GEORGIA INSTITUTE OF TECHNOLOGY
School of Aerospace Engineering

NASA MULTIDISCIPLINARY DESIGN AND ANALYSIS FELLOWSHIP PROGRAM

Training Grant NGT-1-52156

FINAL REPORT

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This report summarizes the results of a multi-year training grant for the development and implementation of a Multidisciplinary Design and Analysis (MDA) Fellowship Program at Georgia Tech. The Program funded the creation of graduate MS and PhD degree programs in aerospace systems design, analysis and integration. It also provided prestigious Fellowships with associated Industry Internships for outstanding engineering students. The graduate program has become the foundation for a vigorous and productive research effort and has produced: 20 MS degrees, 7 Ph.D. degrees, and has contributed to 9 ongoing Ph.D. students. The results of the research are documented in 32 publications (23 of which are included on a companion CDROM) and 4 annual student design reports (included on a companion CDROM). The legacy of this critical funding is the Center for Aerospace Systems Analysis at Georgia Tech which is continuing the graduate program, the research, and the industry internships established by this grant.

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EXECUTIVE SUMMARY

Georgia Tech was one of five leading U.S. engineering universities to receive in 1994 a three year NASA MDA Fellowship grant to be used to implement a new graduate program in multidisciplinary design and analysis and to provide prestigious MDA Fellowships to outstanding engineering students. This key grant has been essential to the success of Georgia Tech over the past five years in developing a strong and vigorous program in aerospace system design, analysis and integration. The first objective of the grant program was to attract some of the brightest students into this area and in this respect we have been able to attract the top graduates from Georgia Tech along with highly qualified students from other institutions. The grant also provided support to revise our MS degree and to create a new Ph.D. degree in aerospace systems design, analysis and integration. A key feature of these new degrees is the provision for periodic industry internships and ongoing technology transfer between the university, government and industry. The Fellows have been key to the development of a powerful research program that has attracted additional sponsors from NASA, DoD and industry. The overall research effort is now above $1.5 million per year. Perhaps the best measure of the success of the MDA Fellowship program is its direct role in fostering creation of the new Center for Aerospace Systems Analysis (CASA) at Georgia Tech that encompasses flight vehicle systems from near-earth to outer space. CASA is carrying on the MDA Fellowship legacy with continued support for outstanding graduate students, strong interaction with industry and government laboratories, and an innovative research program in aerospace systems design, analysis and integration.

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1. INTRODUCTION

Aerospace Engineering has always been identified as a multidisciplinary activity involving aerodynamics, propulsion/combustion, structures/materials, and flight mechanics/controls. The aerospace industry has likewise been identified as a large scale systems integration business which integrates into highly complex products not only the aerospace engineering disciplines, but also the disciplines of other engineering fields, such as electrical, mechanical, industrial and chemical engineering. In fact, most aerospace companies employ as many electrical and mechanical engineers as they do aerospace engineers. Surprisingly, even though large scale systems integration is a core and often dominant competency for aerospace companies, aerospace engineers have not been taught or thought of as systems integrators. Systems engineering is often taught as a separate engineering field or is identified with industrial engineering. Systems analysis is also usually linked with operations research and taught in other departments as well.

Complex new aerospace products based on information-dominated design and manufacturing methods are already forcing the aerospace industry to deal with entirely new scales of complexity. Some products require levels of precision, delicacy, or cleanliness that human assembly can no longer directly provide. International economic competition has grown enormously in the last decade, and several U.S. aerospace companies are no longer the world leaders. Both the technologies and the understanding of how best to use them have been advancing and are changing the way customers think and aerospace companies operate. As a result, from conceptualization of an aerospace system through research, development, source selection, distribution, and marketing, aerospace engineering is becoming a set of information-gathering, analysis, decision-making, dissemination, and archiving activities.

Recognizing the cultural and process changes taking place in the aerospace industry and in aerospace engineering, NASA in 1993 solicited proposals from leading U.S. engineering universities for twenty planning grants to develop proposals for new multidisciplinary design and analysis (MDA) programs with prestigious MDA Fellowships for outstanding graduate students. Georgia Tech received a planning grant, used this to prepare and submit a formal proposal, and was one of five universities selected to receive 3-year NASA MDA Fellowship Grants. The School of Aerospace Engineering has used this key funding to initiate a new graduate program in Aerospace Systems Design along with a growing and vigorous program of research. The program was unique among aerospace schools in that it not only addressed the interdisciplinary interaction of the traditional aerospace engineering disciplines with design, but it also addressed the integration of design and manufacturing to support the Integrated Product and Process Development (IPPD) environment being adopted in industry. The initial NASA funding was critical to the success of the overall effort because it not only provided a measure of legitimacy among traditional faculty peers but it also attracted some of the very brightest of our undergraduate students. In addition the MDA Fellowships included summer internships in industry and this closely tied the research and training to industry needs and direction.

The NASA funding solidified the formation of the Aerospace Systems Design Lab (ASDL) earlier in 1992, and it led to the hiring of two new junior faculty members (Professors Dimitri Mavris and John Olds) in 1995. More recently, it has led to the organization in 1998 of the Center for Aerospace Systems Analysis (CASA) with ASDL and the new Space Systems Design Lab (SSDL) as constituent laboratories. The vigorous growth in this area coupled with the growing national and international visibility for these efforts has indirectly supported the recent endowments of three new chairs in the School of Aerospace Engineering (from Boeing in advanced aerospace systems analysis, from Lockheed Martin in avionics integration and from David S. Lewis in space engineering).

The following sections of this Final Grant Report will summarize the direct accomplishments that were made under the NASA MDA Fellowship grant, including, for example, the numbers of students involved, the research projects undertaken, and the industry internships that were created. Much of the detailed documentation of this grant work including reports, papers and presentations has been assembled into a companion CDROM that accompanies this report. Finally, the report will outline how the NASA MDA Fellowship funding has been critical to the formation of CASA and to the continually evolving new programs in aerospace systems design, analysis and integration that this has initiated.

2. GEORGIA TECH PROGRAM

The Georgia Tech graduate program in aerospace systems design is positioned to address in an integrated fashion the critical issues noted above. The effort is organized in the Center for Aerospace Systems Analysis (CASA) under the direction of Prof's.. Dan Schrage and Jim Craig, which in turn is composed of the Aerospace Systems Design Laboratory (ASDL) under the direction of Prof. Dimitri Mavris and the Space Systems Design Lab under the direction of Prof. John Olds. External funding for CASA programs is currently almost $2 million annually and approximately 45 graduate students are involved in the research programs.

Organization

The organizational structure for CASA is illustrated in Figure 1. The major elements of CASA are its two supporting laboratories, ASDL and SSDL, located on the left and right sides of the figure. These laboratories are where all of the research is conducted. Dashed boxes under each identify the aerospace system areas that they are currently trying to exploit. The center of the figure identifies the major government agencies whose funding provides the basic research support for ASDL and SSDL.

Finally, but certainly most importantly, at the bottom of the figure is the education program which serves as the foundation for CASA and all of its programs. Shown between the educational program and the funding sources are the graduate research assistants who not only conduct the bulk of the research through their masters and doctoral degree studies but also are the "change agents" who will facilitate technology transfer to industry and government.

Figure 1 shows near the top the three newly endowed and as yet unfilled chairs noted earlier. Also shown on the right side at the top is the computing frameworks position that is currently occupied by Dr. Mark Hale as a research engineer..

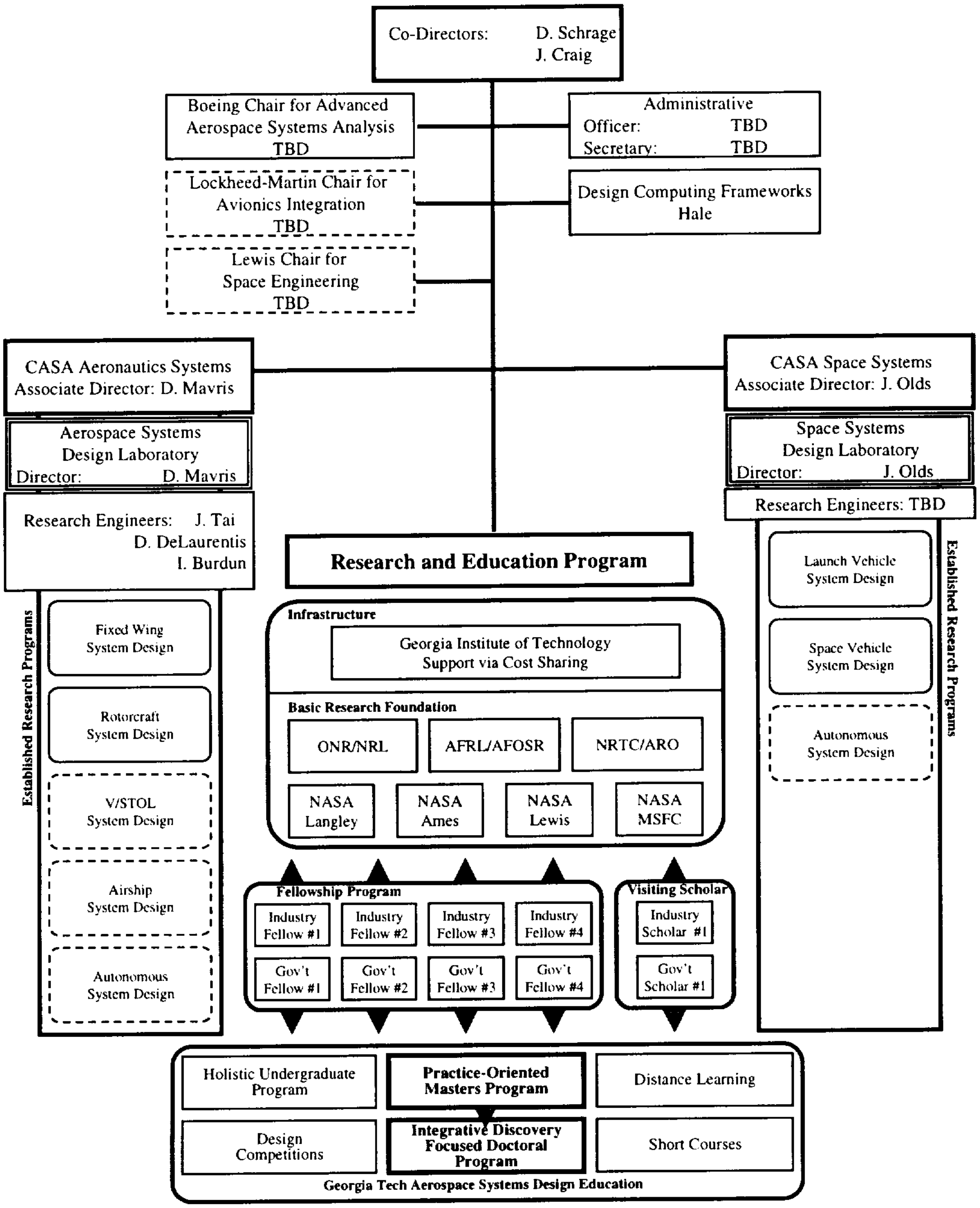

Figure 1. CASA Organizational Structure

Graduate Degree Programs

The graduate program in aerospace systems design is a dynamic and evolving activity that responds to new developments in field of aerospace systems analysis and design in both industry and academia. The overall approach being followed is illustrated in Figures 2 which outlines a concurrent engineering methodology for achieving integrated product and process development (industry has confirmed that, in a generic manner, it is very similar to the IPPD methodologies they are trying to develop and implement).

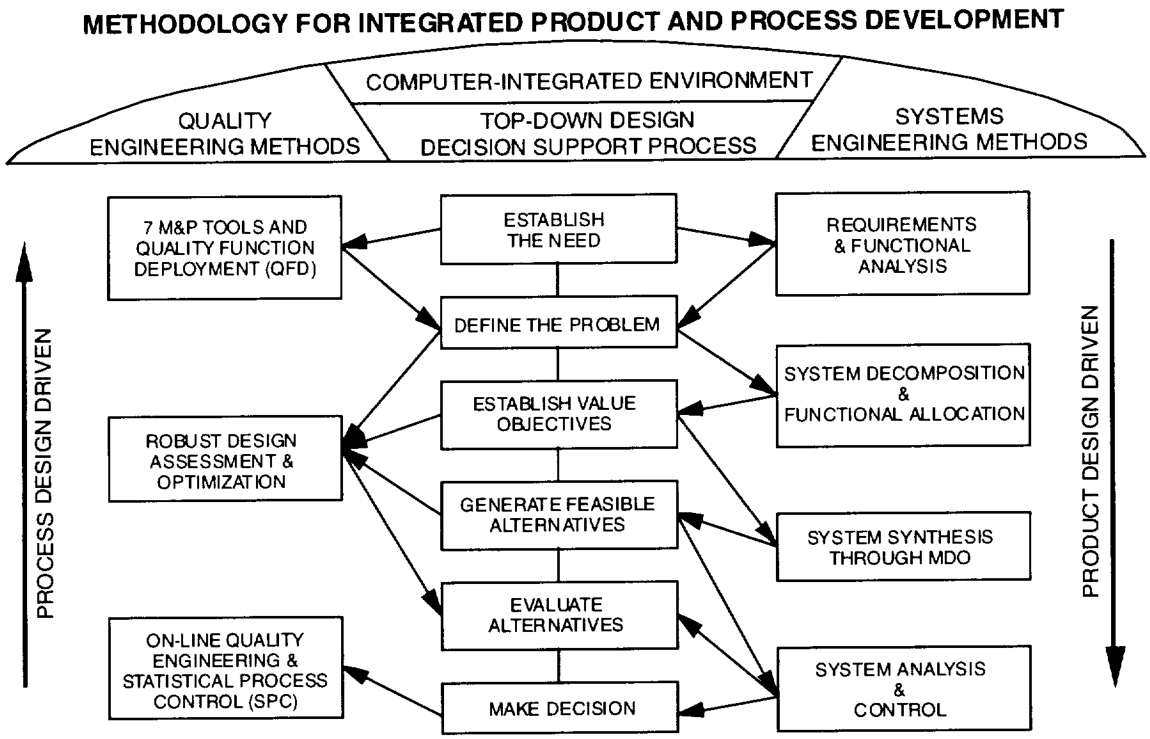

Figure 2 : Georgia Tech Concurrent Engineering Methodology

The methodology incorporates interaction of four key elements necessary for parallel product and process trades to be made at the appropriate level of system decomposition and recomposition. These are: systems engineering methods, quality engineering methods, top down design decision support process, and a computer integrated environment. The interaction among these elements to make parallel product and process design trades is shown below the umbrella. The methodology takes advantages of successful methods and tools for both product and process. It should be noted that system synthesis is achieved through the use of MDO to generate feasible alternatives. These feasible alternatives are then evaluated for process robustness using quality engineering methods and a decision is made on selecting the best alternative based on the criteria established from the value objectives

The graduate program that has been developed to support this approach was begun under NASA MDA Fellowship funding and resulted in a quarter-based program structure. Georgia Tech is moving to a semester system starting in August 1999 and as a result, the quarter-based program has recently been restructured into a semester-based program. This has provided a new opportunity to further adjust and "tune" the program for maximum benefit to the students and participating sponsors. Only the new semester program will be described in this report, but descriptions of the quarter-based curriculum can be found in previous annual reports for the subject grant.

MS Degree Program

The semester program begins with a "Practice-Oriented" Masters degree as illustrated in Figure 3 below. At a minimum it consists of three semesters of study and research training, but this will generally be extended to a full four semesters with one term devoted to an internship in industry. The core curriculum consists of two areas: (a) methods and techniques, and (b) tools and infrastructure, as shown in the figure, and these are supported by two required mathematics courses and other elective courses chosen by the student and advisor. Each box in the figure represents a separate course and the five core courses are highlighted in gray. The two "Systems Design" courses shown in the center of the figure provide the "capstone" design experience and unify the total program. These two courses are offered in one of three "tracks" involving complex systems design projects in either:

- fixed wing vehicle synthesis
- rotary wing vehicle synthesis, or
- space launch vehicle synthesis.

In all cases, the students are organized into teams during the second term and develop vehicle systems designs as a part of a national competition. Over the past 5 years, the student teams have earned top honors in rotorcraft design, airbreathing engine design, space launch vehicle design and in individual student design competitions.

The program includes a design seminar with industry speakers and may include an industry internship and/or a special research project. MS thesis options are available but are discouraged due to the extensive practical content already in the program. Appendix A provides sample MS degree programs of study under the new semester system.

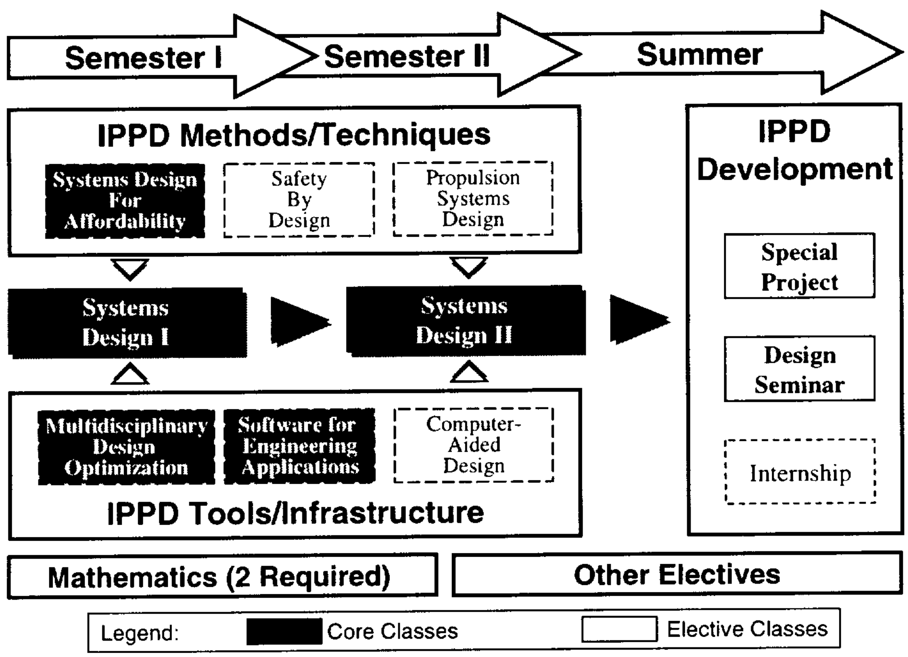

Figure 3. Practice-Oriented Masters Degree Program

Ph.D. Degree Program

The practice-oriented Master's program can be followed by an integrative, discovery-focused Ph.D. program (Figure 4) that is based on a strong and well-developed research program relevant to industry. The program requires two or more years beyond the MS degree depending on research progress. As shown on the right side of the figure, the doctoral program is focused on innovative design research that is supported by disciplinary expertise including design theory and methodology and is guided by industry partnerships through internships or collaborative research projects. Several key features of the program are noted below.

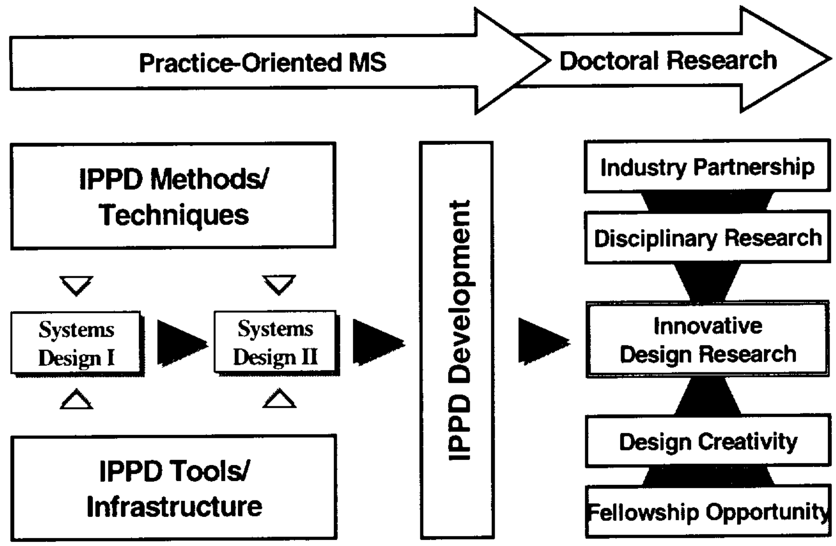

Figure 4. Integrative, Discovery-focused Ph.D. Program

Under the NASA MDA Fellowship Program, a doctoral program of study in Aerospace Systems Design was developed to replace the old *ad hoc* degree program. This involved three steps: (a) initiation of a sustaining program of research, (b) creation of a viable curriculum beyond the MS level, and (c) definition of a relevant doctoral Qualifying Exam (sometimes called Comprehensive Exam).

The doctoral program curriculum is somewhat more broadly defined and can easily be customized to the needs of the individual student and their research interests. It nonetheless incorporates several innovative features beyond the mature core courses. Acknowledging the fundamental importance of disciplinary expertise in one or more of the traditional areas of aerospace engineering, the doctoral program includes provision for the student to concurrently concentrate on one of these areas. For example, a student might concentrate on aerodynamics in order to more deeply pursue systems design methodologies as applied to problems in high speed aerodynamics. Such concentrations are not limited to the traditional aerospace disciplinary areas but may also include manufacturing technologies, software engineering, or avionics to name only a few options. Again, the degree program is arranged by the student in consultation with the advisor and must have a coherent structure and objective. Aerospace Engineering requires a full minor in mathematics (12 hours) and Georgia Tech requires a minimum number of graduate level courses, but otherwise, there are no further departmental requirements. A sample doctoral program of study (beyond the MS degree) is shown in Appendix B. The Program leverages the design-oriented one year MS degree so that students pursuing a Ph.D. in design focus on design theory and methodology electives and intensify their study of other disciplines to prepare for the Qualification Exam.

The Qualifying Examination (also referred to as the Comprehensive Examination) is one of the most formidable challenges to the student pursuing doctoral-level studies. The format for this exam varies greatly among universities and departments, but the objective is to determine the level of preparation and the academic qualifications of the candidate for doctoral-level study. As a result, the examination usually covers broad areas of knowledge that the student should be responsible for understanding, and it requires extensive preparation for the student. In the past, it has been hard to attract promising graduate students into the design area because of the extensive preparation required in areas outside design.

Partly in response to the highly visible NASA MDA Fellowship program and the outstanding students it has attracted, Aerospace Engineering created a new Qualifying Examination area in design theory and methodology. To conform with the current structure of the exam, the new area exam is firmly and explicitly based on designated coursework. The topics for the exam are:

- A/C performance and sizing fundamentals
- Principles of Concurrent Engineering and IPPD
- Multidisciplinary design optimization for design
- Life-cycle cost analysis for design
- Information theory and systems for design
- Decision support methodologies

The MS and Doctoral programs of study in MDA are designed to prepare prospective doctoral students for this qualifying exam area. In addition, each design student, like all other Ph.D. students, is required to take two other Qualifying Examinations, and for the design students these are in one or more traditional discipline-specific areas, thus confirming the broadly based background required for doctoral study in design.

The MDA Fellows were supervised by faculty teams (co-advisors) consisting of a design faculty member, a discipline-specific faculty member and an industry sponsor. This was a key component of the team-building strategy in the MDA Fellowship Program, and it provided the critical balance between breadth across the design process and depth within recognized aerospace disciplines and industry experience. The MDA Fellowship Program was carefully monitored to insure that the Fellows did not migrate away from the central MDA experience into more narrowly defined, discipline-specific research topics with one of the co-advisors.

Closure

Our research under the MDA Fellowship grant has shown that there is a two-fold role for multidisciplinary design and analysis in the design process. The first is with respect to improving multidisciplinary and interdisciplinary analysis, involving the more traditional aerospace disciplines, so that multidisciplinary design optimization of the evolving complex aerospace systems can be achieved in a more effective manner. The second involves the more effective integration of the life cycle disciplines (design, manufacturing, and supportability) so that complex aerospace systems can be produced in a more cost effective manner in reduced time. The Aerospace Systems Design graduate program has achieved noteworthy success in the integration of these roles.

3. ACCOMPLISHMENTS

The NASA MDA Fellowship Program provided the critically important nucleus of support that allowed us to initiate our academic program in aerospace systems design. Progress during the grant period has been very significant and has raised engineering design technology in the graduate curriculum to a high level at Georgia Tech and among our peer institutions. Noteworthy progress has been made in the following areas:

- Further development and refinement of the MS program in Aerospace Systems Design with the introduction of new space related topics in design,

- Formal establishment of the Ph.D. program in Aerospace Systems Design with the introduction of design as one of three Qualifying Examination topics that are chosen by Ph.D. candidates,
- Fellowship support that has attracted outstanding graduate students (typically the top students in the Georgia Tech graduating classes)
- Establishment of student internships with all major aerospace companies in the US,
- Placement of 8 students in 11 different industry internships,
- Publication of over 24 papers at aerospace industry conferences and in archival journals.

The background and structure for the graduate academic program have been described in the previous section, and its implementation must be considered as a direct result of the support and visibility provided by the MDA Fellowship grant. The other accomplishments are summarized in the following sections.

Industry Interaction

Perhaps the most noteworthy feature of our accomplishments is our interaction with industry. There are three essential elements for successful industry-university design interaction and these were pursued vigorously throughout this program. These are: (a) personnel exchange, (b) a focused project and (c) teamwork involvement and experience.

Personnel exchange was implemented by having the NASA MDA Fellows spend summer internships in industry and Figure 5 below summarizes the extent of this activity. These internships (which are available to other graduate students and are presently continuing beyond the term of the MDA Fellowship grant) were quite different from the customary undergraduate co-op experience in that they were focused tightly on a project of significant interest and importance to the industrial host and were appropriate as a topic for graduate research leading to the MS and Ph.D. degrees. The projects were normally arranged after extensive interaction between CASA faculty members and industry counterparts over the year preceding the internship. As a result, the MDA Fellows were able to begin preparation for the internship during the preceding academic year and often interacted with engineers during this period prior to their internship term. Continued interaction and occasional plant trips continued for the balance of the student's program of study. The student in effect could become a part of an industry IPT and contributed to and participated in the activities of the team. With careful design, the information gained from this process was generally directly applicable to the MS or Ph.D. level research being carried out as part of the degree program.

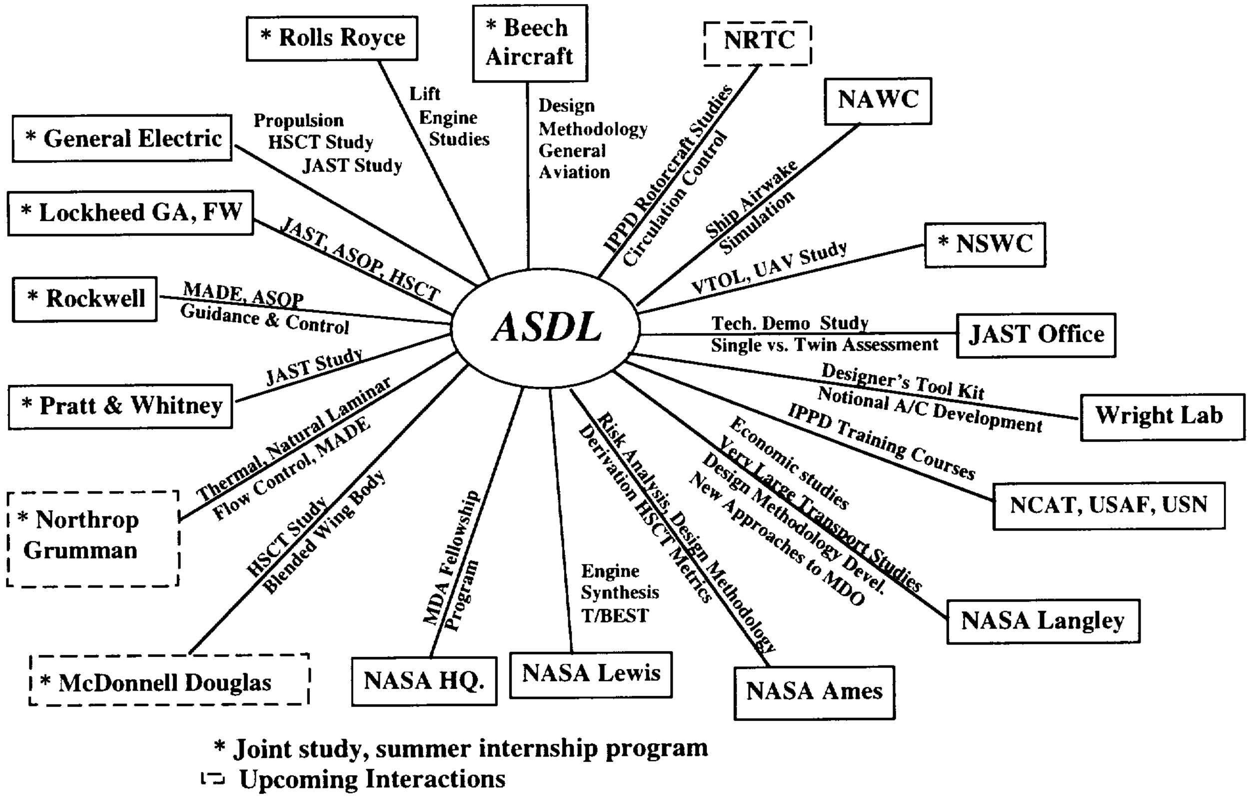

Figure 5 : NASA MDA Fellowship Industry Interaction

Students Supported

The three year MDA Fellowship grant and its subsequent no-cost extensions supported a total of 24 Fellows over the period from 1994 to 1999. While all of the Fellows achieved outstanding academic success (most with undergraduate GPA's above 3.6/4.0), a number of the Fellows were the top graduates from the Georgia Tech undergraduate classes. Perhaps this fact, more than any other, made the strongest impression on some of the more critical faculty in traditional areas of aerospace engineering analysis! Table 1 summarizes the fellowships over the grant term and includes the degrees earned and graduation dates for those students who have completed their degrees. While almost all the MS students have earned their degrees, only about half of the doctoral students have completed their studies. This is a natural consequence of the much more intense and far reaching scope of the doctoral research, and in some cases reflects extended industry interaction that was continued by the students throughout their programs of study. Table 1 also shows the internship companies and some of the dates. The last column lists the permanent job accepted by the Fellows on graduation from the program.

Table 1. NASA MDA Fellowship Student Summary

Compiled: July 1999

Name, last	First	93-94	94-95	95-96	96-97	97-98	98-99	Date of MS	Date of PhD	Internship Company	Internship Dates	Permanent Job
Abel	Reginald	x						Dec-93		Boeing-Seattle	?	Boeing
Brewer	Jason	x	x	x				Sep-94		GEAE	1995-1996	GEAE
Hale	Mark	x						Dec-92	Oct-96	-		ASDL
Lee	Jae-Moon	x		x	x	x		Sep-91	Mar-99	-		
Rohl	Peter	x	x					Jun-92	Jun-95	-		GE-CRD
Delaurentis	Dan		x	x	x	x	x	Sep-93	Dec-98	Rockwell-NAA (Boeing)	1995-1996	ASDL
Donofrio	Kevin		x					Sep-94		-		?
Higman	Jerry		x						Mar-96	-		?
Rysdyk	Rolf		x						Dec-98	-		GT-AE
Baker	Andrew			x	x			Mar-97	current	-		N/A
Macsotai	Noel			x	x	x	x	Jun-97	current	GEAE	1997-1998	GEAE
Mortzheim	Jason			x	x			Sep-97		-		?
Roth	Bryce			x	x	x	x	Dec-97	current	GEAE	1996-1998	N/A
Tapia	Fidencio			x				Dec-92	Jun-96	-		Faculty
Virasak	Jaccques			x				Dec-93	current	-		?
Zink	Scott			x	x	x	x		current	LM-Marietta; LM-Ft. Worth	1996-1998	N/A
Bays	K. Lance				x			Dec-97		-		LM-ASC
Hayden	William				x	x	x	Dec-98	current	Boeing-Seattle	1996-1998	N/A
Hines	Nathan				x	x	x	Dec-97	current	Boeing-Seattle	1998	N/A
McCormick	David				x	x	x	Dec-97	current	?		N/A
Soban	Danielle				x	x		current		-		N/A
Conejan	Luiz					x	x		current	-		N/A
Kannan	Suresh					x		current		-		N/A
Neuhaus	Jason					x	x	Sep-98		-		?

Student Recognition

An important measure of the success of any design program is how well the students can apply the newly gained knowledge to practical problems. One of the most highly visible and rewarding opportunities to do this is to participate in a national aerospace system design competition such as one of those sponsored by the AIAA, the AHS or NASA.

A fundamental component of the NASA MDA Fellowship Program has been the participation of students in one of the national aerospace system design competitions. This started with the rotorcraft design courses and has been continued under the present program. Georgia Tech student teams have held a near lock on first place in the rotorcraft design competition sponsored by the AHS and this has continued. In addition, a team led by NASA MDA Fellows won first place in the AIAA Air Breathing Propulsion competition in 1995 and another Fellow placed second in the 1996 AIAA individual design competition.

Research Results

The research carried out under funding provided by the MDA Fellowship grant has been focused on advanced methods for systems analysis and vehicle synthesis. The primary focus of the grant was on MDA Fellowships for outstanding graduate students, and this unique feature was used to leverage the grant resources to the greatest extent possible. This was achieved by using Fellows to extend promising research already being pursued under other sponsorship and by using Fellows to initiate new research projects with industrial partners through the program's very successful industry internship program. As a result, it is somewhat more difficult to concisely summarize the results of this research effort which has spanned a broad spectrum of activities. The CDROM accompanying this report and whose table of contents is provided in Appendix C contains Adobe PDF files of all major papers and articles along with the annual capstone design project reports.

The thrust of the research from the outset of the grant in 1994 has been on the development of a generic concurrent engineering (CE) and integrated product and process development (IPPD) methodology for aerospace systems design at conceptual and preliminary design stages, while acknowledging downstream manufacturing, logistics and support issues. This methodology is outlined in Figure 2 and was briefly noted earlier in this report in connection with the academic program description. It includes four key elements illustrated in Figure 2 as an "umbrella:"

- *Systems Engineering* methods and tools,
- *Quality Engineering* methods and tools, a
- *Top Down Design Decision Support* process, and a
- *Computer Integrated Environment.*

Together these provide the systems analysis (SA) framework for the basic methodology and this vision has guided the MDA Fellowship research program.

The research focus was maintained by studying these methods and processes as they were applied to the design of a high speed civil transport (HSCT), various advanced rotorcraft, advanced turbojet propulsion systems, and advanced space launch vehicles. Initial efforts examined the problem of providing higher fidelity analysis models at the earliest stages of conceptual design where design decisions with critical implications for downstream must be made, often with only limited knowledge of the downstream consequences. The pioneering use of response surface equations (RSE's) to create simplified conceptual level models from a limited number of higher fidelity preliminary design models proved the key to this problem. The research applied well known methods from experimental statistics and the design of experiments to improve the effectiveness of this process and research into advanced computer frameworks for design provided the means to implement these methods. References 1 to 16 summarize much of this work.

The ability to implement higher fidelity models at the conceptual design stage provided vastly more powerful decision making tools for the designer, but it also served to highlight the stochastic nature of the problem since all too often the fundamental information on which the analysis models and RSE's were based included a great deal of uncertainty. This has led in the final years of the grant to an increased emphasis on studying the probabilistic formulation of these problems in which uncertainty in both information and processes is represented by stochastic methods. This emphasis has led to the association of another acronym, VSLCDE or Virtual Stochastic Life Cycle Design Environment, to describe the effort and the resulting methodology which is shown schematically in Figure 6. In this approach information about parameter values as well as modeling processes can be formulated in probabilistic terms using, for example, appropriate distribution functions to describe parameter values. These distributions are then propagated through the design analysis process using a variety of powerful stochastic modeling and analysis methods, and design decisions are expressed in nondeterministic terms. References 17 to 32 summarize much of this more recent work.

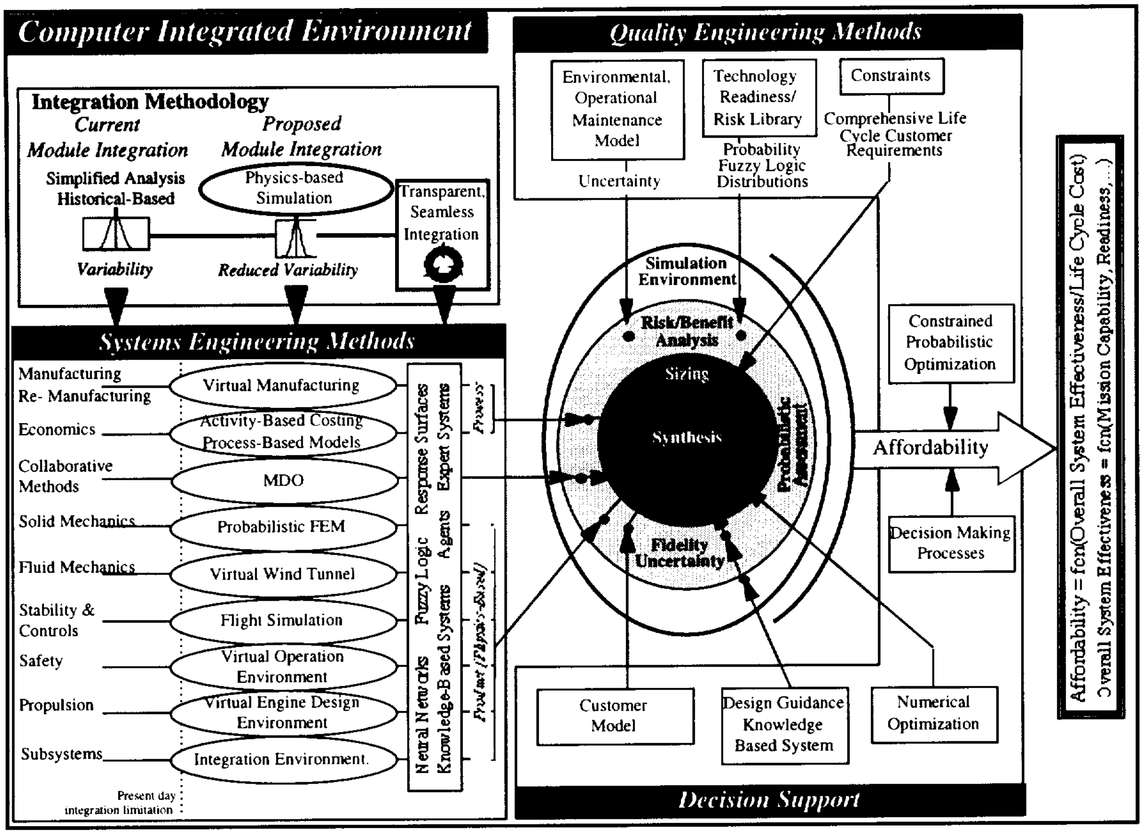

Figure 6. Virtual Stochastic Life Cycle Design Environment

The methodology research has been accompanied by separately funded research to develop the necessary computational environment, GUI tools and information management tools to support the application in both proof of concept studies as well as in the capstone design projects associated with the MS and Ph.D. degree programs. References M+1 to P summarize some of this effort.

In continuing research stimulated by the MDA Fellowship grant, CASA will focus on a *continuous pursuit of robustness* along the system design life cycle (top of Figure 7 below) that seamlessly merges with "on-line" robust manufacturing simulation (bottom of Figure 7). The overall evaluation criterion (OEC) identified will be principally an affordability criterion, since affordability, by our definition, will provide the ability to address the critical issues facing the aerospace community in the next decade.

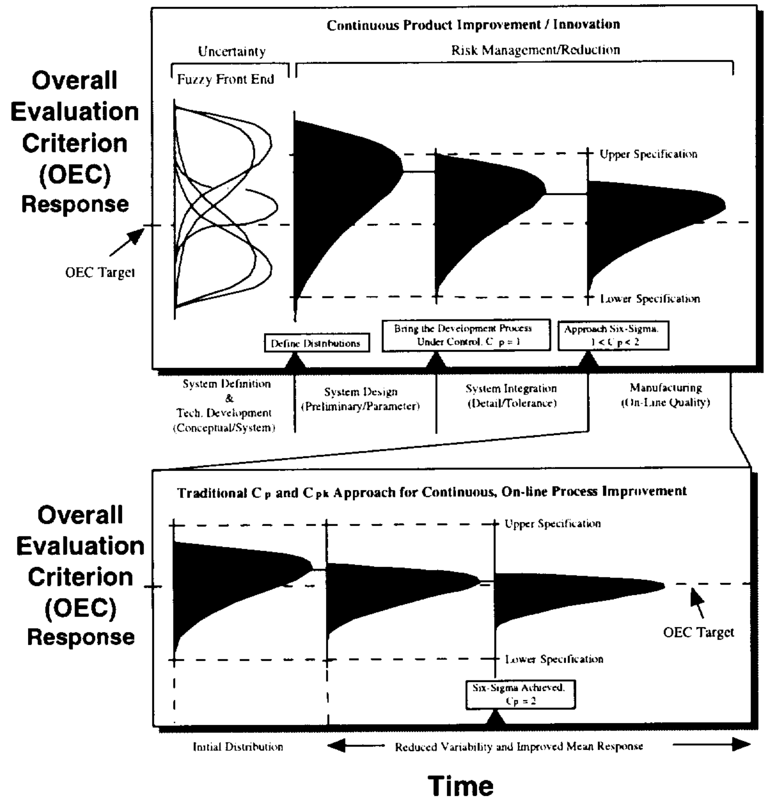

Figure 7. Persistency of Robustness: Design to Manufacture

The research results have been well-received at conferences and by our industry partners. The Fellows have transferred much of this technology into industry through their industry internships over the years and some of it is beginning to be employed in practical engineering situations.

4. SUMMARY

The NASA MDA Fellowship grant to Georgia Tech has over the past five years been essential to the emergence of a strong and vigorous program in aerospace system analysis and design. The first objective of the grant program was to attract some of the brightest students into this area and in this respect we have been able to attract the top graduates from Georgia Tech along with highly qualified students from other institutions. The Fellows have been key to the development of a powerful research program that has attracted sponsors from NASA, DoD and industry and is now above $1.5 million per year. Perhaps the best measure of the success of the MDA Fellowship program is its direct role in fostering creation of the new Center for Aerospace Systems Analysis at Georgia Tech that encompasses flight vehicle systems from near-earth to space. CASA is carrying on the MDA Fellowship legacy with continued support for outstanding graduate students, strong interaction with industry and government laboratories, and an innovative research program.

APPENDIX A: MS SAMPLE PROGRAMS OF STUDY

Sample programs of study for the MS program are shown on the following pages. Two different options are illustrated: a 12 month program that is representative of the shortest possible program, and a 24 month program that is more typical. A 12 month program is normally only feasible if the student is entirely self-supported with no graduate assistantship or other funding. Students on research or teaching assistantships or fellowships are expected to spend at least 15 hours per week engaged in research activities and typically are limited to taking no more than 3 courses on a letter grade basis.

Georgia Tech School of Aerospace Engineering

Systems Design, Analysis and Integration

Sample MS Programs of Study

Twelve Month Program:

Fall	Spring	Summer
AE 6331 Rotorcraft Design I (3), or AE 6341 Aircraft Design I (3), or AE 6320 Astronautics (3) *and* AE 6370 Sys. Design for Afford. IPPD (4) *and* AE 6371 Multidisciplinary Design Optim.(3) *and* Discipline, Design or Math elective (3)	AE 6332 Rotorcraft Design II (4), or AE 6342 Aircraft Design II (4), or AE 6322 Spacecraft & Launch Veh. Design (4) *and* Discipline, Design or Math elective (3) *and* Discipline, Design or Math elective (3) *and* AE 8001 Design Seminar (1)	AE 8900 Special Project (3), *and* Discipline, Design or Math elective (3) *and* Discipline, Design or Math elective (3)

Twenty-four Month Program:

Fall	Spring	Fall	Spring
AE 6331 Rotorcraft Design I (3), or AE 6341 Aircraft Design I (3), or AE 6320 Astronautics (3) *and* AE 6370 Sys. Design for Afford. IPPD (4) *and* Discipline, Design or Math elective (3))	AE 6332 Rotorcraft Design II (4), or AE 6342 Aircraft Design II (4), or AE 6322 Spacecraft & Launch Veh. Design (4) *and* Discipline, Design or Math elective (3) *and* Discipline, Design or Math elective (3) *and* AE 8001 Design Seminar (1)	AE 6371 Multidisciplinary Design Optim.(3) *and* AE 8900 Special Project (1) *and* Discipline, Design or Math elective (3)	Discipline, Design or Math elective (3) *and* AE 8900 Special Project (2)

Notes:

- Course credit shown in parentheses
- Disciplinary electives may be used to develop a concentration in either aerodynamics, combustion, flight mechanics & controls, propulsion, or materials & structures
- Design electives are used to broaden exposure to design methods and techniques; see the sample listing of Design Electives or consult with your advisor.
- At least 6 hours of Math are required (see your advisor for listing of courses outside Math that will also meet this requirement).
- First summer term in 24 month program is typically used for industry internship.
- AE 8001 (Design Seminar) is a one credit-hour case study seminar held every other week with outside speakers.

Sample Listing of Design Electives

(Please consult with your advisor for the most current information. Some courses may only be offered one term or in alternating years.)

AE 4070 Intro. to Propeller and Rotor Theory
AE6354 Advanced Orbital Mechanics
AE6361 Air Breathing Propulsion System Design I
AE6362 Safety by Design
AE6380 Fundamentals of Computer-Aided Engineering and Design
AE6381 Software Development for Engineering Applications
AE6450 Rocket Propulsion

CEE6581 Engineering Programming Methods
CEE6582 Knowledge-based Programming Methods in Engineering
CEE6583 Object-Oriented and Multimedia Programming in Engineering

ISyE6739 Basic Statistical Methods
ISyE6401 Statistical Modeling and Design of Experiments
ISyE6225 Engineering Economy
ISyE6661 Optimization I

ME4041 Interactive Computer Graphics and Computer-Aided Design
ME6101 Engineering Design
ME6102 Designing Open Engineering Systems
ME6103 Optimization in Engineering Design
ME6104 Computer-Aided Design
ME6222 Manufacturing Processes and Systems
ME7227 Rapid Prototyping in Engineering
ME6554 Engineering Database Management

APPENDIX B. PH.D. SAMPLE PROGRAMS OF STUDY

The Ph.D. program of study builds directly on the MS program and extends it in two primary directions. First, additional courses in design methodology and the supporting technical and mathematical areas are included. And at the same time, one or possibly two other tracks are provided to develop a level of expertise in one or two of the traditional aerospace engineering disciplines. The ostensible purpose for this is to provide the needed breadth of exposure to support the fundamental design methodology research, but a more immediate purpose is to provide the necessary preparation for the Ph.D. Qualifying Examination. The Qualifying Examination in Aerospace Engineering is offered in 13 different areas in the form of one-hour oral examinations in the presence of two faculty members. Students must select 3 exams and must receive passes from at least 5 examiners. The following typical Ph.D. program of study lists these areas as "Discipline, Design or Math elective" and they can be combined into one or two disciplinary tracks depending on the student's background.

Georgia Tech School of Aerospace Engineering

Systems Design, Analysis and Integration

Sample Ph.D. Programs of Study (from BS degree)

Year 1 (with summer industry internship):

Fall	Spring
AE 6331 Rotorcraft Design I (3), or AE 6341 Aircraft Design I (3), or AE 6320 Astronautics (3) *and* AE 6370 Sys. Design for Afford. IPPD (4) *and* Discipline, Design or Math elective (3))	AE 6332 Rotorcraft Design II (4), or AE 6342 Aircraft Design II (4), or AE 6322 Spacecraft & Launch Veh. Design (4) *and* Discipline, Design or Math elective (3) *and* Discipline, Design or Math elective (3) *and* AE 8001 Design Seminar (1)

Year 2 (with summer industry internship):

Fall	Spring
AE 6371 Multidisciplinary Design Optim.(3) *and* AE 8900 Special Project (1) *and* Discipline, Design or Math elective (3)	Discipline, Design or Math elective (3) *and* Discipline, Design or Math elective (3) *and* AE 8900 Special Project (2) *and* AE 8001 Design Seminar (1) *and* Ph.D. Qualifying Examination

Year 3 (with research during summer and following terms):

Fall	Spring
AE 6371 Multidisciplinary Design Optim.(3) *and* Discipline, Design or Math elective (3) *and* Discipline, Design or Math elective (3) *and* Doctoral Thesis proposal	Discipline, Design or Math elective (3) *and* Discipline, Design or Math elective (3) *and* AE 8001 Design Seminar (1)

Notes:

- Course credit shown in parentheses
- Disciplinary electives should be used to develop a concentration in either aerodynamics, combustion, flight mechanics & controls, propulsion, or materials & structures in preparation for the Ph.D. Qualifying Examination.
- Design electives are used to broaden exposure to design methods and techniques; see the sample listing of Design Electives or consult with your advisor.
- At least 12 hours of Math are required (see your advisor for listing of courses outside Math that will also meet this requirement).
- First 2 summer terms are typically used for industry internship.
- AE 8001 (Design Seminar) is a one credit-hour case study seminar held every other week with outside speakers.

APPENDIX C. LIST OF PUBLICATIONS

The following publications were produced in whole or in part with funding from the NASA MDA Fellowship Grant. Unless otherwise noted, all these papers along with final reports from the annual student design projects are archived in Adobe PDF format on the CDROM accompanying this report. The list below also serves as a reference list for this Final Report.

1. Röhl, P., Mavris, D.N., and Schrage, D.P., "A Multilevel Wing Design Procedure Centered on the ASTROS Structural Optimization System," 5th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September 7-9, 1994 (no electronic version available on CDROM).

2. Abel, R.W., Mavris, D.N., and Schrage, D.P., "Preliminary Design of the High Speed Civil Transport based on Productivity Index," 19th International ICAS Congress/AIAA Aircraft Systems Conference, Anaheim, California, September 18-23, 1994, (no electronic version available on CDROM).

3. Brewer, J., Donofrio, K., Mavris, D.N., and Schrage, D.P., "Design Manager's Aide for Intelligent Decomposition. A case study involving the High Speed Civil Transport," 5th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Panama City, FL, September 7-9, 1994, (no electronic version available on CDROM).

4. Mavris, D.N., Röhl, P., and Schrage, D.P., "Nacelle-Wing Integration Aspects for the High-Speed Civil Transport Aircraft," 7th European Aerospace Conference: The Supersonic Transport of Second Generation EAC "94, Toulouse, France, October 25-27, 1994, (no electronic version available on CDROM).

5. Kim, H.S., Mavris, D.N., Virasak, J., and Schrage, D.P., "Selection and Design Optimization of a High Speed, Highly Maneuverable Rotorcraft Configuration," 51st AHS Annual Forum, Fort Worth, TX, May 9-11, 1995, (no electronic version available on CDROM).

6. Röhl, P., Mavris, D.N., and Schrage, D.P., "Preliminary HSCT Wing Design Through Multilevel Decomposition," AIAA-95-3944, 1st AIAA Aircraft Engineering, Technology, and Operations Congress, Los Angeles, CA, September 19-21, 1995, (no electronic version available on CDROM).

7. Mavris, D.N., Schrage, D.P., and Brewer, J.L., "Economic Risk Analysis for a High Speed Civil Transport," 16th Annual Conference of the International Society of Parametric Analysts, Boston, MA 1994, Published in *Journal of Parametrics*, 1996, (no electronic version available on CDROM).

8. Hale, MA., Craig, J.I., Mistree, F., and Schrage, D.P., "DREAMS and IMAGE: A Model and Computer Implementation for Concurrent, Life-Cycle Design of Complex Systems," "Concurrent Engineering: Research and Applications, Vol. 4, No. 2, pp. 171-186, June 1996.

9. DeLaurentis, D., Cesnik, C., Lee, J., Mavris, D., Schrage, D., "A New Approach to Integrated Wing Design in Conceptual Synthesis and Optimization," 6th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Bellevue, WA, September 4-6, 1996. AIAA-96-4000.

10. DeLaurentis, D.A., Mavris, A.J. Calise, D.N. Schrage, D.P., "Reduced Order Guidance Methods and Probabilistic Techniques in Addressing Mission Uncertainty," 6th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Bellevue, WA, September 4-6, 1996. AIAA-96-4174.

11. DeLaurentis, D.A., Mavris, D.N., Schrage, D.P., "System Synthesis in Preliminary Aircraft Design Using Statistical Methods," 20th International Council of the Aeronautical Sciences (ICAS) Congress, Sorrento, Italy, September 8-13, 1996

12. DeLaurentis, D.A., Zink, P.S., Mavris, D.N., Cesnik, C.E.S., Schrage, D.P., "New Approaches to Multidisciplinary Synthesis: An Aero-Structures-Control Application Using Stastical Techniques," 1st AIAA/SAE World Aviation Congress, Los Angeles, CA, October 21-24, 1996. AIAA-96-5501.

13. Mavris, D.N. and Hayden, W.T. "Formulation of an IPPD Methodology for the Design of a Supersonic Business Jet," 1st AIAA/SAE World Aviation Congress, Los Angeles, CA, October 22-24, 1996. AIAA-96-5591.

14. Mavris, D.N., Roth, B., "A Methodology for Robust Design of Impingement cooled HSCT Combustion Liners," 35th Annual Aerospace Sciences Meeting and Exhibit, Reno, NV, January 6-9, 1997. AIAA-97-0288.

15. Mavris, D.N., Baker, A., and Schrage, D.P., "IPPD Through Robust Design Simulation for an Affordable Short Haul Civil Tiltrotor," 53rd AHS Annual Forum, Virginia Beach, VA, April 29-May 1, 1997.

16. DeLaurentis, D.A., Mavris, D.N., Calise, A.C., Schrage, D.P., "Generating Dynamic Models Including Uncertainty for Use in Aircraft Conceptual Design," AIAA Atmospheric Flight Mechanics Conference, New Orleans, LA, Aug. 1997. AIAA-97-3590.

17. Mavris, D.N., Hayden, W.T., "Probabilistic Analysis of an HSCT Modeled with an Equivalent Laminated Plate Wing", 1997 World Aviation Congress, Anaheim, CA, October 13-16, 1997. AIAA-97-5571

18. Olds, J. R. and McCormick, D. J., "Component-Level Weight Analysis for RBCC Engines," AIAA 97-3953, 1997 Defense and Space Programs Conference and Exhibit, Huntsville, AL, September 1997.

19. Mavris, D.N., DeLaurentis, D.A., Soban, D.S., "Probabilistic Assessment of Handling Qualities Constraints in Aircraft Preliminary Design," 36th Aerospace Sciences Meeting & Exhibit, Reno, NV, January 12-15, 1998. AIAA-98-0492.

20. Mavris, D.N., DeLaurentis, D.A., Bandte, O., Hale, M.A., "A Stochastic Approach to Multi-disciplinary Aircraft Analysis and Design," 36th Aerospace Sciences Meeting & Exhibit, Reno, NV, January 12-15, 1998. AIAA 98-0912.

21. Mavris, D.N., Baker, A.P., Schrage, D.P., "Development of a Methodology for the Determination of Technical Feasibility and Viability of Affordable Rotorcraft Systems", 54th Annual Forum of the American Helicopter Society, Washington D.C., May 1998.

22. Roth, B., Mavris, D., and Elliott, D., "A Probabilistic Approach to UCAV Engine Sizing," 34th Joint Propulsion Conference, July 13-15, 1998, Cleveland, OH, AIAA98-3264.

23. Zink, P.S., Mavris, D.N., Love, M., Karpel, M., "Robust Design for Aeroelastically Tailored/Active Aeroelastic Wing," 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, September 2-4, 1998. AIAA-98-4781.

24. Mavris, D.N., Macsotai, N.I., Roth, B.R., "A Probabilistic Design Methodology for Commercial Aircraft Engine Cycle Selection," 1998 World Aviation Congress and Exposition, Anaheim, CA, September 28-30, 1998. SAE-985510.

25. Mavris, D.N., DeLaurentis, D.A., "A Stochastic Design Approach for Aircraft Affordability," 21st Congress of the International Council on the Aeronautical Sciences (ICAS), Melbourne, Australia, September 1998. ICAS-98-6.1.3.

26. McCormick, D. J., and Olds, J. R., "System Robustness Comparison of Advanced Space Launch Concepts," AIAA 98-5209, 1998 Defense and Civil Space Programs Conference and Exhibit, Huntsville, AL, October 28-30, 1998.

27. Roth, B., and Mavris, D., "Analysis of Advanced Technology Impact on HSCT Engine Cycle Performance," Presented at the 35th Joint Propulsion Conference, Los Angeles, June 1999, AIAA 99-2379.

28. Zink, P. S., D. N. Mavris, P. M. Flick, and M. H. Love, "Impact of Active Aeroelastic Wing Technology on Wing Geometry Using Response Surface Methodology", CEAS/ AIAA/ ICASE/ NASA LangleyInternational Forum on Aeroelasticity and Structural Dynamics, Williamsburg, VA, June 22-25, 1999.

29. Mavris, D. N., Bandte, O., DeLaurentis, D. A., "Robust Design Simulation: A Probabilistic Approach to Multidisciplinary Design," *AIAA Journal of Aircraft*, Vol. 36, No. 1, pp. 298-307, 1999, (no electronic version available on CDROM).

30. Mavris, D.N., Roth, B.A., and Macsotai, N.I., "A Method for Probabilistic Sensitivity Analysis of Commercial Aircraft Engines," Presented at the 14th ISABE, Florence, Italy, Sept. 1999.

31. Mavris, D.N., Baker, A.P., Schrage, D.P., "Implementation of a Technology Impact Forecast Technique on a Civil Tiltrotor", Proceedings of the 55th National Forum of the American Helicopter Society, Montreal, Quebec, Canada, May 25-27, 1999.

APPENDIX D. ACCOMPANYING CDROM

A CDROM accompanies this Final Report and contains electronic versions of most of the publications, theses, and design project reports developed under Grant funding. The files are all in Adobe PDF format with the exception of 3 Microsoft PowerPoint 97 files that were too complex to convert to PDF format and so are included in their native format.

The simplest way to access this CD is to use a web browser such as Internet Explorer 4 or Netscape Navigator 4 (or newer). Or it is possible to go directory to the appropriate folder and copy the particular file that is needed. Adobe Acrobat Reader will be required to view the PDF files and PowerPoint 97 will be required to display 3 of the Report files.

To access this information using a web browser, insert the CDROM in the appropriate drive and open it on the desktop. The root directory will list the following:

- index.htm (STARTING POINT: double-click on this file to open a browser window that contains an index to the rest of the CDROM)
- Folder: Publications (contains copies of all of the papers presented or published)
- Folder: Reports (contains copies of the design project reports for 1996-1999 along with a PDF copy of this Final Report).
- Folder: icons (contains utility icons used with index.htm)

From the web browser window, it is possible to access all of the contents of the CDROM and to either view them, print them or copy them to local disks. Please note that some of the material is listed but electronic copies are not included because they were unavailable at the time of this printing.