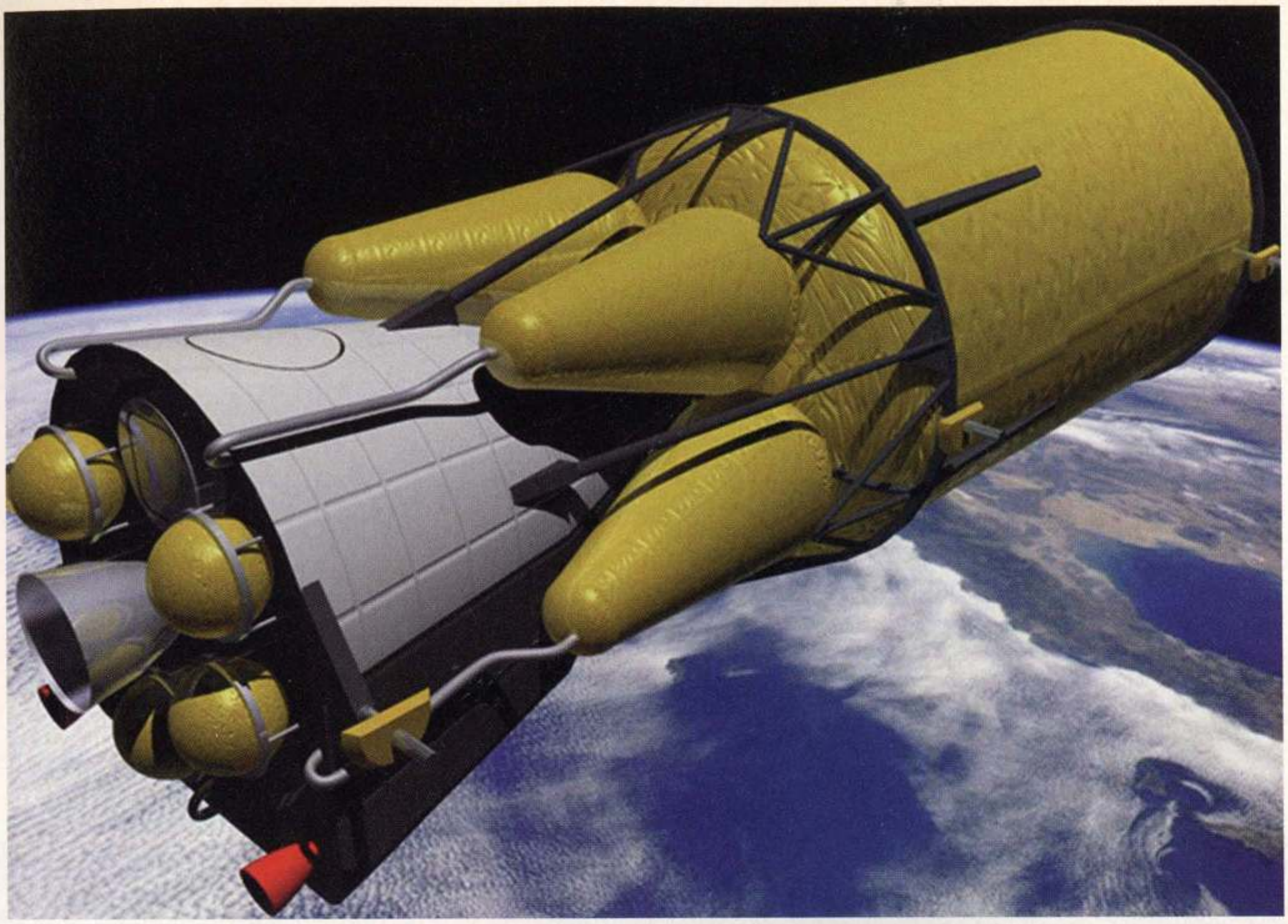

An intelligent synthesis environment will dramatically change the tools and processes used to design future aerospace systems.

HUMAN ASPIRATIONS FOR the conquest of space are higher than ever as new and emerging technologies bring some of the most ambitious missions within scientists' and engineers' reach. At the same time, economic considerations are helping to keep the costs and aims of such missions closer to Earth than ever before. Because space missions must provide a high degree of scientific payoff at an affordable cost, aerospace industries are reducing costs and development time as well as incorporating new technologies in their products to improve performance. Moreover, scientists and engineers are being asked to produce better mission scenarios and product designs in less time.

Recent missions have achieved significant successes, but traditional-mission synthesis approaches, sequential design, and manufacturing processes are clearly inadequate to achieve these goals in the long term. Dramatic changes are needed in how missions are synthesized and in how aerospace systems are designed, produced, operated, maintained, and disposed of. The intelligent-synthesis-environment (ISE) concept being developed by NASA, the University of Virginia's Center for Advanced Computational Technology at NASA's Langley Research Center in Hampton, and the Jet Propulsion Laboratory in Pasadena, Calif., is an attempt to meet the needs and challenges of tomorrow's aerospace systems.

FUTURE AEROSPACE SYSTEMS

Several design features will significantly affect aerospace systems. For example, a high degree of autonomy is emerging as a technological area of strategic importance to future missions. In addition to requiring revolutionary propulsion, an interstellar probe intended to travel past Pluto—to cite just one possibility—must be a "thinking," intelligent spacecraft. Such a probe will feature embedded sensors; actuators; an elaborate information-processing system; and intelligent software agents that can actively monitor a situation, exhibit intelligence by reasoning and responding to tasking, and work toward goals based on the current environment. Because the probe

The new synthesis environment will help improve travel into space. Magneto-hydrodynamic drive capabilities, for example, may reduce payload costs for Earth-to-orbit missions (left). Also, a reusable low-cost commercial orbital transfer vehicle (above) will add mobility in space.

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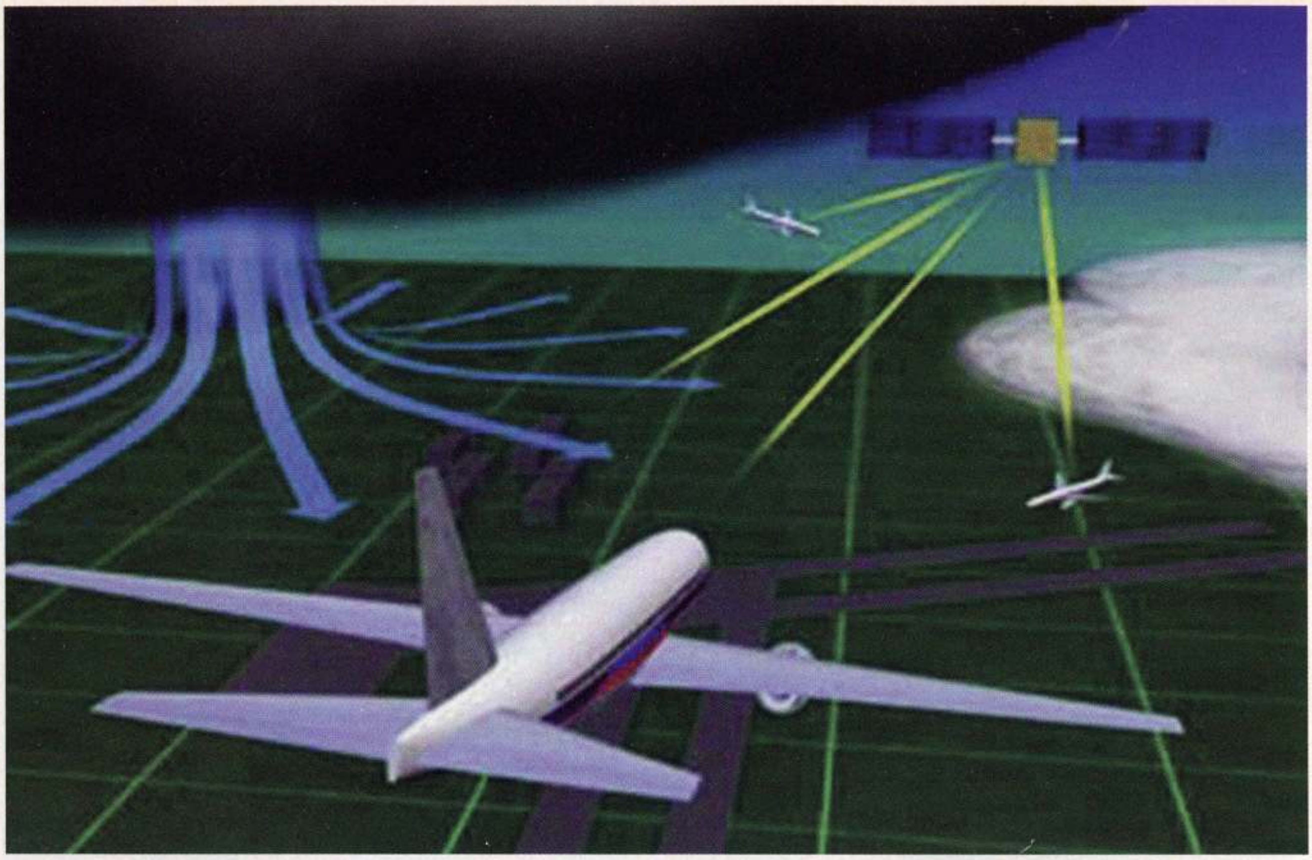

One part of NASA's Aeronautics and Space Technology Enterprise will reduce the cost, triple the capacity, and enhance the safety of air travel.

will be too far away, the time delays will be too great for the craft to be controlled from Earth. Moreover, the spacecraft will need to learn, adapt, and make decisions as it goes, and be self-diagnostic and self-repairing.

The development of such structures promises significant benefits closer to home. These intelligent systems will also be used in near-Earth craft and even vehicles operating in the Earth's atmosphere. They will allow for the safe reuse of future transportation systems with minimal maintenance and operational constraints, which translates into lower costs over the systems' operating life.

Another important design feature is the use of engineered multifunctional materials and structures. In addition to supporting loads, multifunctional structures use sensors to detect and evaluate loads or failure as well as interact with the surrounding electromagnetic environment. They are used for reducing the mass and volume of the aerospace system, lowering its manufacturing and maintenance costs, and improving its performance. Modularity—the use of modules to tailor vehicle capabilities to specific mission needs—will also be significant, as will miniaturization of subcomponents or of the entire vehicle.

Aerospace systems will also need to survive harsh environments. Large areas of air vehicles will be exposed simultaneously to extreme thermal and acoustic load levels (for example, airframe temperatures of 400°F to 1,500°F and noise levels up to 170 decibels). These state-of-the-art designs can easily weigh more than twice that of structures for nonextreme environments. Design-life requirements of future systems also far exceed those of current vehicles. Advanced materials and structural concepts will be needed for primary structures, leading edges and nose caps, cryotanks, and thermal protection systems to reduce their weight and cost as well as improve the reliability of these systems.

Furthermore, unlike current space missions, which require many people in mission control and in the back rooms, future outposts should be fully autonomous with only a skeleton crew in mission control.

Several factors will drive the design of these aerospace systems, including rapid prototyping, which requires reducing design-cycle and development times; affordability, with an emphasis on reducing life-cycle cost; and improved performance from the insertion of new technologies. The benefits of concurrent engineering, which became popular among high-tech companies in the late 1980s, are many, but the techniques involved require immense human engineering effort and have limited capability for full life-cycle cost analysis, multidisciplinary integration and optimization, bounding uncertainties, and the collaboration of geographically dispersed teams. Moreover, even with concurrent engineering approaches, a large percentage of the system cost is committed when very little knowledge is available about the system, thereby limiting the flexibility of design changes.

In an attempt to alleviate the shortcomings of concurrent engineering, several government agencies and industry programs have been devoted to simulation-based-design (SBD) approaches, which rely on simulating the entire life cycle of the engineering system before physical prototyping—from concept development to detailed design, prototyping, qualification testing, operations,

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maintenance, and disposal. This seamless process encompasses risk assessment and life-cycle cost, and it is performed in a distributed environment linking geographically dispersed design and manufacturing teams, facilities, and resources. The new concept of the intelligent synthesis environment is an extension of the SBD concept.

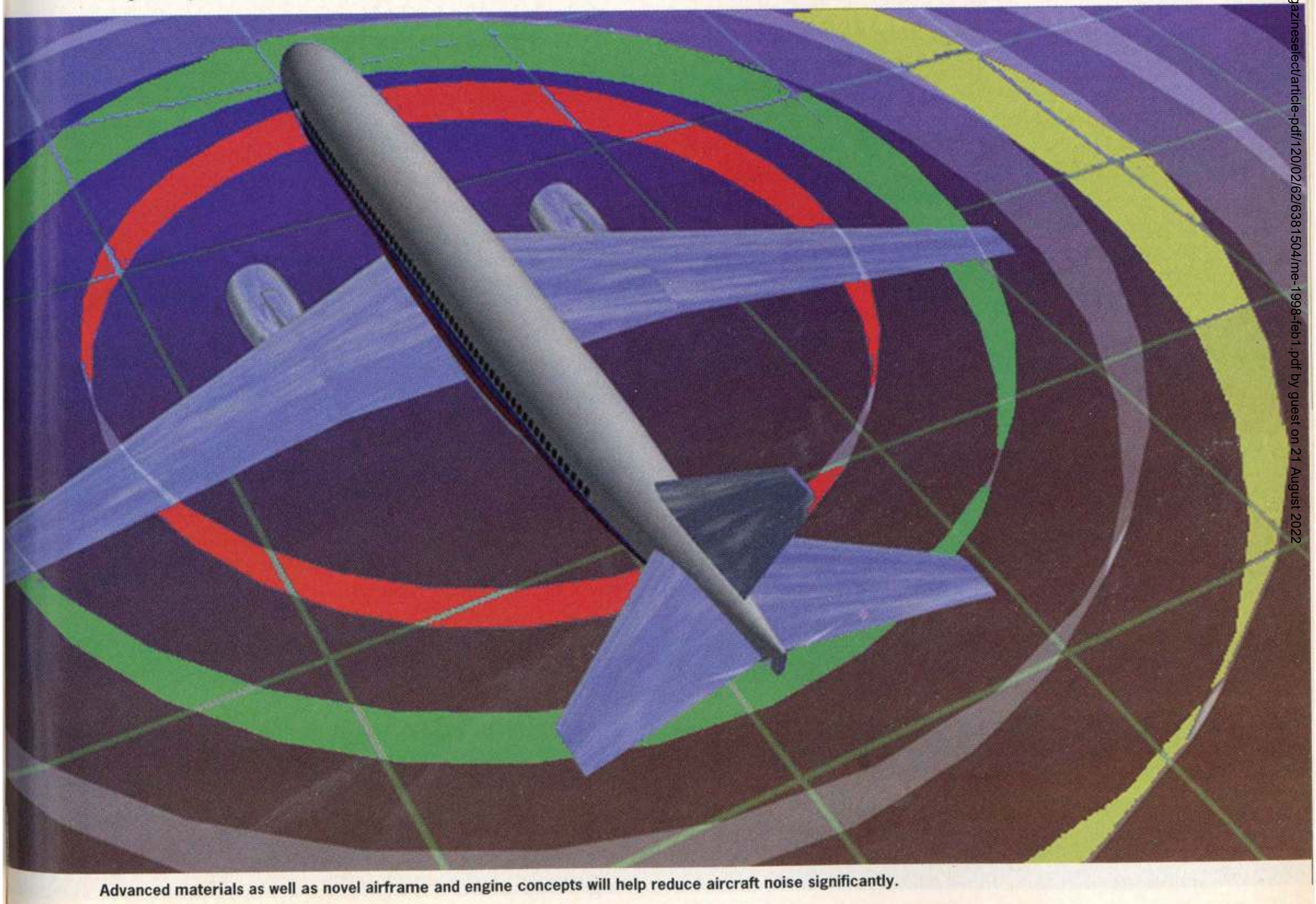
THE ISE CONCEPT

The ISE represents a fundamental cultural change in engineering design and mission synthesis that can significantly enhance the rapid creation of innovative, affordable products and missions. ISE combines leading-edge technologies effectively to build or assemble a widely distributed, integrated collaborative virtual environment for synthesizing missions as well as for designing, testing, and prototyping aerospace systems. The technologies used are high-performance computing, high-capacity communications and networking, virtual product development, knowledge-based engineering, computational intelligence, human-computer interaction, and product information management.

The environment links scientists, design teams, manufacturers, suppliers, and consultants who participate in mission synthesis and in the creation and operation of the aerospace system. To support the entire mission design and management, the virtual environment incorporates advanced computational, communication, and networking facilities and tools. The environment is adaptable and intelligent with respect to end users and hardware platforms. ISE should radically advance the process by which complex science missions are synthesized and high-tech engineering systems are designed, manufactured, and operated. The five components critical to ISE are human-ISE interaction, an infrastructure for distributed collaboration, rapid synthesis and simulation tools, intelligent life-cycle system integration, and cultural change in the creative process.

The objective of the human-ISE interaction component is to increase the productivity and enhance the creativity of the science, engineering, and technology teams by significantly enhancing the communication bandwidth among users as well as between each user and the facilities. ISE will be highly interactive and capable of dynamically mapping information into visual, auditory, or kinesthetic representations. Multimedia information is presented to the user in an intuitive and coordinated form.

The four subelements of the human-ISE interaction component are immersive and advanced interfaces, a distributed scenario builder, interactive agents, and human-system dynamics. The first subelement includes shared displays and effectors. Shared displays refer to group vir-



Advanced materials as well as novel airframe and engine concepts will help reduce aircraft noise significantly.

tual-reality facilities such as the Vision Dome of Alternate Realities and the Reality Center of Panoram, which provide users with a wide field of view without head-mounted displays or stereo glasses. Current interaction devices include position trackers and sensing gloves, as well as facilities for visual, audio, and haptic feedback (head-mounted displays, three-dimensional audio localization, and the like).

By being immersed in the virtual design environment, engineers can create and modify their designs in real time, seeing the effects of their modifications immediately. Emergent virtual environment technology seeks to create perceptual experiences through direct neural stimulation. Also, adaptive reconfigurable interfaces will be developed to take advantage of the advances made in cognitive neuroscience to couple humans with the computing facilities and maximize their performance.

The interactive agents in ISE include not only software agents but also cooperative physical agents such as robots, intelligent devices, and other nonhuman agents. Raw data (small unstructured items) can be organized and refined into more efficient representations. Information, knowledge, and intelligence are progressively smaller subsets of increasingly more organized data. Hierarchical software agents will generate information and knowledge from large unstructured data sets.

DISTRIBUTED COLLABORATION

The infrastructure for the distributed-collaboration component of ISE provides the facilities and resources that make location completely transparent to the mission-synthesis and product-design teams. It enables the assembly of the best knowledge databases, heterogeneous distributed computing, and other resources, as well as diverse, geographically dispersed teams. It has three major subelements: ultrafast computers, high-capacity communications and networking, and diverse team collaboration.

Ultrafast computers include teraflop-scale computers such as those planned for Department of Energy labs. As for communications and networking, the next-generation Internet and Internet 2 should alleviate performance problems associated with constricted network bandwidth and provide rapid communication of the latest project data, a key requirement for reducing project cost and time. They will also enable high-quality real-time interaction between users in heterogeneous distributed virtual-reality facilities.

One feature of diverse-team collaborative computing is the virtual collocation facility, based on the concept of immersive telepresence. Participants are able to interact fully, even exchanging objects and walking around each other, in three dimensions. No special glasses, wands, or gloves are required.

RAPID SYNTHESIS AND SIMULATION

The next component of ISE is rapid synthesis and simulation tools. It comprises four subelements: traditional deterministic and nondeterministic methods, nontraditional methods, life-cycle numerical simulations, and design-synthesis languages. The life-cycle numerical simulation tools include high-fidelity rapid-modeling facilities and physics-based simulation tools for structures, aerodynamics, controls, thermal management, power, propulsion, and optics. They also include tools for mission design, cost estimating, product assurance, safety analysis, risk management, virtual manufacturing and prototyping, testing for qualification, maintenance and operations, training, and life-cycle optimization. Special optimization tools are used for the entire life cycle of the aerospace system as well. For modular vehicles, a group of vehicles is optimized over a spectrum of missions.

Many of the ISE tools are provided by commercial CAD/CAM/CAE systems and by other codes developed under government-supported programs. Several features distinguish these tools from those of traditional design systems. One is the seamless integration of multiphysics analysis software into CAD/CAM/CAE systems to provide a complete mission-simulation and virtual-product-development facility. Parametric, variational, and feature-based solid modeling methods are combined to generate a single "smart" product model. This eliminates data transfers and interfaces, and allows detailed analyses from within the CAD system on the latest model throughout the design process. It can also reduce simulation time and the number of physical prototypes built.

Another feature that distinguishes ISE tools is the incorporation of Internet-enabling software, rapid-modeling facilities, and object-oriented technology, particularly in the user interface and databases for CAD/CAM/CAE systems. The use of object-oriented technology enables a plug-and-play capability for model assembly. *Plug* refers to an object-oriented user interface for the rapid assembly of component models. While developing product models can be time-consuming, model generation via assembly and resizing of parts and components is relatively fast. *Play* refers to immediately available predictions of response, risk, cost, and performance information.

Further distinguishing characteristics include seamless interfaces (translation) from the CAE system to the virtual environment, with mathematically correct visualization of the product and tools, and the use of computational intelligence technology and associated soft computing tools to solve complex design problems with system uncertainties. The principal constituents of soft computing are neurocomputing, fuzzy logic, and genetic algorithms. Soft computing tools exploit the tolerance for imprecision and uncertainty in real aerospace vehicles to achieve tractability, robustness, and low solution cost.

The ISE tools incorporate facilities to assist the designer in selecting the appropriate computational model and analysis technique as well as design-synthesis languages for the rapid generation and modification of engineering specification for large product models. The use of these languages in conjunction with knowledge-based engineering methodologies can make possible the detailed description of the different design and synthesis tasks from a high-level specification of the functional requirements.

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LIFE-CYCLE INTEGRATION

The ISE component that covers intelligent life-cycle system integration has three subelements: system integration methods, national test beds, and large-scale demonstrations.

Focused-area test beds will be developed to assess, validate, and demonstrate the ISE concept and its components. The test beds will be distributed, reconfigurable, and accessible to geographically dispersed diverse teams. They will provide a showcase for demonstrating how state-of-the-art computational and communication facilities and tools can be used by engineering, science, manufacturing, operations, and training teams to dramatically improve productivity, enhance creativity, and foster innovation at all levels of product and mission development. Simulating and testing all mission and life-cycle phases of an aerospace system will be accomplished within the test beds.

These test beds will enable engineers to evaluate several design and mission scenarios and to perform global optimization of the aerospace system relative to mission goals. Each will be accessible, integrated, and information-based. To aid design decisions, tools that provide a global view of the development process, including information on product assembly and test, as well as vehicle and total-mission costs, should be part of the environment. These tools include knowledge discovery in databases, knowledge sharing, and product-information-management software.

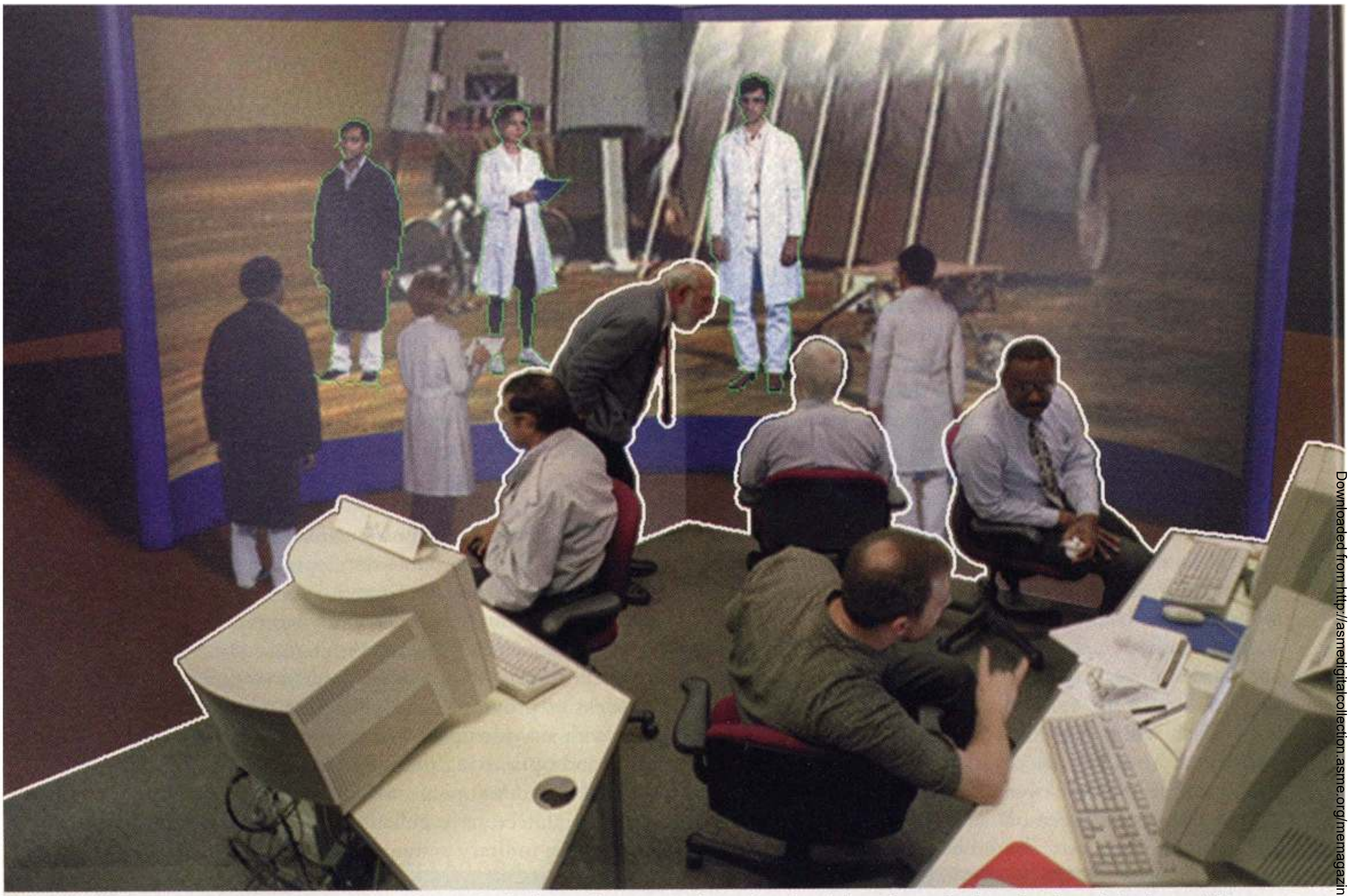
The capabilities described for the test beds require globally accessible object-oriented multidatabase systems. These will initially be used to store simple objects such as drawings, but will later become repositories of information and applications such as intelligent agents. The salient components for semiautonomous agent-based integration of the tools and facilities include mediators, software agents, knowledge-based systems and design advisers, software architecture for design environments, and authoring tools and requirements tracking.

REALIZING ISE

The potential benefits of collaborative, distributed environments for virtual product development and scientific research have led the government to initiate several efforts, including three at the Defense Advanced Research Projects Agency (DARPA) in Washington, D.C.

One effort by DARPA covers simulation-based design, and seeks to provide geographically distributed enterprises with a synthetic environment for planning, developing, and optimizing products through virtual prototyping. SBD is developing and demonstrating a prototype software architecture to enhance the acquisition process for complex military systems. The goals are to reduce

The rocket-based combined-cycle X vehicle is an intelligent, single-stage-to-orbit concept for low-cost access to space.



An immersive telepresence will enable geographically dispersed teams to work together, share information, and reduce planning and development times.

life-cycle cost and acquisition-cycle time for military systems, meet affordability objectives without compromising operational performance, allow requirements to be refined through the product-development process, and enable effective acquisition-process reform.

The second DARPA project, exploring rapid design exploration and optimization (RaDEO), will develop the comprehensive information modeling and design tools for the rapid design of complex electromechanical systems. Efforts focus on technologies that improve the ability to explore, generate, track, store, and analyze design alternatives.

RaDEO addresses the definition and development of personal, organizational, and artifact webs that will build on an existing infrastructure, such as the Internet and the World Wide Web. A major goal is to develop integrated CAD/CAE systems in which the resulting product and process models have underlying representations that can be shared, reused, and merged with other models.

The third program coming from DARPA is for agile infrastructure for manufacturing systems (AIMS). This focuses on creating an Internet-based infrastructure so companies can share resources, and on devising business practices to support the operation of a "virtual organization," an arrangement in which complementary resources that exist in several cooperating organizations are left in place but are integrated to support a particular product effort. Resources are selectively allocated to the virtual organization if they are underused or can be used profitably outside the home organization. AIMS features autonomous intelligent agents performing multiple roles and knowledge-based systems for use in assessing manufacturability and in matching process capabilities and needs with production planning and scheduling.

Other areas of government are also involved with ISE efforts, such as the National Institute of Standards and Technology (NIST) in Gaithersburg, Md. NIST's System Integration for Manufacturing Applications Program provides a mechanism for communicating product and process data among various manufacturing activities, including product and process design, analysis, planning, scheduling, production, and quality control.

Another NIST project, the National Advanced Manufacturing Testbed (NAMT), is an information-based manufacturing project aimed at helping industry develop 21st century manufacturing capabilities—moving from interchangeable parts to interchangeable factories, from mass production to mass customization, and from trial-and-error experimentation to modeling and simulation. At NAMT, cross-disciplinary teams can work together to accelerate the development of standards for facilitating the interoperability of manufacturing systems and the rapid insertion of new technologies into these integrated systems.

In addition, the Knowledge and Distributed Intelligence Program of the National Science Foundation in Washington, D.C., is exploring the potential of the synergistic combination of advances in information, communications, computing, and networking in various science and engineering applications. The program has three major components: learning and intelligent systems, knowledge networking, and new computational challenges.

Another government program, the Advanced Design and Production Technologies Initiative of the Department of Energy in Washington, D.C., actually sponsors three programs: Enterprise integration, for example, provides new and improved information tools, while integrated product and process design and agile manufacturing develop and deploy new design and manufacturing capabilities, and process development implements new processes and improves existing ones.

Several related projects are also under way in the private sector. For example, design-process innovation is currently being pursued by major aerospace companies such as Boeing in Seattle and Lockheed Martin in Fort Worth, Tex. Initiatives have been launched to radically simplify and streamline the design process.

Boeing, for instance, incorporated SBD in its 777 jumbo-jet program. At the peak of design work, 238 design-build teams—comprising approximately 8,000 people, with as many as 6,000 engineers—used SBD in this effort. Data from 4,000 worldwide computer terminals were linked to eight IBM mainframe computers to manipulate more than 3 trillion bytes of information representing 20,000 design releases.

Boeing's St. Louis–based group has a design, manufacturing, and producibility simulation project for virtual manufacturing and virtual prototyping. It focuses on geometric processes for rapidly generating mold-line surfaces for use in various analyses, loads that can be generated early and quickly updated, feature-based finite-element modeling for pushing the analysis early in the design process, feature-based design for efficient generation and updating of drawings, and virtual prototyping for the automatic generation of electronic mock-ups from design drawings. The virtual prototypes determine producibility and ensure early on that system requirements will be satisfied. The new tools being developed in this project cover assembly simulation, process-flow simulation, and numerically controlled machine-tool simulation. These tools are integrated with CAD systems, scheduling tools, work instructions, and planning.

Lockheed Martin, meanwhile, is integrating advanced simulation and modeling tools to create a virtual design and manufacturing environment for the joint strike fighter and the F-22 fighter plane. The Simulation Assessment Validation Environment (SAVE) Program integrates a core suite of off-the-shelf modeling and simulation tools via DARPA-funded rapid prototyping of application-specific signal-processing architecture. The program leverages several related DARPA systems including SBD, AIMS, and the national industrial information infrastructure protocol, which allows integration of different modeling and simulation tools.

SAVE will enable integrated product teams to assess design alternatives quickly and to define a product's cost and risk early and accurately. A follow-up to the SAVE program is the virtual-product-development program now in the works.

FUTURE DIRECTIONS

Advances in computer performance, human-centered systems, communication, and networking technologies will include teraflop- and petaflop-scale machines, mobile computing, optical and wireless communications, new modes of human-computer interaction, and the next-generation Internet and Internet 2. Such developments will occur alongside equally significant changes in the distributed heterogeneous immersive virtual environment and CAD/CAM/CAE suites. These will include miniature wearable computing devices for the immersive environment plus facilities for concurrent engineering and science teams to look at key design criteria early in the mission planning and design process. All of these advances will enable rapid accommodation of new synthesis paradigms as well as dramatic improvements in the mission design and development processes of aerospace systems.

The ISE will create an overall framework that can lead to a revolutionary cultural change in the engineering design and certification process, and radically change engineering and science research in the future. ISE goes beyond connectivity to achieve new levels of multimodal interactivity and integration of diverse teams. It will significantly increase the creativity, knowledge, and cultural bandwidths among these teams. This will significantly reduce development times, lower life-cycle costs, and improve the science payoff of future space missions as well as the quality and performance of future aerospace systems.

In the next decade, simpler, more-efficient design and development tools, including a design language, will likely be created. ISE will evolve into a shared, highly flexible, information-based, responsive synthesis environment with plug-and-play interoperability across dispersed and disparate organizations, including hardware and software facilities. It will expand the scope of tradeoff analysis; allow multicriteria evaluation of mission scenarios and design and manufacturing options; optimize the product characteristics for quality, manufacturability, ease of assembly, and maintainability; and quickly prototype complex products and processes.

Realizing the full potential of ISE will entail educating and training science and engineering teams, not only in the component technologies but also in new approaches for collaborative distributed synthesis and virtual product development. Researchers need to address a number of fundamental issues, including human factors, group and team dynamics, information security, and the costs and benefits of ISE facilities and tools in various categories of applications. Universities can work with industry, government labs, and professional societies in developing effective instructional and training facilities for the new design approach. The challenge facing large aerospace companies is to effect a cultural change that will transform their design and manufacturing sectors into rapidly configurable, flexible learning organizations that are relentless in their focus on improving processes and products. ▪