CAD-Based Multifdelity Analysis and Multidisciplinary Optimization in Aircraft Conceptual Design

Thesis Proposal Defense

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Outline

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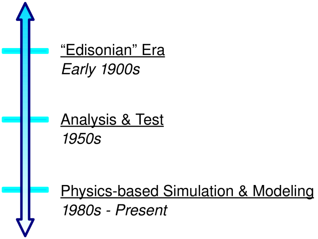
Introduction–Design History

Aircraft Design History

Tam summarizes in [1]:

- "Edisonian" era
  - Little theory available, rely on experiment
- Analysis-and-test
- Physics-based modeling and simulation



Tools & Methodology

Chosen design tools impact the design methodology:

- Reflect schedule constraints
- Analysis fidelity
  - Dictates trustworthiness of results
  - Sets the stage for later design phases
- Consider design phase objectives and experience

Introduction–Definitions

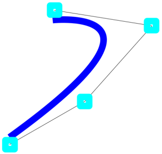
Analysis Fidelity

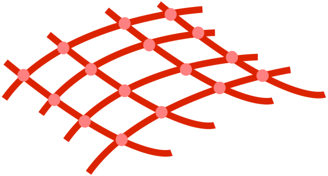
Low-fidelity	Medium-fidelity	High-fidelity
• Empirical & Statistical Analysis	• Physics-based, linear/non-linear analysis	• Physics-based, linear/non-linear analysis
• High-level configuration parameters	• High-level configuration parameters • 3D location of major components • General structural information	• Geometry of detailed surface contours • Body mesh of detailed internal structural components
• Parameter space DOF < 100	• Parameter space DOF ~ 100 or greater	• DOF ~ 10^5 to 10^6

Introduction–Definitions

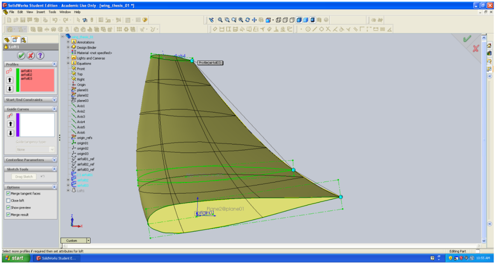
Computer Aided Design (CAD) Usage

CAD-free



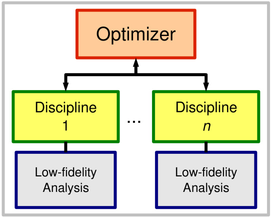


CAD-based

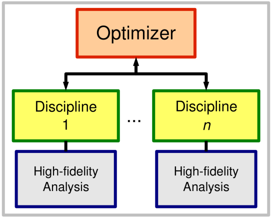


Introduction–Definitions
Fidelity of Analysis in MDO

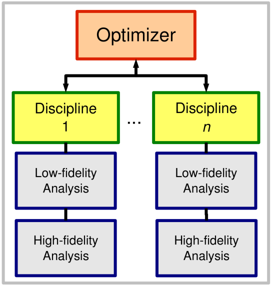
Low-fidelity MDO



High-fidelity MDO



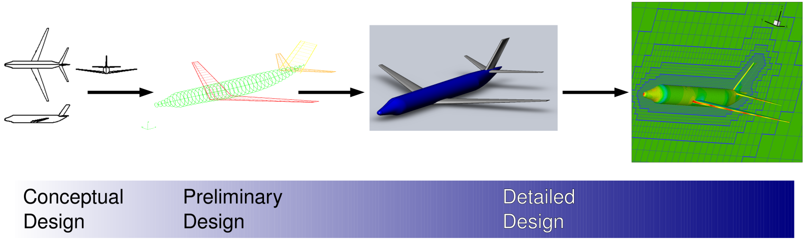
"Multifidelity MDO"

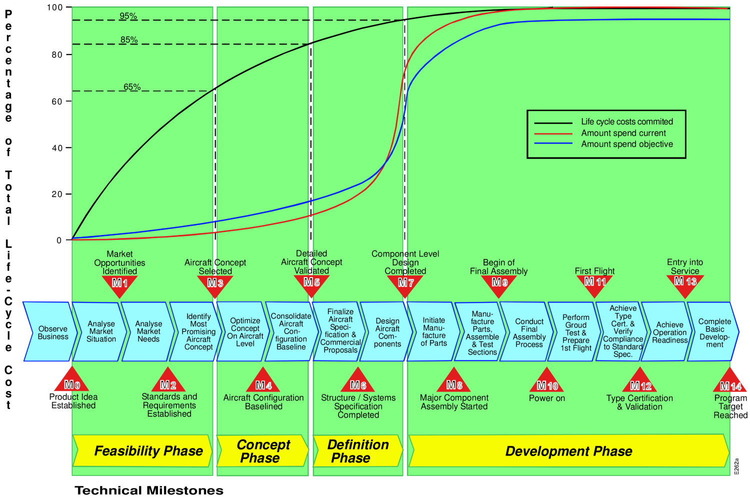


Outline

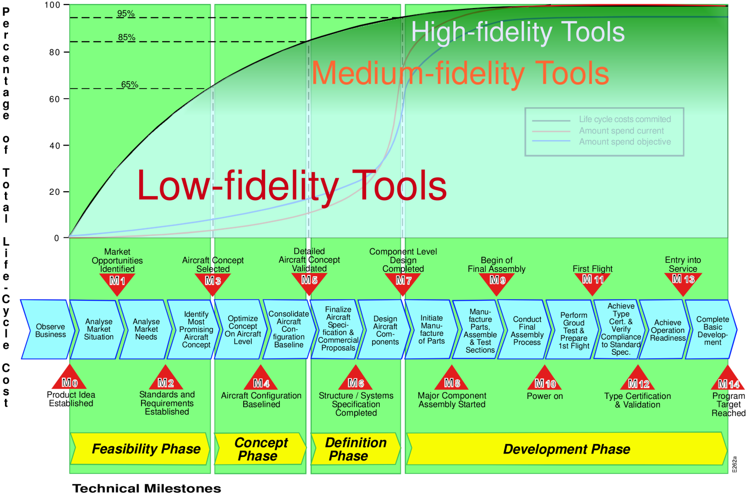
Design Process In-Series

- High-level configuration parameters used [2, 3, 4, 5]
- Low-fidelity analysis permits quick analysis of configuration performance [6]
- Medium- and high-fidelity analysis utilized in later development phases





(Taken from Kesseler [7])



(Taken from Kesseler [7])

Common Available Tools

- Design Sheet [8]
- Program for Aircraft Synthesis Studies (PASS) [9, 10]
- ASWING [11]

New Variable-fidelity Tools

- Design and Engineering Engine (DEE) [12]
- Web-services, CAD-based MDO framework [13, 14, 6]
- Multidisciplinary Aircraft Design and Evaluation (MADE) [15]

In 2003, Bowcutt listed the following areas for advancement [16]:

- Parametric geometry generation
- Automated data transfer between tools
- Automated high-fidelity analysis
- MDO
- Probabilistic tools for systems-level risk assessment, uncertainty-based optimization
- Collaborative/distributed/grid computing
- Quantify system effectiveness by modeling development, manufacturing, operations and campaign use

In 2003, Bowcutt listed the following areas for advancement [16]:

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Parametric geometry generation

- Automatic 3D model creation and regeneration [17, 18], considering:
  - Continuous design variables
  - Design space smoothness or irregularity
- CAD systems are well established in aerospace industry
- Spectrum of parameterization choices depending on geometry representation [19, 20, 21, 6, 22]
  - Shape functions
  - NURBS surfaces
  - Lines, conic sections, algebraic & four-point curves
  - Bezier & B-spline curves

Automated Data Transfer Between Tools

- Generally Input/Output (IO) schemes are incompatible between analysis tools
  - File IO
  - XML, web-services [14, 6]
  - Oracle databases [15]
- Commercial MDO frameworks attempt to simplify data transfer
  - ModelCenter [23] & iSIGHT [24]

Automated High-fidelity Analysis

- Historically mesh/geometry creation is a tedious manual process
- Automatic cartesian mesh generation in Cart3D [25]
- Automatic surface tesselation with CAPRI [26]

MDO

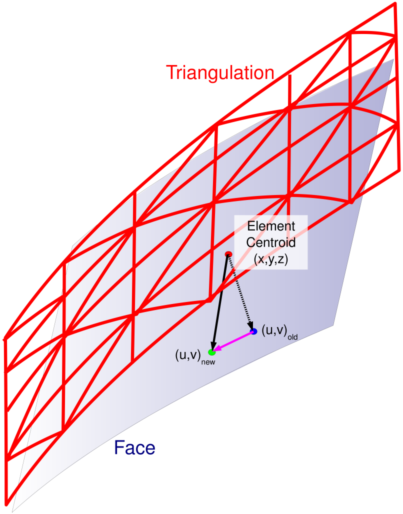
- Optimization methods research
- Integrating low- and high-fidelity analysis in MDO
  - Low-fidelity gradients, high-fidelity objective function evaluations [27]
  - Surrogate methods (Trust Region Model Management–TRMM) [28, 29]
  - Organizational adaptations [30, 31]
  - Aircraft configuration errors found earlier [32]
    - 50% improvement of radically new designs; 10% and 2% for novel and mature designs, respectively.
- Existing frameworks try simplifying low- and high-fidelity analysis integration
  - πMDO [33]
  - Boeing MDOPT [34]
  - DEE [12]
  - Work by Amadori et al. [14, 13] and Jouannet [6]

CAD-free Methods

- Analytic shape functions [35]
- Finite-differencing or adjoint methods of surface geometries
- Free-form deformation (FFD) [36]
- Basis vectors [37]
- Domain element approach
- Partial differential equations [38]
- Discrete approach [39, 40]
- Polynomial/spline approaches [32, 41]
- Topology optimization [42, 43, 44]

CAD-based Methods

- Automatic differentiation–intractable without source code [31]
- Develop in-house CAD system–easily differentiable with source code, as done recently in [45]
- Finite-differencing of nodes or element centroids in surface geometry or body mesh [46, 47, 45, 48, 49]



As stated in Zang [30]:

$$\frac{\partial F}{\partial \boldsymbol{x}} = \underbrace{\frac{\partial F}{\partial \boldsymbol{U}}}_{1} \cdot \underbrace{\frac{\partial \boldsymbol{U}}{\partial \boldsymbol{V}}}_{2} \cdot \underbrace{\frac{\partial \boldsymbol{V}}{\partial \boldsymbol{S}}}_{3} \cdot \underbrace{\frac{\partial \boldsymbol{S}}{\partial \boldsymbol{x}}}_{4}$$

$$F = \int_{\Omega} f \, d\Omega$$

$$f = f(\boldsymbol{x}, \boldsymbol{U})$$

$\boldsymbol{U}$ = CFD Solution

$\boldsymbol{V}$ = Volume Mesh

$\boldsymbol{S}$ = Surface Geometry

$\boldsymbol{x}$ = Configuration Parameters

Sensitivity of:

1. Objective Function to Solution
2. Solution to Volume Mesh
3. Mesh to Geometry
4. Geometry to Parameter

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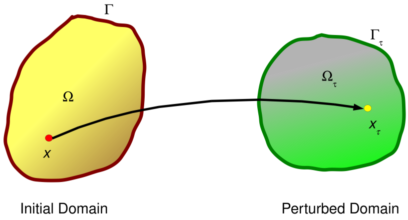
2. Solution to Volume Mesh
3. Mesh to Geometry
4. **Geometry to Parameter**

As derived in Choi & Kim [50]:

$$\boldsymbol{x}_\tau = \boldsymbol{T}(\boldsymbol{x},\tau),$$
$$\Omega_\tau = \boldsymbol{T}(\Omega,\tau)$$
$$\boldsymbol{x} \in \Omega$$
$$\boldsymbol{T} : \boldsymbol{x} \rightarrow \boldsymbol{x}_\tau(\boldsymbol{x})$$

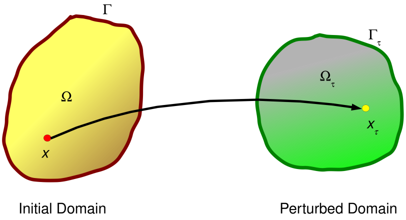


$$\vec{\boldsymbol{V}}(\boldsymbol{x}_\tau,\tau) \equiv \frac{d\boldsymbol{x}_\tau}{d\tau} = \frac{d\boldsymbol{T}(\boldsymbol{x},\tau)}{d\tau} = \frac{\partial \boldsymbol{T}(\boldsymbol{x},\tau)}{\partial \tau} \equiv \text{Design Velocity}$$

$$\boldsymbol{T}(\boldsymbol{x},\tau) = \boldsymbol{T}(\boldsymbol{x},0) + \tau\frac{\partial \boldsymbol{T}}{\partial \tau}(\boldsymbol{x},0) + \cdots = \boldsymbol{x} + \tau\vec{\boldsymbol{V}}(\boldsymbol{x},0) + \cdots$$
$$= \boldsymbol{x} + \tau\vec{\boldsymbol{V}}(\boldsymbol{x})$$

As derived in Chen et al. [51]:

$$\Omega : b \rightarrow \Omega(b)$$
$$\boldsymbol{T} : \boldsymbol{x}(b) \rightarrow \boldsymbol{x}(b+\delta b)$$
$$\Omega(b+\delta b) = \boldsymbol{T}(\Omega(b);\delta b)$$
$$\boldsymbol{x}(b+\delta b) = \boldsymbol{T}(\boldsymbol{x}(b);\delta b) = \boldsymbol{x}(b) + \vec{\boldsymbol{V}}\delta b$$



With $F(b) = \int_{\Omega(b)} f(b, \boldsymbol{x}(b))d\Omega$

$$F(b+\delta b) = \int_{\Omega(b+\delta b)} f(b+\delta b, \boldsymbol{x}(b+\delta b))d\Omega$$
$$= \int_{\Omega(b)} \left[f(b+\delta b, \boldsymbol{x}(b) + \vec{\boldsymbol{V}}\delta b)|\boldsymbol{J}| \right] d\Omega$$

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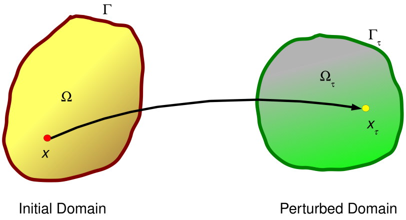

With $\boldsymbol{J} = \nabla \boldsymbol{T} = \boldsymbol{I} + \delta b \nabla \vec{\boldsymbol{V}}$,

$$\boxed{\frac{dF}{db} = \int_{\Omega(b)} \frac{\partial f}{\partial b} d\Omega + \underbrace{\int_{\partial\Omega(b)} f \vec{\boldsymbol{V}} \cdot n d\Gamma}_{\text{Uses design velocity}}}$$

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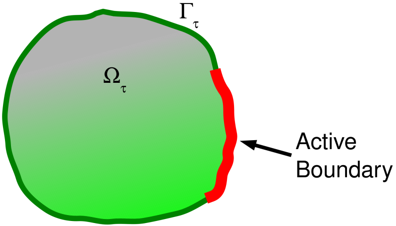

Perturbed Domain

$$\frac{dF}{db} = \int_{\Omega(b)} \frac{\partial f}{\partial b} d\Omega + \int_{\partial\Omega(b)} f\vec{\boldsymbol{V}} \cdot n d\Gamma$$

$$\Rightarrow \int_{\partial\Omega(b)} f\vec{\boldsymbol{V}} \cdot n d\Gamma = \underbrace{\sum_{k \in \mathcal{A}(b)} \int_{\partial\Omega_k} f\vec{\boldsymbol{V}} \cdot n d\Gamma}_{\text{Sum over Active Boundaries}}$$

As derived in Chen et al. [51]:

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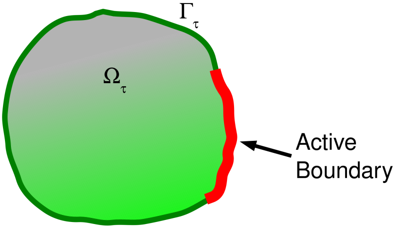


Perturbed Domain

Defining $\boldsymbol{\Phi}$ as an implicit analytical function of a primitive relative to parameters b,

$$\frac{dF}{db} = \int_{\Omega(b)} \frac{\partial f}{\partial b} d\Omega + \int_{\partial\Omega(b)} \frac{f}{|\nabla \boldsymbol{\Phi}|} \frac{\partial \boldsymbol{\Phi}}{\partial b} d\Gamma$$

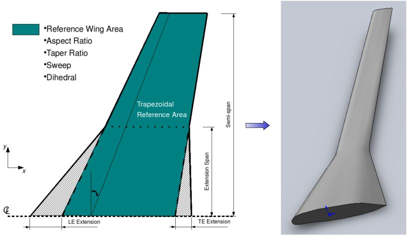
Outline

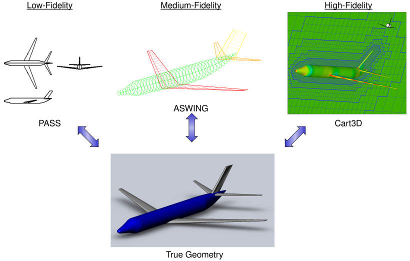
Design Methodology

- Solely low- or high-fidelity analysis in MDO is insufficient
  - Legacy codes are limited in analyzing new configurations [52]
  - Larger design space explored by changing legacy codes [32]
  - Costly work arounds for missed configuration issues [32, 16, 31]
- CAD-free design provides information, yet exact translation into a CAD model is difficult [31]
- CAD model is regenerated post-analysis; analysis relies on CAD-free mesh/geometry [13, 6]

CAD in Design

- 3D model-centered design (Knowledge Engineering)
- Different CAD generation methodology
  - Design intent driven by low- and medium-fidelity configuration parameters (problem-specific)
- Robustly incorporating internal structural assemblies [30]





Design Velocity Calculation

- Need implicit representation of boundary primitives [51]
- Issues in projecting triangulation nodes, or element centroids, onto model faces [49]
  - Topological change modifies the total number of model faces
  - Face IDs may vary even with no topological change (slivers)
- Long computational time for design velocity calculation
- Assumption of constant topology (otherwise need mesh history)
- Difficulty in selecting parameter step-size for finite-differencing [45]
  - Need less than 1% error
- Difficulty in using finite-differencing of nodes on face boundaries

Outline

1. Develop a conceptual design methodology that conducts multidisciplinary, gradient-based optimization of aircraft CAD models using multifidelity analysis

2. Develop a methodology for creating robust, multidisciplinary CAD models, where both outer mold lines and internal subsystem assemblies are coupled and driven by the parameter space from low- and medium-fidelity analysis codes.

3. Develop efficient and robust design velocity calculations when finding performance sensitivities for gradient-based optimization.

1. Literature Review
2. Develop an MDO framework with low-, medium- and high-fidelity analysis codes
   - Investigate efficient data communication methods, such as web-services
3. Develop CAD models with proper design intent (defined above)
   - Include methodology for generating internal structural assemblies
   - Develop codes to automatically generate CAD models
4. Develop algorithms for design velocity calculation from CAD models
   - Explore ways to improve robustness and reduce computational time
5. Demonstrate full functionality of the framework under development
   - Comparison with similar frameworks via certain performance metrics

Selected Analysis Codes

PASS

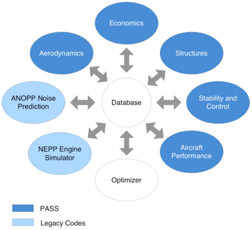
- Empirical models calculate performance
- Internal optimizer
- Configuration parameters
- JAVA

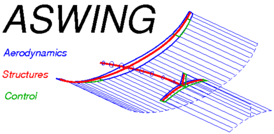
ASWING

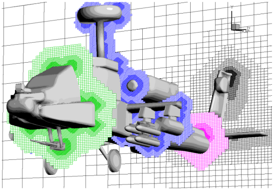
- Coupled lifting-line and vortex-lattice aerodynamic modeling with a nonuniform, nonlinear structural formulation
- 3D location of major structural components and lifting surfaces
- FORTRAN

Cart3D

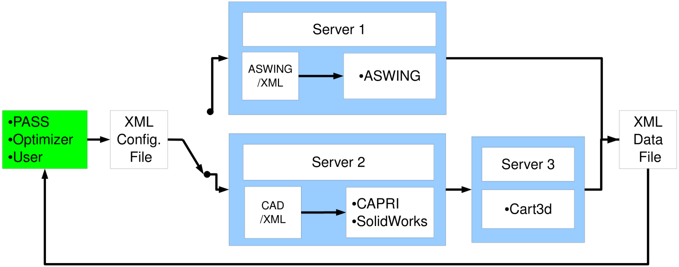
- Euler flow solver
- Use triangulation of model surface







- Connectivity between PASS and SolidWorks model (via CAPRI) to create triangulation for Cart3D
- CAD model regeneration and data extraction via CAPRI
- CAD model information used in all three fidelity levels of analysis



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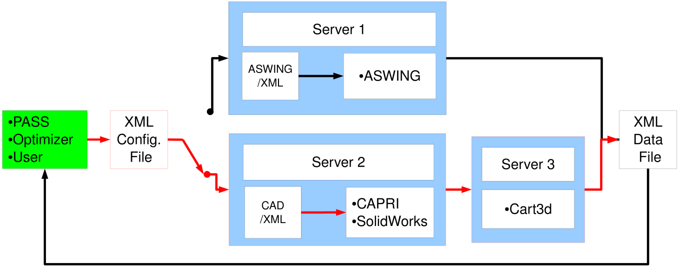

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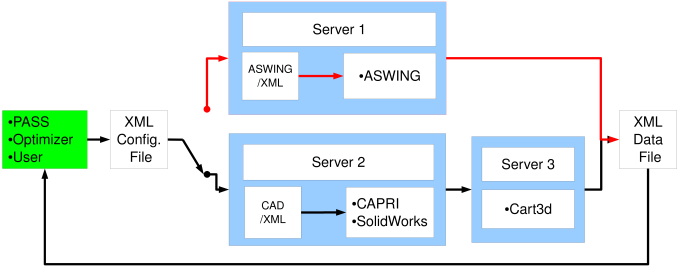


Functionality

- XML post-processing of PASS database
- Iteration history of PASS design variables

PASS XML Data

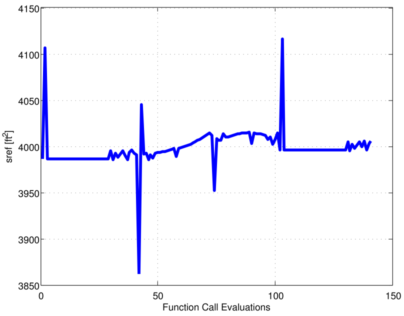
Optimizer Objective Function = weight.to

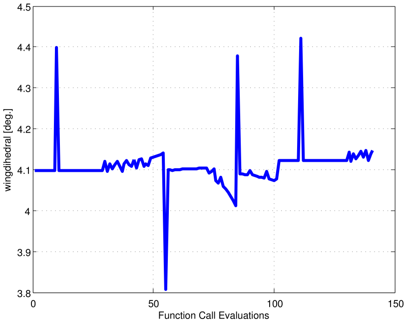
Controls Info.	lastmodified	lastupdated	status	comment	mainClass	objectiveClass	optimizerClass
	Aug 23, 2003	Jul 14, 2008 1:28:58 PM	complete	Arbitrary tube and wing.	simplex	mission	simplex

Optimizer Design Variables			Constraints	Inputs Section		Results Section	
Variable	Min.	Max.	Variable	Variable	Last Iteration Value	Variable	Value
sref	1000.0	5000.0	cruiserange_constraint	sref	3986.2513506528057	cruiserange	6087.184150236626
arw	5.0	12.0	tofieldln_constraint	arw	6.36395625165378	tofieldln	8807.815386650711
sweepw	0.0	40.0	landfieldln_constraint	sweepw	34.00457998697677	landfieldln	5054.328893794097
tovercw	0.1	0.3	climb2grad_constraint	tovercw	0.1354830433194521	initialgrad	0.16019680261679387
taperw	0.1	1.0	dtinitcr_constraint	taperw	0.24157921464318427	climb2grad	0.03484422509035209
lex	0.0	20.0	dtfinalcr_constraint	lex	0.1009097944425963	cutbackgrad1eng	0.018875912627564558
tex	0.0	15.0	minstability_constraint	tex	0.4428266975253171	cutbackgrad	0.12826017769121878
chordextspan	0.0	0.75	clwmargininitcr_constraint	chordextspan	0.34174650932725176	clwingmax	2.498308340186387
wingdihedral	0.0	10.0	clhmargintorot_constraint	wingdihedral	4.097774935996088	clwingmax_mod	2.498308340186387
wingheight	0.0	1.0	clhmargininitcr_constraint	wingheight	0.12337237236061269	clwingmax_agard	2.733890080312557
wingxposition	0.25	0.75	clhmarginlanding_constraint	wingxposition	0.35393081043320507	cltotal.initcr	0.4083623001232923
sh/sref	0.1	0.75	spanw_constraint	sh/sref	0.26812889898450776	cltotal.finalcr	0.4616181401380892
arh	0.5	5.0	totalepnl_constraint	arh	4.851582830411209	d/t.initcr	0.7218167971986561
sweeph	0.0	40.0	LTO_NOx_constraint	sweeph	38.766497899606776	d/t.finalcr	0.7434970872792519
toverch	0.1	0.3		toverch	0.13887937356648636	l/d.initcr	17.25138620770705
taperh	0.1	1.0		taperh	0.4987907151383498	l/d.finalcr	16.48746207803231
dihedralh	0.0	10.0		dihedralh	7.568512718881805	minstability	0.20482812315452176
ttail	0.0	1.0		ttail?	0.0	clwmargin.initcr	0.42475704804450704
sv/sref	0.1	0.5		sv/sref	0.19319336181186555	clhmargin.torot	0.9659897154553745
arv	0.5	5.0		arv	1.7629429175064633	clhmargin.initcr	1.0025025016875597
sweepv	0.0	50.0		sweepv	48.37884912813087	clhmargin.landing	0.47992694575095474

Functionality

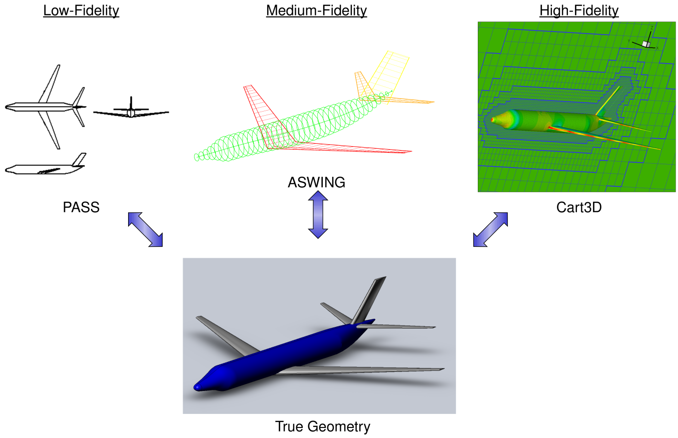
- XML post-processing of PASS database
- Iteration history of PASS design variables





Configuration Representation

- Centralize parameter space for PASS & ASWING in CAD model



Demonstration

Outline

Expected Contributions

Conceptual Design Methodology

- More robust and efficient design velocity calculations
- Demonstrated feasibility of CAD-based multifidelity analysis in MDO
- Applicable methodology for creating CAD models for use in this framework
- Demonstrate exploration of a larger design space and quantitative configuration down-select

Outline

Timeline

Phase Duration	Task
Oct08 – Dec08	Complete integration of PASS with SolidWorks model via CAPRI Create code to construct sensitivity matrix for aerodynamics analysis
Jan09 – Mar09	Create and implement design velocity calculation schemes
Apr09 – Jun09	Create automatic geometry generator for various concept aircraft Test robustness of solid models
Jul09 – Sept09	Create code to construct sensitivity matrix for structural analysis Create code to construct sensitivity matrix for controls or other subsystems Create web-services based framework Integrate NASTRAN module with PASS
Oct09 – Dec09	Resolve issues with multifidelity MDO integration Demonstrate feasibility and effectiveness of the completed CAD-based multifidelity MDO framework
Jan10 – Mar10	Write Thesis Draft
Apr10 – May10	Finish Thesis Thesis Defense

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