Project 050 Over-Wing Engine Placement Evaluation

Georgia Institute of Technology

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University Participants

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- PI: Dr. Dimitri Mavris, Co-PI Dr. Chung Lee
- FAA Award Number: 13-C-AJFE-GIT-057
- Period of Performance: February 5, 2020 to February 4, 2022
- Tasks relevant for this period:
  1. Formulate multidisciplinary analysis and optimization (MDAO) problem.
  2. Create tools to generate parametric geometry.
  3. Automate parametric mesh generation and computational fluid dynamics (CFD) solver on supercomputing cluster.
  4. Create and calibrate single aisle aircraft mission model.
  5. Develop high bypass turbofan propulsion cycle model.
  6. Create noise models.
  7. “Wrap” codes for multidisciplinary analysis.
  8. Perform screening or dimensionality reduction.
  9. Demonstrate MDAO or adaptive sampling scheme on reduced order or “placeholder” functions.

Project Funding Level

Georgia Institute of Technology (Georgia Tech) was funded at $590,000 for a two-year project. Georgia Techy has agreed to a total of $590,000 in matching funds. This total includes salaries for the project director, research engineers, and graduate research assistants, as well as computing, financial, and administrative support, including meeting arrangements. The institute has also agreed to provide tuition remission for the students, paid for by state funds.

Investigation Team

Georgia Institute of Technology
PI: Dimitri Mavris

Co-Investigator: Chung Lee
Propulsion and systems lead: Jonathan Gladin
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Graduate Students: Salah Tarazi, Kenneth Decker, Stephanie Zhu, Christopher Eggert, Christian Perron, Jai Ahuja

Project Overview

The over-wing nacelle (OWN) aircraft concept has promising environmental benefits due to shielding of engine noise by the wings and the potential to reduce landing gear height and therefore gear noise. However, the engine placement may result in penalties in fuel burn due to aerodynamic interactions between the wing and propulsor if not optimized. The proposed work will develop a multidisciplinary analysis and optimization (MDAO) method for OWN aircraft. This task would build on past efforts by including noise shielding effects and analyzing multiple flight conditions to minimize fuel burn. One major challenge is the computational expense of analyses such as computational fluid dynamics (CFD). The proposed approach would rely on MDAO or efficient adaptive sampling techniques to use high fidelity analyses where they are most needed for system analysis.

The optimization of an OWN aircraft configuration over a mission with noise constraints will enable accurate tradeoffs between noise benefits and fuel burn. As a secondary benefit, the MDAO method will demonstrate efficient sampling methods for coupled, computationally intensive simulations in system analysis. These methods are useful to the FAA because many current applications require high fidelity simulations to accurately assess physics phenomena such as noise and emissions. Both the OWN results and the MDAO techniques will enable more physics-informed decisions about the environment.

2020 work focused on preliminary tasks to prepare a software tool chain and workflow for optimization. 2021 will focus on the execution of a full-scale MDAO process using supercomputing resources.

Major goals for this year thus focused on development:

- Creation of a baseline aircraft and engine deck for mission analysis.
- CFD studies for a fixed/non-parametric aircraft to estimate computational cost and requirements.
- Demonstration of MDAO or sampling methodologies using reduced order or “placeholder” analysis functions.

Notation and Abbreviations

α: angle of attack
C_D: drag coefficient
C_L: lift coefficient
CFD: computational fluid dynamics
CRM: NASA Common Research Model
η_{pr}: inlet pressure recovery
MDAO: multidisciplinary design analysis and optimization
OWN: over-wing nacelle
p_{s2}: static pressure at inlet
p_{t8}: total pressure at core nozzle exit
p_{t18}: total pressure at bypass nozzle exit
T_{t8}: total temperature at core nozzle exit
T_{t18}: total temperature at bypass nozzle exit
UWN: under-wing nacelle

Task 1 – Formulate MDAO Problem

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Objectives

The overall goal is to state a MDAO problem to assess a single aisle OWN transport aircraft. The MDAO process will use CFD, noise analysis codes such as the Aircraft NOise Prediction Program (ANOPP), as well as weights, engine cycle, and mission analysis. The formulation will evolve during the project in light of physics results. However, for the performance period, a working MDAO problem statement was adopted:

- **Minimize**: fuel burn.

- **Subject to**: design variables including aircraft range, takeoff field length, and detailed side constraints such as wing/tail ground strike and tip-over requirements.
- **With respect to**: design variables including engine nacelle position (focusing on forward placement), nacelle and wing geometry, engine cycle and operating condition.
- **Given**: baseline single-aisle aircraft model and mission profile.
- **Returning**: fuel burn, noise

In discussion with FAA technical advisors, more emphasis is placed on aerodynamic performance optimization rather than noise, which is necessarily of lower fidelity. Accordingly, the single objective function of fuel burn is being minimized, though noise is evaluated as a response with respect to design variables. It is anticipated that the MDAO problem will undergo several iterations as information accumulates, so noise may be later treated as a constraint or secondary objective.

Given this general MDAO problem, this year's performance on this Task focused on providing more detailed definition to the aero-propulsion aspect of the MDAO formulation.

Research Approach

The most computationally expensive physics discipline is aerodynamics and it is closely coupled with propulsion cycle analysis. Therefore, the 2020 effort focused on the most important aero-propulsion aspects of MDAO, which drive the overall architecture of the problem. Noise and detailed side constraints mentioned above are important, as they allow solutions to capture realistically important physics trade-offs, such as the noise reduction, due to shorter landing gears enabled by over-wing engines. However, those constraints will be added in a full-scale MDAO effort of 2021. The 2020 developmental effort focuses on the following subset of the MDAO:

Preliminary aero-propulsion subset of MDAO problem:

Minimize: fuel burn
With respect to: geometry, angle of attack α, engine mass flow
Given: fixed engine cycle design and throttle assumptions
Subject to: continuity (mass flow balance between inlet and outlet)
momentum balance (e.g. lift = weight, thrust = drag in steady level flight)
Interdisciplinary consistency:
Inlet pressure recovery $p_{t2,CFD} = p_{t2,cycle\ analysis}$
Core nozzle total pressure $p_{t8,CFD} = p_{t8,cycle\ analysis}$
Core nozzle total temperature $T_{t8,CFD} = T_{t8,cycle\ analysis}$
Bypass nozzle total pressure $p_{t18,CFD} = p_{t18,cycle\ analysis}$
Bypass nozzle total temperature $T_{t18,CFD} = T_{t18,cycle\ analysis}$
Returning: fuel burn

Table 1 shows the aerodynamics, propulsion, and mission analyses in qualitative terms.

Table 1. Qualitative list of disciplinary analysis inputs and outputs

		Aerodynamics	Propulsion	Mission
Inputs		wing geometry	engine geometry	drag polar
		nacelle geometry	mass flow target	engine deck
		mass flow target	pressure recovery	
		p_{t8}		
		T_{t8}		
		p_{t18}		
		T_{t18}		
Outputs		pressure recovery	p_{t8}	weights
		net force	T_{t8}	fuel burn
		drag polar	p_{t18}	
			T_{t18}	
			engine deck	

On-Going Development of Design Structure Matrix

This Task is also developing a design structure matrix (DSM) and maintaining a database of raw geometry variable descriptions that are to be included in the final MDAO implementation. Without emphasizing particular details, Figure 1 shows a snapshot in time of the DSM and variable descriptions. Note that geometry parameterization (Task 2), variable reduction/screening (Task 8), and actual MDAO trials will influence the final DSM and list of variables.

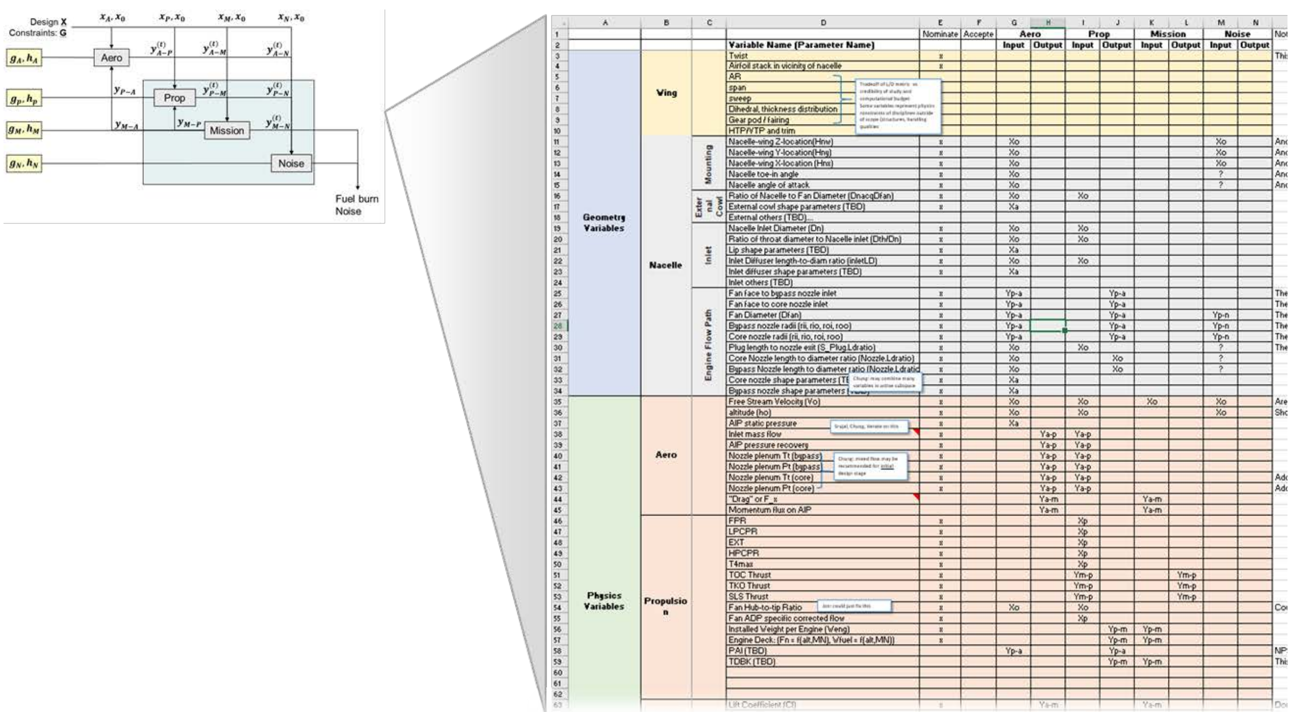

Figure 1. Example snapshot of DSM and variable database under development.

Scope of Design Variables

The parameterization of geometric design variables is covered in the next Task, but the MDAO formulation effort provided bounds for the scope of optimization. In consultation with FAA technical advisors, the NASA Common Research Model (CRM) was chosen as a baseline geometry (Vassberg et al., 2008). Many parts of the aircraft geometry were deemed to be out of scope for the present research. Other than scaling from 300 to 150-passenger size, the fuselage is fixed. The justification for these decisions is an emphasis on credibility and reproducibility in the main research goal: a comparison between under-wing and over-wing nacelle configurations. In actual practice, an aircraft outer mold line (OML) geometry may involve thousands of detailed design variables, many more physics disciplines, flight scenarios, and constraints. For example, one consequence of simply scaling the fuselage shape is that the cockpit windows are much smaller. It is unlikely that pilot visibility requirements simply scale linearly with a fuselage length scale. Yet, this simple scaling of the CRM geometry is easily understood and replicable by the wider aeronautics research and industry communities. It avoids arbitrary detailed design decision by the researchers.

Because of this concern with credible and replicable comparison, several other parts of the aircraft geometry are not included in the MDAO study. The empennage requires flight mechanics and detailed mass estimation (e.g., trimming the horizontal tail plane requires knowledge of the center of gravity). Therefore, it is not included in high fidelity simulation, although mission analysis will include a friction drag penalty for empennage areas based on conceptual-level tail sizing rules. The landing gear pod region is not modified. The wing airfoils design space is constrained to a relatively small domain such that the structural thickness is not radically altered. The wing planform is also fixed.

The current approach is to not design a pylon joining the wing and nacelle, even though it undoubtedly plays an important role in interference drag for an OWN. Because the present effort includes no structural or thermal analysis, the pylon geometry would involve many potentially unrealistic guesses. To give decision-makers a fair assessment of potential benefits of OWN installation, we argue that a comparison of OWN and UWN should be made with no pylons or with thin placeholder/default pylons based on similar geometry rules for the two cases.

Finally, one of the most important variable scoping decisions is to limit the study to forward placement of nacelles. This decision was made in discussion with FAA and was driven by interest in the noise shielding effect from the wing.

Milestones

Milestones for this task are not until 2021, but the MDAO formulation is under continuous development until high-fidelity optimization is executed.

Major Accomplishments

A baseline aircraft design was successfully created based on reduction of the NASA Common Research Model (CRM). Aircraft wing and nacelle design variables were parameterized and implemented in Engineering Sketch Pad scripts. This directly supported Task 3 (parametric mesh generation and CFD solver on a supercomputing cluster), Task 7 ("wrapping" codes for multidisciplinary design analysis and optimization), and Task 8 (screening and reduction of design variables). The geometry generation also allowed preparatory activities for CFD such as initial mesh sensitivity studies.

Publications

None

Outreach Efforts

None

Awards

None

Student Involvement

Kenneth Decker and Bilal Mufti are continuing PhD students who contributed by testing different MDAO formulations on reduced order or inviscid test cases.

Plans for Next Period

The next performance period will focus on the implementation of a specific MDAO architecture rather than a MDAO formulation. Whereas a formulation specifies the problem being solved (e.g., "Minimize fuel burn with respect to …."), an architecture specifies the structure of information passing between the disciplinary analyses that comprise the MDAO. Examples that are currently being explored are the multidisciplinary feasible (MDF) architecture and various multi-level architectures such as collaborative optimization (CO) (Martins and Lambe, 2013).

References

- Vassberg, J., Dehaan, M., Rivers, M., and Wahls, R.,"Development of a Common Research Model for Applied CFD Validation Studies,"26th AIAA Applied Aerodynamics Conference, AIAA Paper 2008-6919, 2008.
- Martins, Joaquim R. R. A. and Lambe, Andrew B., "Multidisciplinary Design Optimization: A Survey of Architectures," AIAA Journal, 2013 51:9, 2049-2075.

Task 2 – Parametric Geometry Generation

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Objective(s)

The solution of the MDAO problem involves reduction of physics disciplines to functions such as f(**X**) where **X** is an array of design variables. An important and time-consuming preparatory step is to select candidate design parameters and create scripts through a CAD or CAD-like software to generate a water-tight geometry suitable for mesh generation. In the performance period, this parametric geometry effort focused on the outer mold line (OML) geometries of the fuselage, wing, and nacelles.

Research Approach

The selection of a baseline aircraft mainly relied on two criteria: 1) applicability of the geometry to our current study of a single-aisle commercial airliner, and 2) existing wind-tunnel/CFD data for such geometry in open domain. By these two criteria, the NASA CRM (Vassberg et al., 2008) was deemed as the most appropriate geometry available in the open domain. Since the CRM geometry was derived from for a twin-aisle 300-passenger Boeing 777 design, it was determined that for the OWN problem, the baseline vehicle shall be a scaled-down version to match the overall dimensions of an Airbus A320 Neo, which is a 150-passenger single-aisle aircraft.

In order to generate the fully parametric CAD model, the section data for CRM fuselage, wing, horizontal tail, etc. were extracted from the original STEP file. Then the data was post-processed using Python-based scripts to make it import-ready for CAD model generation, which required the CST parametrization (explained in the next paragraph) and data re-organization for generating closed profile sketches. Figure 2 shows the sections extracted from the STEP file.

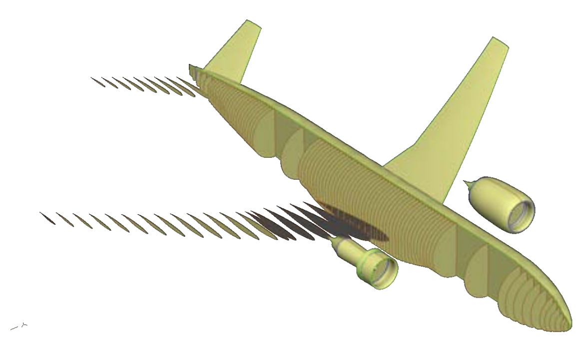

Figure 2. Cross sections extracted from NASA CRM model for parametric model creation.

Implementation in Engineering Sketch Pad (ESP)

Two parametric geometry modeling tools were evaluated for this study: OpenVSP and Engineering Sketch Pad (ESP). ESP was chosen mainly due to two advantages over OpenVSP: a) ESP's ability to design complex shapes and apply additional features to those shapes such as blending/fillets that are crucial in aerodynamic optimization studies based on CFD, and b) OpenVSP initially did not interface to an adjoint feature in the inviscid CFD tool CART3D, which was the major drawback for its use in this study.

The ESP tool allows for a script-based bottom-up modeling approach to build the complex CAD models using constructive solid geometry concepts (Haimes et al., 2013). The tool generates complex geometries using feature-trees and parameters commonly used in CAD software and allows creation of both wire-bodies and sheet-bodies. The tool's backend runs on LINUX, OSX, and Windows. The user interface is browser-based and is compatible on Firefox, Chrome, and Safari browsers. In the following subsections we will discuss how various OWN baseline aircraft components were modeled in ESP.

Wing Design

The wing was modeled using airfoil sections extracted from the original CRM wing geometry and then lofting the sketches through those sections, as shown in Figure 3. The airfoil geometry was specified using ESP's built-in Kulfan function which uses the CST parametrization method (Kulfan, 2008).

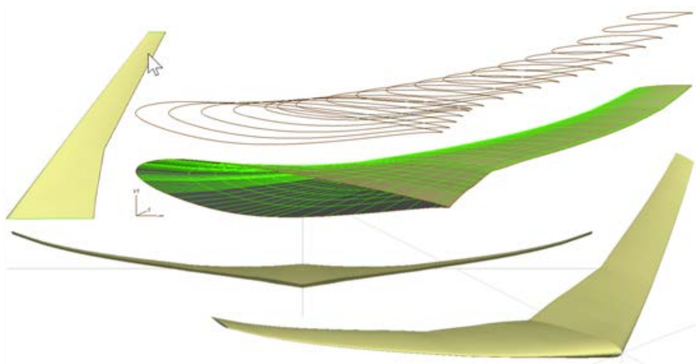

Figure 3. Example ESP output for wing.

The CST method allows for defining the airfoil shape using a simple analytic and well-behaved "shape function" that describes the geometry. The shape function provides the ability to directly control key geometry parameters that affect the airfoil drag, such as leading-edge radius, trailing edge boat-tail angle, and closure to a specified aft thickness. The shape function is mathematically represented by simple Bernstein polynomials, the coefficients of which become the parameters for controlling the airfoil shape. Therefore, the CST method requires relatively few variables to represent a large enough design space to contain optimum aerodynamic shapes for a variety of design conditions and constraints. Initially, the wing was parameterized with twist and four CST coefficients each for the top and bottom of airfoils at 21 spanwise stations. However, it was found that this parameterization allowed for physically unreasonable designs such as the exaggerated view in Figure 4.

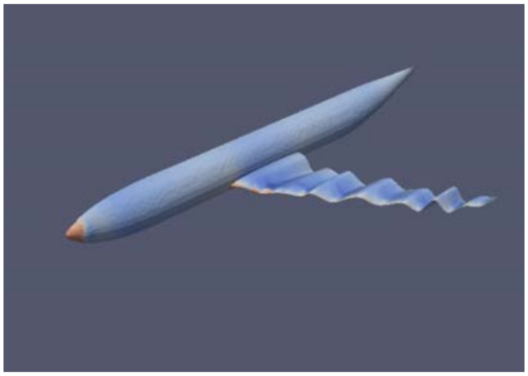

Figure 4. Example: parameterization of a physically unreasonable case in the design domain.

In particular, this parameterization did not account for spatial correlation or dependence of design variables. For example, the twist in one spanwise station is highly correlated to its adjacent, neighboring stations. Therefore, the twist and airfoil CST coefficients were modified such that each parameter type across 21 stations is governed by a spline with control points. In later Tasks such as design variable screening and reduction (Task 8), this spline parameterization was found to be much more efficient in terms of the fraction of feasible designs produced in sample domains.

Engine/Nacelle Design
The engine geometry was derived from approximating the overall dimensions of Pratt & Whitney PW1000G engines, which are part of the high-bypass geared turbofan engine family commonly seen on today's aircraft, for example the Airbus A220, Mitsubishi SpaceJet, Embraer's second-generation E-Jets, and as an option on the Irkut MC-21 and Airbus A320neo.

For CFD solver stability reasons, the engine bypass and core flows were implemented with plenums in CFD. The powered engine boundary conditions were implemented on surface patches in the plenums and the flow was allowed to expand through channels. These channels are non-physical (i.e., not a realistic representation of actual engines) but are used to represent the exhaust flow. The main reason for this strategy is numerical stability and robustness of the CFD solver setup across a wide range of nacelle designs and boundary conditions.

Particular geometry requirements arose because of this CFD strategy. The propulsion cycle analysis predicts properties such as mass flows that are linked to exit areas of bypass and core streams using 1D governing physics equations. However, it is difficult to define a corresponding area in 3D or 2D axisymmetric CFD. The geometry was parameterized using Bézier curves such that there is a constriction near the exit from bypass and core channels. This constriction was created such that the flow would choke (Mach = 1) close to the exit planes of the channels. This allows the estimation of an exit area that corresponds to the nozzle exit area in propulsion cycle analysis.

These geometry modeling decisions are not without drawbacks. In particular, there are difficulties in defining design domains *a priori* that produce physically reasonable designs. For example, if the tail cone angle is high, then the outer wall of the bypass channel (under the surface of the outer nacelle "airfoil") must be deflected inward to avoid large regions of separated flow. Yet, this requires accompanying changes near the trailing edge of the outer airfoil for geometric compatibility. This can cause failed geometries or at least highly unfavorable aerodynamic designs. The nacelle parameterization was thus a compromise between robustness of CFD, ease of propulsion-aerodynamics integration, and the desire to yield feasible/reasonable geometries for much of the design space. Figure 5 shows the finished engine geometry ready for CFD simulation.

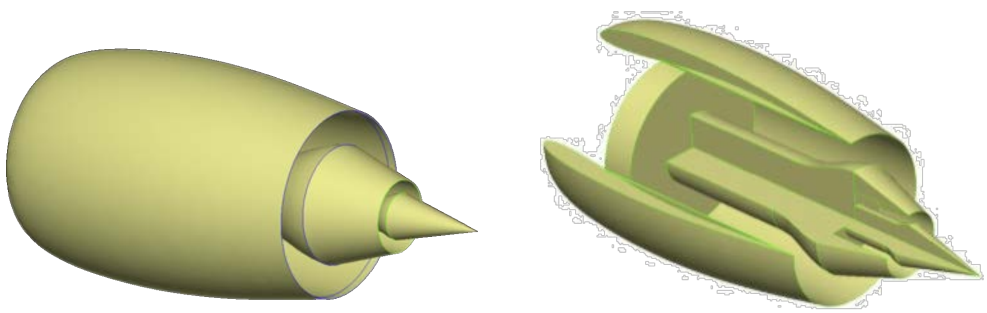

Figure 5. Fully parametric OWN engine geometry generated in ESP.

Fuselage/Horizontal Tail Design
A process similar to the previously described Wing Design was used to model the horizontal tail and fuselage of the aircraft, i.e., by generating sketches from extracted section data and then lofting those sketches together generate the respective surfaces. As described earlier, the OWN aircraft geometry is a scaled-down version of the original CRM geometry. Figure 6 depicts the complete CRM aircraft before and after the scale-down process for comparison.

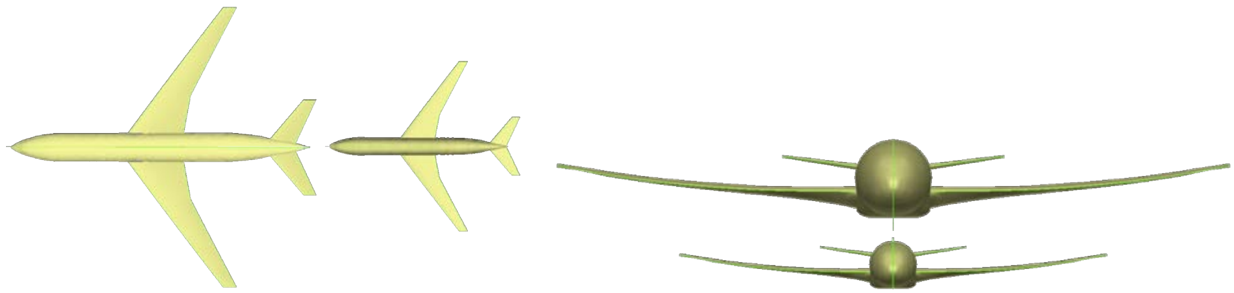

Figure 6. Side-by-side comparison of the original NASA CRM aircraft and scaled-down version of the OWN baseline aircraft (modeled in ESP), top view (left) and front view (right), with Fuselage scale factor 60.2%, wing scale factor 60.9%, and horizontal tail scale factor 62.25% (scaled with respect to longest dimension).

Milestone

The entire aircraft including the engine geometry was parametrically modeled and is ready for CFD simulations.

Major Accomplishments

A baseline aircraft design was successfully created based on reduction of the NASA CRM. Aircraft wing and nacelle design variables were parameterized and implemented in ESP scripts. This directly supported Task 3 (parametric mesh generation and CFD solver on a supercomputing cluster), Task 7 ("wrapping" codes for multidisciplinary design analysis and optimization), and Task 8 (screening and reduction of design variables). The geometry generation also allowed preparatory activities for CFD such as initial mesh sensitivity studies.

Publications

None

Outreach Efforts

None

Awards

None

Student Involvement

Salah Tarazi (continuing PhD student) played a major role in adapting the NASA CRM and implementing the baseline vehicle geometry in ESP.

Stephanie Zhu (continuing PhD student) was involved in wing parameterization in ESP and its linkage to CFD software.

References

- Vassberg, J., Dehaan, M., Rivers, M., and Wahls, R.,"Development of a Common Research Model for Applied CFD Validation Studies,"26th AIAA Applied Aerodynamics Conference, AIAA Paper 2008-6919, 2008.
- Kulfan, Brenda M. "Universal parametric geometry representation method." Journal of aircraft 45.1 (2008): 142-158.
- Haimes, Robert, and John Dannenhoffer. "The engineering sketch pad: A solid-modeling, feature-based, web-enabled system for building parametric geometry." 21st AIAA Computational Fluid Dynamics Conference. 2013.
- Tejero, Fernando, et al. "Multi-objective optimisation of short nacelles for high bypass ratio engines." Aerospace Science and Technology 91 (2019): 410-421.

Plans for Next Period

In order to generate a more robust engine geometry, an extension of the CST parametrization approach (Tejero et al., 2019) will be explored. If this approach is successful, nacelle surfaces defined by Bézier curves will be replaced by the new parametric equations defined in the reference paper.

Task 3 – Automation of Parametric Mesh Generation and CFD

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Objective

In order to solve an MDAO problem, the workflow between geometry generation to CFD solution and post-processing must be reduced to a robust function call. CFD meshing in particular is difficult to automate as a “fire-and-forget” process without human inspection or intervention. Yet, a high degree of automation is needed to allow modern design techniques such as active subspace, adaptive sampling, and multi-fidelity methods described in later tasks. This detailed development work may be of less interest to the stakeholder or decision-maker, but it is identified as a separate Task because it accounts for a large share of actual effort and calendar time.

Research Approach

As with other Tasks, this is Task is currently under development until the first walk-through of an MDAO in 2021. In the example below, an off-line design of experiments (DoE), or sample specification, is used as a placeholder for an MDAO driver or optimizer.

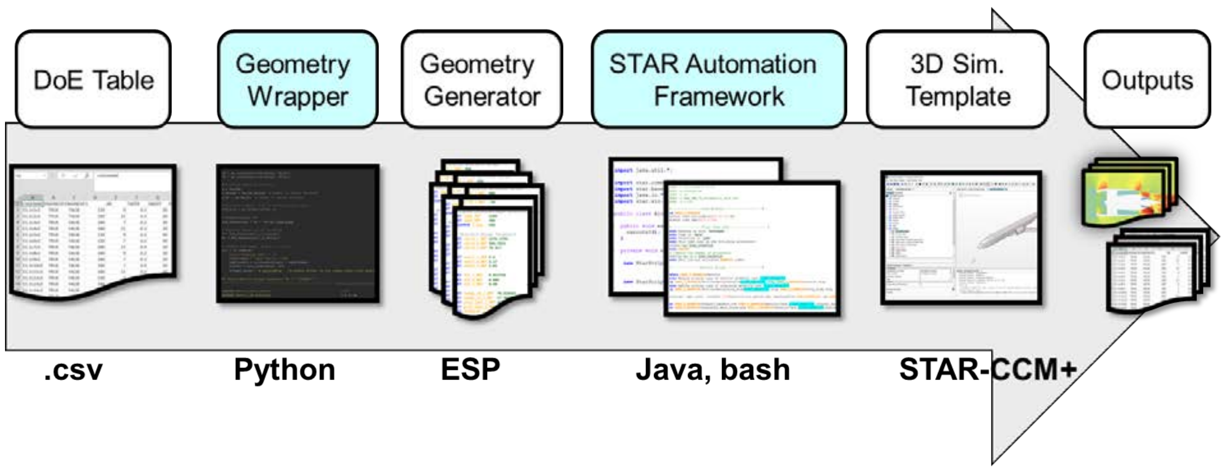

Figure 7. Automated work-flow for example design activity (design of experiments, or DoE).

Risk Mitigation Strategies

Current development focuses on “wrapping” the Siemens STAR-CCM+ CFD suite. There have been delays in the performance period in legal arrangements to allow use of the tool on supercomputing resources supported by NASA. Therefore, two other CFD mesh and solver tool-chains have been linked to the parametric geometry generation as mitigation options. CREATE Capstone unstructured mesh generator and NASA’s Chimera Grid Tools were also “wrapped” with Python scripts and linked to ESP geometry for reduced cases in a pattern similar to Figure 7 above. These efforts leveraged ongoing academic efforts at Georgia Tech.

Milestone

Related to this Task, initial grid sensitivity studies on the entire wing-body-nacelle geometry were conducted to fulfill a September 2020 milestone.

Major Accomplishments

Initial automation of 2D axisymmetric CFD nacelles contributes to development of screening/variable reduction methods and MDAO techniques in later tasks.

Publications

None

Outreach Efforts
None

Awards
None

Student Involvement
Salah Tarazi (continuing PhD student) played a major role in adapting the NASA CRM and implementing the baseline vehicle geometry in ESP.

Stephanie Zhu (continuing PhD student) was involved in wing parameterization in ESP and its linkage to CFD software.

Plans for Next Period
CFD automation and scripting shall be completed and tested with the full configuration on the NASA Advanced Supercomputing (NAS) facility.

Task 4 – Creation and Calibration of Single Aisle Aircraft Mission Model
Georgia Institute of Technology

Objectives
The study focuses on the impact of OWN installation on a specific aircraft class. An aircraft mission model is needed for a 150 passenger ("pax") single-aisle aircraft. This mission model uses the propulsion cycle analysis and aerodynamic drag polars from CFD to yield fuel burn and other responses for a typical mission. The model is also used for comparison of OWN and UWN configurations.

Research Approach
The mission analysis uses FLOPS (flight optimization system), which is a NASA code. The model discretizes a mission into segments and enforces conservation laws essentially for a point-mass representation of the aircraft. Even though the conservation laws are applied on a point mass, the aircraft has attributes such as drag and engine performance data from internal models and external data tables that are based on physics/geometry inputs such as wing area, aspect ratio, etc. Georgia Tech actually combines FLOPS along with the Numerical Propulsion System Simulation (NPSS) engine cycle analysis code and other tools in a multidisciplinary suite called the Environmental Design Space (EDS) (Kirby, 2008).

The detailed geometry used for CFD is substantially based on the NASA CRM in Task 2. For example, the baseline airfoil stack is adopted from the CRM. However, conceptual-level sizing parameters were adopted from the Airbus 320neo because this aircraft model has been used previously in FAA-sponsored mission analyses. Figure 8 below describes the development of the aircraft model.

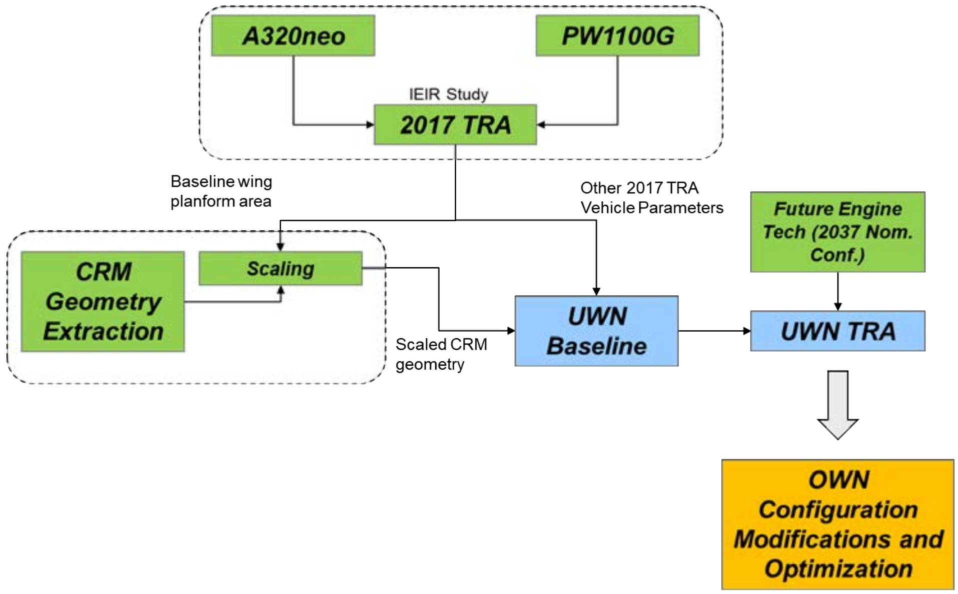

Figure 8. Development of 150-pax single-aisle aircraft model.

Milestones
FLOPS aircraft baseline model and engine deck completed.

Major Accomplishments
Baseline aircraft and engine model allow the propagation of aero-propulsion analysis to mission fuel burn and other system-level responses.

Publications
None

Outreach Efforts
None

Awards
None

Student Involvement
Andrew Burrell is a continuing graduate student.

Plans for Next Period
The aircraft model is mainly complete, but detailed adjustments will be made as needed to the evolving aircraft design in the next period of performance.

References

- Kirby, M.R. and Mavris, D.N., “The Environmental Design Space,” 26th International Congress of the Aeronautical Sciences, Anchorage, AK, ICAS-2008-4.7.3, 2008.

Task 5 – High Bypass Turbofan Propulsion Cycle Model

Georgia Institute of Technology

Objectives

A cycle analysis is required to solve a coupling problem between aerodynamics (CFD) and mission analysis to compute thrust, fuel burn, and other key quantities. In particular, an engine model is created in the NPSS code to represent an appropriate technology level.

Research Approach

The baseline engine was chosen to represent a future technology level (2027/2037) in consultation with FAA technical advisors. This was based on publicly available data for the PW1100G engine. The nominal bypass ratio is approximately 18. The large bypass is assumed because one of the main potential benefits of the OWN configuration is to enable larger diameter engines with their accompanying propulsive efficiency advantages.

This cycle information is linked to CAD and aerodynamic analysis through key geometry boundary conditions at different parts of the mission. For example, NPSS and its accompanying weight model WATE provides fan height as well as exit areas for core and bypass streams (at station 8 and 18) to the geometry generator. The cycle analysis also provides mass flow targets at the inlet as well as total pressure and temperature information at CFD core and bypass nozzle plenums.

Milestone

Baseline engine deck (accompanying aircraft mission model) completed.

Major Accomplishments

None

Publications

None

Outreach Efforts

None

Awards

None

Student Involvement

Andrew Burrell is a continuing graduate student.

Plans for Next Period

An approach is being developed for landing gear sizing and constraint analysis for the 2037 engine, as the engine may be too large for reference/comparison UWN installations. The cycle shall be adjusted with respect to revised landing gear constraints. In addition, CFD analysis will likely reveal additional constraints and detailed modifications, especially due to nacelle shape.

Task 6 – Noise Models

Georgia Institute of Technology

Objective

One of the main benefits of the OWN configuration is noise shielding from the wing. Despite the importance of modeling noise, high fidelity physics modeling is out of scope for this present project due to the complexity and computational cost of analysis. Rather than a direct objective function in optimization, a lower-order analysis is used to model noise as a constraint (or simply tracked as a response) while optimization emphasizes aero-propulsion responses.

Research Approach

Acoustics are modeled using a lower fidelity mode of ANOPP software. The code is used to model engine noise as a single source. Because of the relatively coarse spatial representation of noise, it is assumed that the dependence of noise responses with respect to nacelle geometry placement are crude at best. In other words, because the acoustical effect of the engine is concentrated at a point source, the ANOPP code in this lower fidelity mode cannot be used to capture the noise impact of moving the nacelle possibly within a tolerance of feet.

Nonetheless, keeping the above caveats in mind, initial configuration studies addressed the following questions:

- Does aft engine noise dominate the conversation moving forward?
- How much benefit does shielding provide for the forward mounted configuration?

A preliminary study was conducted by decomposing forward-radiated versus aft-radiated engine noise. The engine was simply moved above and below the wing by +/- 1.38 nacelle diameters for a baseline engine geometry. Comparisons were made for different technology assumptions (2017, 2027, 2037) for sideline and cutback noise. An example result is shown in Figure 9. It should be noted that these are preliminary results only, and results will change as geometry is optimized in the overall MDAO process.

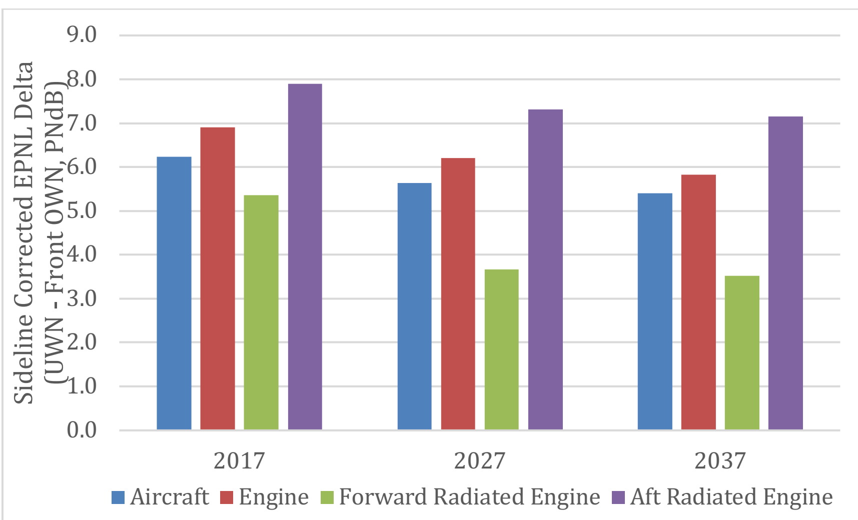

Figure 9. Sideline noise comparison of UWN and front-mounted OWN configurations under different technology assumptions. This example result is preliminary and before optimization.

Milestones

None. This task contributes to an overall MDAO process for which a manual walk-through will be demonstrated in early 2021.

Major Accomplishments
None

Publications
None

Outreach Efforts
None

Awards
None

Student Involvement
Andrew Burrell is a continuing PhD student who performed the ANOPP noise comparisons.

Plans for Next Period
Noise models will be continually adjusted to reflect design changes in the high fidelity MDAO in the next period.

Task 7 – "Wrapping" of Codes for Multidisciplinary Analysis
Georgia Institute of Technology

Objectives
The multiple disciplinary codes such as CFD, engine cycle, mission, and noise analysis are scripted such that an MDAO driver script can direct function calls. This is essentially the preparation of interfaces to allow the codes to be connected to modern MDAO methods described in other Tasks.

As with other geometry and automation tasks, this present Task is also development work that is possibly of less direct interest to the stakeholder other than accounting for project schedule and workforce. There is considerable overlap with the automated meshing for CFD, which is emphasized separately (Task 3) due to its particular importance.

Research Approach
In the period of performance, this wrapping of disciplinary codes focused on aerodynamics (also see Task 3), propulsion, and mission analysis. Interfaces are being prepared to allow each disciplinary analysis to be called from Python in a high-performance computing (HPC) environment. The use of Linux-based HPC initially posed a challenge because the propulsion, mission, and noise codes (NPSS, FLOPS, and ANOPP) have mainly been used in Windows. For this and related reasons, surrogate models (multivariable regressions) of these tools will be used rather than directly linking with Linux-based CFD.

Several regression options were investigated, including neural networks, linear regression, ridge regression, and lasso regression. For a full-scale optimization, larger DoE sample sizes will be used.

Full automation has been achieved for propulsion-aerodynamics integration (PAI) using STAR-CCM+ CFD on an axisymmetric nacelle case. Figure 10 below shows three columns, each with randomly generated nacelle designs. CFD is coupled with a NPSS polynomial surrogate model, and the plots show the evolution of responses as the two codes reach consistent flow properties.

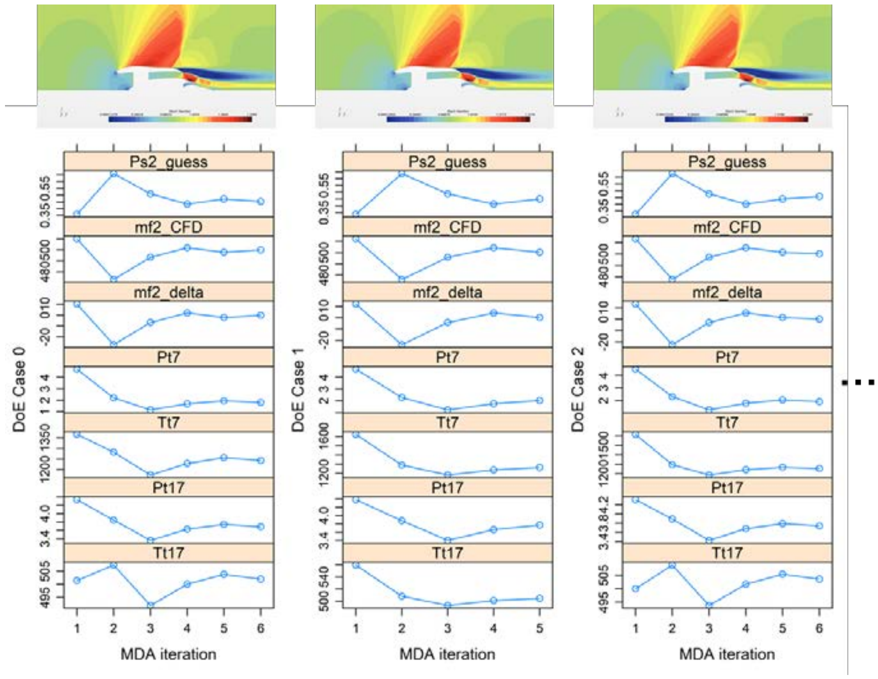

Figure 10. Automated CFD and propulsion analyses are shown in axisymmetric nacelle cases. The work is to be extended to the entire wing-body-nacelle configuration.

Milestones
None

Major Accomplishments
Preliminary methods for MDF method using a 2D nacelle inform later decision on MDAO architectures for the full wing-body-nacelle MDAO.

Publications
None

Outreach Efforts
None

Awards
None

Student Involvement
Bilal Mufti focused on Reynolds Averaged Navier-Stokes (RANS) CFD interfaces and propulsion surrogates. Stephanie Zhu and Kenneth Decker developed scripts to wrap inviscid CFD analysis. All are continuing graduate students pursuing PhDs.

Plans for Next Period
Surrogate models for mission and noise analysis shall be created. Interfaces to a Python MDAO driver shall be demonstrated.

Task 8 – Screening and Dimensionality Reduction

Georgia Institute of Technology

Objective

Realistic assessment of the OWN configuration depends on the degree of optimization. The degree of optimization depends on the dimensions or number of design variables. However, the computational cost of optimization can increase sharply with the number of design variables due to the "curse of dimensionality." Therefore, the number of design dimensions must be minimized by finding the most important contributors to key metrics.

Research Approach

The main approach to dimensionality reduction is the active subspace method (Constantine reference). Related variants of this method have been previously demonstrated for OWN at Georgia Tech. The method uses gradients of responses with respect to design variables to essentially rotate the design space such that new, hybrid design variables are aligned in directions where sensitivities have most variability.

The method requires the evaluation of gradients at a sample of design points. An eigen-decomposition problem is solved to yield new design variables that linear combinations of the former design variables. The new design variables are rank-ordered by their relative impact on a key metric such as lift-to-drag ratio for the aerodynamics discipline. In favorable cases, a small number of new, "active" design variables capture most of the effect of a much larger original set of design variables.

Active Subspace Implementation with Adjoint Inviscid CFD

A key step in the active subspace method is to evaluate design gradients. For many simple analyses, this could be accomplished through finite differences. In other words, at each sample design point **X**, the geometry would be perturbed by ΔX_i for each design variable *i* and evaluated by a function (e.g., CFD). This is in turn used to estimate the gradient at the reference point. However, this finite differencing can become computationally expensive if there are many design variables. Many sample points **X** are needed, and many perturbations are needed around each point.

Adjoint CFD is a type of analysis that modifies the original CFD governing equations to yield not just output functions like lift or drag but also their gradients with respect to design variables (Jameson 1988). This requires a relatively modest computational cost increase over the cost of a simple function evaluation of f(**X**). The adjoint feature in the CART3D inviscid CFD code was used in this task (Aftosmis et al., 2011), as shown in Figure 11.

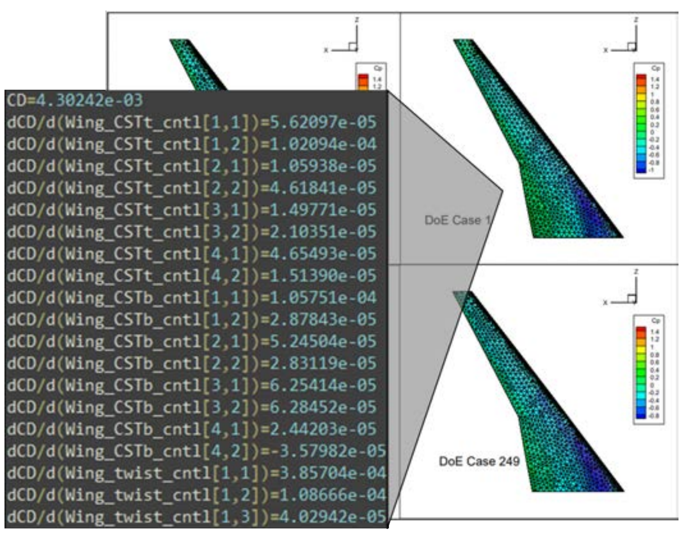

Figure 11. Adjoint inviscid CFD (CART3D) yields gradients for drag and other responses for a wing example.

A key hypothesis is that an active subspace for the OWN configuration learned from inviscid CFD is applicable to a viscous CFD design problem because there are enough similarities in the flow physics such that the relative impact of variables' contributions to an objective may also be similar. This of course may not always be the case. In a design domain, if the principal physics phenomena that affect performance are inherently viscous (e.g., flow separation at the top of the wing near a nacelle), then the inviscid active subspace may not yield a major computational saving. However, the design variables under consideration include wing twist and airfoil variables that affect thickness, etc. These variables affect both lift distribution (associated with vortex induced drag that can be captured at low fidelity without viscosity) as well as wave drag (which also can be modeled to some degree without viscosity). This physical reasoning has justified taking the risk of using an inviscid CFD code to find an active subspace for a viscous/RANS CFD design task. Without performing two separate MDAO efforts in a controlled experiment, it is difficult to estimate beforehand the computational efficiency due to this active subspace implementation. The technique is therefore justified based on the above reasoning and may be tested with small-scale experiments.

Preliminary Results

Initial trials were performed using the OWN wing-body-nacelle configuration with relatively coarse grids in CART3D. A sample size of 48 was evaluated. The gradients for lift, drag, mass flow, and net thrust were calculated for a design domain around a CRM-based baseline geometry. Gradients were calculated for 28 design variables, including airfoil CST variables, wing twist, nacelle shape variables, flight conditions, and an engine boundary condition (fan face velocity). In Figure 12, the normalized eigenvalue corresponds to relative impact on response functions. The new, active subspace variables are ordered by their relative impacts. It can be seen that a small number of variables capture most of the effect of the original design variables.

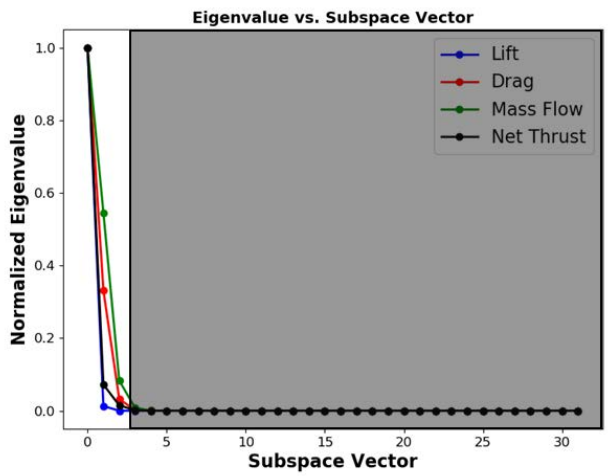

Figure 12. The first three or four new, “active” design variables (subspace vectors) have high eigenvalues which measure their relative contribution to variability in lift, drag, mass flow, and net thrust. It should be noted that this test was performed with a relatively coarse grid and with a small number of design variables.

Milestones

None

Major Accomplishments

Active subspace scripts written and demonstrated for wing-body-nacelle using a small sample of coarse-grid, inviscid CFD. A larger scale active subspace analysis will be used to finalize the reduced design space for full-scale MDAO.

Publications

None

Outreach Efforts

None

Awards
None

Student Involvement
Kenneth Decker performed the majority of the work for this task. Stephanie Zhu also contributed. They are continuing PhD students.

Plans for Next Period
Currently, grid refinement studies are being conducted to more accurately estimate gradients. A future, larger scale DoE will be conducted to finalize the active subspace variables.

References

- Jameson, Antony. "Aerodynamic design via control theory." Journal of scientific computing 3.3 (1988): 233-260.
- Aftosmis, Michael, Marian Nemec, and Susan Cliff. "Adjoint-based low-boom design with Cart3D." 29th AIAA Applied Aerodynamics Conference. 2011.

Task 9 – Demonstration of MDAO or Sampling Methods on Reduced Order or Placeholder Functions
Georgia Institute of Technology

Objective
The credibility of OWN assessment depends on the degree of design optimization. With limited computational resources, there is a strong need to use efficient, modern MDAO techniques. This Task focused on testing and down-selecting promising candidate methods from recent MDAO literature. The methods are first tested on reduced-order examples before committing large computer resources for final optimization.

Research Approach
In addition to the active subspace method discussed in Task 8, this Task investigated two additional techniques in combination: Bayesian adaptive sampling and multi-fidelity methods.

Bayesian Adaptive Sampling
This class of methods relies on a type of surrogate model that yields probabilistic metrics of interpolation uncertainty for regions of the design space that have not yet been evaluated. The most famous of these methods relies on kriging or Gaussian process (GP) models (Jones, Schonlau, Welch, 1998). Different probabilistic criteria such as expected improvement are used to select the next design point for evaluation. This essentially behaves similarly to an optimizer, though if it is not run to convergence, it can be treated as an adaptive or sequential sampler that concentrates points near the optimum.

Bayesian adaptive sampling techniques are well-suited for batch analyses in HPC. Parallel or batch sampling techniques were tested on canonical algebraic test functions to sample multiple design points at a time. This is beneficial because multiple CFD or MDAO cases can be queued in a supercomputer job scheduler rather than running single design cases at a time.

Multi-fidelity Methods
Another potentially beneficial design technique combines two or more disciplinary analyses of different fidelity level and computational cost. The two codes are used in concert, with the cheaper low-fidelity code assisting in the estimation of a high-fidelity function across a design space. In the present research, we focused on inviscid and viscous CFD. A particular multi-fidelity method called hierarchical kriging was tested with the CRM-based wing parameterization discussed earlier (Han and Görtz, 2012).

Initial Findings
The two methods were combined and multi-fidelity adaptive sampling was tested on a wing example with three variables and coarse grids. NASA's FUN3D code was used in viscous/RANS mode for high-fidelity and in inviscid/Euler mode for low fidelity. For this coarse test case, the cost ratio was roughly 8:1. Results in Figure 13 show that both codes are used in combination to concentrate analyses in regions of favorable lift-to-drag ratio.

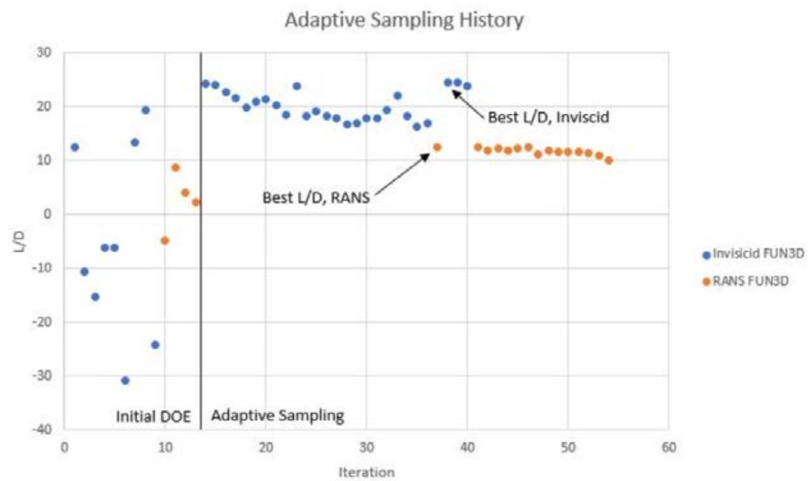

Figure 13. Multi-fidelity adaptive sampling concentrates low- and high-fidelity CFD analyses in regions of favorable lift-to-drag ratio.

Adaptive sampling balances between exploiting knowledge of favorable regions versus exploring regions that have not yet been sampled. In the example above, both low- and high-fidelity codes concentrate on designs with relatively high lift-to-drag ratio (L/D). Yet, after finding a favorable result (the current best result labeled in the figure), the algorithm continues exploring in other parts of the design space due to the remaining uncertainty. This explains why the L/D does not monotonically increase. This small-scale example will be expanded to the entire wing-body-nacelle using finer CFD meshes.

Milestone
MDAO techniques were tested on reduced order/placeholder functions.

Major Accomplishments
None

Publications
None

Outreach Efforts
None

Awards
None

Student Involvement
Christopher Eggert contributed to this task; he is graduating with a master's degree in December 2020 and will begin work at the NASA Langley Research Center.

Plans for Next Period
The Bayesian adaptive sampling method will be implemented for full wing-body-nacelle CFD. A major challenge then is to adapt single-discipline (aerodynamics) adaptive sampling to a multidisciplinary problem. Currently, probabilistic design criteria are used to guide CFD analyses in isolation. In the future, a goal is to use the Bayesian approach to guide not only favorable design points but also efficient coupling between disciplines such as aerodynamics and propulsion.

References

- Jones, D.R., Schonlau, M. & Welch, W.J. "Efficient Global Optimization of Expensive Black-Box Functions," *Journal of Global Optimization,* Volume 13, 1998, pp. 455–492. https://doi.org/10.1023/A:1008306431147
- Han, Z.-H., and Görtz, S. "Hierarchical Kriging Model for Variable-Fidelity Surrogate Modeling." *AIAA Journal*, Vol. 50, No. 9, 2012, pp. 1885–1896. https://doi.org/10.2514/1.J051354.