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## REQUIREMENTS FOR MULTIDISCIPLINARY DESIGN OF AEROSPACE VEHICLES ON HIGH PERFORMANCE COMPUTERS

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# REQUIREMENTS FOR MULTIDISCIPLINARY DESIGN OF AEROSPACE VEHICLES ON HIGH PERFORMANCE COMPUTERS

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## Abstract

The design of aerospace vehicles is becoming increasingly complex as the various contributing disciplines and physical components become more tightly coupled. This coupling leads to computational problems that will be tractable only if significant advances in high performance computing systems are made. In this paper we discuss some of the modeling, algorithmic and software requirements generated by the design problem.

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## Introduction

The classical scientific method is undergoing a fundamental change that has the numerical experiment or simulation taking its place alongside the more traditional laboratory experiment. More detailed experiments require more sophisticated models, and in turn, more powerful computational systems. Thus it is becoming increasingly clear that a pacing technology for advances in many areas of science and engineering is high performance computing.

In 1987 the Federal Coordinating Council for Science, Engineering and Technology (FCCSET) Committee on Computer Research and Applications conducted a review of high performance computing issues and opportunities. The result of this study was a report issued by the Executive Office of the President, Office of Science and Technology Policy on November 20, 1987, entitled "A Research and Development Strategy for High Performance Computing." The report concluded that maintaining leadership in the development and application of high performance computing is crucial to continued preeminence in science and engineering and that this leadership position is being challenged by advances in Europe and Japan. Four areas were singled out as focal points to address this challenge: development of high performance computing systems including parallel systems, development of algorithms and software to bring the power of such systems to bear efficiently on complex problems, development of the networking technology required to make the systems readily accessible for collaboration among scientists who are geographically dispersed and finally support of the research infrastructure to assure that the trained personnel will be available to make effective use of the systems resulting from the first three areas. To stimulate the desired development and assure its relevance, the FCCSET report suggests pursuing "Grand Challenges." As defined in the report, a Grand Challenge "... is a fundamental problem in science and engineering, with broad application, whose solution will be enabled by the application of the high performance computing resources that could become available in the near future."

Various federal agencies responsible for support of research and development in the U.S. are selecting and refining Grand Challenges to provide a focus for the research programs they are developing to respond to the FCCSET report. In the remainder of this paper, one such challenge put forth by the National Aeronautics and Space Administration (NASA) will be described, and some of the issues arising in its pursuit will be discussed.

## A Grand Challenge

The NASA Grand Challenge in aerosciences as first put forth in [2], and subsequently refined, is the integrated multidisciplinary design of aerospace vehicles and their numerical simulation throughout a mission profile. The goal is to demonstrate the utility of advanced parallel computer systems, including hardware, software and algorithms, capable of delivering teraflop performance for the design of new generations of aerospace vehicles. Such a demonstration requires separate developments within a number of disciplines as well as the tight integration of those disciplines.

The integration of multiple disciplines arises in at least three different ways. First there are the various components of the vehicle that must function in a tightly coupled fashion. These include the airframe, the propulsion system, the control systems, etc. Second there are the scientific disciplines required for the basic understanding and modelling of the components. Here one must involve aerodynamics, chemistry, combustion, structural dynamics, solid mechanics and control theory to name a few. Finally there are the disciplines such as applied mathematics, numerical analysis and computer science that must come together for the successful numerical simulation of a complex physical phenomena on a parallel computer.

Most of these disciplines have been involved in traditional aerospace vehicle design and analysis, but present trends toward improved performance are leading to a tighter coupling of these disciplines. The impact of this trend on the design process will be discussed in the next section.

## The Design Problem

The traditional approach to the design of aerospace vehicles is to treat each discipline separately and in turn. A simplified and exaggerated example may serve to illustrate the point. The aerodynamics team working under the requirement to keep weight to a minimum while providing a specified range completes a clean aerodynamic design and passes it to the structure team. Their analysis reveals that the juncture between the wing and the fuselage may fail under extreme load conditions. They correct for this weakness by increasing the thickness and thus the weight of the root of the wing. This design is passed to the propulsion team who must now provide for more power than originally intended to overcome the added weight. This requires a larger engine which adds additional weight and changes the flow characteristics of the original aerodynamic design. Finally, to improve maneuverability, a controls team includes an active device to increase lift at takeoff. This device adds weight and changes the flow characteristics. At this point there is a design dilemma: accept the reduced range made necessary by the increased weight or return the design to the aerodynamics team to improve the efficiency of the design. The difficulty with the latter approach is that the process may not produce a solution to the original design objectives; that is, it may not converge to an optimal design.

As designs become more sophisticated and approach finer and finer tolerances, the various disciplines involved become more tightly coupled. This tight coupling inhibits convergence of the design resulting in higher design costs or compromises in the design objectives. It may also lead to modifications in the design based on prototype performance resulting invariably in higher costs and decreased performance.

### An Optimization Approach

One obvious way to overcome the design dilemma described in the previous section is to approach the problem as a coupled, multidisciplinary optimization problem. Thus one might seek to minimize the gross take off weight of a vehicle subject to the requirement or constraint that the range be a certain number of miles, or in general

$$\left.\begin{array}{l}\text{minimize } G(y^{(1)},\cdots,y^{(p)},x)\\[1ex] \text{subject to } c(y^{(1)},x)=0\end{array}\right\}. \tag{1}$$

The complication in this deceptively simple formulation is that the dependent variables in $G$ and $c$ may be specified implicitly through a complex exquation

$$F(y^{(1)},x)=0.$$

For example, $y^{(1)}$ might represent the pressure distribution over the vehicle and $F(y^{(1)},x)$ could be the full Navier-Stokes equations. Optimization algorithms for solving (1) require repeated evaluations of $G$ and $c$, and thus in the example, repeated solutions to the Navier-Stokes equations. Now if we consider that there are many other factors contributing to the weight of a vehicle that may be tightly coupled, we see that $p$, the number of dependent variables, may be quite large; furthermore, each one may be specified by a complex system of partial differential equations and hence be very expensive to obtain.

Figures 1 and 2, reproduced from [2], provide some indication of the computational complexity and the present state of the art for two disciplines: aerodynamics and structural analysis. The underlying assumption is that a single simulation must be completed in 15 minutes. Figure 1 shows a range of configuration complexities from an airfoil through a wing to a full aircraft. The underlying models also increase in complexity beginning with a greatly simplified version of the Navier-Stokes equations which includes nonlinear effects but neglects viscous terms. The Reynolds-averaged Navier-Stokes equations include all terms but averages over time are taken and turbulence models are required. Finally, large eddy simulation involves the direct numerical simulation of turbulent eddies over a large range of scales but still requires turbulence models for the smallest scales.

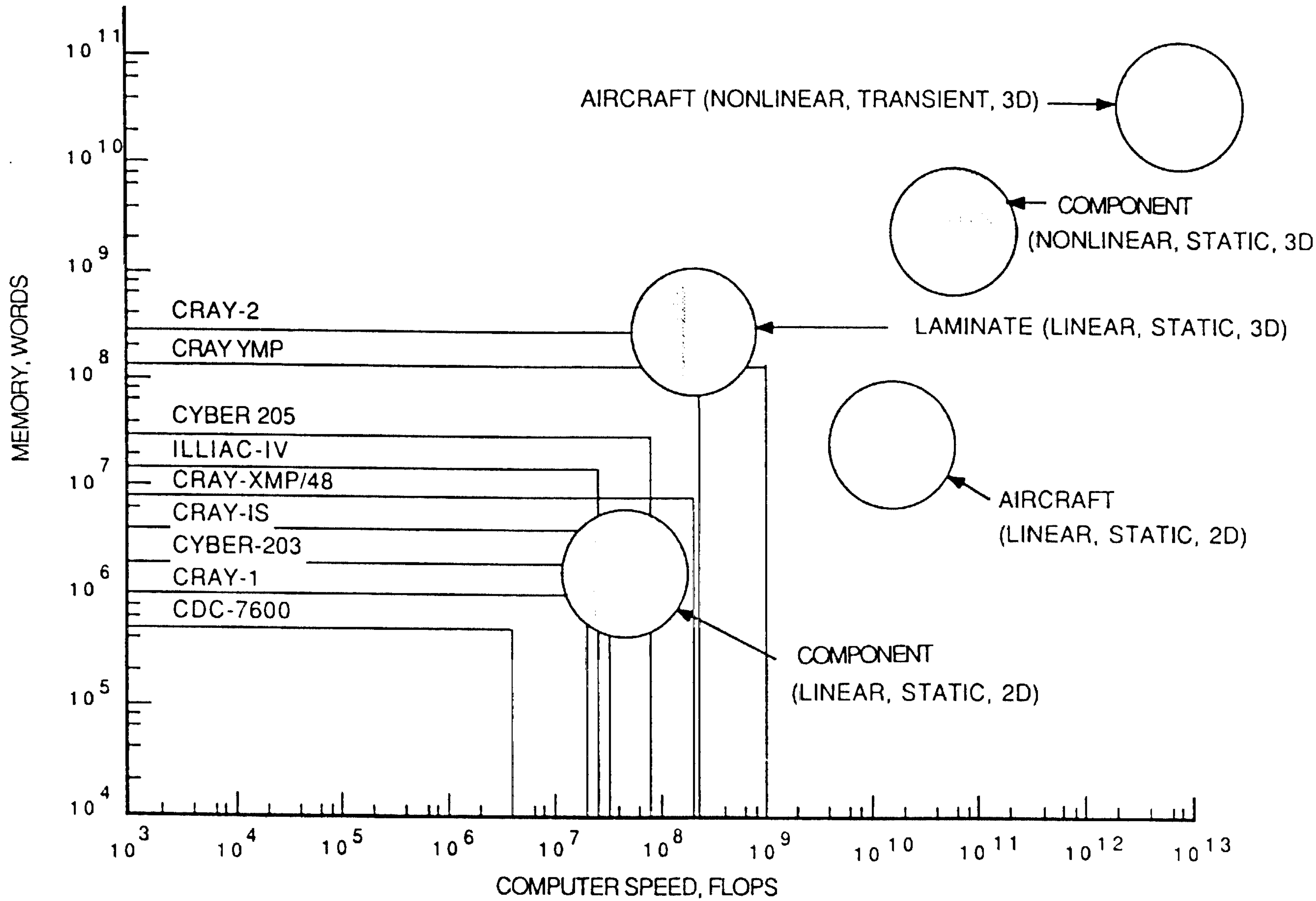


**Figure 2. Memory and Speed Requirements for Computational Structural Analysis**

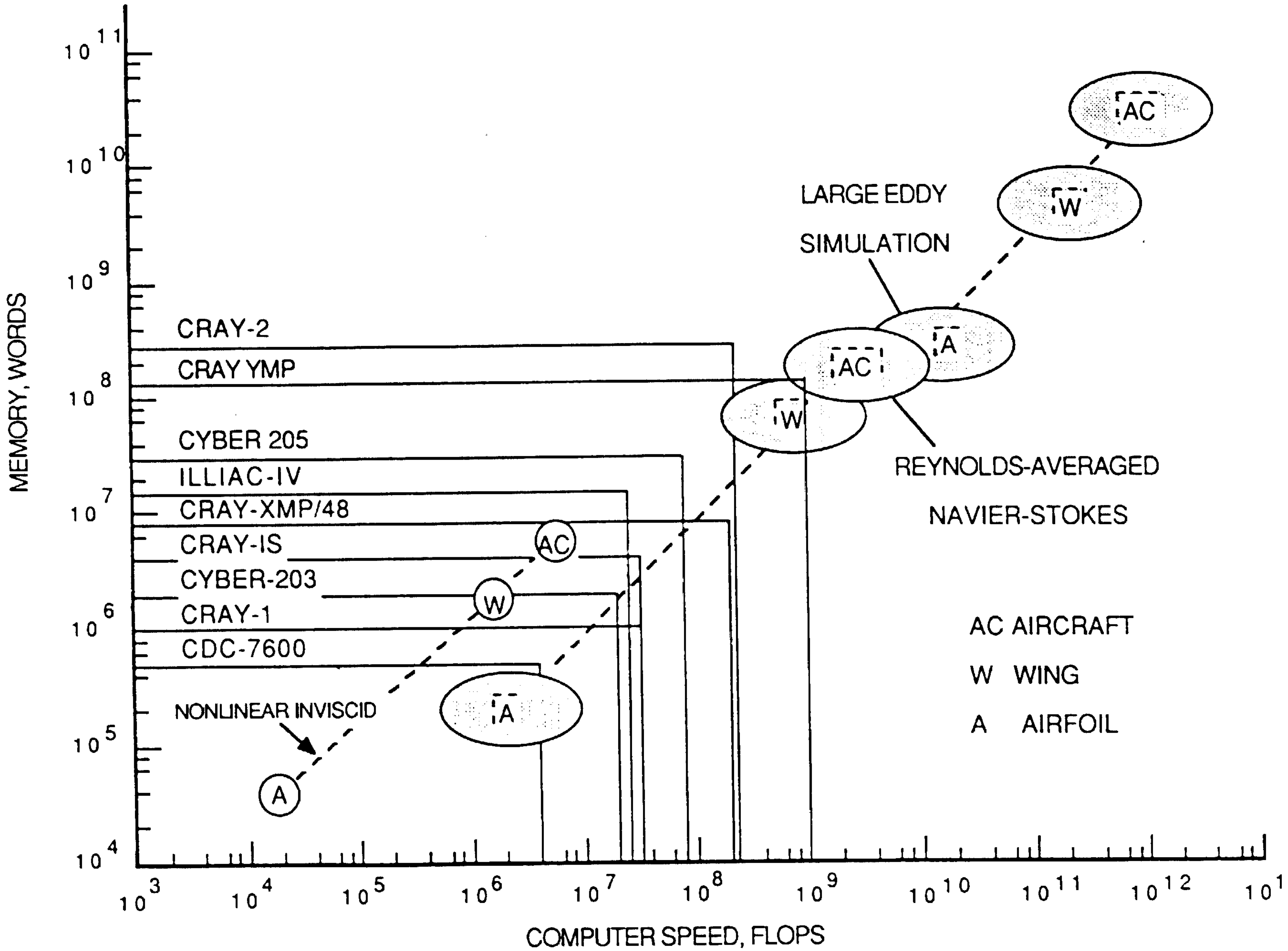


**Figure 1. Memory and Speed Requirements for Computational Aerodynamics**

Figure 2 also shows a range of computational requirements relative to past and present high performance computers. Again the configuration complexity moves from a simple laminated material through a component to a full aircraft. The models range from simple linear two dimensional models for static analysis to nonlinear three dimensional models appropriate for studying transient behavior.

The computational requirements implied by these figures are severe in their own right. When one thinks of coupling these and other disciplines that are equally computationally demanding through an optimization formulation that requires repeated evaluation of these models the "challenge" is truly "grand."

## Alternative Approaches

We have seen that attacking the aerospace vehicle design problem with traditional optimization techniques leads to potentially enormous computational requirements and may be only slightly more attractive than the brute force approach involving parametric studies. One alternative that has received increased attention is based on sensitivity analysis (see, for example, [1] and [7]). The idea is that if the designer knew how sensitive the dependent variable was to changes in the independent variable he could use that information to guide the design process to an optimal solution.

For example, if $F(y,x) = 0$ represents the Navier-Stokes equations with $y$ the pressure and $x$ the vehicle geometry, the designer would like to know the sensitivity of $y$ to changes in $x$, that is $\partial y/\partial x$. This partial is readily available through the implicit function theorem:

$$dF/dy = \partial F/\partial y \; \partial y/\partial x + \partial F/\partial x.$$

But since $F(y,x) = 0$, a change in $x$ must be compensated for by a change in $y$. Setting $dF/dy = 0$ yields

$$\partial F/\partial y \; \partial y/\partial x = -\partial F/\partial x. \tag{2}$$

For some disciplines, $\partial F/\partial y$ and $\partial F/\partial x$ are available analytically, for others they must be obtained numerically. In either event if $y$ is a vector of length $n$, equation (1) is an $n \times n$ matrix equation for the vector of unknown derivatives of $y$ with respect to a single $x$. Thus $\partial y/\partial x$ is available for a number of different $x$'s by factoring $\partial F/\partial y$ and solving (1) with different right-hand sides. It is important to note that if $\partial F/\partial y$ and $\partial F/\partial x$ are not available analytically, they can be obtained numerically by computing differences with respect to $x$; this only requires evaluation of $F(y,x)$ not the solution of $F(y,x) = 0$. Of course, this approach yields only an approximation to $\partial F/\partial y$ and $\partial F/\partial x$.

Other disciplines may be coupled through a large block matrix equation similar to Equation (2). Thus if the sensitivity information can be incorporated into an automatic design process, the computational burden of solving repeatedly the equivalent of $F(y,x) = 0$ will be removed.

Recently Jameson, [3] and [4], has suggested a design procedure in which the design problem is treated as a control problem with the control chosen as some appropriate design objective. This approach has been demonstrated for a three dimensional wing design using the Euler equations [3]. By considering the design problem as a problem in control, a variety of formulations are available based on the theory for control of systems governed by partial differential equations. It remains to be seen if this approach can be extended to solve efficiently the more complex multidisciplinary design problem.

## Implementation Issues

A number of interrelated issues arise in the implementation of a multidisciplinary design problem on a high performance parallel computer. The first of these is the choice of the appropriate models for the physical phenomena of interest. When conducting an analysis within a single discipline the model choice is normally based on the need to resolve the phenomena of interest; for multidisciplinary analysis the demands of one discipline on the quality of the results from another may influence the model choice as well. For example, a simple panel method might be adequate to provide data on the pressure distribution at cruise conditions, where as the Navier-Stokes equations would be required if a prediction of pressure at high angle of attack were needed. The issue of model choice also arises in the need to maintain a particular level of realism from discipline to discipline. For example, there might be little point in using the Navier-Stokes equations for aerodynamics if linear thin shell theory was to be used for structural analysis.

Another factor influencing the model selection, and to an even greater extent the numerical algorithm, is the computer system and its utilization of parallelism. It is a well established fact that different algorithms exhibit different degrees of parallelism, but this is also true of models. For example, the cellular automata model for fluid dynamics contains a high degree of parallelism that is easier to exploit on most parallel systems than the parallelism available in differential equation models.

For multidisciplinary design problems to execute efficiently on high performance parallel computers, advances will have to be made in several software areas. Providing a programming environment including compilers, debuggers and performance monitors is crucial to achieving good utilization of the hardware and productive use of the scientists trying to use the system. Special language constructs and data structures may be appropriate for different disciplines and then there must be an efficient linking of these across disciplines. For example, a rectilinear grid may be appropriate for an aerodynamic calculation involving a wing-engine configuration whereas an unstructured triangular mesh may be required by the finite element analysis of the structural properties of that same configuration.

System software must also be developed to automate some of the tedious yet crucial aspects of implementing a large simulation on a parallel computer. Areas of particular importance include communication and synchronization constructs, mapping the data and program onto distributed processors, and dynamically load balancing the processors when computational changes cause some processors to be overloaded while others are idle.

Programming communication and synchronization for a distributed memory system is both time consuming and error prone; furthermore, it clutters up a program and makes it hard to read and modify in the future. Several research efforts are underway to provide compilers which generate the necessary code automatically. One such compiler, Kali Fortran 1, uses sequential Fortran annotated with a "distribution clause" appended to array declarations, [5] and [6]. Using this distribution the compiler is able to generate the necessary message passing code to handle communication. Such compiler concepts must mature if implementation of the multidisciplinary design problem on a parallel system is to become feasible.

The various data structures and changing computational requirements of the design problem are going to make dynamic load balancing an essential software tool. Static load balancing or the mapping problem must be accomplished with heuristics as it is known that there are no polynomial-time algorithms. When the load changes during execution, the problem becomes even worse. First a mechanism must exist to detect and evaluate the imbalance. Then a new mapping must be computed. The cost of carrying out the remapping must be calculated and the improvement resulting from the remapping must be estimated. The improvement and its cost must be compared with the strategy of continuing the computation without remapping. Finally, if deemed appropriate, the remapping is carried out. Obviously, very efficient algorithms must be found and the process must be automated if all the processors in a parallel system are to be used effectively.

## Conclusions

The NASA aerosciences Grand Challenge is the integrated multidisciplinary design of aerospace vehicles and their numerical simulation throughout a mission profile. This challenge will require the interaction and cooperation of scientists and engineers from a wide range of disciplines. In addition, it will require advances in the numerical simulation of a wide range of physical phenomena and the close integration of a number of these. Finally, a number of advances in parallel high performance computing hardware and software will be required. The wide range of expertise required may well necessitate forming research teams whose members are geographically distributed. This "institute without walls" will put an extra burden on national networks, but if it is successful, it may represent a new way of doing science that is as important as the results themselves.

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