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Multidisciplinary Concurrent Design Optimization via the Internet

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March 2001

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Abstract

A methodology is presented which uses commercial design and analysis software and the Internet to perform concurrent multidisciplinary optimization. The methodology provides a means to develop multidisciplinary designs without requiring that all software be accessible from the same local network. The procedures are amenable to design and development teams whose members, expertise and respective software are not geographically located together. This methodology facilitates multidisciplinary teams working concurrently on a design problem of common interest. Partition of design software to different machines allows each constituent software to be used on the machine that provides the most economy and efficiency. The methodology is demonstrated on the concurrent design of a spacecraft structure and attitude control system. Results are compared to those derived from performing the design with an autonomous FORTRAN program.

CONTENTS

Nomenclature

$\tilde{\mathbf{B}}$ state-space control influence matrix
$\mathbf{C}_{\text{perf}}$ performance output influence matrix
d_i *ith* structural design variable outer diameter
$d_{\max}$ maximum allowable outer diameter
$d_{\min}$ minimum allowable outer diameter
$\mathbf{D_r}$ modal open-loop damping matrix
$\mathbf{e}$ pointing error vector
$E(\ )$ expected value of $(\ )$
$\mathbf{G}_p$ position gain matrix
$\mathbf{G}_r$ rate gain matrix
$\mathbf{I}_{\mathbf{r}\times\mathbf{r}}$ r $\times$ r identity matrix
J objective function
$\mathbf{J_r}$ modal inertia matrix
$\mathbf{K_r}$ modal stiffness matrix
$\mathbf{L}_p$ Cholesky factor of position gain matrix
$\mathbf{L}_r$ Cholesky factor of rate gain matrix
$M_{\max}$ maximum allowable mass
M_{str} structural mass
$P_{\max}$ average control power
$\mathbf{q_r}$ modal amplitude
t time
$\text{Tr}(\ )$ trace of $(\ )$
$\mathbf{u}$ control input vector
$\boldsymbol{y}_p$ position measurement vector
$\boldsymbol{y}_{\text{perf}}$ performance measurement vector
$\boldsymbol{y}_r$ rate measurement vector
$\mathbf{\Gamma}$ modal control influence matrix
$\mathbf{\Phi_r}$ retained open-loop eigenvector matrix

1. Introduction

Multidisciplinary optimization provides a means to integrate two or more design disciplines under the same optimization umbrella. The design discourse includes all design parameters concurrently. This allows a means of determining the tradeoffs between design parameters in the constituent design disciplines. Furthermore, the design parameters are varied until they satisfy a particular performance criteria [1-8]. Hence, system level performance objectives and constraints can be achieved. This paper presents a procedure for performing multidisciplinary optimization using the Internet and UNIX commands. The paper illustrates the design procedure on a spacecraft design problem that involves the disciplines of attitude control system design and structural design.

Performing multidisciplinary optimization via the Internet has many advantages. Ref. 7 (Messac et al) has demonstrated that multidisciplinary design and optimization has matured beyond the research domain to industrial use. Messac has demonstrated a more general approach to multidisciplinary design by implementing the design with commercial software packages. The goal of this research effort has been to extend multidisciplinary design and optimization such that it is amenable to design and development teams whose members and respective expertise and software are not geographically located together. The Internet provides a means of communication, transfer of data and transfer of process control. The advantage of such an approach is that it allows for more efficiency and economy. For example, this approach does not require that one design software package reside on a particular mainframe computer simply because the other software is there or putting the more computationally intensive software on a less computationally effective machine because other necessary design software is on the machine. Because software license costs are dependent upon the machine where the software is installed, software can be placed on the platform that will result in the least expensive license. Hence, logistically, this allows for a better use of resources.

The method presented in this paper uses the UNIX operating system [9]. Although not presented, this method can similarly produce results with the commercial software packages on computer systems with VMS, Windows NT and UNIX operating systems. On all operating systems, it is necessary to use the TCP/IP protocol [10].

The philosophy used in the development of this design methodology was to extend the existing design and analysis methodology beyond implementation using the same local file server (i.e., computers networked together such that they share the same files) while making such methods suitable for incorporation into modern industry engineering procedures. Although only the facets of control system design and structural design are presented here, the procedure used in this paper can be easily be applied to other multidisciplinary design and analysis (i.e. thermal, acoustic, plume impingement, etc.) to make a combined computer aided design (CAD) and computer aided engineering (CAE) environment.

2. Design Optimization Procedure

The integrated design problem is that of incorporating the two or more disciplines concurrently instead of sequentially developing each facet of the system design. All design parameters from each discipline are placed in a system level design vector, $\boldsymbol{\alpha}$. An objective function is prescribed such that as it is reduced in value the overall system performance improves. Furthermore, the objective must be explicitly or implicitly dependent upon a set of design parameters. Design parameters are given such that they can be varied to change the overall performance (design objective). Thus, the design objective is to

$$\text{Minimize } F(\boldsymbol{\alpha})$$

subject to

$$G_j(\boldsymbol{\alpha}) \leq 0 \qquad j = 1,m \tag{1}$$

and

$$\alpha_{l_i} \leq \alpha_i \leq \alpha_{u_i} \qquad i = 1,n \tag{2}$$

where $F(\boldsymbol{\alpha})$ is an objective function which, when minimized, will result in a desired performance of the system. The design vector, $\boldsymbol{\alpha}$, contains n system parameters which are varied through the iterative optimization process. $G_j(\boldsymbol{\alpha})$ is the jth constraint on the design parameters. There are m constraints. Each design parameter, α_i, is bounded by lower and upper limits, α_{l_i} and α_{u_i}, respectively. System physical limitations in hardware or software such as controller torque output (magnitude vs. frequency), measurement sampling rate, measurement sampling range (i.e., limits), structural loads limits, structural resonance, hardware size, etc. can either be included in the constraint equations or in the design parameter upper or lower bounds.

A flowchart of the optimization procedure is shown in Fig. 1. The procedure is iterative. The first iteration requires the user to develop an optimization objective, constraint equations, and bounds for the elements of the design vector. In the first iteration, the objective function is evaluated. If the objective value is less than some desired value, the process is complete. If the objective value is greater than some desired value, the optimization process searches for new values for the elements of the design vector, $\boldsymbol{\alpha}$, which will reduce the value of the objective function and satisfy the constraint equations. The permissible values for elements of $\boldsymbol{\alpha}$ are those that are within the limits of the upper and lower bounds of $\boldsymbol{\alpha}$. After the constraints are satisfied, the design vector is used to generate a new system design. Next, the new system produces another response. The response is used to generate another objective function evaluation that is then compared to the desired objective value. Iteration of the optimization process is continued until some desirable value of $F(\boldsymbol{\alpha})$ is achieved or the number of iterations has reached some prescribed maximum. Finite differencing is used to develop design gradients.

3. Design Process Management and Control

To implement the design process on an internet level, it is necessary to have a means to regulate all machines as necessary. The design is regulated by using process status interrogation, copy to remote machine and executing remote commands. User privilege (i.e., having a valid account) must exist on all machines. Each constituent machine should have a "**.rhost**" file established which will allow remote shell commands to be mutually executed among all machines. This is done by placing the Internet protocol (IP) address and user name for each system used. An example of information which needs to be placed in the "**.rhost**" file is given below:

(IP address **A**) (username on **A**)
(IP address **B**) (username on **B**)
.
.
.
(IP address **N**) (username on **N**)

The example given above considers the case where each constituent piece of software needed for each discipline (e.g., **A**, **B**, ... **N)** resides on a different machine. The entire process is regulated by a single FORTRAN or C program. In the example which will be presented, all programs are written in FORTRAN and all operating systems are UNIX.

In the first iteration:

1. The regulating program reads a file containing the initial design vector.
2. If the design objective is not achieved, the optimization program is called to generate new design parameters.
3. The new design vector is partitioned to files which are used as inputs to the design software at each respective internet site.
4. Design and analysis software is executed at each site.
5. Objectives and constraints are evaluated using results from the design software.

In succeeding iterations, step 2 through 6 are repeated until the optimization is complete or the optimization has gone through a predetermine number of iterations (Fig. 1). The regulating program has a system level call to the UNIX procedural files. These procedure files execute design and analysis software. It is through the procedure files that the analysis required in the optimization can be multiplexed to different machines at remote sites.

For example, the complete system is compose of two disciplines, **A** and **B** (e.g., control design and structural design). All software for discipline **A** resides on the machine **A.** All engineering and technical expertise for discipline **A** is located at site **A.** Similarly, all software and expertise for discipline **B** resides at site **B**. The optimization software resides at **A**. The logistics for implementing analysis on machine **A** is relatively simple. All design parameters used in **A** are saved to a file, the analysis software for **A** is then executed. Results from the analysis are saved into a file. Similarly, the design parameters used in **B** are saved to a file, **design_var_B**. When the optimization regulating program requires analysis results from site **B**, a system call inside the program such as:

.
.

```
                .
1               call system('get_results_from_B')
2        42     call system('read_status_B')
3               open(3,file='job_status')
4               read(3,*) jobstat
5               close(3)
6
7               if(jobstat.eq.1.0) then
8                 call  system('read_results_B')
9                 go to 31
10              else
12                call system('sleep 10')
13                go to 42
14              endif
15       31     continue
                .
                .
                .
```

The procedural file '**get_results_from_B**' contains the following instructions

```
echo "0.0" > 'job_status'
rcp "design_var_B" "122.133.45.67:design_var_B"
rsh 122.133.45.67 run_B_software
```

The instructions above execute a remote process, **run_B_software,** on the machine **B** with IP address 122.133.45.67. The procedural file **run_B_software** exists on **B** and does the following:

```
echo "0.0" > 'job_status'
design_software_B
wait
echo "1.0" > 'job_status'
```

The design and analysis software at site **B**, **design_software_B**, uses the design variables that were placed in the file, **design_var_B**, runs its analysis and places results in the file **results_B**. The "wait" command prevents other processes from running until the command preceding the "wait" is finished. The optimization regulating program (lines 2-14) will constantly interrogate the file **job_status** using the procedural file **read_status_B** which contains the following command:

```
rcp "122.133.45.67:job_status" job_status
```

If the contents of **job_status** is 0.0, the program sleeps (i.e., remains idle) for 10 sec. and then re-examines the file **job_status.** If the contents of **job_status** is 1.0 the optimization regulating program copies the results from machine **B** to machine **A** using the procedural file **read_results_B** which contains the following instructions:

```
rcp "122.133.45.67:results_B" "result_B"
```

The results from the analysis process from machines **B** and **A** can be used to evaluate constraints and objectives and the optimization process continues.

4. Numerical Example: Integrated Design of the Earth Pointing System

4.1 System Modelling

The methodology of partitioning the design problem to various Internet remote sites has been demonstrated using the system presented in Ref. 1 (Maghami et al). The results used in Ref. 1 are also compared to those produced in this paper. Results produced by Maghami et al used an aggregate FORTRAN program for structural design, control design and optimization. The system used in Ref. 1. and this paper is the NASA Earth Pointing System (EPS). The EPS is shown in Fig. 2. The EPS is a generic geostationary platform that was used as a means to compare the results of various control and structural design methodologies. Although the model is fictitious, it is a realistic representation of existing Earth observing spacecraft. The model also has coupling between the structure and the control system. Any change in inertia distribution will effect the controller response inversely. If the controller bandwidth is higher than the fundamental (lowest) structural frequency, then there could be possible adverse interaction between the controller and the structure. A concurrent multidisciplinary optimization approach will allow designers to take advantage of interaction. The EPS system is designed for fine attitude control and vibration suppression. It is a 30-m-long truss structure consisting of 10 structural bays, a 7.5 m diameter radial antenna and a 15 m diameter radial antenna. All structural members, including the antenna, are hollow tubes with circular cross section and 1.59 mm thickness.

The Automated Design Synthesis (ADS) (Ref. 11) program is used for optimization. All control analysis is evaluated using Matlab (Ref. 12). NASTRAN (Ref. 13) is used for all structural analysis A FORTRAN program regulates the optimization process. Two machines with different IP addresses are used in this demonstration. NASTRAN, ADS and the regulating program reside at one of the addresses. The control software on Matlab resides at the other address.

Finite element modeling using NASTRAN is used to generate the structural model in physical space. Usually the models are very large. Modal truncation is used to reduced the size of the model. Modes beyond the controller bandwidth are eliminated in the modal model. Ref. 1 presents a more detailed discussion of model formulation and development of controller design. The system equations in modal space using modal coordinates are

$$\mathbf{J_r}\ddot{\mathbf{q}}_\mathbf{r} + \mathbf{D_r}\dot{\mathbf{q}}_\mathbf{r} + \mathbf{K_r}\mathbf{q_r} = \Phi_\mathbf{r}^T\tilde{\mathbf{B}}\mathbf{u} \equiv \Gamma^T\mathbf{u} \tag{1}$$

where $\mathbf{q_r}$ is a r $\times$ 1 vector of modal amplitudes; $\mathbf{J_r}$, $\mathbf{D_r}$, $\mathbf{K_r}$, are, respectively, the generalized inertia, damping, and stiffness matrices; $\mathbf{\Phi_r}$ is a r $\times$ n matrix whose columns are the r open-loop eigenvectors associated with the included modes; $\tilde{\mathbf{B}}$ is a n $\times$ m control influence matrix and $\mathbf{u}$ is the m $\times$ 1 control input vector. If mode shapes are normalized with respect to the inertia matrix and modal damping is assumed then $\mathbf{J_r} = \mathbf{I_{r\times r}}$, $\mathbf{D_r}$ = Diag $2(\zeta_1\omega_1, \zeta_2\omega_2, \ldots, \zeta_r\omega_r)$, $\mathbf{K_r}$ = Diag $(\omega_1^2, \omega_2^2, \ldots, \omega_r^2)$, where ω_i and ζ_i (i = 1,2,...,r) are the open-loop frequencies and damping ratios, respectively.

$$\begin{aligned} y_p &= \Gamma\mathbf{q_r} \\ y_r &= \Gamma\dot{\mathbf{q}}_\mathbf{r} \\ y_{\text{perf}} &= \mathbf{e} = \mathbf{C}_{\text{perf}}\begin{bmatrix}\mathbf{q_r} \\ \dot{\mathbf{q}}_\mathbf{r}\end{bmatrix} \end{aligned} \tag{2}$$

The position and rate measurements used in the feedback loop are $\boldsymbol{y}_p$ and $\boldsymbol{y}_r$, respectively. The part of the output used in the performance evaluation is given by y_{perf}.

$$\mathbf{u} = -\mathbf{G}_p \boldsymbol{y}_p - \mathbf{G}_r \boldsymbol{y}_r$$

$$\mathbf{G}_p = \mathbf{L}_p \mathbf{L}_p^T$$
$$\mathbf{G}_r = \mathbf{L}_r \mathbf{L}_r^T \tag{3}$$

The static dissipative (Ref. 1) controller position and rate gain matrices are $\mathbf{G}_p$ and $\mathbf{G}_r$, respectively. The elements of their respective Cholesky factorization matrices, $\mathbf{L}_p$ and $\mathbf{L}_r$ are used as control design variables.

4.2 EPS Optimization

Minimization of the steady-state RMS pointing error at the large antenna is used as a design objective. Because geostationary satellites must maintain very high pointing tolerances, the objective is a relevant design concern. The objective is represented by the following function:

$$J = \lim_{t \to \infty} \left(\mathrm{Tr} \left\{ E \left[\mathbf{e}(t) \mathbf{e}^T(t) \right] \right\} \right)^{1/2} \tag{4}$$

Average control power , $P_{\max}$, limitation must be considered in real-world applications and can be included as a design constraint

$$\lim_{t \to \infty} \left(\mathrm{Tr} \left\{ E \left[\mathbf{u}(t) \mathbf{u}^T(t) \right] \right\} \right) \leq P_{\max} \tag{5}$$

Tr is a trace of its argument and E is the expected value of its argument. The average control power, $P_{\max}$, is limited to $3N^2$ - m^2. Launch vehicle payload is also a design concern. Spacecraft mass must be less than the maximum allowable for the launch vehicle. Furthermore, any savings in spacecraft mass can be used to increase the amount of fuel on the spacecraft and thus give the spacecraft a longer life. Therefore structural mass is included as constraint

$$M_{str} \leq M_{\max} \tag{6}$$

Although structural truss diameters can be used as design variables, their size must be within some bounds to maintain the structural integrity of the spacecraft and to also bound the spacecraft size. Therefore

$$d_{\min} \leq d_i \leq d_{\max} \tag{7}$$

5. Discussion of Results

The method presented in this paper is compared to the design produced in Ref. 1 by Maghami et al. Ref. 1 uses a single FORTRAN program for concurrent optimization of the EPS control system and structure. This paper produced results using separate software packages for control design, structural design and optimization. The regulation of the optimization process was done via Internet commands. The Internet also was used a means of passing data between processes. The final spacecraft total mass in both designs had a 1.4% difference. In this study, the mass was reduced from 5760.1 Kg to 5676.0 Kg. Both designs final average control power differed by only 0.07 N^2-m^2. Ref. 1 produced a RMS pointing error that was 2.1 rad. larger than that produced in this paper. This method reduced the pointing error from 71.55 microradians to 14.68 microradians. The attitude gain Cholesky matrix produced using both methods differed by as high as 16.2%. However, the elements for the attitude rate gain Cholesky matrix were within 5.6% of each other. The major differences between the two methods were in the final structural design.

Both designs resulted in stronger (larger diameter) large antenna mounts and weaker small antenna mounts. The design produced in this paper had smaller truss diameters in section 3 than Ref. 1. The smaller diameter resulted in more structural flexibility near the small antenna. In section 2, only the longhorn diameters differed significantly. The section 1 longhorns produced by Magma et al were twice the diameter produced in this paper. The section 1 battens produced by the Internet design 1.8 times those of Ref. 1.

In Figs. 3 through 11, the optimization design history is presented. The EPS RMS pointing error (Fig. 3) converges to the final value of 14.68 rad. after approximately 240 iteration steps. During the course of the design the mass and average control power constraints (Figs. 4 and 5) are violated between steps 75 and 270. The rate and attitude gain elements follow the same trends. At approximately step 100 and 210, they increased their values and the values remain relatively constant. The structural variables follow the same trend (Figs. 8-10) until iteration step 150. After step 260 they converge to their final values. The small antenna mount diameters (Fig. 11) reach their final value at approximately step 97. After step 260, process converged on a final large antenna mount design (Fig. 11). The process is continued beyond step 270 to allow all constraints to be satisfied.

The total time involved in the parceling of the total design to different machines and the design orchestration via the Internet was very insignificant compared to the run-time of the structural design software (NASTRAN)

6. Concluding Remarks

A method has been presented that demonstrates how multidisciplinary optimization can be accomplished using two or more computers with design discipline partition among the computers using the Internet. Use of the Internet provides a means for multidisciplinary design teams to interact remotely to accomplish a system level design. The system level design process was accomplished using a FORTRAN program that regulated the design analyses on all the computers involved. The method presented in this paper used the UNIX operating system. The TCP/IP protocols were used for data transfer and remote computer process control. Each discipline design was accomplished using commercial software.

Structural and control design of the Earth Pointing System (EPS) was used to demonstrate the methodology. The system is fictitious but possesses the detail of a realistic Earth observing spacecraft. Results from the design process were compared to those produced by Magma et al (Ref. 1). Ref. 1 used single FORTRAN program for control design, structural design and multidisciplinary optimization. The final design produced using the method presented in this paper. Average power control, total mass and structural member size were included as design constraints. The design objective was to minimize the RMS pointing error of one the antenna.

The final design resulted in a better pointing performance than Ref. 1. The final power required and the final total spacecraft was within 1% of that produced by Ref. 1. Other final design results were commensurate with Maghami et al. This method has demonstrated that multidisciplinary design can be automated and regulated among different computers. The results produced also show the viability of using concurrent multidisciplinary design partitioned to remote internet sites.

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Appendix Summary of Procedure Files, Matlab M-files and Fortran Programs

File	Description	Input	Output
abcd.m[1]	Produces the system **A, B, C**, and **D** matrices.	Eigenvalues, Eigenvectors	**A, B, C,** and **D** matrices
ADS.f[2]	General purpose optimization program for solution of nonlinear constrained optimization problems.	optimizer for ADS; print options; gradient specification; number of design variables; number of constraints; design variables; bounds on design variables; objective; and, constraint.	status of optimization; gradient of objective function with respect to all design variables; gradient of constraints with respect to all design variables; and, number of active constraints.
adss.f[2]	Fortran program is the main driver for the design architecture. Its role is to take initial design variables and parameters, design constraints, and, design objectives; form initial structural design and initial control design; regulate all processes in the concurrent integrated design of the structure and the control system using structural analysis software (NASTRAN), control design software (Matlab), and, optimization software (ADS); develop final design.	Initial variables and initial parameters	Final design, final design variables, and design history
control[3]	Executes **control.m** as batch process	None	None

[1] Matlab M-file
[2] Fortran program

control.m[1]	Using eigenvalues and eigenvectors from the structural analysis, produces **A**, **B**, **C**, and **D** matrices and control gain matrices; computes closed-loop system matrices; computes performance function; and, generates constraints and objective.	Eigenvalues and components of eigenvectors from the structural analysis; control gain matrices	Objective function and constraints evaluation
eigen.f[3]	Converts NASTRAN binary eigenvalue and eigenvector matrices to ASCII	Binary files from NASTRAN containing eigenvalues and eigenvectors	ASCII files containing eigenvalues and elements of eigenvector matrix necessary to develop control influence matrix **B**
masget[3]	reads mass from NASTRAN **model.f06** output file, computes the value of the mass constraint and puts value in file **mass.get**	**model.f06** file.	Constraint value
mkphi.m[1]	Develops the **Φ** matrix	**B** matrix	**Φ** matrix
newdesn[2]	Generates a new structural design based on output from the the design optimization	Structural design variables	A file called **PROP.dat** which has all new NASTRAN PBAR cards
structure[3]	Removes output files from prior iterations and submits NASTRAN model file as batch process. After the NASTRAN run is complete, it runs **eigen** followed by **control** and masget .		

Table 2 Procedural files used to implement design.

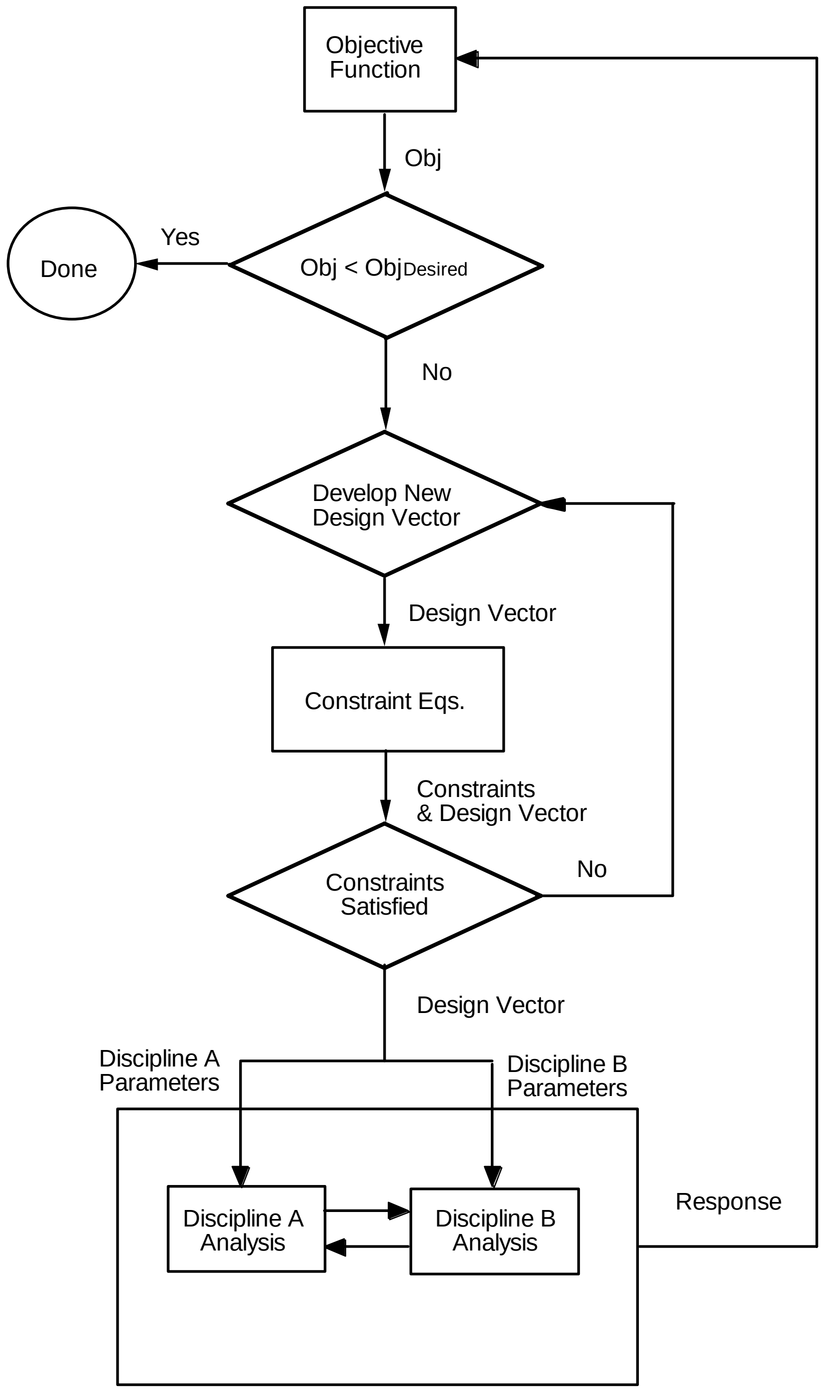

Fig. 1 Flowchart for concurrent multidisciplinary design optimization.

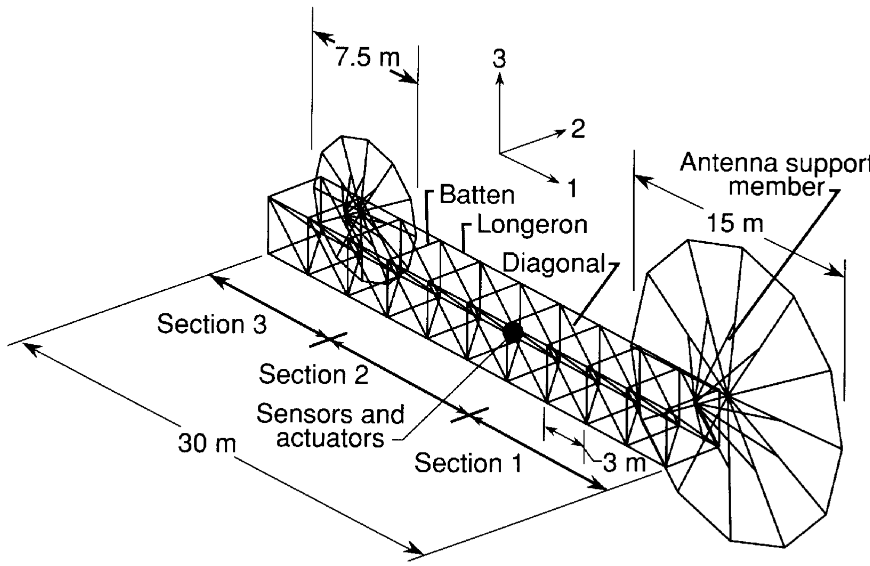

Fig. 2 Earth Pointing System.

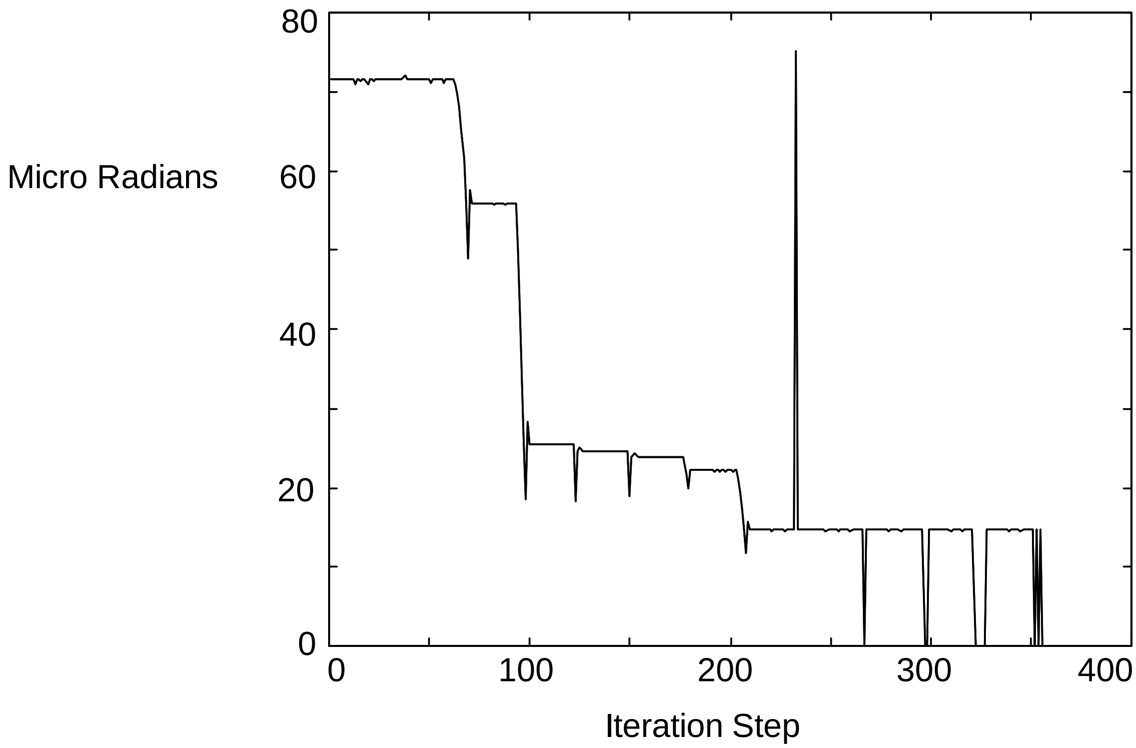

Fig. 3 Earth Pointing System RMS pointing error.

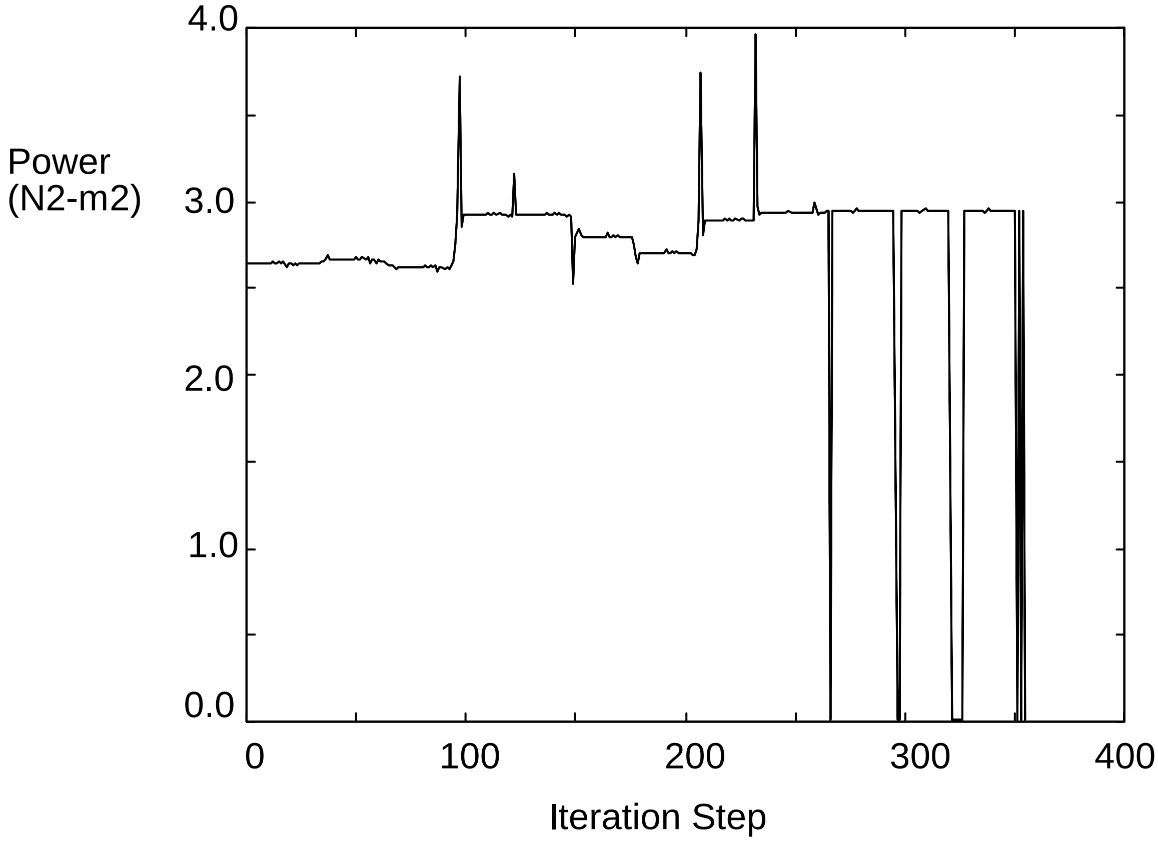

Fig. 4 Earth Pointing System power requirement.

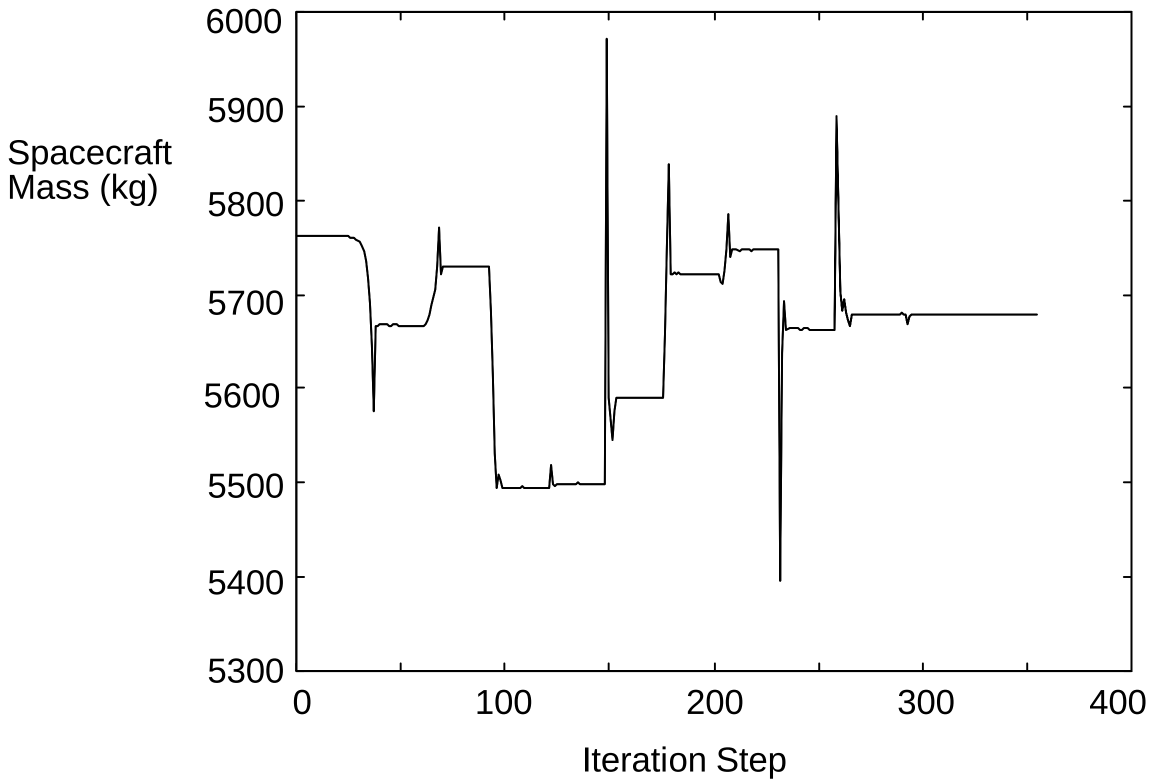

Fig. 5 Spacecraft mass.

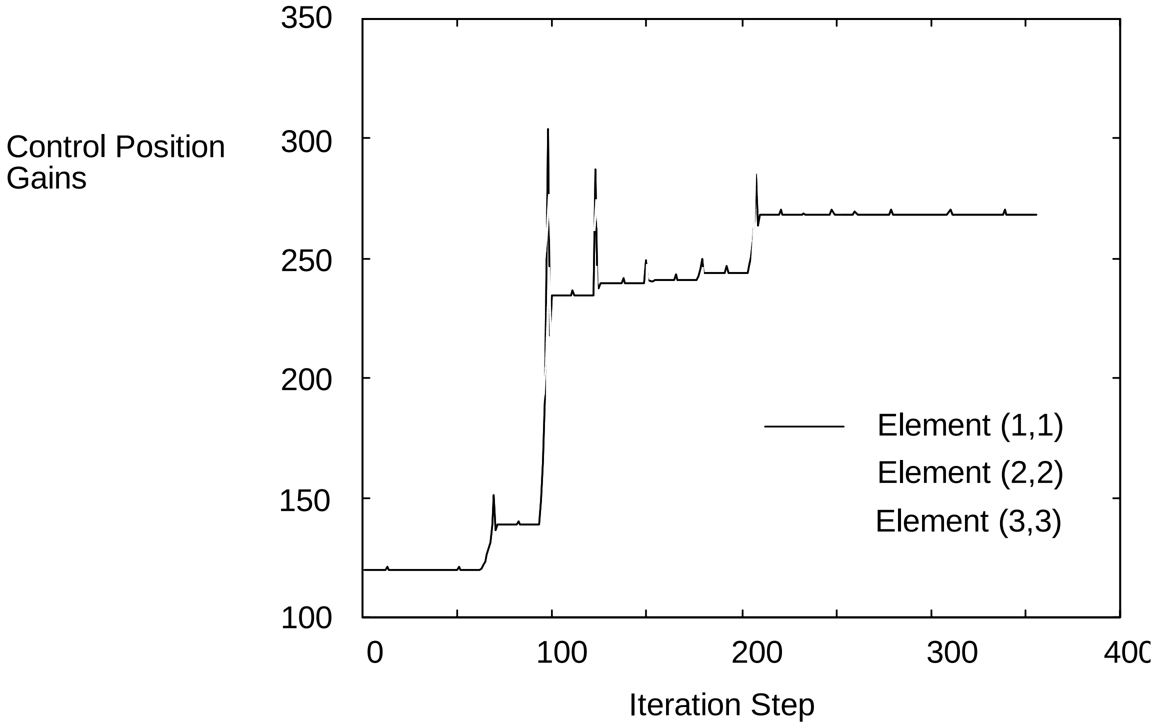

Fig. 6 Diagonal Elements of Cholesky Matrix of the attitude gain matrix.

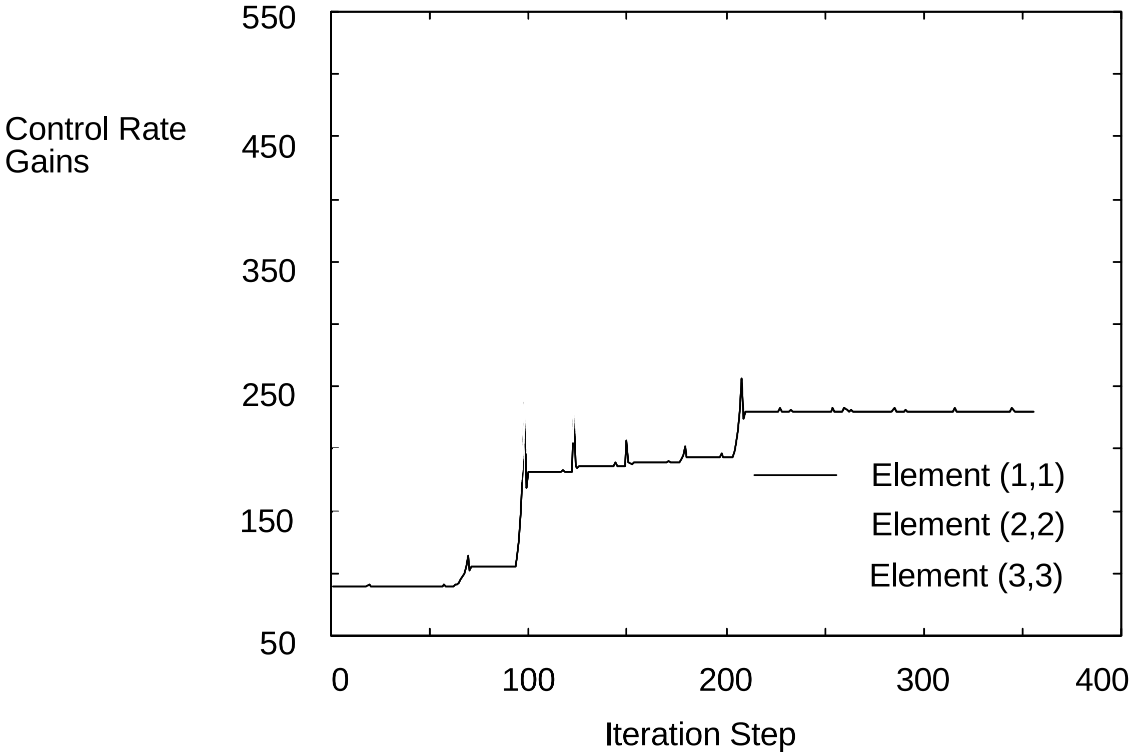

Fig. 7 Diagonal Elements of Cholesky Matrix of the rate gain matrix.

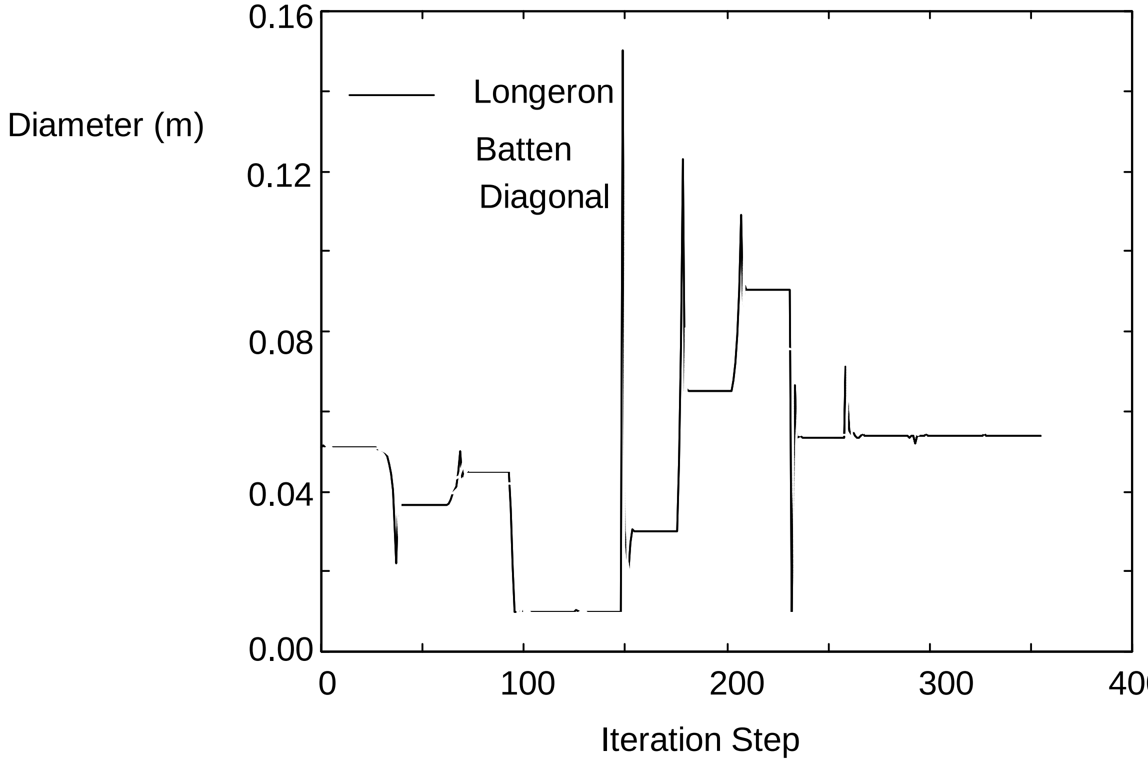

Fig. 8 Section 1 structural variables.

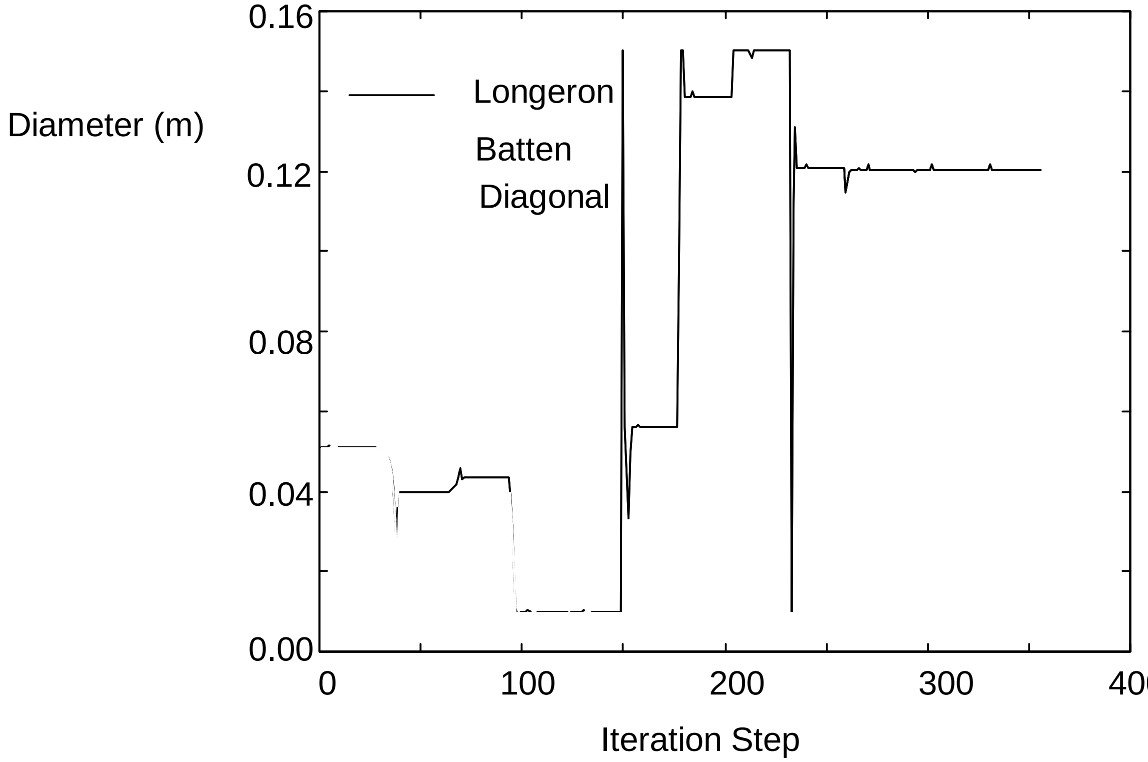

Fig. 9 Section 2 structural variables.

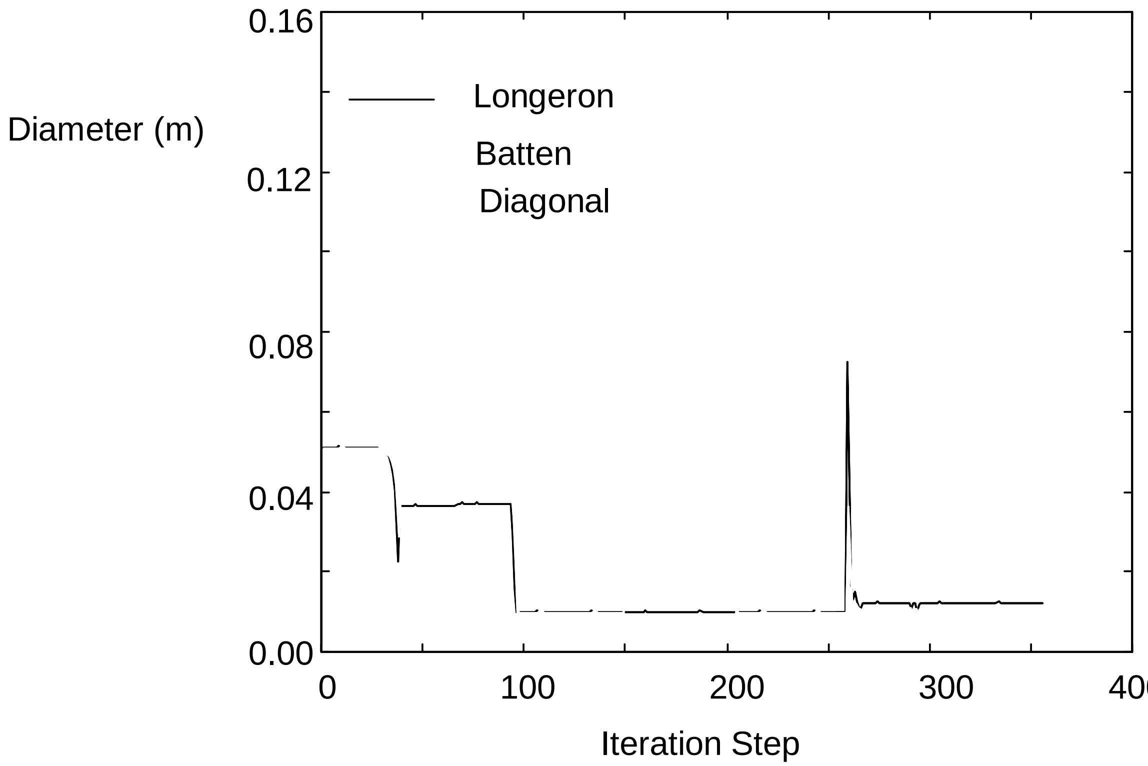

Fig. 10 Section 3 structural variables.

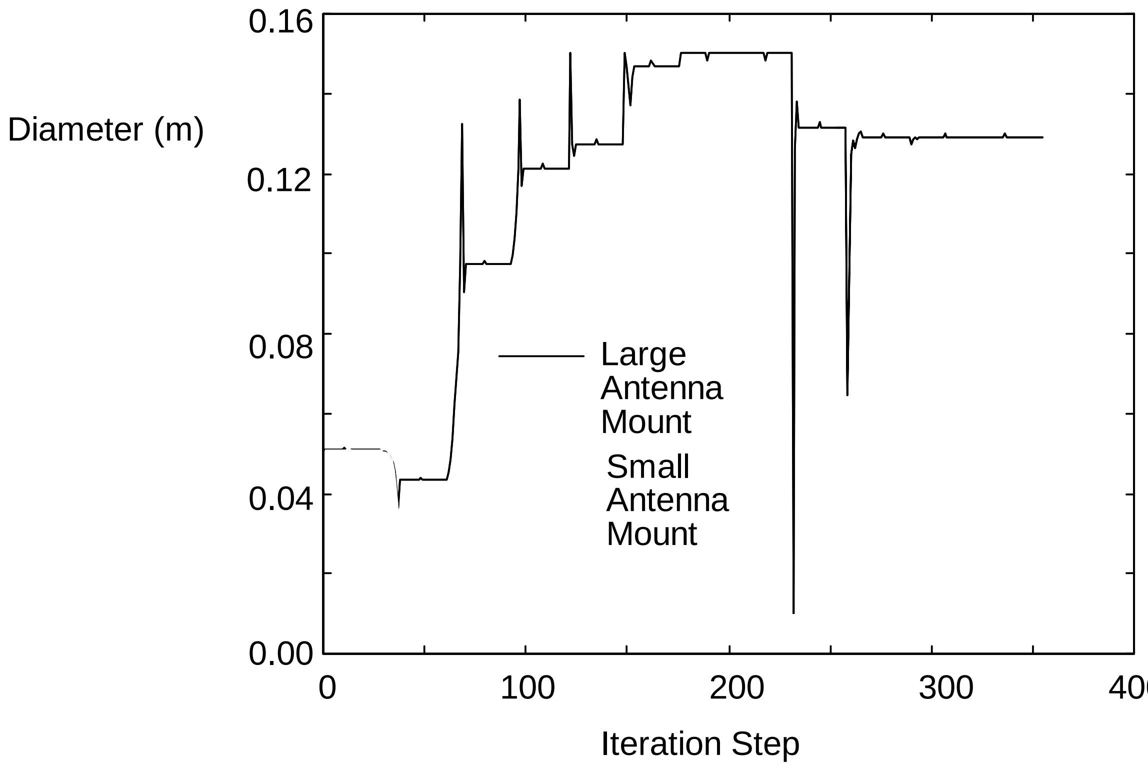

Fig. 11 Large and small antenna mount diameters.

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13. ABSTRACT *(Maximum 200 words)*
A methodology is presented which uses commercial design and analysis software and the Internet to perform concurrent multidisciplinary optimization. The methodology provides a means to develop multidisciplinary designs without requiring that all software be accessible from the same local network. The procedures are amenable to design and development teams whose members, expertise and respective software are not geographically located together. This methodology facilitates multidisciplinary teams working concurrently on a design problem of common interest. Partition of design software to different machines allows each constituent software to be used on the machine that provides the most economy and efficiency. The methodology is demonstrated on the concurrent design of a spacecraft structure and attitude control system. Results are compared to those derived from performing the design with an autonomous FORTRAN program.

14. SUBJECT TERMS
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