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Aerospace and Mechanical Engineering

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Dear sirs/madams:

I have enclosed our Final Technical Report for our NASA Grant - NAG 1-1561. Please let me know if you need anything else regarding the closure of this grant.

Sincerely yours,

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MULTIDISCIPLINARY DESIGN TECHNOLOGY DEVELOPMENT:
A Comparative Investigation of Integrated Aerospace Vehicle Design Tools

1999 FINAL TECHNICAL REPORT

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Period Covered by Report:.................................. January 1, 1997 – September 30, 1998
Grantee's Institution:.. University of Notre Dame
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Introduction

This research effort is a joint program between the Departments of Aerospace and Mechanical Engineering and the Computer Science and Engineering Department at the University of Notre Dame. Three Principal Investigators; Drs. Renaud, Brockman and Batill directed this effort. During the four and a half year grant period, six Aerospace and Mechanical Engineering Ph.D. students and one Masters student received full or partial support, while four Computer Science and Engineering Ph.D. students and one Masters student were supported. During each of the summers up to four undergraduate students were involved in related research activities.

The purpose of the project was to develop a framework and systematic methodology to facilitate the application of Multidisciplinary Design Optimization (MDO) to a diverse class of system design problems. For all practical aerospace systems, the design of a systems is a complex sequence of events which integrates the activities of a variety of discipline "experts" and their associated "tools". The development, archiving and exchange of information between these individual experts is central to the design task and it is this information which provides the basis for these experts to make coordinated design decisions (i.e., compromises and trade-offs) - resulting in the final product design. Grant efforts focused on developing and evaluating frameworks for effective design coordination within a MDO environment.

Central to these research efforts was the concept that the individual discipline "expert", using the most appropriate "tools" available and the most complete description of the system should be empowered to have the greatest impact on the design decisions and final design. This means that the overall process must be highly interactive and efficiently conducted if the resulting design is to be developed in a manner consistent with cost and time requirements. The methods developed as part of this research effort include; extensions to a sensitivity based Concurrent Subspace Optimization (CSSO) MDO algorithm; the development of a neural network response surface based CSSO-MDO algorithm; and the integration of distributed computing and process scheduling into the MDO environment. This report overviews research efforts in each of these focus. A complete bibliography of research produced with support of this grant is attached.

Sensitivity Based CSSO-MDO

In order to extend the efficiencies of sensitivity based CSSO-MDO algorithm, investigations are currently underway which address the use of automatic differentiation techniques for improved sensitivity calculation and the development of an effective move limit strategy for use in the subspace optimizations and in the coordination procedure of system approximation. These strategies are reported on in Wujek and Renaud, 1996 and Su and Renaud, 1996.

Automatic Differentiation for Improved Analysis and Optimization

In Wujek and Renaud, 1996, two applications are investigated in which the use of automatic differentiation (AD) is observed to improve efficiency. The efficiency of solution strategies for non-hierarchic (i.e., coupled) system analysis is improved using automatic differentiation generated sensitivities. Calculation of sensitivities via AD allows for efficient application of Newton's method and a modified form of Newton's method to converge non-hierarchic system analyses. The line search strategy employed within a generalized reduced gradient(GRG) optimizer has been improved through the use of AD generated sensitivities. Using the AD-based line search strategy within the GRG method results in a significant reduction in the number of system analyses and the CPU time required for optimization.

Automatic Differentiation in Robust Design

In Su and Renaud, 1996 a new methodology is introduced which incorporates manufacturing and operational variances in design optimization to achieve robust optimal performance of multidisciplinary systems. The procedure introduced in Su and Renaud, 1996 uses Taguchi's orthogonal array to approximate the expected value of the objective function in multidisciplinary design. The use of orthogonal arrays, reduces the number of function evaluations required for robust optimization. This is particularly important in problems where the objective function is obtained through the use of computationally intensive simulation programs. To further reduce the number of objective function calls required for robust optimization, this study makes use of automatic differentiation techniques. While the use of Taguchi orthogonal arrays allows for reduced effort in calculating the approximation of the expected value of the objective function, the expected value approximation is itself many more times computationally expensive than the original objective. This is due to the fact that the expected value of the objective function is calculated by evaluating the original objective function many times in the neighborhood of the current design depending on both the size of the design space and the particular Taguchi orthogonal array selected for approximation. The use of automatic differentiation allows for gradient calculations of this intensive expected value function without resorting to the costly finite differencing of this multi-component objective. A methodology to account for variation in constraints due to variations in design variables is introduced which makes use of the familiar penalty function formulation for optimization. This formulation is particularly effective in multidisciplinary design problems where the objective function and constraints are often coupled.

SAND Investigation

In an effort co-sponsored by General Motors Corporation, Tappeta and Renaud, 1996 investigated a concurrent approach for design optimization. The method of Simultaneous ANalysis and Design (SAND) was tested in application to three Multidisciplinary Design Optimization (MDO) test problems. A Generalized Reduced Gradient (GRG) optimizer and a Sequential Quadratic Programming (SQP) optimizer were compared with respect to their efficacy in handling three different forms of equality constraints referred to as compatibility constraints in the SAND based optimization procedure. Results highlight the need for both strategies in application of SAND based design to different engineering test problems. More importantly significant savings in the number of analyses required for design optimization were observed when using the SAND approach of concurrent design. SAND based design is used to exploit the potential of concurrent engineering, namely to develop optimal designs, working concurrently, while reducing design cycle time.

CSSO vs. Workflow Management

Wujek, et al., 1996 provided a detailed comparison of two ongoing efforts, one centered in the more traditional multidisciplinary design arena of optimization algorithm development and the other introducing a technique for workflow management in a multidisciplinary design environment. A multidisciplinary design test problem involving aircraft concept sizing was used in implementation studies for both optimization and workflow management. A Concurrent Subspace Optimization (CSSO) approach for MDO was successfully implemented in application to the aircraft concept sizing test problem. The CSSO approach implemented in this study provided for design variable sharing and distributed computing across disciplines. Significant "real" time savings were observed when using distributed computing for concurrent design. More importantly, a significant savings in the number of complex, analytic simulations required for optimization was observed as compared to a traditional optimization strategy. In this research an approach for workflow management of complex multidisciplinary problems was introduced in application to the aircraft concept sizing test problem. The approach implemented in this study was based upon a novel information model, called the task schema, that classifies the various tool and data objects used in a design process, and defines the rules by which tools and data may be used to form tasks. This schema-based approach to workflow management has been successfully adapted for use in the aircraft concept sizing problem.

Response Surface Based CSSO-MDO and Application Studies

The major goals in year three of this effort involve the evaluation and documentation of the response surface based CSSO/NN framework. This involved the codification and subsequent application of this approach to a variety of test problems and an evaluation of the results from these studies. A number of specific implementation issues have resulted from our earlier work and have been pursued with some emphasis. These involve the use of gradient information in the neural network training, quantifying the uncertainty associated with the approximations, evaluating the role of discipline specific versus global design variable and constraints in the CSSO/NN formulation and the use of hybrid design variable problems(i.e. those including both discrete and continuous design variables).

Response Surface Based CSSO-MDO Implementation Study

The analysis and subsequent design of engineering systems must often be conducted using complex, non-hierarchic, coupled, discipline-specific methods. When the cost of performing these individual analyses (the primary source of the information to be used in design "decisions") is high, it is impractical to apply many current optimization methods to this type of system to achieve improved designs. Consequently, a framework has been developed which attempts to reduce the cost of designing or optimizing non-hierarchic systems. Sellar et al., 1996a, and Sellar, et al., 1996b details the development and application of an extension of the Concurrent Subspace Optimization (CSSO) approach through the use of neural network based response surface mappings. The response surface mappings are used to allow the discipline designer to account for discipline coupling and the impact of design decisions on the system at the discipline level as well as for system level design coordination. The ability of this method to identify globally optimal designs has been demonstrated using a number of example system design problems. The application to the design of a "hover craft" which includes external configuration, structures, performance and propulsion disciplines has been developed. To date these applications have been relatively simple problems (two, three and four contributing disciplines) and they have served to assist in the evaluation of the framework and have not been intended to provide practical engineering solutions to specific products. Comparisons between this algorithm and full system optimization have been made with regard to computational expense associated with obtaining optimal system designs as well as the capability of the response surface to both archive the design information and characterize the design space for subsequent design studies.

One of the primary issues of concern in the development of the CSSO/NN framework has been related to the size or "dimensionality" of design problems. This is of particular concern in the manner in which it impact the size of the neural networks and the associated requirements on the data base. Earlier research using hierarchic design problems which incorporated both global and local design variables and constraints in order to limit the size of the required approximations have indicated one approach to this issue and this work continues. The development of methods to determine how the sorting and allocation of design variables and constraints can be accomplished in order to reduce the "dimensionality" of a given design problem are considered critical but have not yet been resolved. It is anticipated that this would be a highly problem dependent activity and involve each of the discipline "experts". This activity is closely associated with our efforts in design problem formulation, framework development and computing.

CSSO/NN Using Gradient-Enhanced Neural Network Approximations

In some cases a contributing analysis may be formulated in a way that not only are state variables determined by gradient information is "automatically" developed as part of the analysis. It appears that if this information is available and is integrated into the design data base that the neural network response surfaces can be "trained" using both state and gradient information and that this would improve the accuracy of the approximation particularly as one moves away from the immediate vicinity of the specific point. Since one can directly extract response surface gradient information from the weights and bias parameters of the neural network, a procedure has been developed in which one can directly incorporate gradient information into the training process. This has be developed and demonstrated using a number of test problems. In Sellar, et al., 1996c this approach is applied to the Concurrent Subspace Optimization (CSSO) framework for a nonhierarchic test problem in which the sensitivity information is provided using the Global Sensitivity Equations (GSEs).

Design Space Mapping of Systems Represented by Both Continuous and Discrete Design Variables

One of the issues considered is related to the fact that many design problems contain components in which the designer is required so to select from a discrete set of values or characteristics for a class of design variables. In these cases either the design variables must be transformed to some realistic continuous domain or the selection process must be amenable to discrete design variables (a characteristic lacking in number of well established optimization methodologies). This has prompted continued studies of the ability of neural network based response surface to approximate this class of design variables. A version of the CSSO/NN framework has been developed and demonstrated on a rather simple test problem which contains two contributing analyses and mixed continuous and discrete design variables. Issues related to the appropriate optimization algorithms to invoke at both the discipline optimization and system level coordination for the constrained combinatorial optimization problem have been evaluated and these results are being studied. The extension of this approach to the hovercraft problem is currently underway.

Computing Infrastructure

Grant efforts in support of developing a computer infrastructure which supports CSSO - MDO have been focused in two areas. One being, the continued development of an architecture for an open framework that supports distributed, multidisciplinary design. The other area of research within computer infrastructure development focuses on improved strategies for design workflow management.

MDO Framework Development

Verification of the MDO Framework proposed in Yoder, 1995 and reported in Yoder and Brockman, 1996 has proceeded and application to the suite of MDO test problems currently available at Notre Dame is underway. The key components of the framework's architecture are; a library of MDO objects and relationships; a message server; a graphical user interface that allows for MDO problem formulation; concurrency in subspace optimization and subspace analysis; and passing of messages among designers and subspaces. Verification measurements include; evaluation of time and effort required to transform a given MDO problem into a model; system flexibility, (i.e., openness to the formulation of various MDO problems); assessment of system performance, (e.g., speedup due to concurrent analysis and optimization). Implementation and verification of these features within an object oriented environment in application to the aforementioned suite of MDO test problems has been pursued in order that the MDO Framework objectives defined in Yoder, 1995 and Yoder and Brockman, 1996 can be achieved.

Workflow Management and Design Process Refinement

We are continuing our CAD Framework development efforts (Johnson , et al., 1996a,b,c) during the third year of the effort. The CAD Framework, "Hercules" is a workflow management tool that has been modified for use in conjunction with our CSSO algorithm as a design process tracking and archiving tool. This framework allows "human"/designer interaction with the CSSO-MDO process, which has to date been developed as an automated optimization tool (NDOPT).

Johnson, et al., 1996a, details the investigation the use of Markov models for making improvements in design processes. Although much attention has been paid to tools and methodologies for improving hardware/software designs, surprisingly little work has been done in the area of tools and techniques for improving the design process itself. To address this issue, we have developed a system for measuring, diagnosing, and simulating iterative, sequential design processes that is based on the use of a Markov model. To demonstrate the efficacy of the system, an experiment was performed on a group of designers, each working on the same design problem (the development of a computer program), wherein the methodologies used by each of the designers were observed, quantified, and fit as parameters of the model. Simulation results show that the model accurately represented the time spent in each of the stages of the design process, as well as in the process as a whole.

Johnson, et al., 1996b,c also addresses several important issues related to the application of the model. Specifically, they describe techniques for collecting design (meta-)data, and have developed a variety of instruments for analyzing the impact of outside factors and resources on design time through sensitivity analysis. These results are encouraging and they imply that the Markov model parameters show great promise as a means for benchmarking iterative design processes.

Related Efforts (MDO in Integrated Circuit Design)

In Lokanathan, et al., 1996a,b methodologies for concurrently optimizing an IC fabrication process and a standard cell library in order to maximize overall yield are investigated. The approach uses the Concurrent Subspace Optimization (CSSO) algorithm, which has been developed for general coupled , multidisciplinary optimization problems. Examples are developed demonstrating the application of the algorithm to optimizing a mixed analog-digital library on a CMOS process.

Recent Efforts (1997-1998)

Although, MDO technology originated in the design phase, it is now being extended to the other principle phases of the product life cycle (Su and Renaud, 1997), such as the requirements formulation, the manufacturing processes, product operation and service. The main purpose of these MDO extensions will be to account for the mutual interaction between these phases and the design phase, which allows one to consider early and comprehensively the economic factors that affect the product cost throughout its life cycle.

In an effort co-sponsored by General Motors Corporation, Tappeta and Renaud, 1997a,b, 1998 investigated a concurrent approach for design optimization. The method of Simultaneous ANalysis and Design (SAND) was tested in application to three Multidisciplinary Design Optimization (MDO) test problems. A Generalized Reduced Gradient (GRG) optimizer and a Sequential Quadratic Programming (SQP) optimizer were compared with respect to their efficacy in handling three different forms of equality constraints referred to as compatibility constraints in the SAND based optimization procedure. Results highlight the need for both strategies in application of SAND based design to different engineering test problems. More importantly significant savings in the number of analyses required for design optimization were observed when using the SAND approach of concurrent design. SAND based design is used to exploit the potential of concurrent engineering, namely to develop optimal designs, working concurrently, while reducing design cycle time. This work will continue during the 1997- 1998 grant period.

Research related to the development of a proof of convergence for sequential approximate constrained optimization using response surfaces is ongoing (Rodriguez, Renaud and Watson, 1997, 1998a,b). This research makes use of an approximate augmented Lagrangian approach for MDO coordination combined with a trust region model management strategy. The mathematical community has been critical of MDO efforts in past years citing a lack of formal math based methods development. A new adaptive move limit strategy is under investigation which is targeted toward improving the rate of convergence in trust region methods. This work has been presented in Wujek and Renaud, 1998a,b.

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Master's Theses

Ms. Jian Su
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Doctoral Dissertations
(completed)
Mr. Eric Johnson
Mr. Richard Sellar
Mr. Brett Wujek
Mr. A. Lokanathan
Mr. Stanley Yoder
Mr. Mark Stelmack
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July 19, 1999

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Subject: **Final report for Grant No. NAG1-1561**

Attached is the final report for the subject grant. Dr. Renaud submitted the final report to the administrative office for the grant, ONR Chicago Regional office but apparently a copy was not forwarded to you. Please let me know if you need additional information. Thank you.

Sincerely,

Howard T. Hanson, Director,
Post Award Administration

Enclosure

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