CACR Small Grants for Computational Research

2005-2006 Proposal Cover Page

[Please see proposal guidelines regarding submission of signatures.]

Project Title ____Design Optimization of a Morphing Wing Aircraft: A Computational Investigation

Principal Investigator (dept , # release hrs requested) __Amit Shukla (MME)__

Co-Investigators (dept, # release hrs requested): _Olga Brezhneva (Math/Stat)_and Mark A. Abramson (AFIT)

Project Category (see solicitation; please check one) **RFG-A** __ RFG-B____ CRC ____

Total funding amount requested from the CACR: $ __3,255__________

Signature of Principal Investigator (for the co-investigators):

____ Date _____________

Department Chair's signature is required for the PI's department. Chairs' signatures are also required for any department providing matching funds or in which a course-release is requested (whether funded by the department or by CACR).

Dept MME_______ Matching funds $__1,379___ Matching release: 0____ hrs in term ___________

Chair's Signature _______________________________________ Date _____________

Dept **Math/Stat** Matching funds $ **Research Status to Graduate Student**

Chair's Signature _______________________________________ Date _____________

Dept _______ Matching funds $_________ Matching release: ____ hrs in term ___________

Chair's Signature _______________________________________ Date _____________

Dept _______ Matching funds $_________ Matching release: ____ hrs in term ___________

Chair's Signature _______________________________________ Date _____________

RFG-A Grant Proposal

Title: Design Optimization of a Morphing Wing Aircraft: A Computational Investigation

PI(s): Amit Shukla, Olga Brezhneva, and Mark A. Abramson

1. **Project Summary**:

Morphing aircraft design is an area of relevance to the US Air Force, and Air Force Research Laboratory (AFRL) is looking for teams of interdisciplinary collaborators to advance the state-of-the-art in the area of computational design optimization using innovative methods and techniques that result in novel design and control strategies. This will lead to the next generation of morphing aircraft design and development. This proposal is to initiate and conduct preliminary interdisciplinary collaborative studies involving faculty from Mechanical and Manufacturing Engineering and Mathematics and Statistics Departments at Miami in the area of design optimization of morphing aircraft using *mesh adaptive direct search* (MADS) methods [Audet 2004] in conjunction with the *surrogate management framework* [Booker 1999] in a parallel computing environment. This collaboration will also include faculty from Air Force Institute of Technology (Dr. Mark Abramson) and research scientists from AFRL (Vehicles Directorate: Dr. Brian Sanders). In line with the *CACR Small Grant Program goals* this proposal will lead to the following:

- *early investigations* in a collaborative research area of morphing aircraft optimization new to Miami University;
- *enhanced submission of external proposals* to fund multidisciplinary research to DAGSI, AFOSR and NSF involving multidisciplinary teams and could provide return on investment to CACR in form of purchase of additional computational nodes for RedHawk.
- *increased use of high-performance computing* in research (specifically in the MATLAB® environment) involving PIs, one undergraduate student (Mr. Ryan Rineke, MME) and a graduate student (Mr. Casey Trail, Math/Stat), thus leading to development of the expertise in HPC and RedHawk use by Miami faculty and students.
- *expanded collaboration across disciplines* (MME and Math/Stat) and between Miami, AFIT, and AFRL.
- *increased numbers of publications* from Miami on this topic.

The timeline for this proposed project is from May 2006 thru May 2007. The support for this project during the academic year has been acquired (see budget and explanation); however, CACR funding is essential to the success of this collaboration, since to submit the revision of DAGSI proposal (due Jan 2007), we need to actively conduct investigations in the summer with the graduate student and then collaborate with Dr. Sanders of AFRL in Fall 2006 to justify the use of our proposed method on the full system models of use to AFRL.

2. **Project Overview**:

This research proposal focuses on the optimal design of an aircraft structure that can undergo structural shape change for the purpose of optimized flight and maneuvering control authority using a parallel computing environment. There is both computational (mathematical) and engineering novelty in this project.

The next generation aircraft could have two objectives: one to carry large payloads and another to travel at high speeds when carrying no cargo. Hence, the design of a morphing aircraft wing should allow for in-flight changes in airfoil cross-section and wing shape to respond to various mission needs, which may include hovering, high speed light maneuvering, and attack maneuvering. This requires adaptive structures and distributed actuation systems to affect the dynamic and controlled in-flight morphing. The primary components to be synthesized include rigid-body mechanisms, aero-elastic surfaces, and actuator placement. The novel aspect of this proposal from the engineering point of view includes coupling between aero-elastic and rigid-body flight dynamics, integration of distributed control and actuation in the topology optimization, and inclusion of continuum structural models. This problem is highly coupled in terms of optimal actuator placement, mechanism design and aero-elastic surface design and hence must be evaluated as a multi-objective optimization, in which objectives may include maximizing stability, minimizing actuation energy, maximizing flexibility for morphing, and minimizing drag. Each objective function evaluation requires the use of large simulations or finite element codes, which are generally time-consuming and often provide little derivative information. The “black box” nature of the underlying optimization problem makes direct search methods, such as pattern search and MADS, a logical choice for attacking such problems. Specifically, the US Air Force has in-house software which provides objective function evaluations. Numerical differentiation is not encouraged, as a single function evaluation itself is computationally prohibitive. The computational expense normally incurred by these derivative-free methods can be further reduced by making use of less expensive surrogate functions during the optimization process. The computational bottleneck is envisioned to be in the objective function evaluations. From a computational (mathematical) point of view, the proposed project is to integrate MADS into a surrogate management framework for solving multi-objective optimization problems and apply it to the problem of optimizing the design of a morphing wing.

The key aspects of this proposal are: 1. Application of derivative-free MADS for optimization; 2. Use of surrogate management framework (SMF) for modeling objective function evaluations; 3. Multi-Objective Optimization via methods such as Normal Boundary Intersection (NBI) Method [Das 1998]; 4. Use of MatlabMPI to conduct parametric space investigations and optimization studies in a parallel computing environment; and 5. Integration of MADS, SMF, and NBI into one comprehensive parallel optimization tool.

To compare the proposed approach with others, we first would like to note that in the design of morphing aircraft there are a number of questions involving the efficiency of physical structures that must be answered using methods of optimization. One method alone is insufficient to adequately solve every optimization scenario and as a result a number of different methods of optimization have been used on a variety of aspects involved in the development of morphing aircraft. Multi-objective optimization is utilized in situations where are number of conflicting criteria must be considered in order to achieve an optimal design. Khire, Mullur, and Messac [Khire 2005] proposed a methodology for the use of multi-objective optimization when designing flexible systems under changing operating conditions. Joo and Sanders [Joo 2005] also used multi-objective optimization techniques for the simultaneous design of a morphing aircraft wing shapes and the mechanical systems within the wing to morph the airfoil into theses shapes. Clearly, more adaptive airfoils deliver better performance under a greater variety of conditions; however, the weight or complexity of the mechanics required to make these adaptations may inhibit the aircraft's overall performance. Heuristics, such as genetic algorithms, have been successfully applied to these types of problems (Ramrkahyani, Lesieutre, Frecker, and Bharti [Ramarkahyani 2005], Simpson and Hansen [Simpson 1996]); however, there is no formal convergence theory; i.e., no guarantees of convergence to a limit point satisfying necessary conditions for optimality.

We propose augmenting the class of mesh adaptive direct search (MADS) algorithms to handle multi-objective problems and its application to the Morphing Wing Design Optimization in a parallel computing environment. MADS is a derivative-free approach in which points on a carefully constructed mesh are evaluated in an attempt to find a better point than the current one. Each iteration is characterized by an optional search step and a local poll step. The search step is very flexible and allows the user to employ a variety of strategies, while the poll is more rigidly defined and drives the theoretical convergence properties of the algorithm. A common choice for the search step is to construct and optimize a less-expensive surrogate function at each iteration. This approach, referred to as the surrogate management framework (SMF), often leads to significant improvement at the beginning of the optimization process, which is especially advantageous when function values are expensive. This MADS-SMF approach was used successfully by Marsden [2004] in studying the optimal design of airfoils, in which the objective was to minimize aerodynamic noise.

3. Proposed activities

The PIs and the graduate students have been working on this problem since Nov 2005 in developing a timeline for this research and submitting a proposal to the AFRL/DAGSI for collaborative research in Jan 2006. This proposal was declined as being "too aggressive" for a year long project. However, the program managers noted that "*The unique aspect of the proposal is the use of an adaptive direct search technique. This is a search algorithm that does not require the determination of derivatives, so it may enable faster solutions to systems with a large number of design variables. This is a technique that Dr. Mark Abramson at AFIT has a considerable amount of expertise and experience, and may prove to be a powerful tool in the design environment. We feel that this technique has the potential to be useful for us in the future, but it requires some additional understanding before we bring it into our environment. We would like to see this work funded if the PI's would agree to work with us to establish a more tractable problem. It would still be within the morphing structures area but would involve defining planform geometry for different mission segments (e.g., multiple position, multiple constraint problem)"*. Further the composition of the team would also complement the research group at AFRL as noted below: *"This proposal is heavily dominated by PI's with strong mathematics background. Their strengths would make an excellent complement to the more physics based team we have in place"*.

Using this as a starting point, the PIs and the graduate student involved have expertise in the computational and optimization issues. The identification of a reduced problem for solution with-in the MADS framework will be started in summer 2006 in collaboration with the AFRL. In May 2006, an existing *reduced system model* presented in [Joo 2005] will be optimized using MADS to compare performance and results. In June-July 2006, a model of a continuum-based structure with distributed actuation and aero-elastic loads and feedback control will be developed. This model will not include thermal effects on the flexibility of the aircraft. The purpose for doing so is twofold. First, this will assist in further understanding and gaining an appreciation of the system dynamics involved in this project via simulation and optimization studies. Second, the developed model can then be integrated with existing MATLAB-based optimization tools (NOMADm developed by Dr. Mark Abramson of AFIT, and Normal Boundary Intersection (NBI) Method developed by Drs. Indraneel Das and John Dennis of Rice University) for use in later stages of the project in conducting multi-objective optimization. This will also assist in developing a baseline methodology for modeling, parametric space investigations, design sensitivity analysis, and optimal design. Primary tasks in developing the methodology for this problem are shown in Figure 1. The essential computational tasks which will be explored with MatlabMPI include parametric space investigations, development of the SMF and the computation of the *Pareto* curve for the Multi-Objective Optimization problem. The MatlabMPI will assist in both compute time reduction and memory management by distributing parts of these computational tasks. The PIs will restrict their investigations to MatlabMPI and MATLAB environment due to the following reasons: 1. MATLAB and MatlabMPI are available on RedHawk. 2. PIs and the students have expertise in MATLAB and one of the PI has utilized MatlabMPI for parallel computations in other investigations. 3. NOMADm and NBI implementations are available freely in MATLAB environment.

If the proposed project is funded, the student and faculty team will immediately begin the development of the model for optimization as applied to the identified structure related to the morphing aircraft. In parallel, an integration of the design optimization will be undertaken in July 2006, in consultation with the members of AFRL/VASA, including Dr. Sanders. The duration of this study will be for one year from May 2006-May 2007. A tentative timeline is given in Table 1.

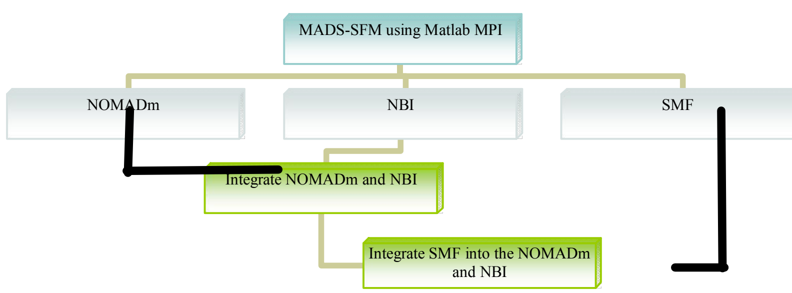

Figure 1: Schematic of the proposed computational methodology for optimal design of morphing aircraft.

The proposed project will rely on published information and is not classified. In this project, the specific roles and expertise of the participants is as follows:

Amit Shukla	PI, Expertise in computational methods, tools for engineering design including MATLAB and MatlabMPI environment. He will lead the development of the optimization models, validation of the results and integration of the methods such asNBI into MADS-SMF in a MatlabMPI environment. Note that all computational investigations will be performed on RedHawk.
Olga Brezhneva	Co-PI – Expertise in optimization methods and applications. She will lead the incorporation of SMF into MADS in collaboration with Dr. Abramson.
Mark A. Abramson	Co-PI – Expertise in optimization methods and developer of NOMADm and the surrogate management framework in NOMADm. He will provide key expertise for integration of methods such as NBI and SMF into NOMADm.
Casey Trail	Graduate Student – will work on optimization and sensitivity analysis of various models, and mission configurations and conduct computational investigations in guidance with the PIs in

the MATLAB environment using MatlabMPI.

Ryan Rineke — Undergraduate Student – will work on simulation and validation using MATLAB environment.

Table 1: Proposed Timeline

Task	**Dates**
Develop and integrate a *reduced* optimization model for morphing aircraft structure.	May 06
Training students on using MATLAB and MatlabMPI on RedHawk.	May-July 06
Implement computational framework in MatlabMPI to utilize RedHawk for optimization of an embarrassingly parallel problem using the existing NOMADm.	May-June 06
Conduct optimization and sensitivity studies on the reduced model on RedHawk.	June-July 06
Share results and conduct collaborative visits with AFRL in Dayton.	June-July 06
Parametric space analysis and simulation studies for validation of optimization results for the reduced model.	July-Aug 06
Develop and integrate multi-objective optimization model for morphing aircraft structure using MADS-SMF.	Aug– Dec 06
Submit manuscript based on results of this research to the SPIE Smart Structures Conference (to be held in March 2007 in San Diego, CA).	Nov 06
Conduct optimization and sensitivity studies on the multi-objective optimization model on RedHawk using MATLAB and MatlabMPI.	Jan-May 07
Develop proposal to AFRL/DAGSI for continued work (including AFRL/VA summer faculty fellowship program as well as DAGSI student/faculty research teams).	Dec 06- Jan 07
Submit a manuscript to the journal, *Optimization and Engineering*	March 07
Develop and submit research proposals to various agencies (NSF, AFOSR)	March-May 07

4. **Plans for dissemination**

The graduate student will present this as his thesis project in Mathematics and Statistics Department (Plan-B) and at the Second MU Symposium on Computational Research. The undergraduate student plans to develop an honor's thesis based on this research and will share findings at the Undergraduate Research Symposium (during April 2007). The results of this project will lead to publications to be presented at the SPIE Smart Structures Conference in San Diego during March 2007, as well as ASME Design Engineering Technical Conference in Las Vegas in September 2007. Further, at least one journal manuscript will be submitted to the *Engineering and Optimization* journal during the proposed project duration. To continue research on this topic and to build upon the preliminary research, one proposal to DAGSI for graduate student-faculty fellowship will be developed and submitted during Jan 2007. Further, a proposal for the PIs to continue collaboration with the AFRL will be submitted in Jan 2007 to obtain funding. The result of this proposal will be increased collaboration with AFRL in this area and will lead to significant external support for collaborative research. It is essential to note that this collaboration will open other avenues in Engineering and Mathematics fields to explore in joint work with AFRL. A collaborative research proposal will also be submitted to NSF in May 2007 on this topic.

In addition, an optimal design framework for MADS-SMF will be made available online for the wider research community in optimization and mechanical engineering to use. This will bring national recognition to Miami and the divisions involved in this project.

References:

[Audet 2004]: Charles Audet and John Dennis. Mesh Adaptive Direct Search Algorithms for Constrained Optimization, *SIAM Journal on Optimization*, to appear.

[Booker 1999]: Andrew J. Booker, J. E. Dennis, Jr., Paul D. Frank, David B. Serafini, Virginia Torczon, and Michael W. Trosset. A Rigorous Framework for Optimization of Expensive Functions by Surrogates. *Structural Optimization*, 17 (1), 1-13.

[Das 1998]: Indraneel Das and J. E. Dennis, Jr. Normal Boundary Intersection: A New Method for Generating the Pareto Surface in Nonlinear Multicriteria Optimization Problems, *SIAM Journal on Optimization*, 8, 631-657.

[Khire 2005]: Ritesh A. Khire, Anoop A. Mullur, and Achille Messac. An Optimization Based Methodology To Design Flexible Systems Subjected To Changing Operating Conditions. *Proceedings of IDETC/CIE 2005ASME 2005 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*; September 24-28, 2005.

[Joo 2005] James J. Joo and Brian Sanders. Simultaneous Structure and Mechanism Design for an Adaptive Wing Using Topology Optimization. *Proceedings of ASME/IMECE: 2005 ASME International Mechanical Engineering Congress and Exposition*, November 5-11, 2005.

[Ramarkahyani 2005] Deepak S. Ramrkahyani, George A. Lesieutre Mary Frecker, Smita Bharti. Parallel Genetic Algorithm for Design of Morphing Cellular Truss Structures. *Proceedings of IMECE2005 2005 ASME International Mechanical Engineering Congress and Exposition* November 5-11, 2005.

[Siegler, 2005] M. Siegler, 2005, *Dynamics and Control of Morphing Aircrafts*. Ph.D. Dissertation, Virginia Polytechnic and State University.

[Simpson 1996] M.T. Simpson, and C.H. Hansen, 1996, Use of Genetic Algorithms for Optimizing Vibration Actuator Placement for Minimizing Sound Transmission into Enclosed Spaces, *Proceedings of SPIE -The International Society for Optical Engineering*, v 27 17, 409-421.

[Marsden 2004] A. L. Marsden. *Aerodynamic Noise Control by Optimal Shape Design*. Ph.D. Dissertation, Stanford University, 2004.

Budget Details and Justification

Item	Budget	Cost Share	Justification
Graduate Student Support –Summer (Student Master 2)	40 hours/week X 8 weeks X $10 per hour X 1.017=$3,255	--- (Requested from CACR)	This will enable the graduate student to work full time on this project during summer 2006 to develop the preliminary results.
Graduate Student Support – Fall, Spring 06-07	Equivalent RGA amount.	Partial RGA will be provided by the Math/Stat Dept.	Math/Stat will provide significant support in terms of graduate student support by assigning research status to the graduate student (part time in Fall 2006 and full time in Spring 2007), this will enable us to work continuously on the project thorough out the academic year to develop results and proposal to DAGSI for AFRL support in the following year.
Under graduate student support – Fall and Spring 2006	10 hours per week X 24 weeks X $5.65 per hour X 1.017= $1,379	MME and SEAS via various grants and scholarships for undergraduate research	The undergraduate student will conduct computational studies in collaboration with the graduate student to develop parametric studies and analyze results for the optimization of the proposed system. This will be part of his honor's thesis and could be extended to include USS research during Summer 2007 (if awarded).
Support for PIs	No funds are requested		
Travel support	Travel to AFRL for PIs will be funded via the regular departmental travel funds. Same applies to the proposed travel for dissemination of results at conferences.		
Total budget Not including the RGA : $4634 CACR Share: $3,255 and MME/ SEAS Share $1,379			

5. **Computational Infrastructure Request**

a. Software Request:
This proposal, even though it is relevant to US Air Force, will contain no classified information for the duration of the project. The essential software required will be: MATLAB (including the Optimization Toolbox and MatlabMPI. Both of these are available on RedHawk.

The results will not require any high performance visualization software and the Matlab tools for plotting data are deemed sufficient.

The existing tools specific to the optimization problem are: NOMADm and NBI. Both of them are implemented in MATLAB and are freely available for use. This would require installation of these set of m-files as modules on RedHawk.

b. Hardware Request:
It is impossible to exactly predict the computing resources needed for this project; however, a rough estimate is given below:

For preliminary studies:

Number of parameters in the model	15
Number of competing objectives	3
Wall time per optimization evaluation with exact simplified objective function model (on a IBM Thinkpad X31 with 1.5 GB RAM)	30 minutes
Total number of optimization evaluations envisioned	5,000
Total wall-time requested	30 × 5000/2 = 75,000 hrs
Number of processors requested	15
Wall time per processor	5,000 hours
Total number of users involved in this project	4

Note that this estimate does not include testing of the proposed methodology on the black-box based objective function evaluation, but is only intended for development of the methodology and tests on a preliminary model.

The disk space requested for this project is calculated to be approximately 50 GB. It would be requested that all people involved in this project be able to see the same disk space for ease of sharing information (if possible – perhaps via a temp directory).

c. Research Computing Support Group Consulting/ Training Request:

It is envisioned that from time to time this research project would require the assistance of RCS on training, debugging and other software issues related to this project. Hence PIs would like to request up to one man-hour per week for the duration of the project for such consultation. This consultation would include requests on issues of integration, performance enhancement, parallel computation and resource management. PIs would also request some training for the students involved on the use of RedHawk and MATLAB during summer of 2006.