Development and Evaluation of a Novel Fuel Injector Design Method using Hybrid-Additive Manufacturing

Project DE-FE12806463, Oct. 2019 – Sept. 2022 (Sept. 2024 NCE)
Program Monitor: Mark Freeman

Project Review – September 28, 2022

PIs: Jacqueline O'Connor, Guha Manogharan, Yuan Xuan
Graduate students: Sagar Jalui, Pratikshya Mohanty

Mechanical Engineering
Pennsylvania State University

Industry Partner: Solar Turbines Incorporated
Engineers: Hanjie Lee, Michel Akiki, Dave Voss

PennState

Overview of presentation

- Background and technical approach
- Highlights from Year 3
  - Geometry definition and watertightness
  - Impact of optimization step size
- Next steps
- Publications and outreach

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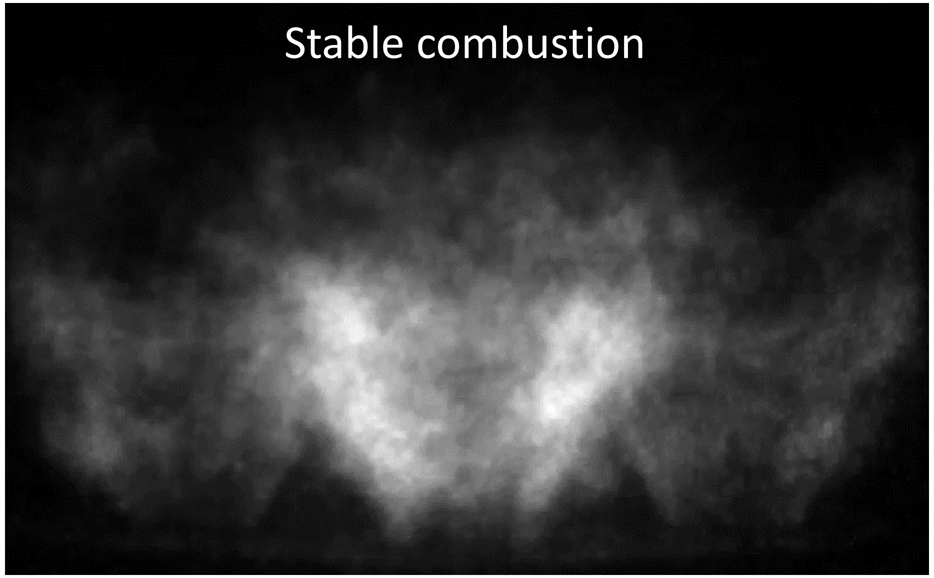
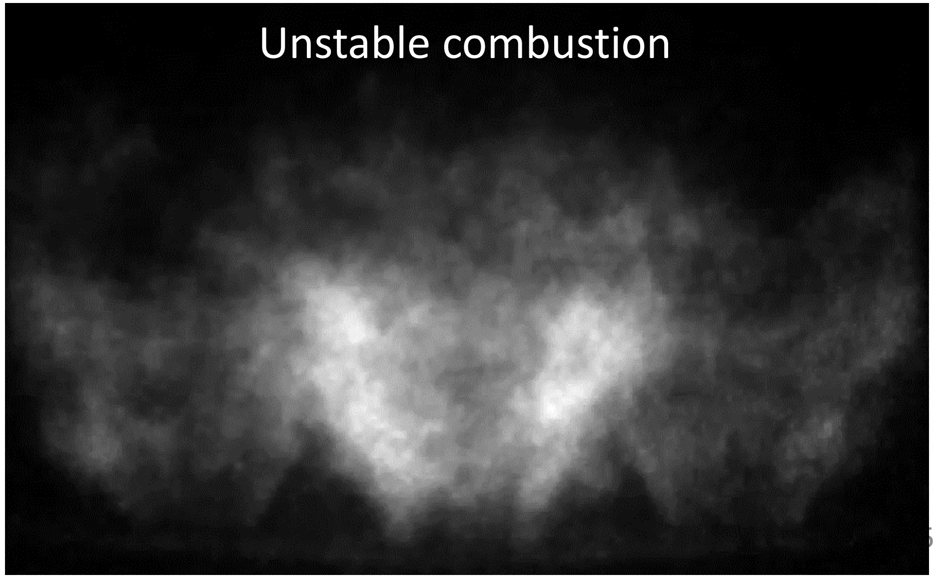
Project origin: Discussions with industry about issues related to combustion operability and fuel injector manufacturing

"Why do fuel injectors have to look like fuel injectors?"

Current fuel injector designs do well at flame stabilization for a moderate range of fuel compositions, operating conditions



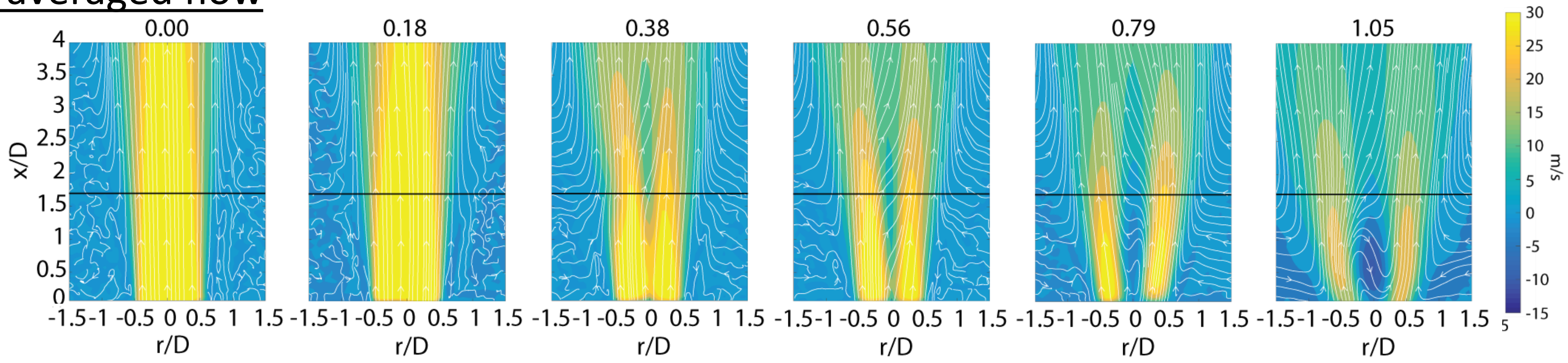
Off-design operation



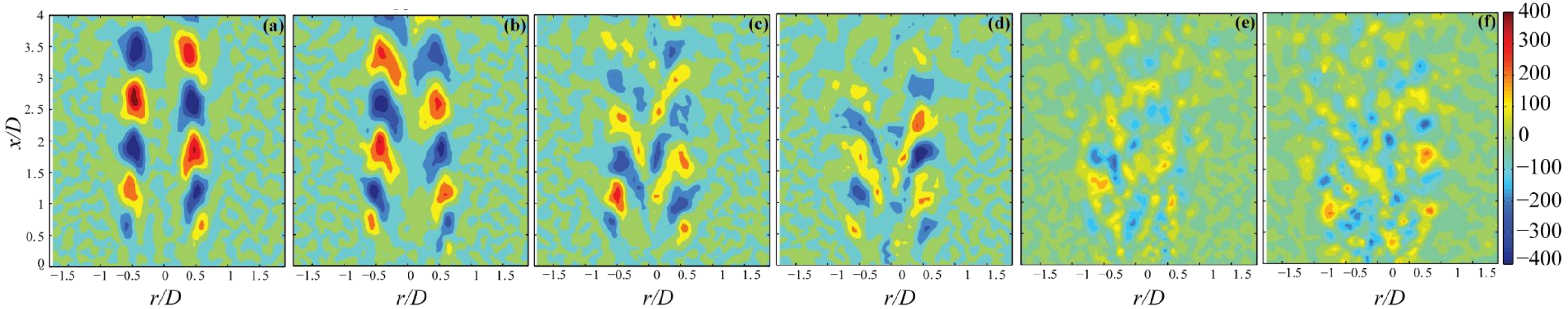
DOE University Turbine Systems Research Program, Mark Freeman (contract monitor), Grant DE-FE0025495

Work by PI and collaborators has showed that a stable flow can be “designed” using hydrodynamic stability analysis

Time-averaged flow

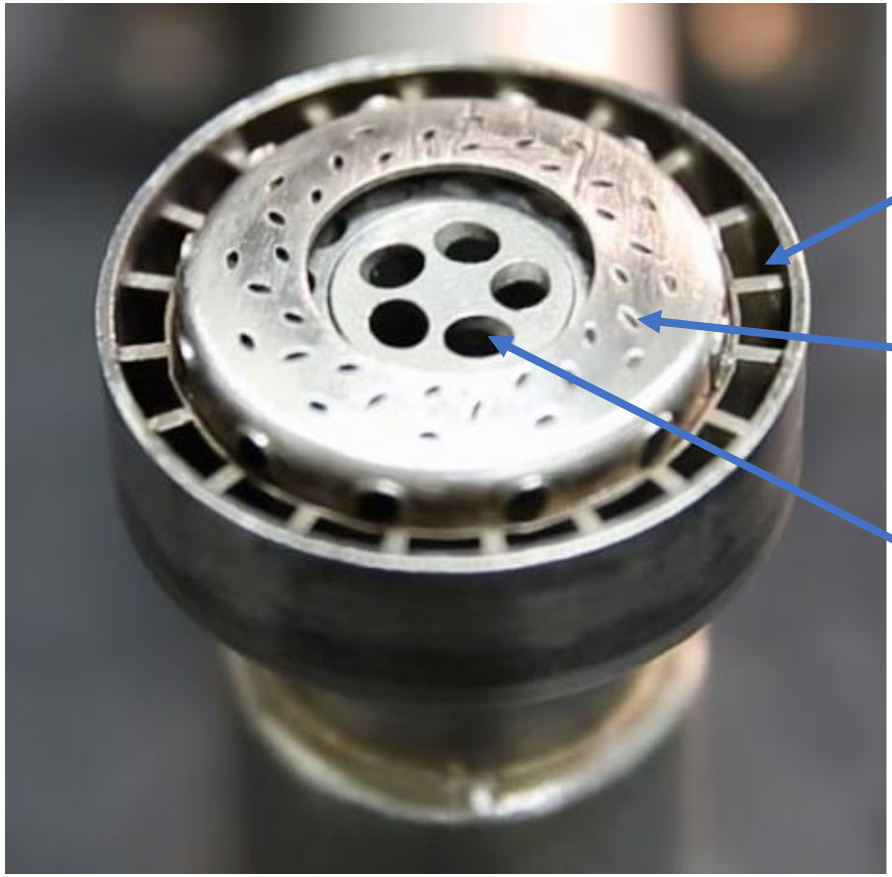


Coherent response



Flow parameter variation

Fuel injectors are notoriously difficult to manufacture and can be comprised of dozens of components, assembled by hand



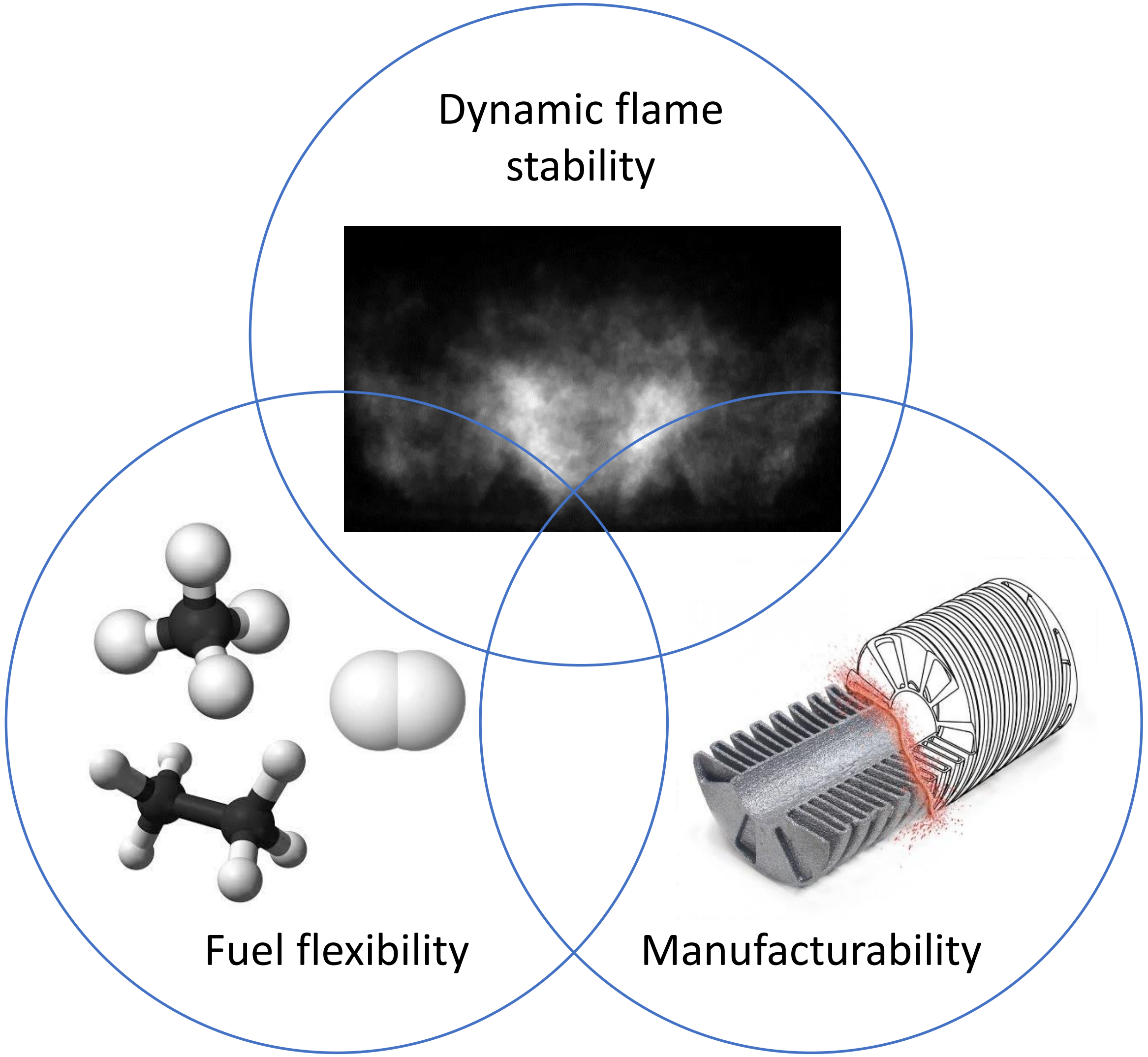
Solar Turbines, https://www.youtube.com/watch?v=hrOYuGM-tfQ

Complex aerodynamic surfaces

Small orifices with specified surface finish

Internal flow passages

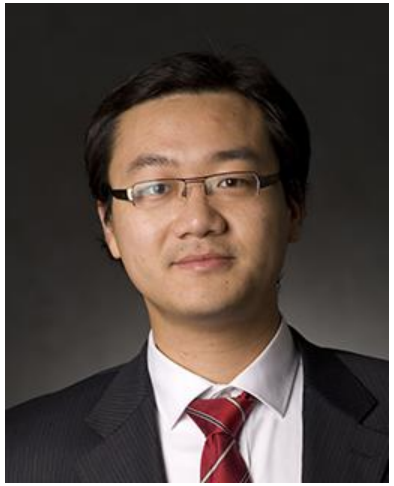
Goal of this project is to create a design optimization paradigm that marries combustion physics and manufacturing



The team is comprised of three PIs and two grad students from Penn State and industrial partners Solar Turbines

PI: Jacqueline O'Connor
Associate Professor of ME
Combustion/Gas Turbines

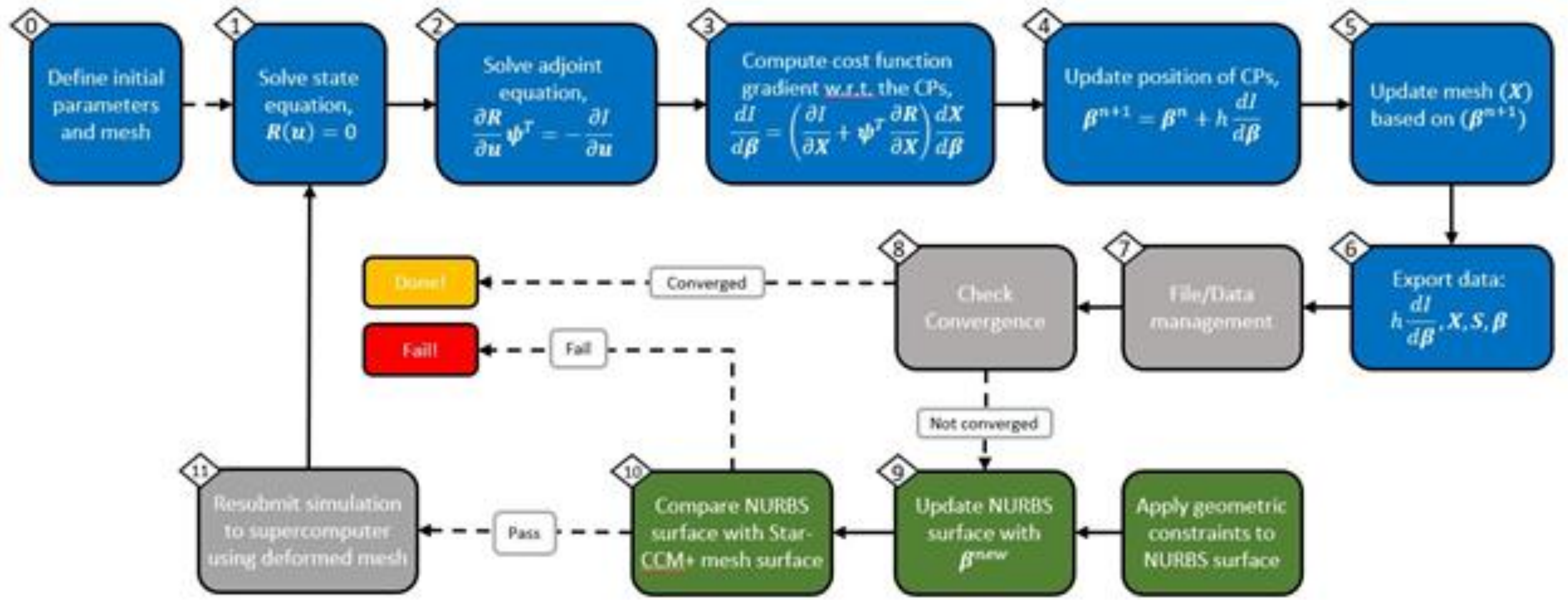
Co-PI: Guha Manogharan
Associate Professor of ME, IME
Hybrid-Additive Manufacturing



Co-PI: Yuan Xuan
Associate Professor of ME
Combustion simulation

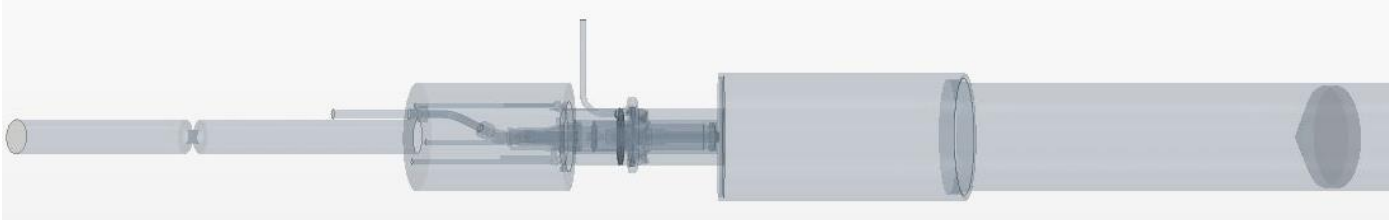
Solar® Turbines
A Caterpillar Company

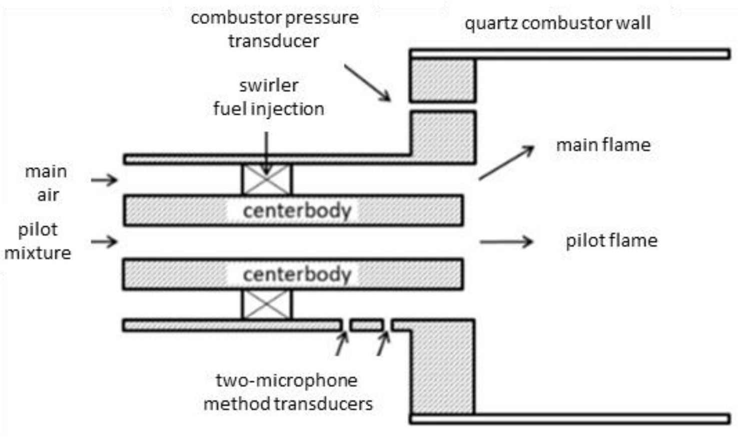
Technical approach uses an optimization framework for incorporating combustion and manufacturing constraints

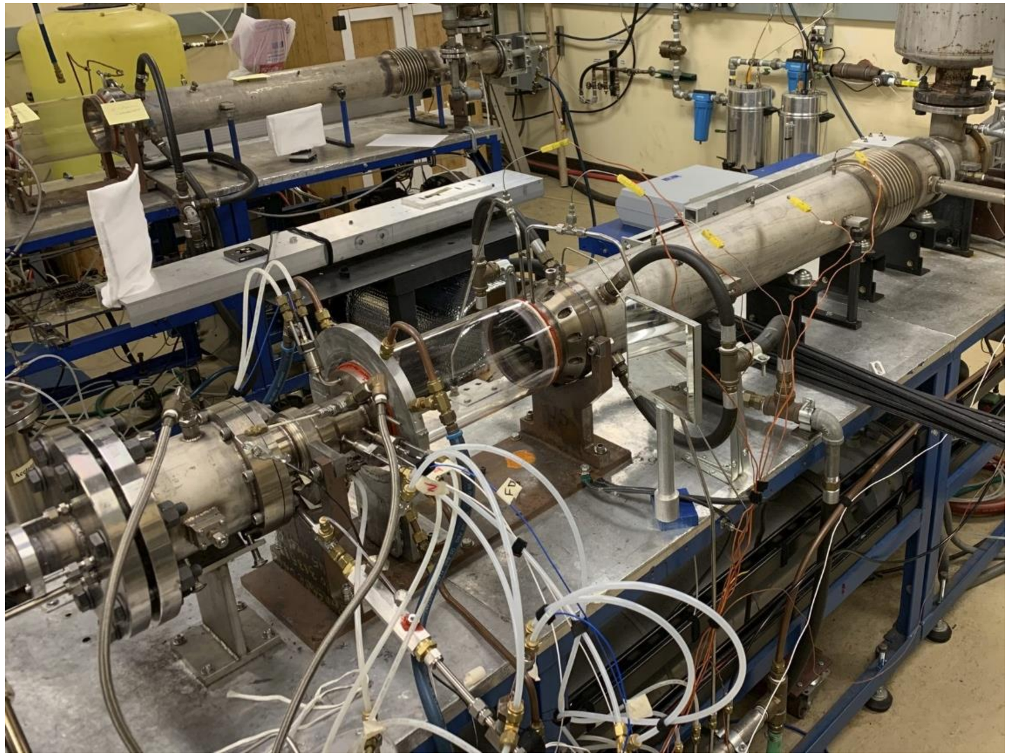


High-fidelity combustion simulation uses STAR-CCM+ to allow more rapid industry adoption

- Large eddy simulation (LES) using STAR-CCM+
- Flamelet generated manifold (FGM) model
- Unstructured polyhedral mesh (~16.7 million cells)







Project objectives center around four gaps in the fuel injector design process to help industry

— Integrate issues related to flame static and dynamic stability more seamlessly into the design process

— Incorporate the use of hydrodynamic stability analysis for prediction of dynamic stability issues for efficient computational prediction

— Incorporate high-fidelity, multi-physics modeling into optimization processes

— Link post-processing steps of the AM component into the design optimization process

Project objectives center around four gaps in the fuel injector design process to help industry

- Task 1: Project management and planning
- Task 2: Establish baseline
- Task 3: Develop design optimization tool
- Task 4: Implement optimization process on baseline configuration
- Task 5: Design process improvement
- Task 6: Integration of improved design process
- Task 7: Final process testing and technology transfer

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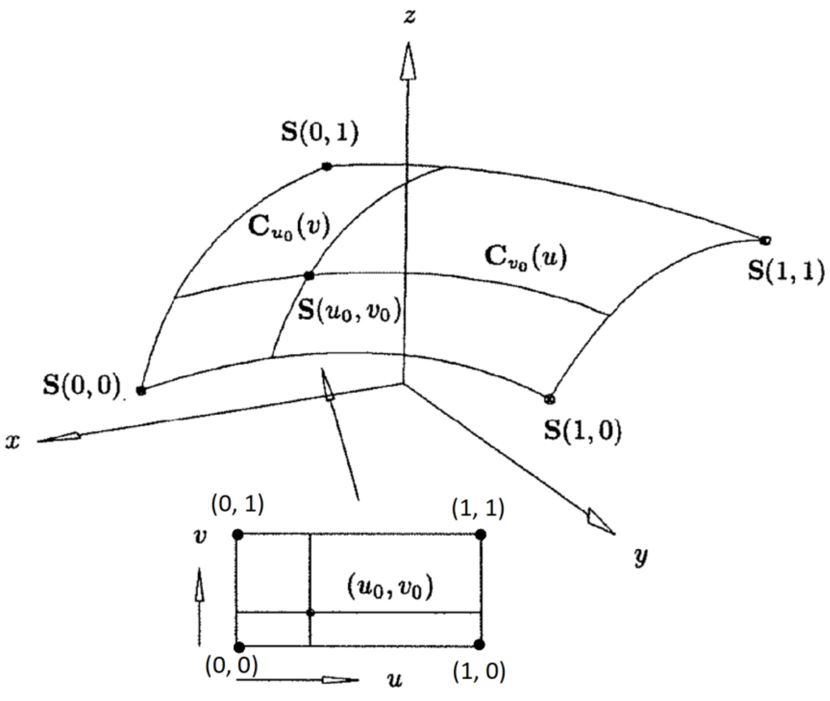
Injector surfaces are defined using NURBS to allow for precise shape quantification and flexibility in changing the shape

NURBS Surface:
Non-**U**niform **R**ational **B**asis **S**plines

- Super set of all surfaces:
    - Standard
    - Free-form

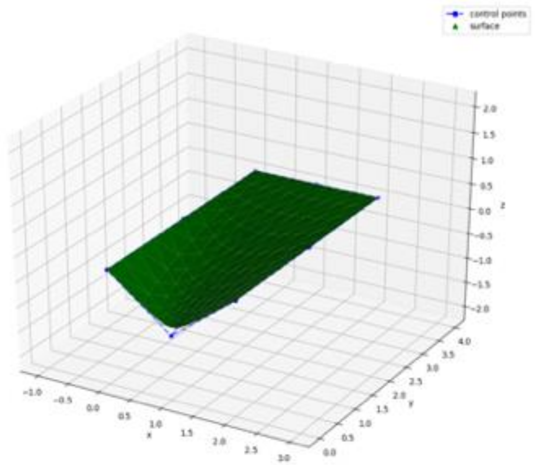
- Enable local control



Source: The NURBS Book (1997)

- Control points coordinates (in u & v)
- Number of control points (in u & v)
- Weights (for all control points)
- Degree (in u & v)
- Knot vectors (in u & v)

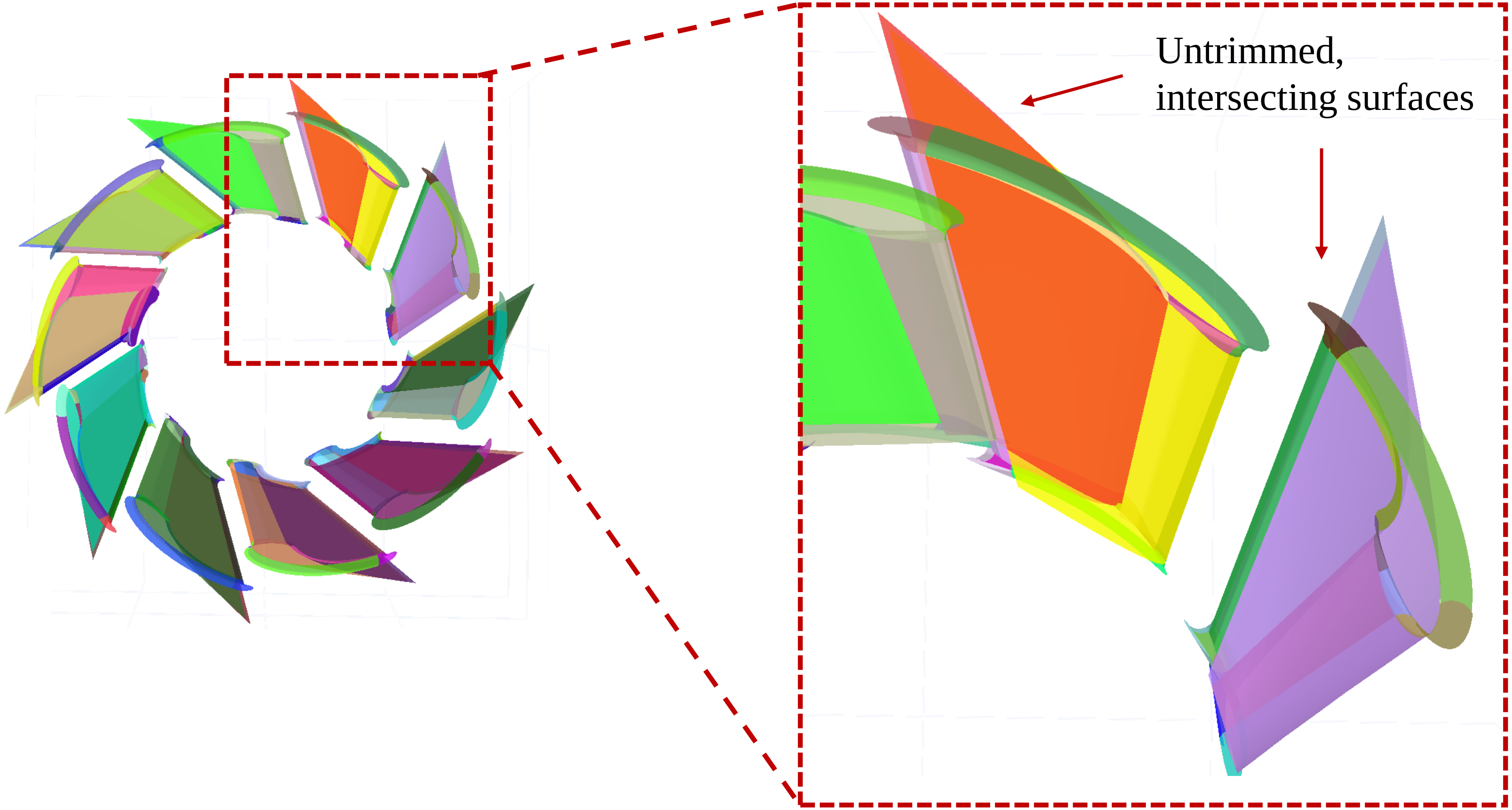
$$S(u,v) = \frac{\sum_{i=0}^{n}\sum_{j=0}^{m} N_{i,p}(u)N_{j,q}(v)w_{i,j}P_{i,j}}{\sum_{i=0}^{n}\sum_{j=0}^{m} N_{i,p}(u)N_{j,q}(v)w_{i,j}} \quad 0 \leq u,v \leq 1$$



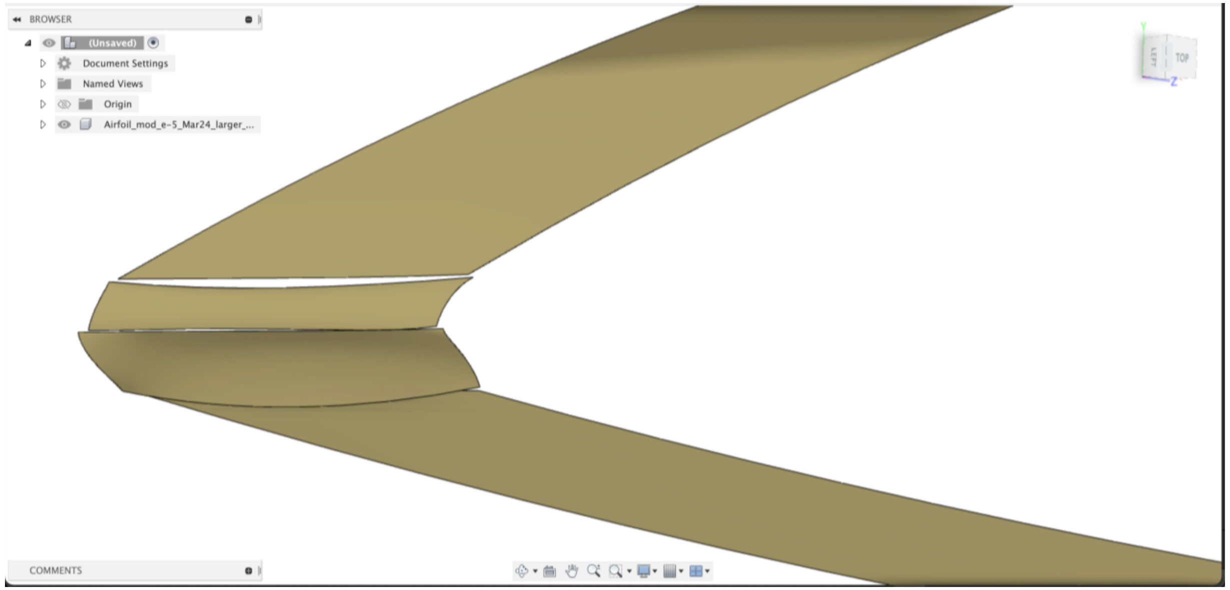
NURBS Python (geomdl)

- Visualization
- Manipulation

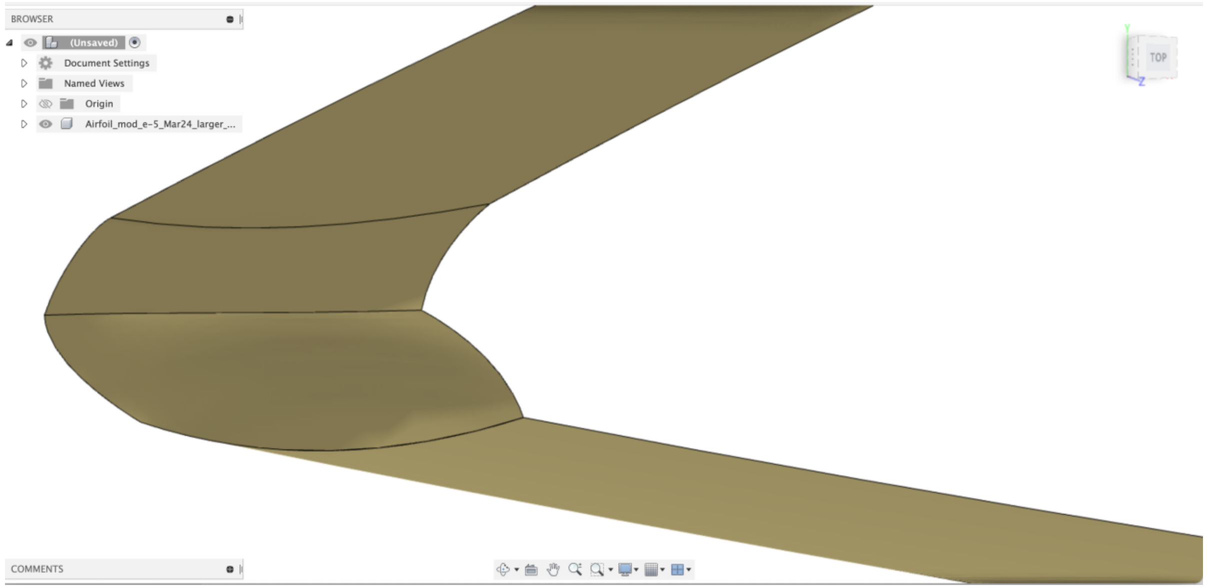
However, defining aerodynamic surfaces requires “trimmed” NURBS to account for interfaces, holes, etc.



Trimmed NURBS do not work well with import to CFD – new solution developed that works for each optimization iteration



Modifying only Type 128



Modifying Type 128 + Type 126

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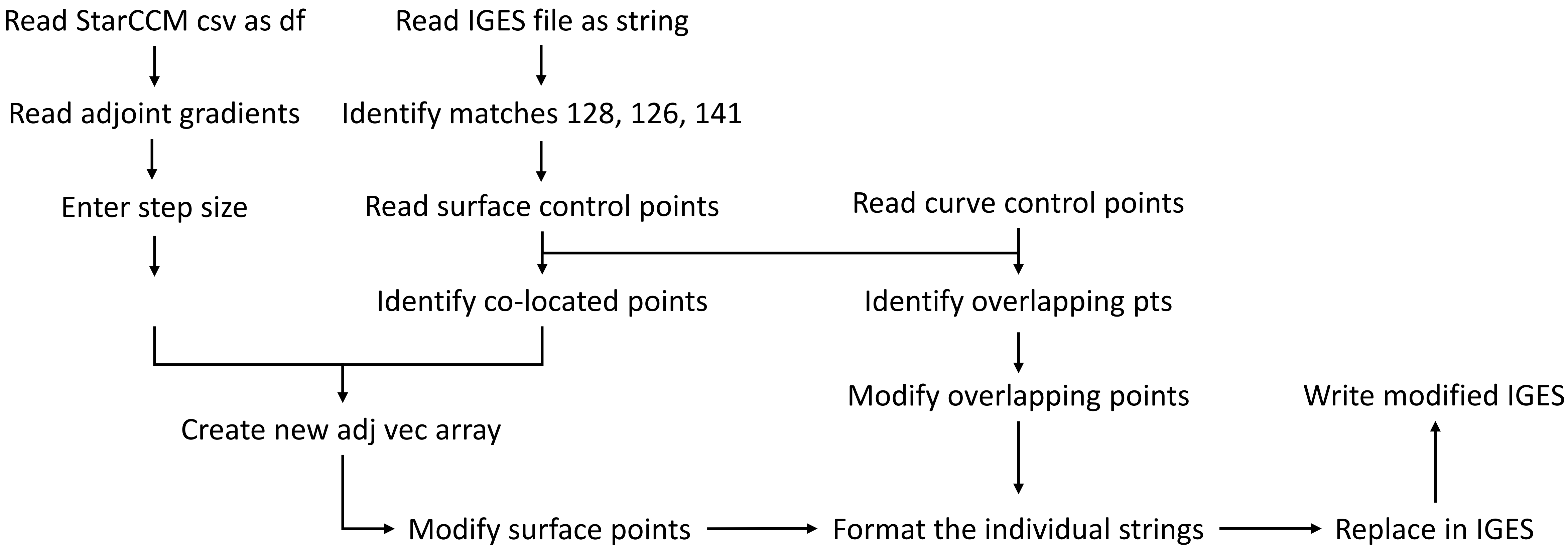

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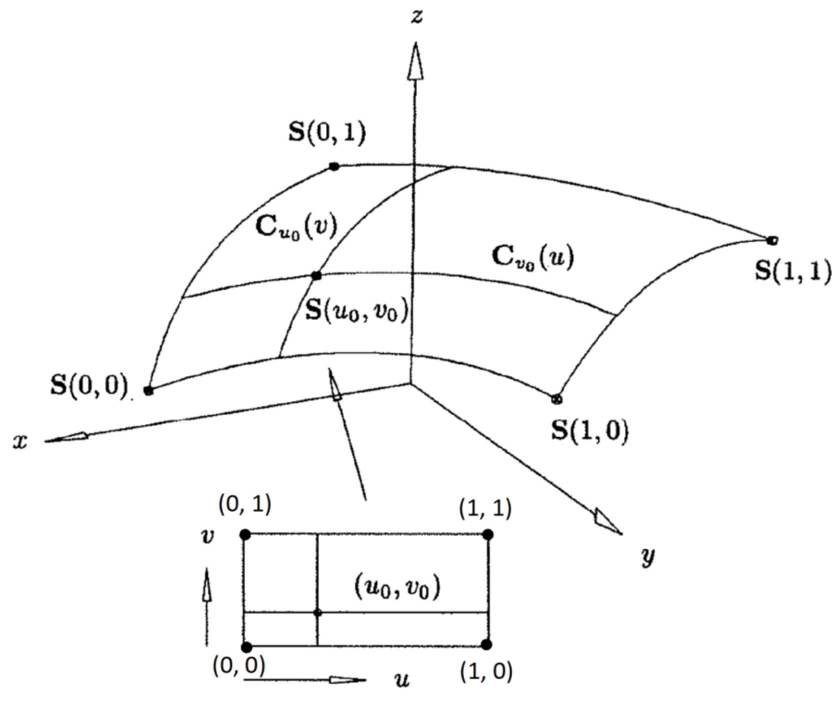

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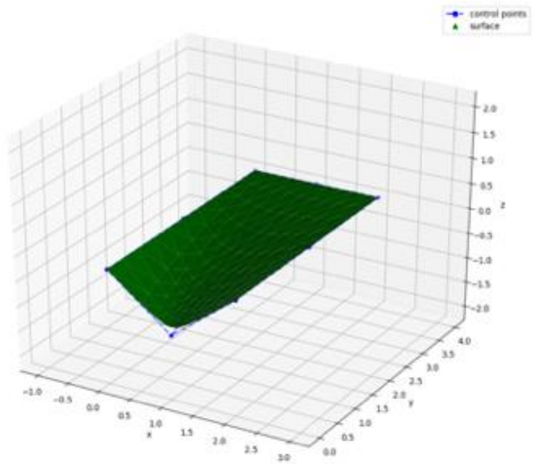

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However, STAR-CCM uses radial basis functions for defining surfaces in the adjoint calculation – not optimal for AM

$$y(\mathbf{x}) = \sum_{i=1}^{N} w_i \, \varphi(\|\mathbf{x} - \mathbf{x}_i\|),$$

RBF	$\boldsymbol{\phi(r)}$
Spline type (R_n)	$\lvert r\rvert^n, n$ odd
Thin plate spline (TPS_n)	$\lvert r\rvert^n \log\lvert r\rvert, n$ even
Multiquadric	$\sqrt{1+r^2}$
Inverse multiquadric	$\frac{1}{\sqrt{1+r^2}}$
Inverse quadratic	$\frac{1}{1+r^2}$
Gaussian	e^{-r^2}

(Cella et. al. (JCM 2016))

Calculation of the adjoint solution for optimization depends on the formulation of the geometry

$$\left(\frac{dJ}{d\alpha}\right)_{RBF} = \frac{\partial J}{\partial V}\frac{\partial V}{\partial S}\frac{\partial S}{\partial RBF}\frac{\partial RBF}{\partial \alpha_{RBF}}$$

$$\left(\frac{dJ}{d\alpha}\right)_{NURBS} = \frac{\partial J}{\partial V}\frac{\partial V}{\partial S}\frac{\partial S}{\partial NURBS}\frac{\partial NURBS}{\partial \alpha_{NURBS}}$$

J = Objective function
V = Volumetric grid
S = Surface grid
RBF = Surface shape parameterized by Radial Basis Function
NURBS = Surface shape parameterized by NURBS
$\boldsymbol{\alpha}$ *= Control points*

We need to show that the sensitivity of the surface to the mathematical definitions is the same for RBF and NURBS

$$\left(\frac{dJ}{d\alpha}\right)_{RBF} = \frac{\partial J}{\partial V}\frac{\partial V}{\partial S}\frac{\partial S}{\partial RBF}\boxed{\frac{\partial RBF}{\partial \alpha_{RBF}}}$$

$$\left(\frac{dJ}{d\alpha}\right)_{NURBS} = \frac{\partial J}{\partial V}\frac{\partial V}{\partial S}\frac{\partial S}{\partial NURBS}\boxed{\frac{\partial NURBS}{\partial \alpha_{NURBS}}}$$

IF… $\frac{\partial RBF}{\partial \alpha_{RBF}} = \frac{\partial NURBS}{\partial \alpha_{NURBS}}$ *for small dα and* $\boldsymbol{\alpha}_{RBF} = \boldsymbol{\alpha}_{NURBS}$

THEN… $\left(\frac{dJ}{d\alpha}\right)_{RBF} = \left(\frac{dJ}{d\alpha}\right)_{NURBS}$

Several considerations are necessary when passing a geometry between multiple different types of solvers

Export geometry from .sim files

Convert to NURBS

Get point set

Define point set in StarCCM+

Run primal

Run adjoint

Get shape sensitivities

Adjust step size

Deform RBF mesh

Adjust step size

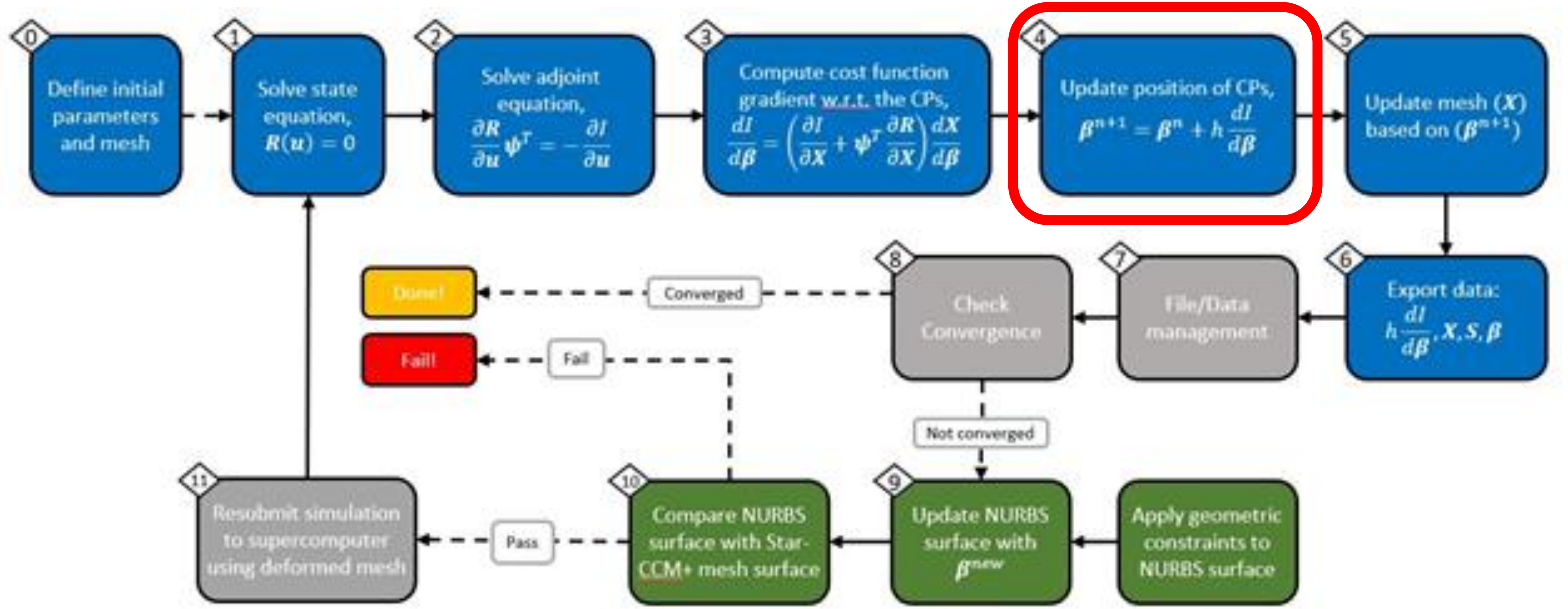
Deform NURBS CAD

Control X 3D Compare

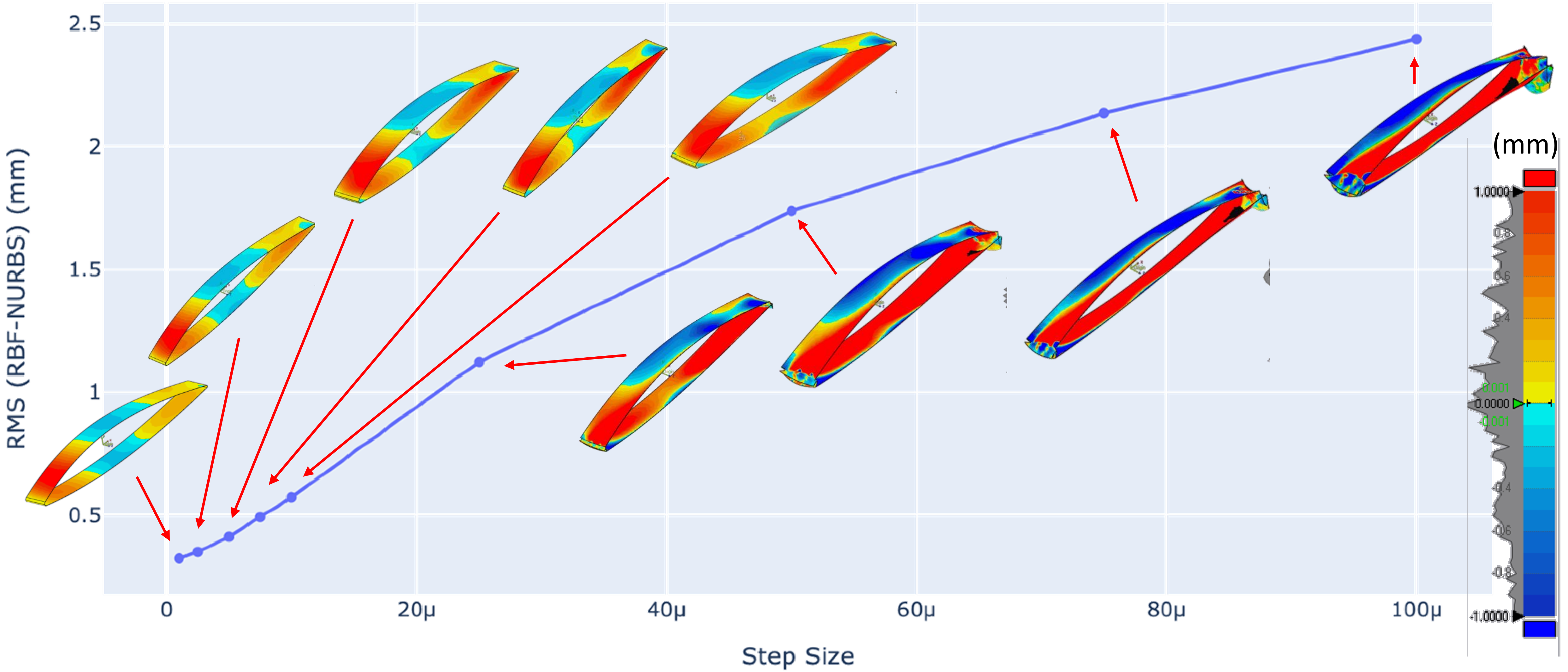
Discuss results

- How different are RBF & NURBS?
- How much time does it take to solve?
- How different are results when we use dense NURBS v/s reduced NURBS?
- How to extract the deformed mesh?
- Understanding set up, export options, etc.

The step size you use to change the shape of your injector with each optimization loop changes final shape, convergence, and accuracy between NURBS/RBF



Example: Optimizing airfoil for drag reduction results in significantly different shapes between NURBS and RBF based on step size



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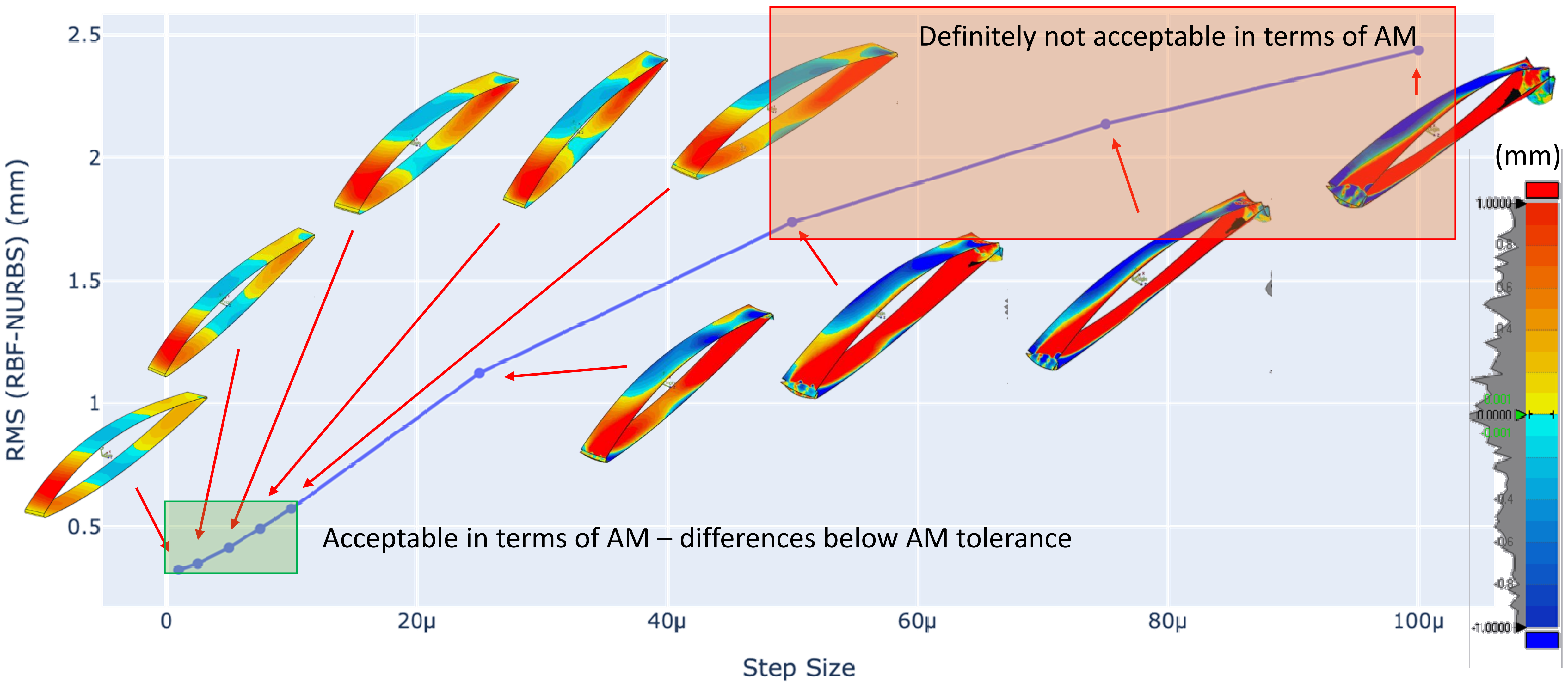
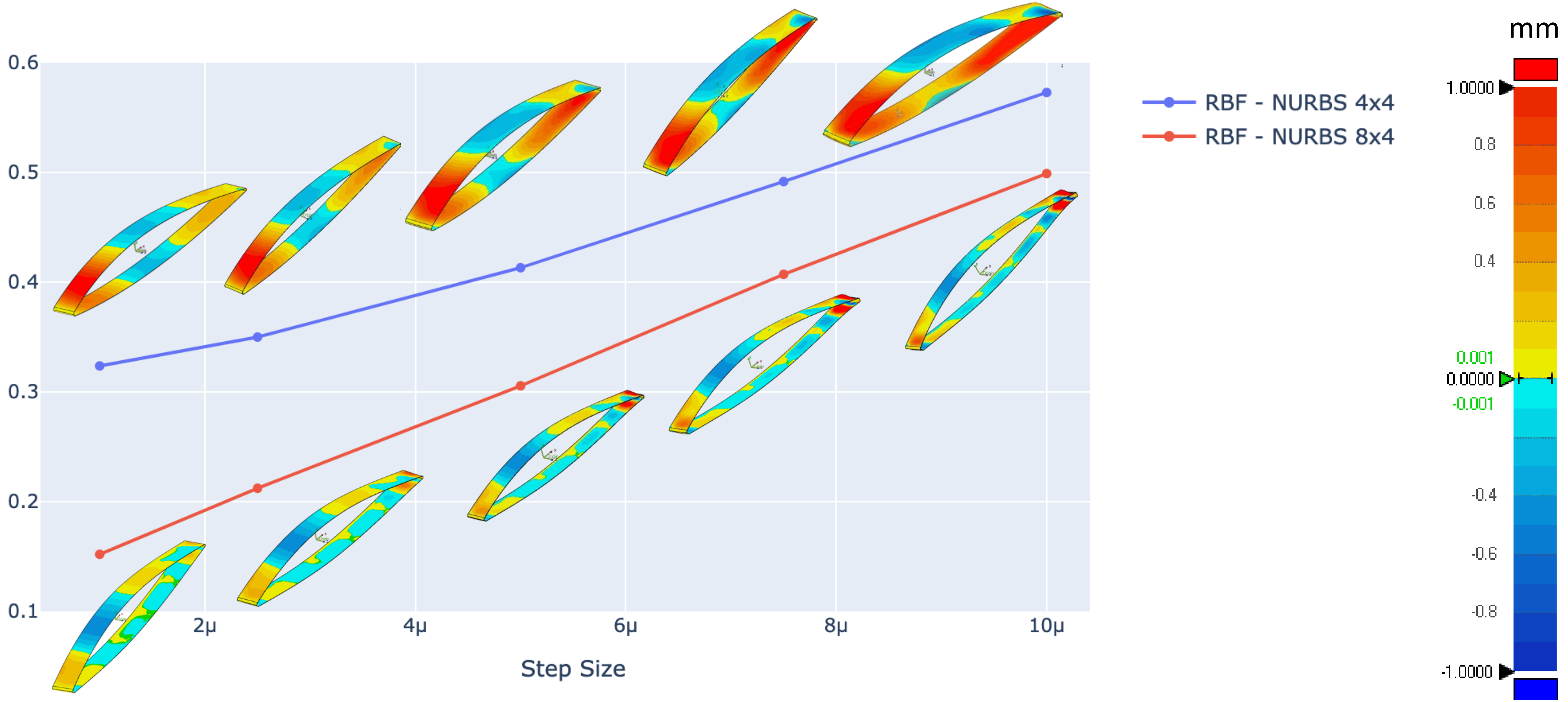
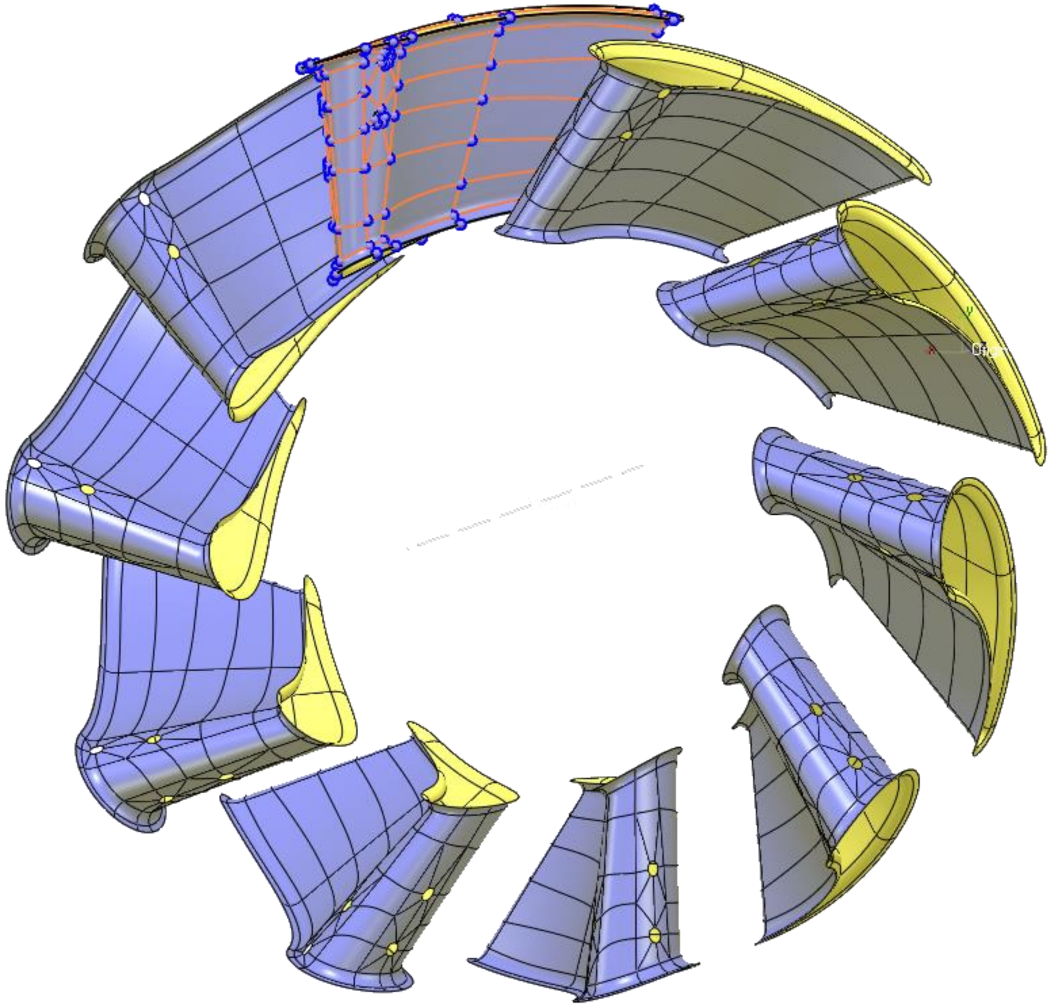


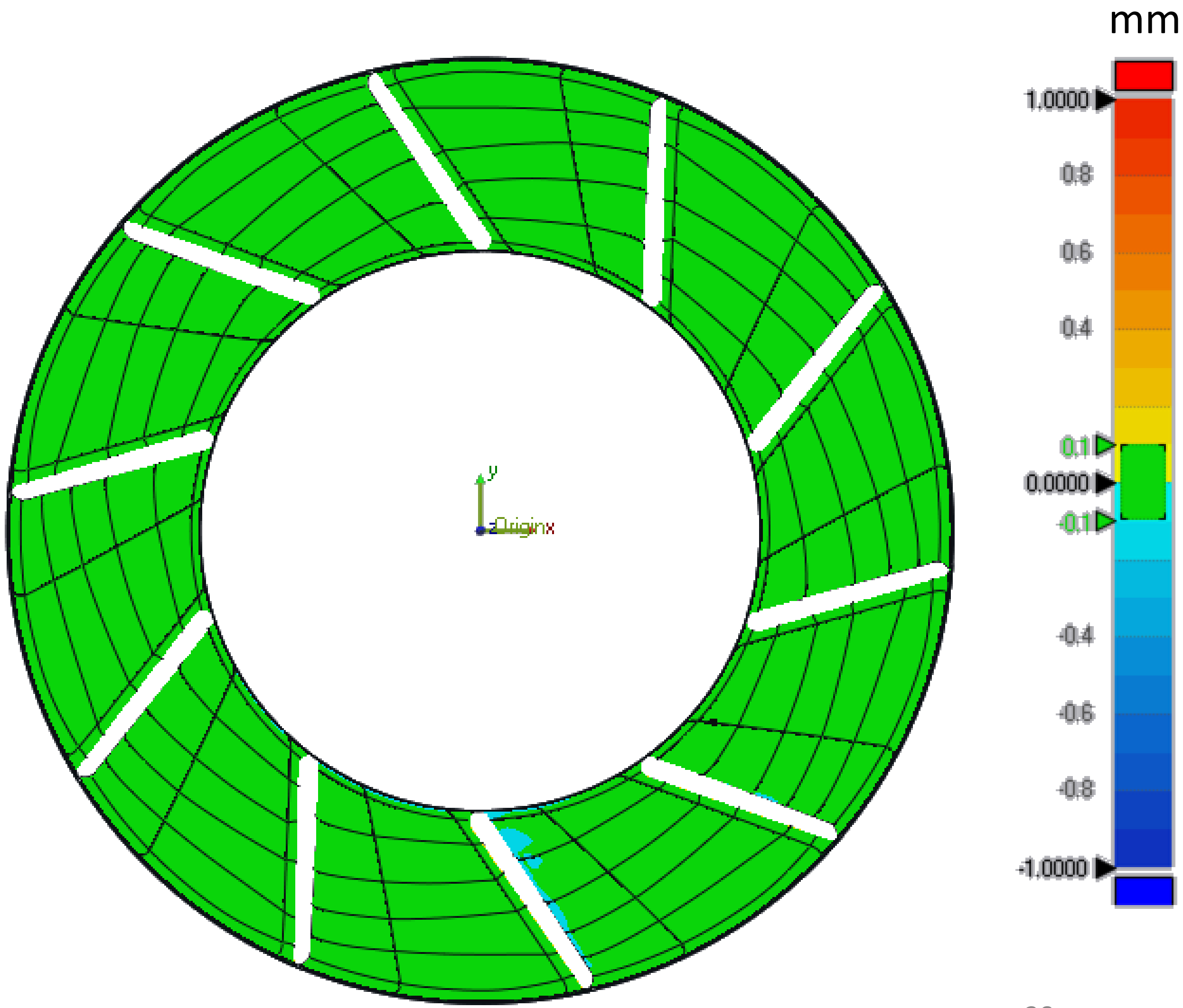
Solution also strongly depends on the number of control points that define the surface, where more control points and smaller steps = higher computational cost



Once we understood these dependencies on a simplified geometry, we moved to our injector geometry with more complexity

850 NURBS patches; 54,400 Control Points; All NURBS surfaces are trimmed by boundary edges





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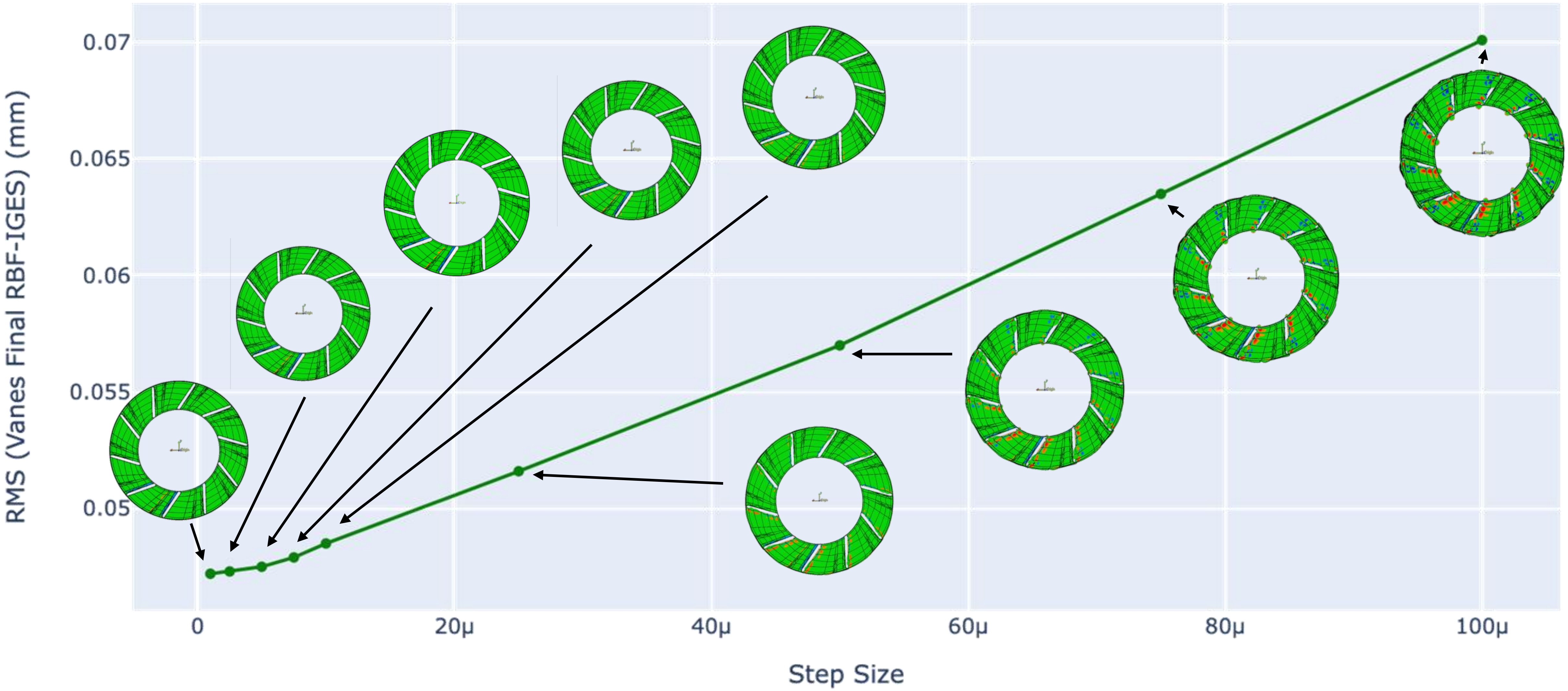
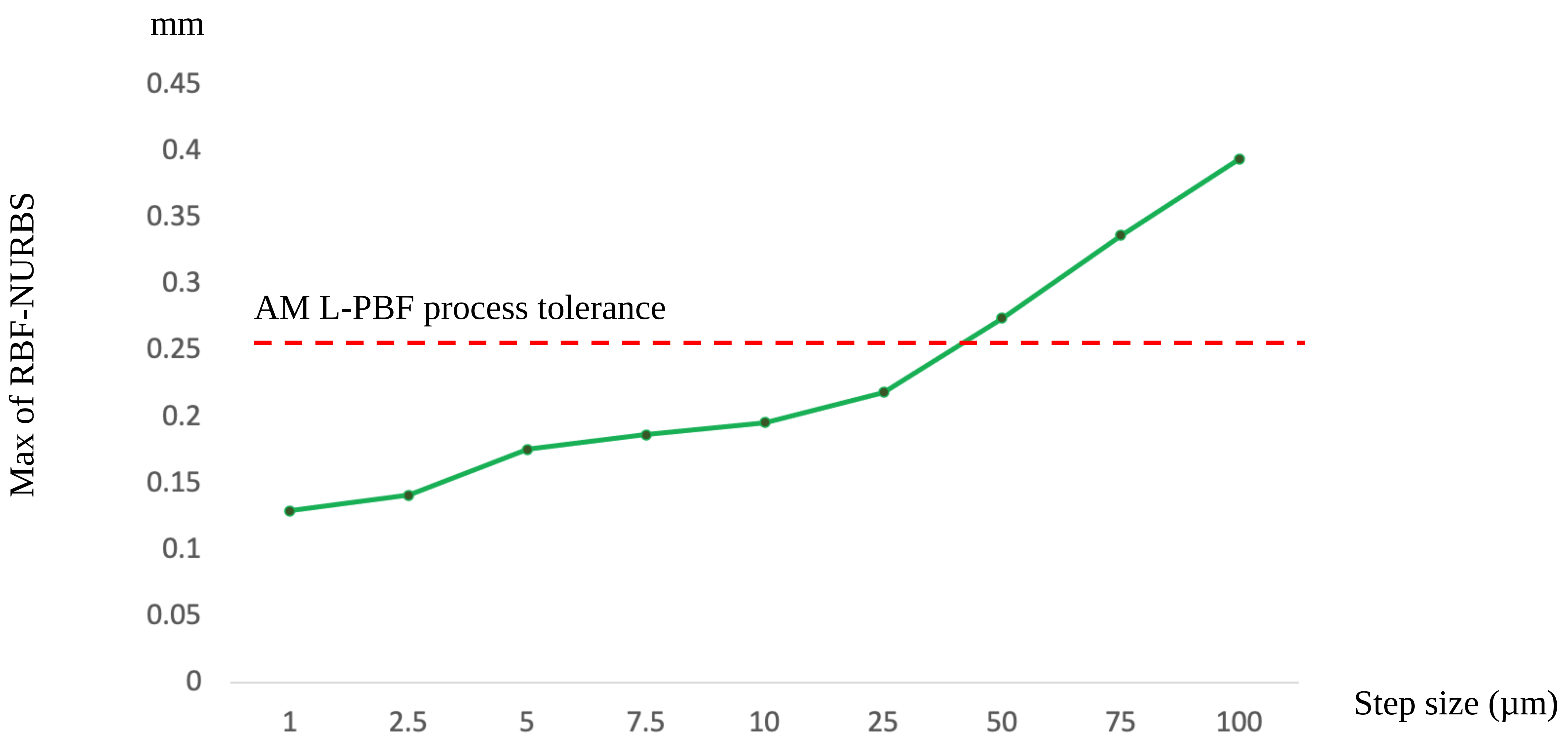


Have identified the step size and number of control points necessary to balance computational cost and accuracy below the AM process tolerance



Learnings from this study

- As we increase CP density, NURBS and RBF behave similarly from an AM L-PBF standpoint
- Any Shape can be represented as a set of NURBS quad patches → Above rule applies to any design (CPs/Surface area)
- For our configuration of 54,480 CPs, RBF and NURBS are similar (from AM standpoint) for all step sizes
- Choosing step size is based on user discretion – 2.5e-5 or lower, because after that differences are large (in general)
- Primal takes ~33 hours
- Adjoint takes ~6-8 mins
- Comp mesh sense + Def mesh takes ~9-12 mins

ACI – 80 cores

- Exporting STL takes ~6-7 mins

ACI GUI (4 cores)

- Python deformation takes ~7 mins

Personal laptop (4 Cores)

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Next steps

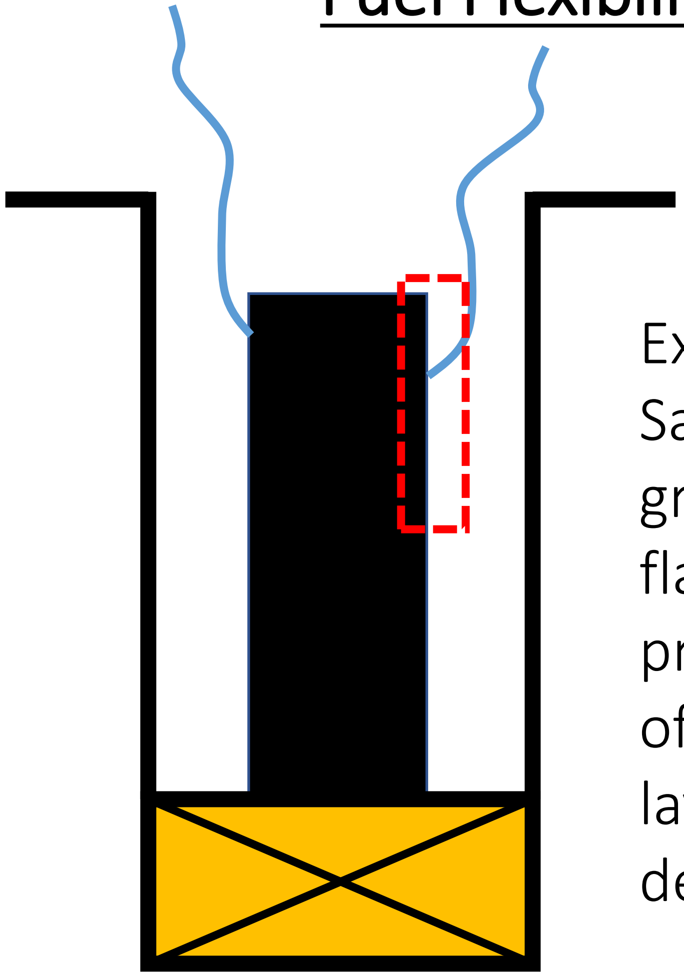
— Integrate the pieces and optimize for fuel flexibility with AM constraints

— Integrate hydrodynamic instability constraints and generate more understanding of the impact of AM choices on hydrodynamic instability

— Continue outreach and larger collaborations

Integration the pieces and optimize for fuel flexibility with AM constraints

Fuel Flexibility



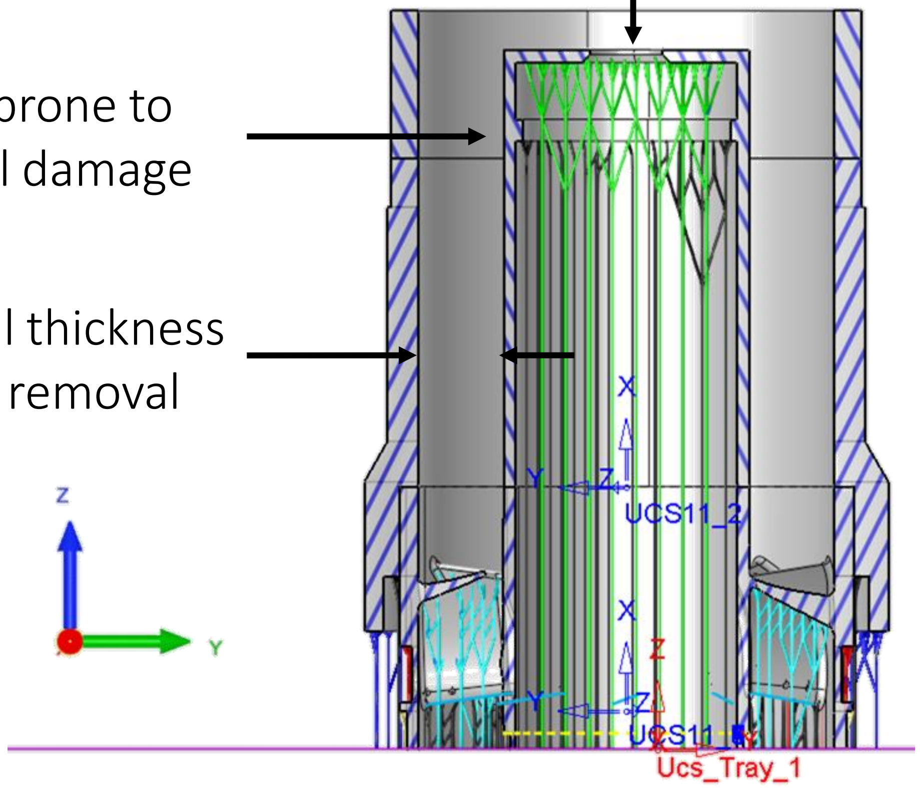
Extend theory by Sattelmayer's group to predict flashback propensity based off boundary layer development

AM Constraints

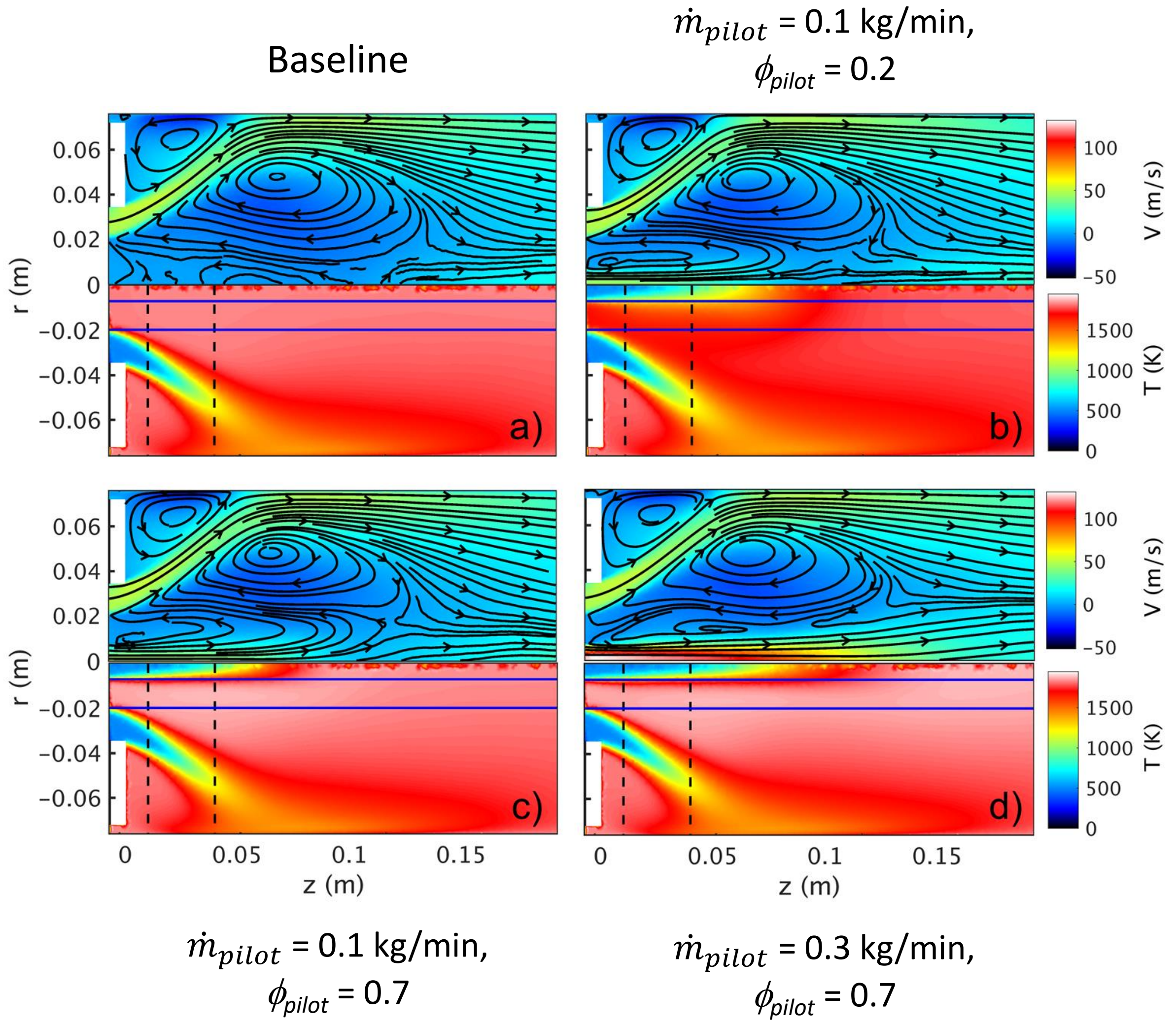
Support structures required for overhanging areas

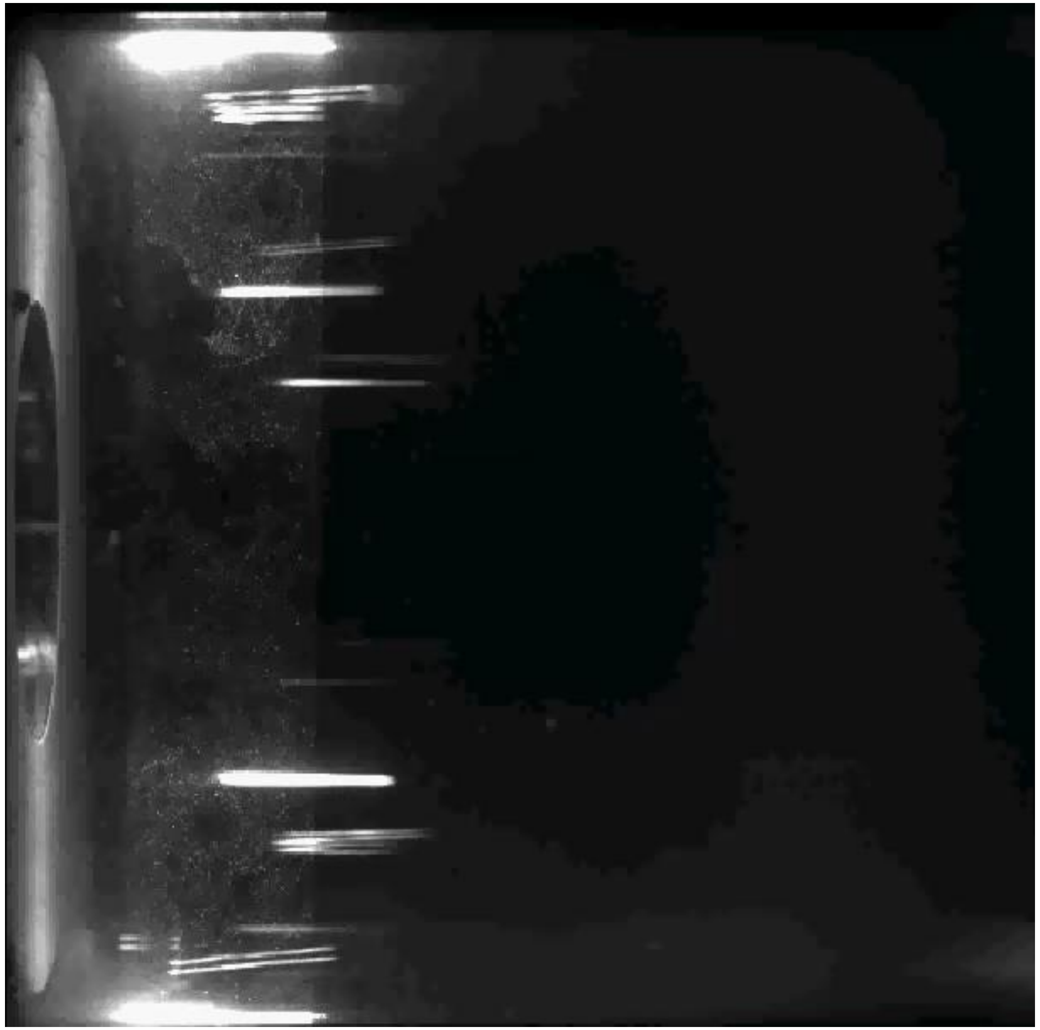
Thin walls prone to mechanical damage

Wall-to-wall thickness for powder removal



Integration hydrodynamic instability constraints and understand more about the hydrodynamic instability of these complex flows





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Publications

Published

- Li, J., Kwon, H., Seksinsky, D., Doleiden, D., O'Connor, J., Xuan, Y., Akiki, M. and Blust, J., (2022) “Describing the Mechanism of Instability Suppression Using a Central Pilot Flame With Coupled Experiments and Simulations,” *Journal of Engineering for Gas Turbines and Power*, 144(1), p. 011015.
- O’Connor, (2022) “Understanding the Role of Flow Dynamics in Thermoacoustic Combustion Instability,” *Proceedings of the Combustion Institute*
- *Jalui, S. S., Spurgeon, T. J., Jacobs, E. R., Chatterjee, A., Stecko, T., and Manogharan, G. P., (2021) “Abrasive Flow Machining of Additively Manufactured Titanium: Thin Walls and Internal Channels,” Proceedings of Solid Freeform Fabrication Symposium 2021.*

In progress

- Seksinsky, D., Jalui, S., Manogharan, G., Xuan, Y., & O'Connor, J. (2022) “Mesh sensitivity of adjoint solutions for aerodynamic design optimization.” *AIAA Journal*
- Jalui, S., Seksinsky, D., O’Connor, J., Xuan, Y., Manogharan, G. (2022) “A novel framework for NURBS-based adjoint shape optimization for metal AM.” *Computer Aided Design*
- O’Connor, J., and Hemchandra, S. (2022) “The Role of Hydrodynamic Instability on Combustor Operability and a Pathway to Better Combustor Design,” *Progress in Energy and Combustion Science*
- Mohanty, P., Xuan, Y., O'Connor, J. (2023) "Impact of pilot flow on swirling flow stability," *ASME Turbo Expo*

Outreach

Trade Publications

— Feature in *Additive Manufacturing Magazine* and *The Cool Parts Show*

  — https://www.youtube.com/watch?v=no_7eZe-Muo

  — https://www.youtube.com/watch?v=B9ScUHspMQs

Conferences

— Manogharan, G. (2021) “A Design for Additive Manufacturing Challenge for Gas Turbine Industry,” *Additive Manufacturing 2021 Conference*, Cincinnati, OH

Curriculum

— ME 556: Design for Additive Manufacturing – two teams design challenge for gas turbine swirler design to enhance lean blow-off limits

— ME 404: Gas Turbines – case study on additive manufacturing in gas turbine engines

Undergraduate Research

— Summer Research Experience for Undergrads hosted by Penn State Center for Gas Turbine Research, Education, and Outreach (GTREO) and Center For Innovative Materials Processing Through Direct Digital Deposition (CIMP-3D) on additive manufacturing for fuel injectors

Questions?

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