FINAL REPORT
NASA Cooperative Agreement NCC-1-263

CENTER FOR ADVANCED COMPUTATIONAL TECHNOLOGY

Submitted to:

National Aeronautics and Space Administration
Intelligent Synthesis Environment Program Office
Office of Director
Mail Stop 202
Hampton, VA 23681-2199

Attention:

Kimberly A. Cannon


Submitted by:

Ahmed K. Noor
Ferman W. Perry Professor of
Aerospace Structures and Applied Mechanics

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DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF VIRGINIA
CHARLOTTESVILLE, VA 22903

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# Abstract

The Center for Advanced Computational Technology (ACT) was established to serve as a focal point for diverse research activities pertaining to application of advanced computational technology to future aerospace systems. These activities include the use of numerical simulations, artificial intelligence methods, multimedia and synthetic environments, and computational intelligence, in the modeling, analysis, sensitivity studies, optimization, design and operation of future aerospace systems. The Center is located at NASA Langley and is an integral part of the School of Engineering and Applied Science of the University of Virginia. The Center has four specific objectives: 1) conduct innovative research on applications of advanced computational technology to aerospace systems; 2) act as pathfinder by demonstrating to the research community what can be done (high-potential, high-risk research); 3) help in identifying future directions of research in support of the aeronautical and space missions of the twenty-first century; and 4) help in the rapid transfer of research results to industry and in broadening awareness among researchers and engineers of the state-of-the-art in applications of advanced computational technology to the analysis, design prototyping and operations of aerospace and other high-performance engineering systems.

In addition to research, Center activities include helping in the planning and coordination of the activities of a multi-center team of NASA and JPL researchers who are developing an intelligent synthesis environment for future aerospace systems; organizing workshops and national symposia; as well as writing state-of-the-art monographs and NASA special publications on timely topics.

The Principal Investigator for this Cooperative Agreement is Dr. Ahmed K. Noor, Ferman W. Perry Professor of Aerospace Structures and Applied Mechanics, who is serving as the Director for the Center, and the NASA Langley monitor is Ms. Kimberly A. Cannon, ISE Program Office, NASA Langley Research Center.

## Overview of Activities

During the course of the grant (January 1, 1997-December 31, 2000), the Center activities included:

1. Conducting research in the following areas: a) intelligent synthesis environment for future aerospace systems; b) application of virtual reality, multimedia and computational intelligence to aerospace systems; c) dynamic simulations of flexible multi-body systems; d) innovative computational strategies for large-scale nonlinear structural problems; e) prediction and analysis of damage and failure of structural components; f) thermo-mechanical buckling, post-buckling and failure-analysis of composite and sandwich panels and shells; g) high-fidelity modeling of flight vehicle structures; h) design-oriented CST; and i) reanalysis strategies for large-scale design optimization. The research activities will be coordinated with on-going research at NASA Langley, NASA Ames, JPL, and whenever appropriate, with other NASA Centers. A brief description of each research activity is given in Appendix I.

2. Help in the planning of the Intelligent Synthesis Environment (ISE) Project and taking charge of the cultural change component of the project. This involves, among other things, developing advanced multimedia and virtual reality training and educational facilities, and coordinating the activities of university teams, commercial software vendors, industrial firms on ISE, with those of NASA and JPL researchers. A brief description of the ISE Project is given in Appendix II.

3. Organizing one or two workshops every year.

4. Organizing training workshops and seminars by leading experts in different areas of ACT at NASA Langley Research Center.

5. Writing and editing special publications and monographs on timely topics.

6. Working out collaborative agreements with leading centers in the U.S. in areas that significantly impact the development of ACT. Some of the resources of these centers were used in our research projects at no cost to the grant.

## Facilities

The computational and experimental facilities at NASA Langley Research Center were used in performing part of this research. Other computational facilities (e.g., at NSF Illinois and San Diego Supercomputer Centers, CRAY Research, and the High Performance Computing Center at Vicksburg, MS) were used by special arrangement with Dr. Ahmed K. Noor at no cost to the grant.

## Summary of Accomplishments

During the course of the grant a total of seven research scientists, three visiting scientists, one senior programmer/analyst, one programmer, three program support technicians, three graphic designers/artists, one executive secretary, two office service specialists, and twelve co-op students were supported by the Center. The list of the Center staff (and dates of their appointments) is given in Appendix III. The accomplishments of the Center during this period, under Cooperative Agreement NCC-1-263 included completing three monographs; publication of eight NASA CP's, five technical articles, thirty-four multimedia presentations; organizing five seminars; and maintaining cooperative agreements with thirteen commercial software vendors. These accomplishments are listed in Appendices IV-VII and are briefly described subsequently.

1. Conducting research in the following general areas: a) application of multimedia, virtual reality and computational intelligence to engineering problems; b) prediction and analysis of failure of structural components made of composite materials, and subjected to combined thermal and mechanical loads; c) uncertainty analysis for large structural systems; and d) nonlinear structural dynamics.

   A total of five technical publications and thirty-four presentations have been made under Cooperative Agreement NCC-1-263 during the course of the grant. A list of the publications

and presentations are given in Appendix IV. Also, the abstracts of the publications are included in Appendix VII.

2.  Completing three monographs:

>   Noor, A. K. and Venneri, S. L. (eds.), *Future Aeronautical and Space Systems*, AIAA Progress in Aeronautics and Astronautics Series, Washington, D.C., Vol. 172, 1997.

>   Noor, A. K. (ed.), *Structures Technology: Historical Perspective and Evolution*, AIAA, Reston, VA, 1998.

>   Noor, A. K. (ed.), *Structures Technology for Future Aerospace Systems*, AIAA Progress in Aeronautics and Astronautics Series, Washington, D.C., Vol. 188, 2000.

3.  Organizing seven workshops. Proceedings containing the presentations made at each of the workshops were published. A list of the workshops is included in Appendix V.

4.  Organizing a seminar series by experts in computational technology and related areas. The list of seminars is given in Appendix V.

## Appendix I - Research Projects

**Intelligent Synthesis Environment for Future Aerospace Systems.** A distributed, collaborative virtual synthesis environment is being developed for radically advancing the process by which complex aerospace systems are designed, manufactured and operated. The environment will be used for simulating the entire life cycle of aerospace systems from concept development, detailed design, and prototyping to qualification testing, operations and disposal. It will incorporate the state-of-the-art computational, communication and synthetic environment facilities and tools. The environment will be highly interactive and capable of dynamically mapping information into visual, auditory or kinesthetic representations. It will include computational intelligence modules (fuzzy logic, evolutionary strategies and neural networks), and the infrastructure for collaborative computing among geographically dispersed teams. The computational tools in the environment cover the entire life cycle of the aerospace system and include high-fidelity rapid modeling facilities, and physics-based simulation tools for structures, dynamics, controls, optics, thermal management, power and propulsion. They also include tools for mission design, cost modeling and estimating; product assurance, safety analysis and risk management; as well as tools for simulation of prototyping, testing for qualifications and operations. The environment will help in assessing the manufacturability and in the rapid insertion of new product technology. It will significantly shorten the design and development times of future aerospace systems, reduce their life-cycle cost, and improve their performance.

**Innovative Computational Strategies for Large-Scale Structural and Coupled Problems.** The scope of this research covers transient thermal and dynamic problems, nonlinear static problems, and postbuckling problems. The three major activities are:

*Hierarchical adaptive modeling strategies* for simulating response phenomena occurring at disparate spatial and time scales, using reasonable computer resources. The strategies use multiple mathematical models in different regions of the structure to take advantage of efficiencies gained by matching the model to the expected response in each region. Adaptivity in the strategy minimizes reliance on *a priori* assumptions about the response. An object-oriented interactive environment is being developed which not only allows the use of different numerical algorithms in different parts of the structure, but allows the algorithms to be changed dynamically during computation.

*Strategies for the effective use of diverse high-performance computing platforms.* The platforms considered include supercomputers such as the Cray 916 and Cray 3, massively parallel systems, and other scaleable MIMD platforms such as the Intel Paragon XP/S, Cray T3D and IBM SP2. General guidelines are produced for designing future large-scale structural analysis programs that will run efficiently on distributed heterogeneous computing platforms or on hardware tailored for structural calculations.

*Effective hybrid strategies*, including numerical/analytical and numerical/ neurocomputing methods.

**Prediction and Analysis of Damage and Failure of Structural Components.** Practical numerical simulation techniques are sought for predicting the failure initiation and propagation in structural components, especially those made of new high-performance materials in terms of measurable and controllable parameters. Examples of these materials are high-temperature materials for hypersonic vehicles; piezoelectric composites; electronic, optical, and smart materials for space applications. For some of the materials, accurate constitutive descriptions, failure criteria, and damage theories are needed, along with more realistic characterization of interface phenomena (such as contact and friction). The constitutive descriptions may require investigations at the microstructure level or even the atomic level; as well as carefully designed and conducted experiments. Current work at the Center focuses on: a) *development of computational models and effective strategies* for simulating the dynamic failure and damage of metallic structures, and evaluating the sensitivity of failure initiation and propagation to variations in both the microstructure and macrostructure material parameters. An elastic-viscoplastic material model is used, with a temperature-dependent flow strength. The model incorporates thermal softening due to adiabatic heating, and ductile failure by void nucleation; b) *identification of structural response quantities which can be used in predicting failure initiation and propagation* in new materials; and c) *effective coupling between numerical simulations and experiments* to understand the physical phenomena associated with material-level damage, damage growth, and the subsequent structural failure.

**Thermomechanical Buckling, Postbuckling and Failure Analysis of Composite and Sandwich Panels and Shells.** This area includes the study of buckling and postbuckling responses as well as failure characteristics of laminated composite and sandwich panels subjected to combined thermal and mechanical loads. Both stiffened and unstiffened, flat and curved panels, as well as panels and shells with cutouts are considered. Current work is focused on understanding the thermomechanical response and studying the role of transverse stresses in the failure of composite panels and shells. The overall objective of this research is to develop a verifiable failure analysis capability for fibrous composite and sandwich panels and shells subjected to various loading conditions.

**High-Fidelity Modeling of Flight Vehicle Structures.** One of the most important steps for the accurate prediction of the response of a complex aerospace structure is the proper selection and sequencing of mathematical and discrete models, with varying degrees of complexity. Hence, there

is a need for the development of automatic model generation facilities as well as smart interfaces to the analysis and design systems. The smart interfaces will be AI-based expert systems which run on workstations, can help the engineer in the initial selection of the model, its adaptive refinement, selection of the solution procedure, constraint representation, and the interpretation of results. The work at the Center focuses on identification of modeling details (e.g., computational material models, modeling of joints and damping) needed for accurate description of the response of the structure.

**Design-Oriented CST.** The realization of new complex aerospace vehicles (e.g., hypersonic vehicles and control-configured aircraft and spacecraft) requires high levels of integration between the structures discipline and other traditionally separate disciplines such as aerodynamics, heat transfer, propulsion, controls, and electro-magnetics. This is because of the significant interdisciplinary interactions and couplings, and the need to account for these couplings in predicting the response, as well as for the optimum design of these vehicles.

New methodologies are needed for integrated design and optimization of aerospace vehicles in the presence of strong interdisciplinary couplings. Work at the Center focuses on: a) development of sensitivity and computational intelligence methods for large-scale problems; and b) effective approaches for linking of CST to other disciplines through modular integration and/or simultaneous treatment of the different disciplines (at the governing equations level).

**Reanalysis Strategies for Large-Scale Design Optimization.** Effective reanalysis strategies are being developed for use in the optimum design of large structural components (with large numbers of degrees of freedom, loading cases, design variables, and constraints). Current work focuses on use of multilevel sub-structuring; lumping of design variables into tracing parameters that identify the effect of structural modifications on individual substructures; and application of operator splitting/reduction technique to generate the response of the modified structure as a large perturbation from that of the original structure. Quantitative measures for the sensitivity of the response quantities to modifications of the individual substructures are generated as an integral part of the proposed strategy. The strategy is being applied to both static, free vibration, nonlinear and dynamic problems.

**Nonlinear Structural Dynamics for Space Systems.** The tasks included in this research are: a) development of efficient computational strategies for predicting the transient response and internal loads of large spacecraft subjected to impact loads (e.g., docking forces), simulating the response of articulated dynamical systems, and evaluating the sensitivity of the dynamic response of large actively controlled spacecraft to variations in geometric and material parameters, as well as to actuator/sensor locations; and b) development of model reduction techniques for use in control/structural interaction problems of large spacecraft. The articulated dynamical systems considered are flexible multi-body systems that include deployable space structures, space robots and manipulators. An attempt is made to exploit the major characteristics of high-performance computers in the strategies developed.

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## Appendix II - Intelligent Synthesis Environment

1. Overall Goal

The overall goal of the activity is to build/assemble an advanced synthesis environment for aerospace systems incorporating the state-of-technology in computational, communication and networking facilities and tools. The environment links scientists, design teams, manufacturers, suppliers and consultants who participate in mission synthesis and in the creation and operation of aerospace systems. The environment is adaptable and intelligent with respect to end users and hardware platforms. It is expected to radically advance the process by which complex aerospace missions are designed and vehicles are designed, manufactured and operated. It will significantly shorten the design and development times of future aerospace systems, reduce their life-cycle cost, and improve their performance.

The specific objectives of ISE are to:
- Advance engineering and science practices across all organizational and expertise levels.
- Develop advanced analytical methods and tools to rapidly conduct complete mission life-cycle simulations and identify and quantify the impact and benefit of new technology
- Develop prototype virtual collaborative engineering and science environments
- Demonstrate advanced ISE capability on large-scale applications for selected NASA missions
- Develop and demonstrate life long learning methods and procedures applicable to all organizational levels.

2. Scope of the Activity

The applications include reusable space transportation systems, shuttle and ground processing, international space station operations, integrated exploration and science, and advanced earth observation system.

3. Major Components

The following four major components of the environment have been identified:
- Life-cycle simulation
- Environment
- Product integration
- Cultural infusion.

The four components are described subsequently.

3.1 *Life-Cycle Simulation*

This component covers the integrated life-cycle design and analysis tools with emphasis on cost, risk and probabilistic modeling. It has two sub-components; namely, life-cycle toolbox and multidisciplinary analysis technology.

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## 3.2 *Environment*

The objective of this component is to provide the computational framework for collaborative infrastructure, systems architecture, user interfaces, maintenance and operations support.

## 3.3 *Product Integration*

This component aims at integrated validation of ISE technology throughout the formulation, development and operation phases of the NASA life cycle. It has three sub-components; namely, core integrated product set, enterprise-specific products, and integration test and validation.

## 3.4 *Cultural Infusion*

This involves infusion of ISE advances throughout NASA. It has three sub-components; namely, collaboration and teaming, learning systems, and measurement and assessment.

A critical strategy of ISE is a three-pronged approach addressing revolutionary research and development, insertion into practice and cultural change in the way the agency does engineering and science for its missions. ISE research and development laboratories are being established to focus on strategic technologies, such as non-traditional tools, non-deterministic methods to bound uncertainty, knowledge capture and knowledge bases, implementation of information technologies, virtual prototyping, synthetic environments and seamless interoperability for integrated life cycle engineering and science. Emerging ISE technologies derived from research and development are applied to selected NASA large scale applications, focused on high priority NASA missions such as reusable space transportation system concepts, operations processes for the International Space Station and Shuttle, advanced earth observation system concepts, and integrated exploration and science mission concepts. Cultural change focuses on pioneering the advanced engineering and science practices that must accompany the ISE-derived research and development in order to achieve the desired reductions in design cycle time, and test and fix time and costs. The inclusion of the large-scale applications and cultural change, in conjunction with research and development, give this initiative a unique character. Computational large-scale application testbeds are being established at selected NASA Centers and the Jet Propulsion Laboratory.

**Appendix III - Center Staff**

A. Research Scientists

1. Abdel-Tawab, Khaled I. (Ph.D.), Univ. of Texas at Austin (appointed Aug. 18, 1997; terminated Nov. 20, 1998).
2. Elmustafa, Abdelmageed A. (Ph.D.), University of Wisconsin, Madison (appointed July 10, 2000).
3. Leamy, Michael J. (Ph.D.), University of Michigan, Ann Arbor (appointed Sept. 27, 1999; terminated June 9, 2000).
4. Malik, Moinuddin (Ph.D.), Univ. of Oklahoma, Norman, OK (appointed Aug. 18, 1997; terminated Aug. 23, 1999).
5. Wasfy, Tamer M. (Ph.D.), Columbia University, NY (appointed Mar. 13, 1955; terminated Feb. 23, 1999; appointed Dec. 29, 1999 as part-time Research Scientist).

6. Xu, Yonglin (Ph.D.), Northwestern University (appointed Oct. 7, 1998; on extended medical leave).

B. Supporting Staff

1. Carlson, Richard F., Office Services Specialist (appointed July 12, 1999 part time; terminated July 26, 1999).
2. Copeland, Michael K., Graphic Designer (appointed March 30, 1998 part time; Dec. 1, 1999 full time).
3. Fox, Mary L., Executive Secretary (appointed July 1, 1990).
4. Ganoe, Thea E. M., part-time Program Support Technician (appointed Dec. 19, 1996; terminated Aug. 16, 1999).
5. Grey III, Sinclair, Graphic Artist (student intern appointed June 1998; terminated Jan. 1999)
6. McCoy, Alan R., Programmer (appointed Jan. 8, 1997; terminated Dec. 15, 2000).
7. Mesibov, Linda P., Program Support Technician (appointed Jan. 6, 1997; terminated April 9, 1998).
8. Peters, Jeanne M., Senior Programmer Analyst (appointed July 1, 1990).
9. Richter, Catherine M., Program Support Technician (appointed June 21, 1993; terminated February 7, 1997).
10. Tran, Khanh T., Office Services Specialist (appointed Nov. 15, 1999; terminated Jan. 28, 2000).
11. Wilson, Derrick E., Graphic Designer (appointed Sept. 19, 1996 part time student intern; Oct. 18, 1999 full time Graphic Artist; Oct. 2000, Graphic Designer).

C. Visiting Scientists/Scholars (Courtesy Appointments)

1. Habib, Sami, Fulbright Scholar, King Abdulaziz Univ., Jeddah, Saudi Arabia, (June 9-Aug. 21, 1997)
2. Rolfes, Raimund, Visiting Scientist, German Aerospace Research Establishment (DLR), Braunschweig, Germany (Jan. 10, 1997-March 15, 1997)
3. Sparr, Holger, Visiting Research Assistant, German Aerospace Research Establishment (DLR), Braunschweig, Germany (Nov. 1, 1997-Oct. 31, 1998).

D. Summer Students

1. Chin, Tammy E., Univ. of Mississippi (appointed May 18-July 31, 1998)
2. Fox, Brent S., Univ. of Mississippi (appointed May 18-July 31, 1998)
3. McAfee, Jason A., Univ. of Mississippi (appointed May 18-July 31, 1998)
4. Phillips, Albert M., Univ. of Mississippi (appointed May 18-July 31, 1998)
5. Bettis, Jeffrey A., Univ. of Mississippi (appointed May 20-June 29, 1999)
6. Fine, Amanda G., Univ. of Mississippi (appointed May 20-June 29, 1999)
7. Reichley, Christopher M., Univ. of Mississippi (appointed May 20-June 29, 1999)
8. Zegledi, S. Tammy, Univ. of Mississippi (appointed June 3-Aug. 13, 1999)
9. Early, Christopher M., Univ. of Virginia (appointed June 5-Aug. 18, 2000)
10. Greenlee, Christopher C., Univ. of Mississippi (appointed May 21-Aug. 11, 2000)
11. Strohm, Luke S., Univ. of Virginia (appointed May 21-Aug. 18, 2000)
12. Thompson, Robert M., Univ. of Mississippi (appointed May 21-Aug. 11, 2000)

# Appendix IV - Publications and Presentations
## (Jan. 1, 1997 – Dec. 31, 2000)

A. Publications

Books Edited:

1. Noor, A. K. and Venneri, S. L. (eds.), *Future Aeronautical and Space Systems*, AIAA Progress in Aeronautics and Astronautics Series, Reston, VA, Vol. 172, 1997.

2. Noor, A. K. (ed.), *Structures Technology: Historical Perspective and Evolution*, AIAA, Reston, VA, 1998.

3. Noor, A. K. (ed.), *Structures Technology for Future Aerospace Systems*, AIAA Progress in Aeronautics and Astronautics Series, Reston, VA, Vol. 188, 2000.

Journal Articles/Book Chapters/Papers in Conference/Workshop Proceedings/Reports:

1. Xu, Y. and Noor, A. K., "Perturbation Mapping Method for Sensitivity Analysis of Three Dimensional Cracks Near a Free Surface," *Computer Methods in Applied Mechanics and Engineering*, Vol. 189, No. 2, Sept. 2000, pp. 613-624.

2. Wasfy, T. M. and Noor, A. K., "Multibody Dynamic Simulation of the Next Generation Space Telescope Using Finite Elements and Fuzzy Sets," *Computer Methods in Applied Mechanics and Engineering* (to appear).

3. Noor, A. K., Doyle, R. L. and Venneri, S. L., "Autonomous, Biologically-Inspired Systems for Future Space Missions," *Advances in Engineering Software*, Vol. 31, No. 7, July 2000, pp. 473-480.

4. Noor, A. K., "Computational Structures Technology," in *Structures Technology for Future Aerospace Systems*, A. K. Noor (ed.), AIAA Series Progress in Astronautics and Aeronautics, Reston, VA, Vol. 188, pp. 351-406.

5. Wasfy, T. M. and Noor, A. K., "Object-oriented Virtual Environment for Visualization of Flexible Multibody Systems," *Advances in Engineering Software* (to appear).

Special Journal Issues Edited:

1. Argyris, J. A., Noor, A. K. and Papadrakakis, M. (eds.), Recent Advances and Trends in Composite Materials and Structures, *Computer Methods in Applied Mechanics and Engineering*, Vol. 185, Nos. 2-4, May 2000.

2. Noor, A. K. and Birman, V. (guest eds.), *Journal of Sandwich Structures and Materials* (special issue honoring the 70th Birthdays of Charles W. Bert and Jack R. Vinson), Vol. 2, No. 3, July 2000.

3. Noor, A. K. and Birman, V. (guest eds.), *Composites Science and Technology* (special issue honoring the 70th Birthdays of Charles W. Bert and Jack R. Vinson), to appear.

4. Noor, A. K. and Birman, V. (guest eds.), *Composite Structures* (special issue honoring the 70th Birthdays of Charles W. Bert and Jack R. Vinson), to appear.

5. Noor, A. K. and Birman, V. (guest eds.), *International Journal of Solids and Structures* (special issue honoring the 70th Birthdays of Charles W. Bert and Jack R. Vinson), to appear.

Conference Proceedings Edited/Compiled:

1. Noor, A. K. and Malone, J. B. (compilers), *Computational Tools and Facilities for the Next-Generation Analysis and Design Environment*, Proc. of the workshop held Sept. 17-18, 1996, Hampton, VA, NASA CP-3346, March 1997.

2. Noor, A. K. and Malone, J. B. (compilers), *Next Generation CAD/CAM/CAE Systems*, Proc. of the workshop held March 18-19, 1997, Hampton, VA, NASA CP-3357, Sept. 1997.

3. Noor, A. K. and Malone, J. B. (compilers), *Government-Sponsored Programs on Structures Technology*, Proc. of the workshops held April 6, 1997 in Kissimmee, FL and Sept. 4, 1997 in Hampton, VA, NASA CP-97-206241, Nov. 1997.

4. Noor, A. K. and Malone, J. B. (compilers), *Computational Tools and Facilities for the Next-Generation Analysis and Design Environment*, Proc. of the workshop held Sept. 17-18, 1996, Hampton, VA, NASA CP-3346, March 1997.

5. Noor, A. K. and Malone, J. B. (compilers), *Advanced Technology for Engineering Education*, Proc. of the workshop held Feb. 24-25, 1998, Hampton, VA, NASA CP-1998-208443, July 1998.

6. Noor, A. K. and Malone, J. B. (compilers), *Intelligent Agents and Their Potential for Future Design and Synthesis Environment*, Proc. of the workshop held Sept. 16-17, 1998, Hampton, VA, NASA CP-1999-208986, Feb. 1999.

7. Noor, A. K. and Malone, J. B. (compilers), *Advanced Training Technologies and Learning Environments*, Proc. of the workshop held March 9-10, 1999, Hampton, VA, NASA CP-1999-209339, July 1999.

8. Noor, A. K. (compiler), *Nanobiotechnology*, Proc. of the workshop held June 14-15, 2000, Hampton, VA, NASA CP-2000-210546, Nov. 2000.

B. Presentations

1. Noor, A. K., "Some Future Directions for Computational Structures Technology," Interdisciplinary Symposium on Advances in Computational Mechanics, University of Texas, Austin, TX, January 13-15, 1997; International Conference on Computational

Engineering Science (ICES'97), Costa Rica, May 4-9, 1997; Spring Conference, Virginia Consortium of Engineering and Science Universities, Hampton, VA, June 11-12, 1997.

2. Noor, A. K., "Recent Advances in Sensitivity Analysis for Nonlinear Structural Mechanics Problems," IUTAM/IACM Symposium on Discretization Methods in Structural Mechanics II, Vienna, Austria, June 2-6, 1997.

3. Noor, A. K., "Application of Automatic Differentiation to the Sensitivity Analysis for Failure and Damage in Dynamically-Loaded Tensile Bars," Fourth U.S. National Congress on Computational Mechanics, San Francisco, CA, Aug. 6-8, 1997.

4. Noor, A. K., "Leading the Revolutionary Changes in Engineering Processes and Scientific Investigations," ASME International Mechanical Engineering Congress and Exposition, Nov. 16-21, 1997, Dallas, TX; also presented at NASA Headquarters, Washington, D.C., Jan. 1998; and NASA Managers Workshop, Hagerstown, MD, Feb. 22, 1998 (invited talk); also presented at Johnson Space Center, March 14, 1998.

5. Noor, A. K., "Future University Environment and Scenario for Engineering Education," Workshop on Advanced Technology for Engineering Education, Feb. 24-25, 1998, Hampton, VA.

6. Noor, A. K., "Intelligent Synthesis Environment for Future Aerospace Systems and Its Impact on Engineering Education," University of Virginia, Charlottesville, VA, March 5, 1998 (invited talk); also presented at Ohio Aerospace Institute Distinguished Lecture Program, Cleveland, OH, May 14, 1998 (invited talk).

7. Wasfy, T. M. and Noor, A. K., "Application of Fuzzy Sets to Transient Analysis of Space Structures," 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Long Beach, CA, April 20-23, 1998.

8. Noor, A. K., "ISE - Intelligent Synthesis Environment and Its Impact on Engineering Research and Education," Fourth International Conference on Computational Structures Technology and First International Conference on Engineering Computational Technology, Heriot-Watt University, Edinburgh, Scotland, Aug. 18-20, 1998 (invited Keynote Lecture); Second Symposium on Multidisciplinary Environments and Applications, WPAFB, OH, Aug. 25-26, 1998 (invited talk); ICES '99, Atlanta, GA, Oct. 6-9, 1998; ASME International Mechanical Engineering Congress and Exposition, Anaheim, CA, Nov. 15-20, 1998; AIAA CFD Conference, Hampton, VA, June 30, 1999.

9. Noor, A. K., "Overview of Intelligent Software Agents," Workshop on Intelligent Agents and Their Potential for Future Design and Synthesis Environment," NASA Langley Research Center, Hampton, VA, Sept. 16-17, 1998.

10. Goldin, D. S., Venneri, S. L. and Noor, A. K., "Pathway to the Future of Engineering Processes," Delphi Automotive Systems Forum, Warren, MI, March 17, 1999 (invited talk); also presented at University of Virginia, Charlottesville, March 25, 1999 (invited talk); also presented at Delphi, July 1, 1999 (invited talk).

11. Noor, A. K., "Pathway to the Future of Simulation and Learning," Purdue University, May 13, 1999 (invited talk); Fifth U.S. National Congress on Computational Mechanics, Boulder, CO, Aug. 4-7, 1999; Fifth NASA Symposium on Large-Scale Analysis, Design and Intelligent Synthesis Environment, Williamsburg, VA, Oct. 12-15, 1999; Technology Day, Naval Air Warfare Center, Solomon Island, MD, Dec. 9, 1999 (invited talk); University of Virginia, March 9, 2000 (invited talk); Fifth International Conference on Computational Structures Technology and Second International Conference on Engineering Computational Technology, Leuven, Belgium, Sept. 6-8, 2000 (invited Keynote Lecture); Old Dominion University, Oct. 6, 2000 (invited seminar); University of Florida, Gainesville, Nov. 29, 2000 (invited seminar).

12. Noor, A. K., "Pathway to the Future of Learning," Workshop on Advanced Technologies for Engineering Education and Consortium Planning," NASA Langley Research Center, Hampton, VA, Nov. 3-4, 1999.

13. Noor, A. K., "Pathway to the Future of Simulation," FEMCI Workshop, NASA Goddard Space Flight Center, Maryland, May 18, 2000 (invited talk).

14. Noor, A. K., "Pathway to Future Research and Learning Environments," Workshop on Global Transdisciplinary Education, Research and Training, Izmir, Turkey, Sept. 4-6, 2000.

15. Noor, A. K., "Forecast Revolutionary Learning Environment: A UVA ACT Center Vision," Revolutionary Learning Systems Panel Meeting, NASA Langley Research Center, Hampton, VA, Sept. 21-22, 2000 (invited talk).

16. Noor, A. K. and Venneri, S. L., "Research and Learning Environments in the New Century," 19th ASME Young Engineers Forum, International Mechanical Engineering Congress and Exposition, Orlando, FL, Nov. 5-10, 2000.


## Appendix V – Workshops and Seminars
### (Jan. 1, 1997 – Dec. 31, 2000)


A. Workshops

1. Next Generation CAD/CAM/CAE Systems, March 18-19, 1997, Hampton, VA
2. Government-Sponsored Programs in the Structures Area, April 6, 1997, Orlando, FL
3. Advanced Technology for Engineering Education, Feb. 24-25, 1998, Hampton, VA
4. Intelligent Agents and Their Potential for Future Design and Synthesis Environment, Sept. 16-17, 1998, Hampton, VA
5. Advanced Training Technologies and Learning Environments, March 9-10, 1999, Hampton, VA
6. Advanced Group Support Systems and Facilities, July 19-20, 1999, Hampton, VA
7. Nanobiotechnology, June 14-15, 2000, Hampton, VA

B. Seminars

1. Richard Petti, "Next Generation Mathematical Analysis Tools," Macsyma, Inc., Arlington, MA, Jan. 7, 1997.
2. Fritz Hasler, "VisAnalysis of HyperDatasets for Earth Science and Public Outreach," NASA Goddard SFC, Greenbelt, MD, Dec. 9, 1997.
3. Dona Crawford and Jim Costa, "Advanced Computing Programs at Sandia National Laboratories," Livermore, CA, Dec. 16, 1997.
4. Stephen Thaler, "Delivering What AI Originally Promised: The Creativity Machine Paradigm," Imagination Engines, Inc., St. Louis, MO, July 30, 1998.
5. Jim Webb, "Systematic Innovation: It Isn't an Oxymoron Anymore," Invention Machine Corp., Oak Hill, VA, Nov. 5, 1998.

## Appendix VI - Cooperating Organizations

1. The MacNeal-Schwendler Corp.
   815 Colorado Blvd.
   Los Angeles, CA 90041

2. ANSYS, Inc.
   Johnson Road
   P.O. Box 65
   Houston, PA 15342

3. Hibbitt, Karlsson & Sorensen, Inc.
   1080 Main Street
   Pawtucket, RI 02860

4. Centric Engineering Systems, Inc.
   3801 East Bayshore Road
   Palo Alto, CA 94303

5. ADINA R&D, Inc.
   71 Elton Avenue
   Watertown, MA 02172

6. Superscape, Inc.
   2479 East Bayshore #706
   Palo Alto, CA 94303

7. CEI, Inc.
   P.O. Box 14306
   Research Triangle Park, NC 27709

8. IBM
   321 West Rio Road
   Charlottesville, VA 22901

9. Center for Educational Computing
   Initiatives
   Massachusetts Inst. of Technology
   Cambridge, MA 02139

10. Wolfram Research, Inc.
    100 Trade Center Drive
    Champaign, IL 61820

11. UniSQL, Inc.
    2111 Wilson Blvd., 7th Floor
    Arlington, VA 22201

12. Macsyma, Inc.
    20 Academy Street
    Arlington, MA 02174

13. CAI Consulting Associates, Inc.
    1300 Diamond Springs Rd., Suite 500
    Virginia Beach, VA 23455

# Appendix VII - Abstracts of Publications

## Perturbation Mapping Method for Sensitivity Analysis of Three-Dimensional Cracks Near a Free Surface

Yonglin Xu and Ahmed K. Noor

A perturbation mapping method and a computational procedure are presented for evaluating the sensitivity coefficients of the stress intensity factors for three-dimensional planar cracks near a free surface. The boundary integral equations for evaluating the sensitivity coefficient are solved by using the boundary element method. Each of the geometric parameters that affect the stress intensity factor (such as, crack orientation, distance from the free surface, and crack shape parameters) is given a perturbation that defines a mapping between the original and perturbed coordinate systems, from which the sensitivity coefficients are derived. The sensitivity coefficients obtained by the perturbation mapping method are validated by comparing them with those obtained by the finite difference method. Numerical results for penny-shaped and elliptical cracks are presented showing the variation of the sensitivity coefficients with various geometric and material parameters.

## Multibody Dynamic Simulation of the Next Generation Space Telescope Using Finite Elements and Fuzzy Sets

Tamer M. Wasfy

Multi-body dynamic simulations are performed for a large deployable space structure using finite element models and an explicit temporal integration procedure. The structure considered is NASA's lightweight, 8 m-aperture next generation space telescope (NGST). The NGST structure consists of beam components (modeled using super-elements, each composed of two truss elements and a torsional spring), thin-surface shell-type components (modeled using super-elements, each composed of one brick, twelve truss elements, and six surface elements), revolute and prismatic joints, and reaction wheels. Detailed numerical simulations are conducted for the vibrational response, attitude control, and deployment. A fuzzy set technique is used to assess the effect of changing the dwell time of the various deployment actuators on the total strain energy of the structure.

## Autonomous, Biologically Inspired Systems for Future Space Missions

Ahmed K. Noor, Richard J. Doyle and Samuel L. Venneri

Future space missions will go beyond reconnaissance, enabling sustained in-situ scientific studies. Such missions require space platforms that operate in a closed-loop fashion in its environment. The platforms must be autonomous, evolvable, resilient and highly distributed. The present article describes these characteristics, along with the mission concepts considered by

NASA that require these characteristics. Autonomy is a practical application of AI. Evolvability and highly distributed characteristics are biologically inspired.

## Computational Structures Technology

Ahmed K. Noor

Computational structures technology (CST) blends the insightful modeling of structural response with the development of computational methods. CST is an outgrowth of matrix and finite element methods of structural analysis that were developed over the past five decades. Brief historical reviews of the finite element method are given in two articles.[1,2] Computing technology is the technological foundation of CST. The advances made in computer hardware, firmware and software have significantly impacted all aspects of CST development. Current CST activities include computational material modeling, computational methods for predicting the response, performance, failure and life of structures and their components, and automated methods of structural synthesis and optimization.

Application of CST to contemporary structures problems typically involves a sequence of five steps: observation of the response phenomena of interest; development of computational models for the numerical simulation of these phenomena; development and assembly of software and/or hardware to implement the computational models; post-processing and interpretation of the predictions of the computational models; and utilization of the computational models in the analysis and design of structures (Fig. 1).

Development of a computational model includes selection of the mathematical model that describes the phenomena; mathematical analysis of the model to ensure that the problem is properly formulated; testing the range of validity of the model; and development of a discrete model, computational strategy, and numerical algorithms to approximate the mathematical model. Successful computational models for structures are those based on thorough familiarity with the response phenomena being simulated and a good understanding of the mathematical models available to describe them.

Within the aforementioned general framework, CST is currently being used in a broad range of applications including aerospace, automotive, naval, and nuclear structures. Reviews of some of the activities in the U.S. and European aerospace industries are given in Refs. 3 and 4. Other industrial applications of CST are described in Refs. 5 and 6. Large structural calculations performed to date account for complicated geometry, complex loading history and material behavior.

Computational Structures Technology (CST) represents one of the most significant developments in the history of the structures field. Its use has transformed much of theoretical structural mechanics and materials science into practical tools that affect all phases of the design, fabrication, testing and operation of engineering systems. Although CST led the way among computational aero-sciences until the 1970s, the emphasis has shifted in the early 1980s to other disciplines, particularly computational fluid dynamics. However, since the late 1980s, there has been renewed interest in CST. There are three compelling motivations for vigorously pursuing CST development: the practical problems awaiting solutions; the need for reducing dependence on extensive and costly testing; and the desire to use the power of new and emerging computing paradigm in the design and operation of future engineering structures.

A number of survey papers and monographs have been written on various aspects of

computational structures technology. Also, a number of workshops and symposia have been devoted to CST and proceedings have been published. The objectives of the present paper are: to present a brief review of the history of the development of CST software, summarize some of the recent developments and trends in CST, and identify research areas in CST that have high potential for meeting future technological needs. The number of publications on CST has been steadily increasing, and a vast amount of literature currently exists on various aspects and applications of CST. The cited references are selected for illustrating the ideas presented and are not necessarily the only significant contributions to the subject. The discussion in this paper is kept on a descriptive level and for the details the reader is referred to the cited literature.


**Object-oriented Virtual Environment for Visualization of Flexible Multibody Systems**
Tamer M. Wasfy and Ahmed K. Noor
*Advances in Engineering Software* (to appear).

An object-oriented event-driven virtual environment (VE) for viewing the simulation results of flexible multibody systems (FMS) is developed. The VE interfaces with the following output devices: immersive stereoscopic screen(s) and stereo speakers; and a variety of input devices including head tracker, wand, joystick, mouse, microphone, and keyboard. The VE incorporates the following types of primitive software objects: user-interface objects, support objects, geometric entities, and finite elements. Each object encapsulates a set of properties, methods, and events that define its behavior, appearance and functions. A "container" object allows grouping many objects into one object, which inherits the properties of its "children" objects. The VE allows real-time viewing and "fly-through" of photo-realistic models, vibrational mode-shapes, and animation of the dynamic motion of FMS. An application of this VE is presented for visualization of the dynamic analysis results of a large deployable space structure – NASA's Next Generation Space Telescope.