Multidisciplinary Optimization for Design of Low Emissions Aircraft

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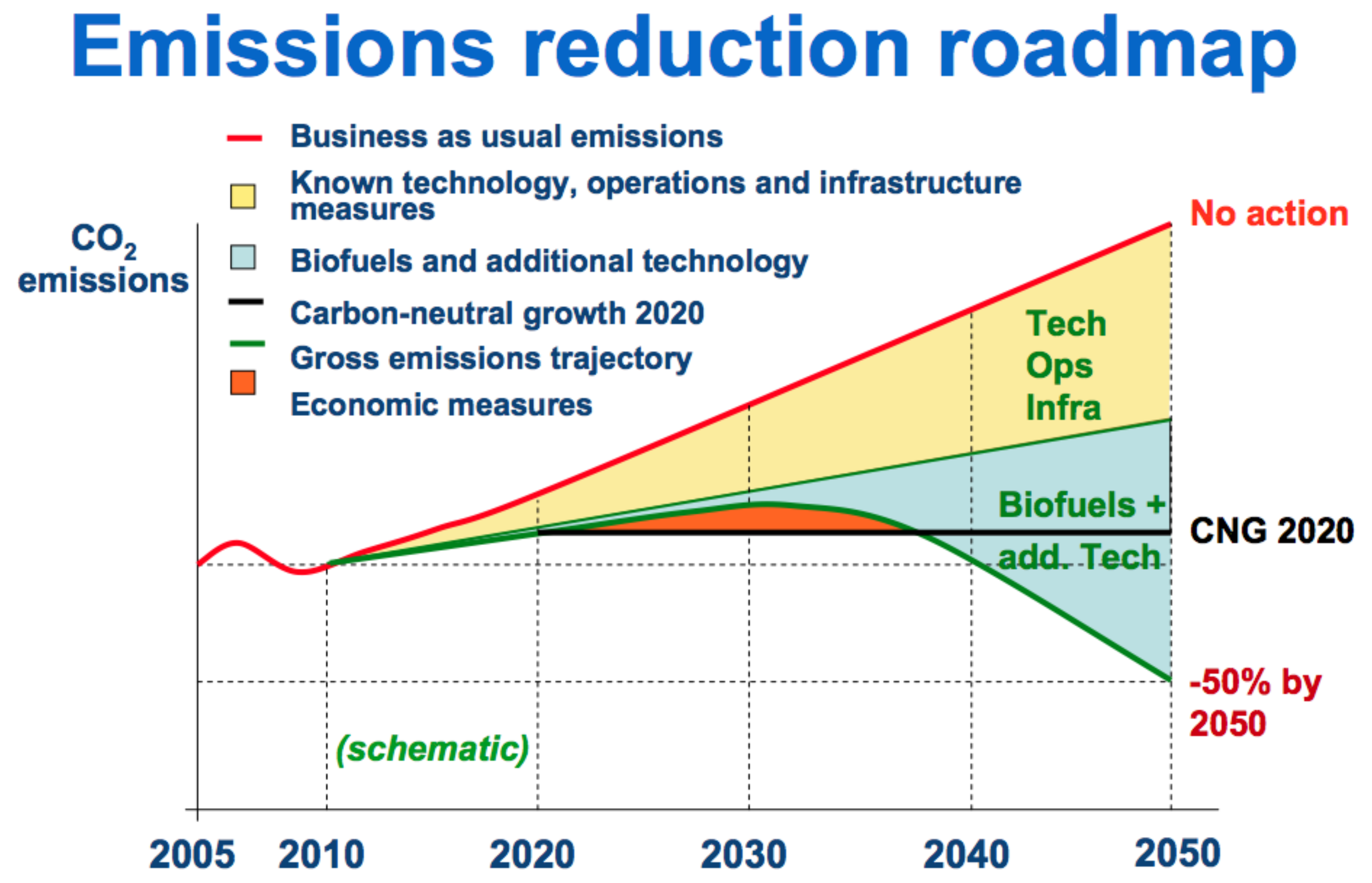
MOTIVATION



Emissions reduction roadmap

Reducing CO_2 Emissions

- operational measures, e.g. continuous descent
- biofuels (many issues to consider, including CO_2 emissions during production, land use, availability)
- engine efficiency (without increasing NO_x emissions)
- aircraft efficiency (drag, weight)
- more emphasis needed on aircraft efficiency

Aircraft Efficiency

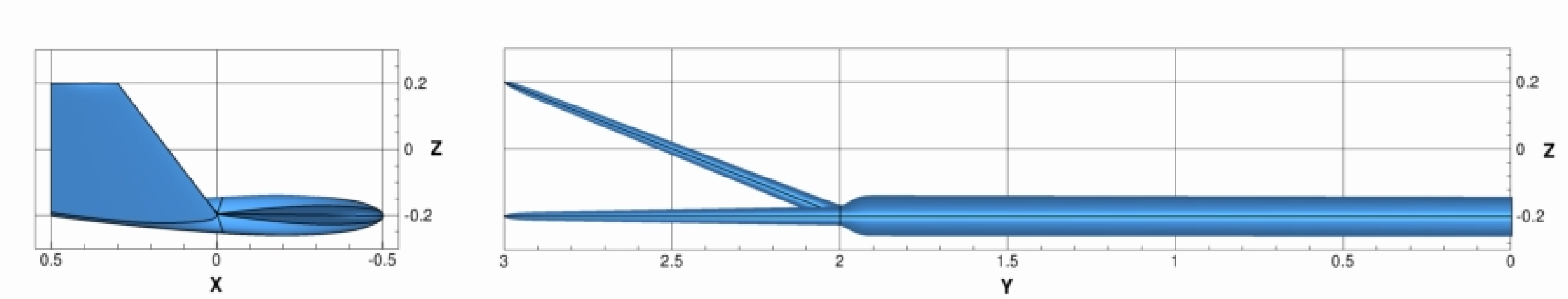
- weight reduction through materials, e.g. composites, multifunctional microarchitectured materials
- drag reduction through aerodynamic concepts, e.g. wing tip treatments, and laminar flow control
- drag and weight interdependent, e.g. through the Breguet range equation
- unconventional aircraft configurations; potential for improved efficiency

PREMISE

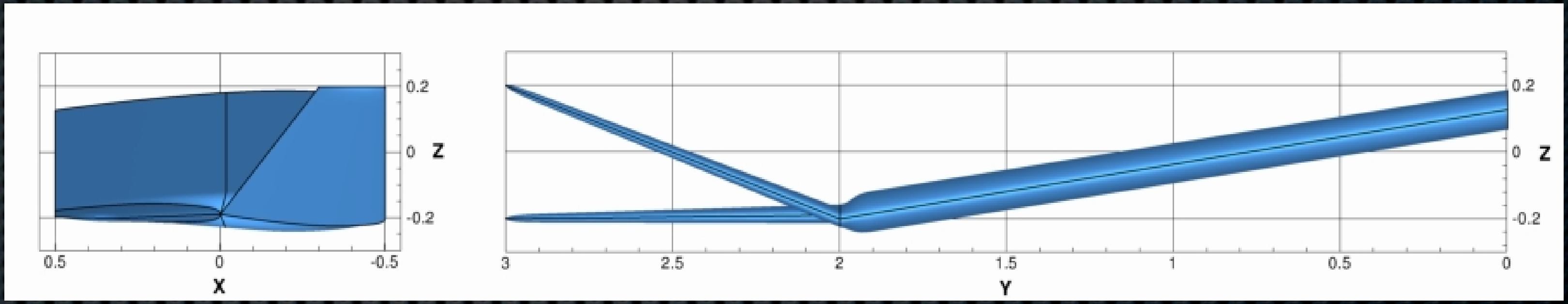
- High-fidelity multidisciplinary optimization is critical for the development, design, and evaluation of future aircraft with reduced emissions incorporating novel configurations and technologies

Why? E.g. the Split Tip Wing

- down-up configuration: span efficiency = 1.159



- up-down configuration: span efficiency = 1.167



- Hicken, J.E., and Zingg, D.W., Induced Drag Minimization of Nonplanar Geometries Based on the Euler Equations, AIAA Journal, Vol. 48, No. 11, 2010

Why high-fidelity MDO?

- with Euler equation aerodynamic shape optimization, optimized split tip configurations reduces induced drag

★ does not account for viscous drag

- RANS equation aerodynamic optimization accounts for viscous drag, enables optimization of split tip to minimize drag

★ minimizing drag does not ensure minimum fuel burn

- aerostructural optimization needed

Why high-fidelity MDO?

- complex interdependencies, e.g. laminar flow control
- complex physics
- absence of design experience with new configurations
- potential for “fast” development and evaluation of new concepts and configurations
- provides clear understanding of tradeoffs

Challenges
for high-fidelity MDO

- speed: high cost of function evaluations, large number of design variables
- potential for multimodality - need for global optimization algorithms
- robust geometry handling permitting large shape changes
- an aircraft has an enormous number of configurations, maneuvers, and cases that must be considered
- uncertainty and robust design
- metric (or objective) for global warming impact not well defined

OBJECTIVE

- Development of high-fidelity design tools for future aircraft
- Application to
  - unconventional configurations
  - integration of new technologies, such as laminar flow control

Strategy

- CAD-free geometry parameterization
- High-fidelity aerostructural optimization
  - CFD solver for RANS equations
  - finite-element solver for structural analysis (J. Martins, Michigan)
  - adjoint method for efficient computation of sensitivities with large number of design variables
- Global optimization based on gradient-based algorithms

FLOW SOLVER

- Structured multi-block grids
- High-order finite-difference method with summation-by-parts operators and simultaneous approximation terms
- Parallel implicit Newton-Krylov-Schur solver (scales well to thousands of processors)
- Jacobian-free Newton-Krylov algorithm with approximate Schur parallel preconditioning
- Promising dissipation-based continuation method for globalization

➡ Hicken, J.E., and Zingg, D.W., A parallel Newton-Krylov solver for the Euler equations discretized using simultaneous approximation terms, AIAA Journal, Vol. 46, No. 11, 2008

INTEGRATED GEOMETRY PARAMETERIZATION AND MESH MOVEMENT

- Must provide flexibility for large shape changes with a modest number of design variables
  - B-spline patches represent surfaces
  - B-spline control points are design variables
- Mesh movement must maintain quality through large shape changes
  - through tensor products, B-spline volumes map a cube to an arbitrary volume with the appropriate topology
  - can be arbitrarily discretized in the cube domain to create a mesh
  - B-spline volume control points can be manipulated to move the mesh in response to changes in the surface control points
  - efficiently generates a high quality mesh

➡ Hicken, J.E., and Zingg, D.W., Aerodynamic Optimization Algorithm with Integrated Geometry Parameterization and Mesh Movement, AIAA Journal, Vol. 48, No. 2, 2010

DISCRETE-ADJOINT GRADIENT COMPUTATION

- Cost independent of the number of design variables
- Efficient if the number of design variables exceeds the number of constraints
- Hand linearization complemented by judicious use of the complex step method for difficult terms
- Adjoint equation solved by parallel Schur-preconditioned modified Krylov method GCROT(m,k)

➡ Hicken, J.E., and Zingg, D.W., A Simplified and Flexible Variant of GCROT for Solving Nonsymmetric Linear Systems, SIAM Journal on Scientific Computing, Vol. 32, No. 3, March 2010

Problem Formulation

- Define weighted integral of on-design flight envelope
- Replace weighted integral with a multipoint objective function using a quadrature rule
- Define off-design constraints, e.g. dive requirements
- Vary weights on multiple objectives to obtain Pareto fronts

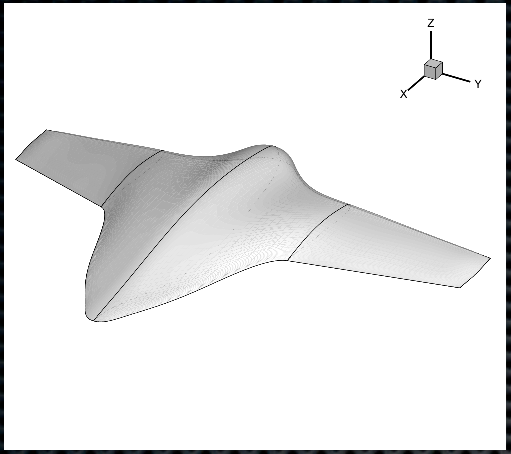
➡ Buckley, H.P., Zhou, B.Y., and Zingg, D.W., Airfoil Optimization Using Practical Aerodynamic Requirements, Journal of Aircraft, Vol. 47, No. 5, 2010

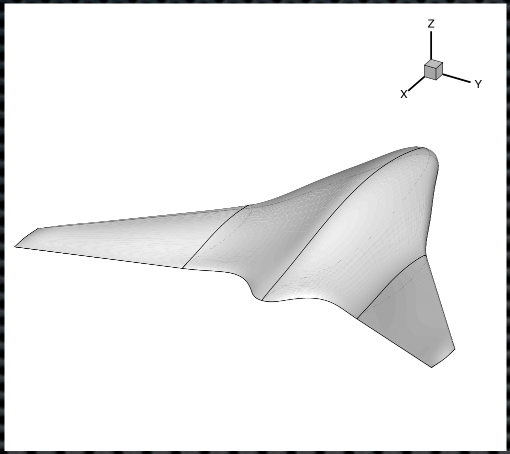
Gradient-based multi-start algorithm for global optimization

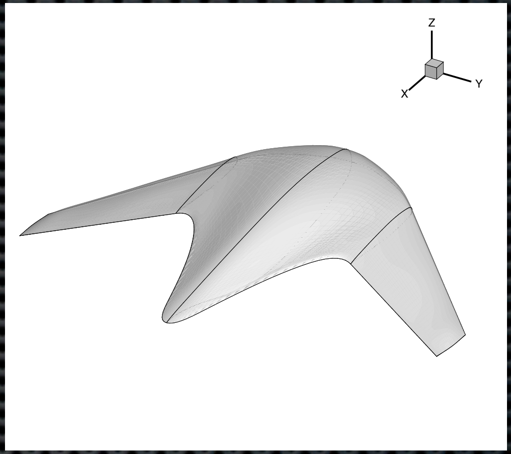
- Global optimization algorithms, e.g. genetic algorithms, are generally slow
- Gradient-based algorithms converge to a local minimum
- Developed multi-start algorithm based on Sobol sequences to achieve global optimization while exploiting the speed of a gradient-based algorithm

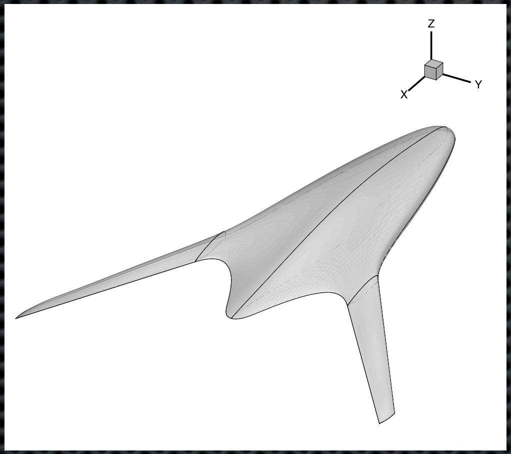
➡ Chernukhin, O., and Zingg, D.W., An Investigation of Multi-Modality in Aerodynamic Shape Optimization, 20th AIAA Computational Fluid Dynamics Conf, June 2011

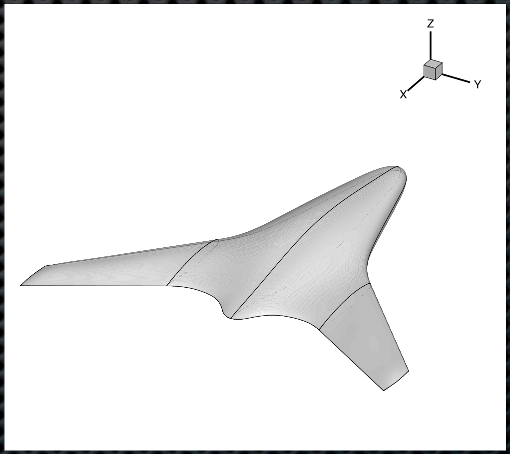
Hybrid wing-body optimization











- 16 initial geometries ... 5 local optima ...

CONCLUSIONS

- More emphasis needed on improving aircraft efficiency in parallel with other means of reducing emissions
- High-fidelity MDO can play a key role in development, design, and evaluation of future aircraft, including unconventional configurations and advanced concepts such as laminar flow control, and in understanding tradeoffs
- Progress made toward an effective high-fidelity MDO capability
  - efficient and robust flow solver based on higher-order SBP-SAT discretization and parallel Newton-Krylov-Schur algorithm
  - integrated geometry parameterization with mesh movement permitting large shape changes
  - discrete-adjoint gradient computation based on improved variant of linear solver GCROT
  - multi-point optimization - a strategy for optimizing over an entire flight envelope
  - gradient-based multi-start algorithm for global optimization

FUTURE WORK

- incorporate laminar-turbulent transition prediction into our methodology
- develop and investigate monolithic aerostructural analysis and optimization algorithms
- develop and investigate multilevel and multifidelity approaches for improved efficiency
- refine problem formulation to reduce the number of operating conditions to be computed
- application to the design and evaluation of unconventional aircraft concepts and to the understanding of tradeoffs