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

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

Project Review – November 10, 2021

PIs: Jacqueline O'Connor, Guha Manogharan, Yuan Xuan
Graduate students: Sagar Jalui, Hyunguk Kwon, Drue Seksinsky
Undergraduate students: Nathan Love

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 2
  - Defining the optimization process
  - Geometric definitions
  - Sensitivity of the adjoint to geometric definition
- Next steps
- Publications and outreach

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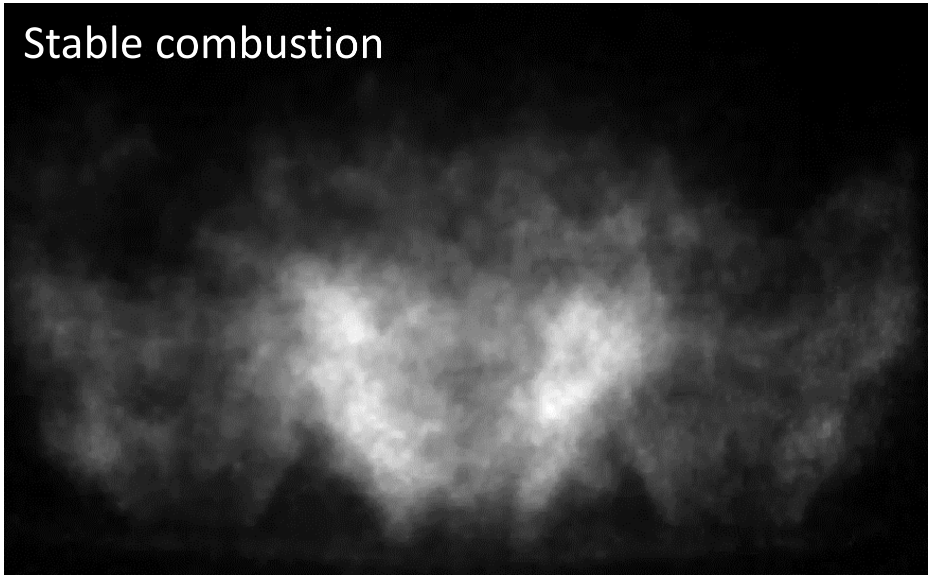
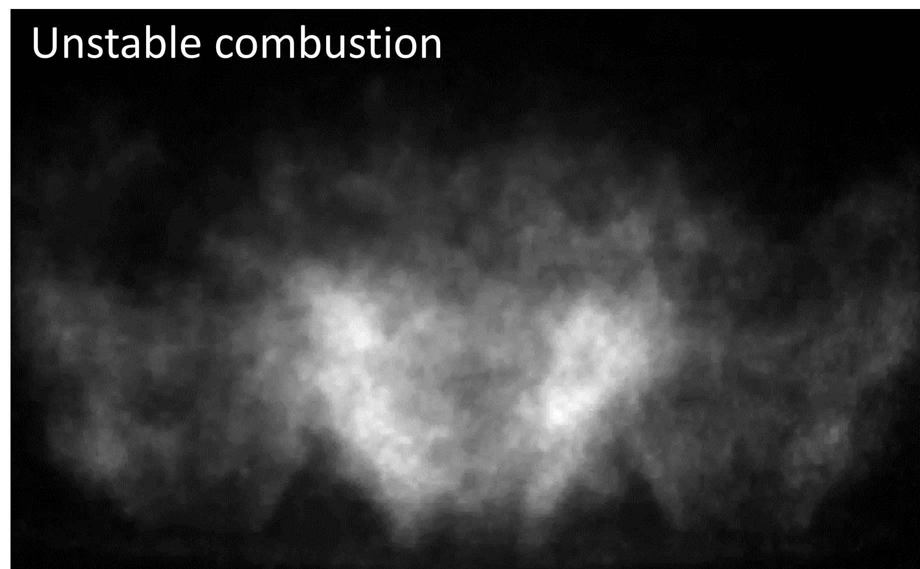
Project origin: Discussions with industry about issues related to combustion operability and fuel injector manufacturing

"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



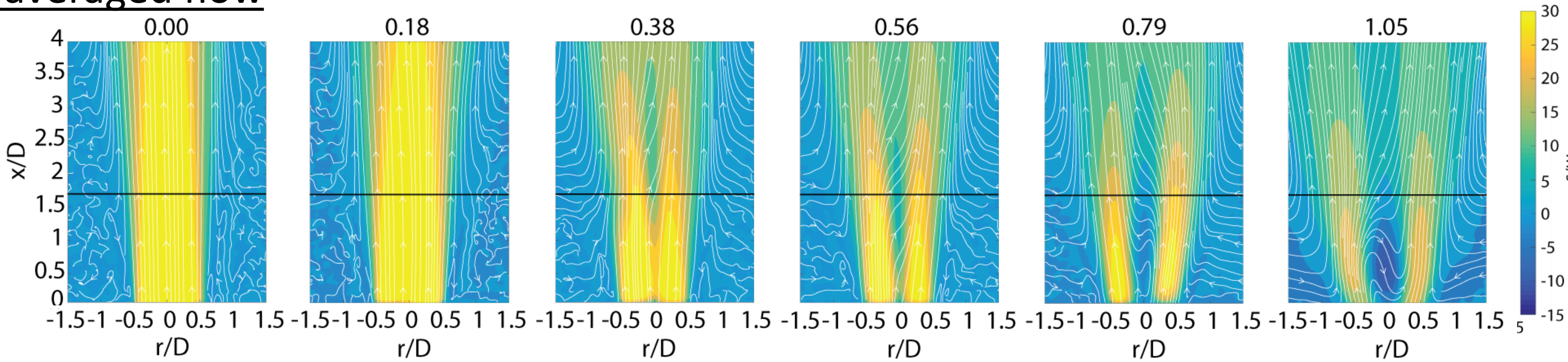
Off-design operation



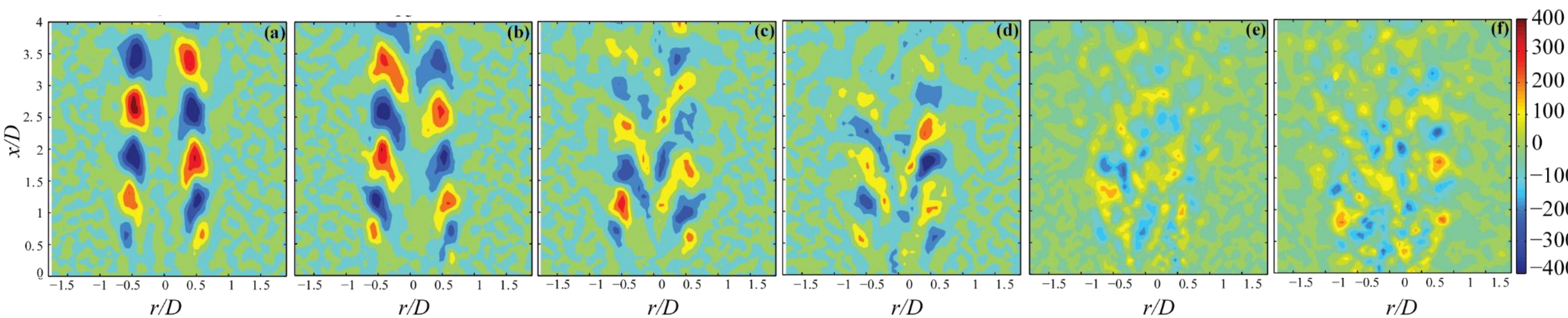
DOE University Turbine Systems Research Program, Mark Freeman (contract monitor), Grant DE-FE0025495

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

Time-averaged flow

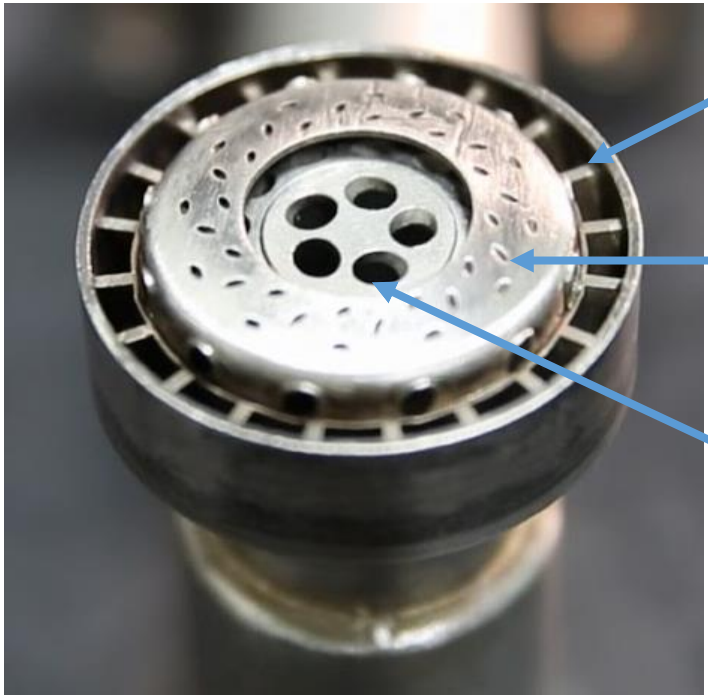


Coherent response



Flow parameter variation

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



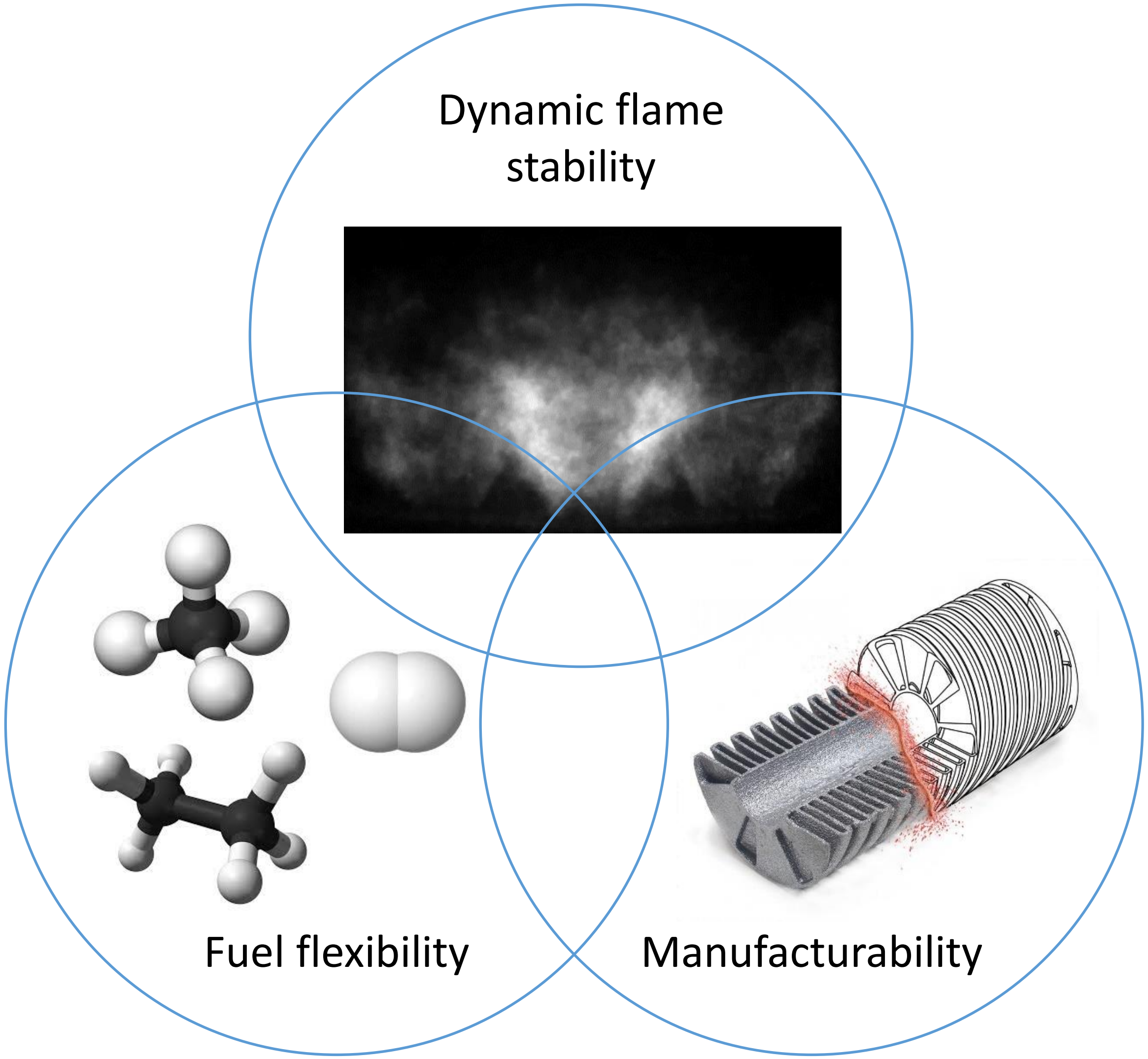
Solar Turbines, https://www.youtube.com/watch?v=hrOYuGM-tfQ

Complex aerodynamic surfaces

Small orifices with specified surface finish

Internal flow passages

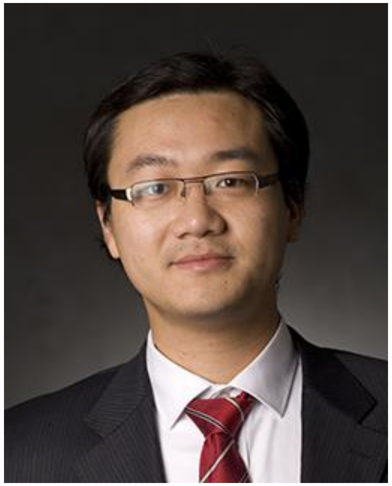
Goal of this project is to create a design optimization paradigm that marries combustion physics and manufacturing



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

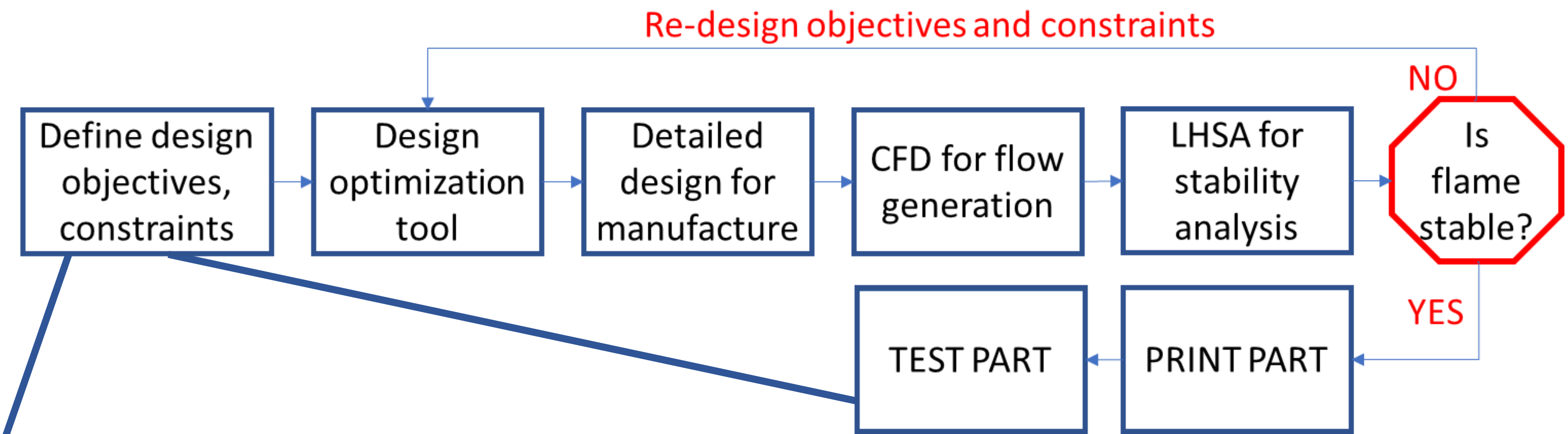
Co-PI: Guha Manogharan
Assistant Professor of ME, IME
Hybrid-Additive Manufacturing



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

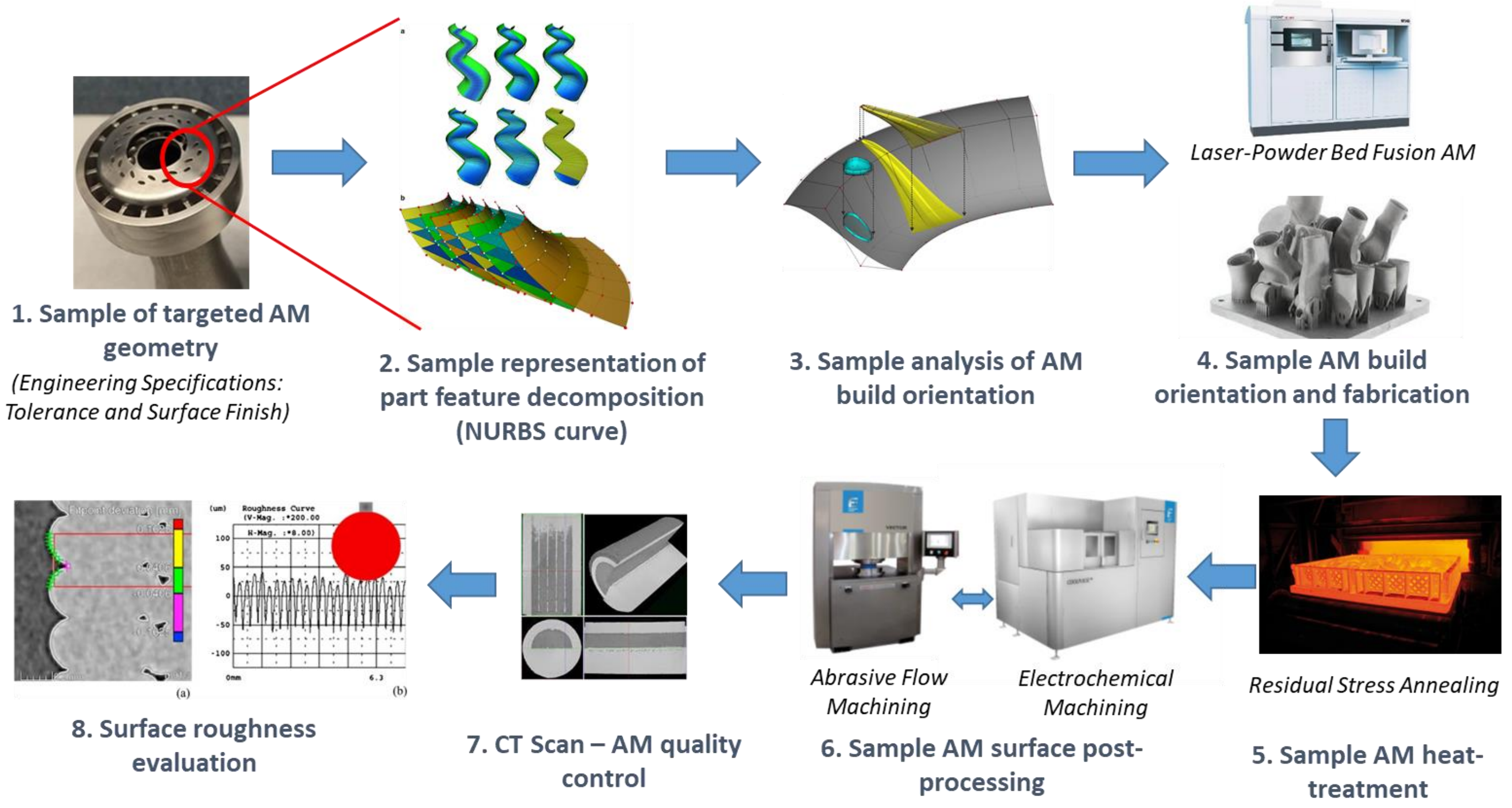
Solar® Turbines
A Caterpillar Company

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



1. Flame dynamic stability through flow response modeling
2. Flame static stability through computational fluid dynamics
3. Fuel flexibility through computational fluid dynamics
4. Additive manufacturing considerations for laser powder bed fusion
5. Surface finishing considerations for abrasive flow machining

Parametric design-process planning advanced manufacturing approach is proposed for fuel-injector applications



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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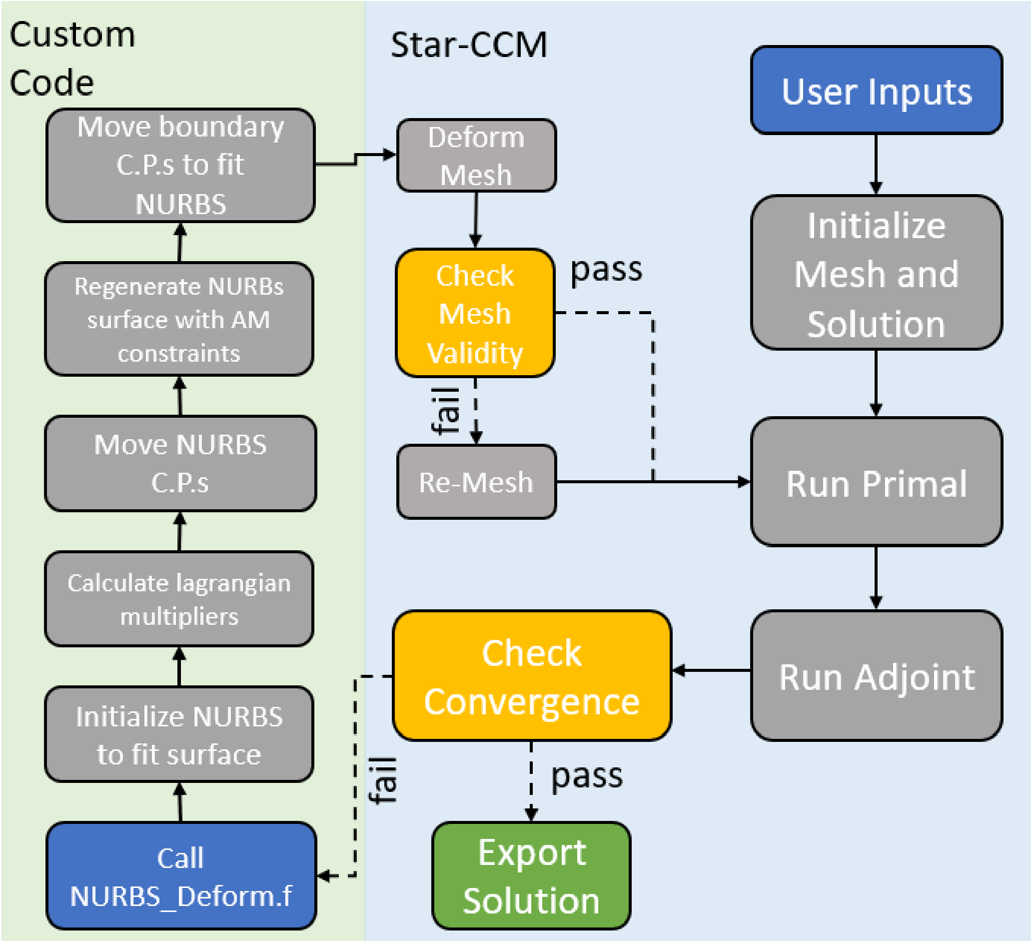
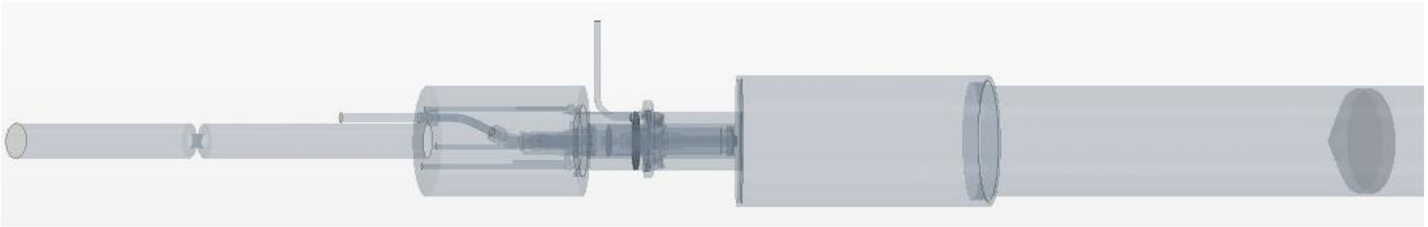
Initial optimization process was relatively simplistic, not accounting for several issues

- Optimization loop using an in-house FORTRAN code
- Code forces Star-CCM into recognizing NURBs for the mesh deformation
- NURBs allow us to include AM constraints
- Langrangian multipliers allow us to weigh the cost functions against each other



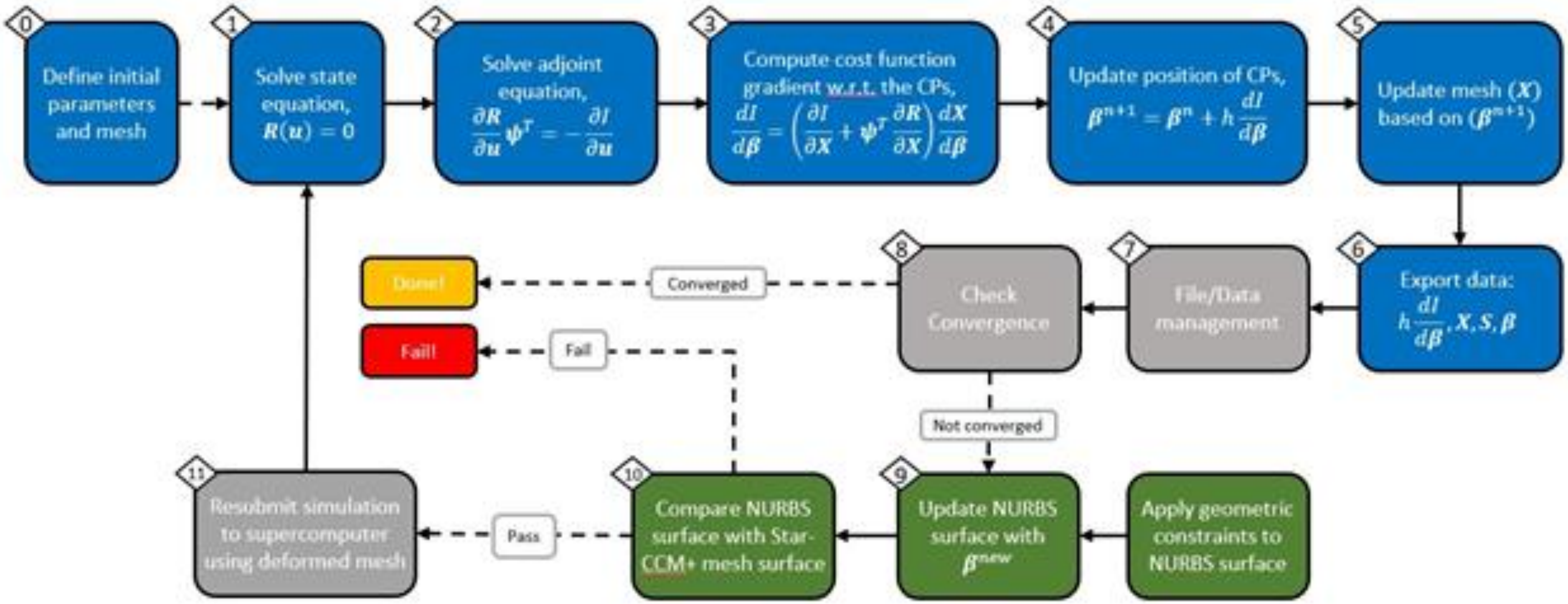
High-fidelity combustion simulation uses STAR-CCM+ to allow more rapid industry adoption

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



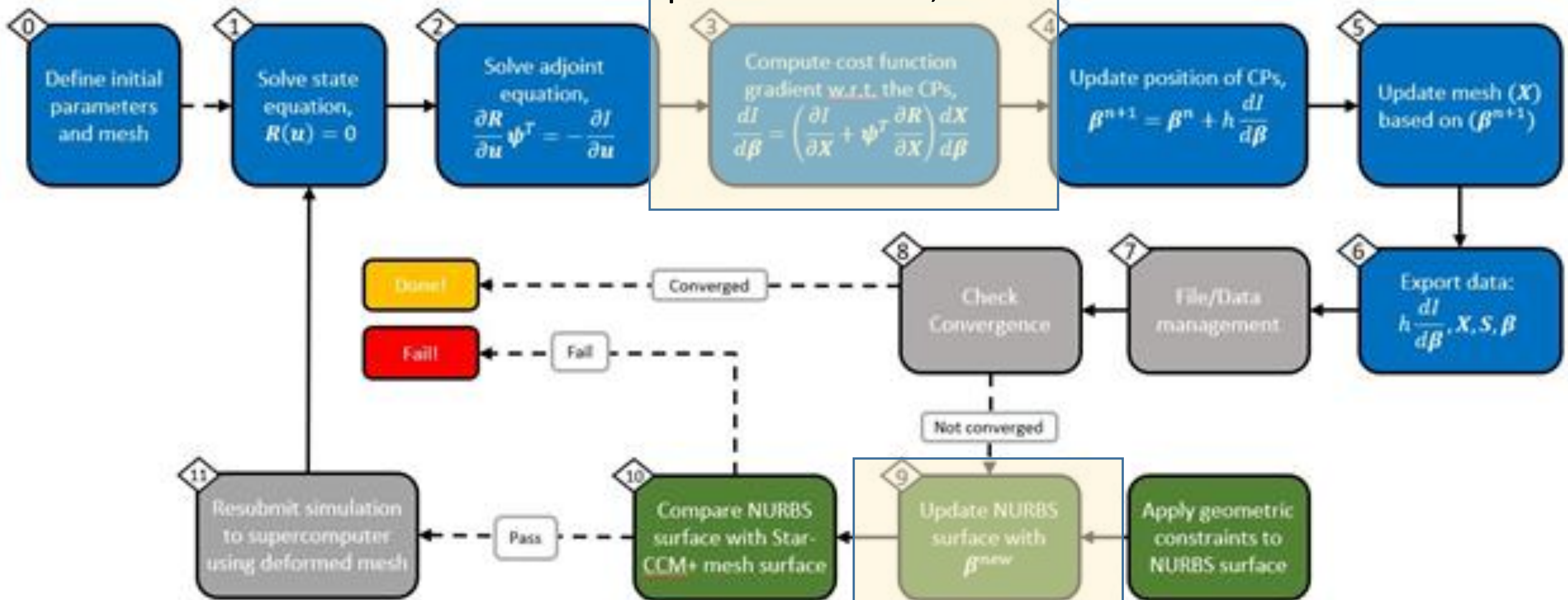
Main-flame equivalence ratio (φ_{main})	**0.6**
Combustor length (L_{comb})	711.2 mm
Air inlet temperature (T_{in})	250° C
Pilot flame equivalence ratio (φ_{pilot}) and Pilot mixture flow rate ($\dot{m}_{pilot}$)	case a) $\dot{m}_{pilot}$ = 0 kg/min case b) $\dot{m}_{pilot}$ = 0.1 kg/min, φ_{pilot} = 0.2 case c) $\dot{m}_{pilot}$ = 0.1 kg/min, φ_{pilot} = 0.7 case d) $\dot{m}_{pilot}$ = 0.3 kg/min, φ_{pilot} = 0.7

New optimization process integrates with STAR-CCM, solves issues with geometry, adjoint, computing infrastructure



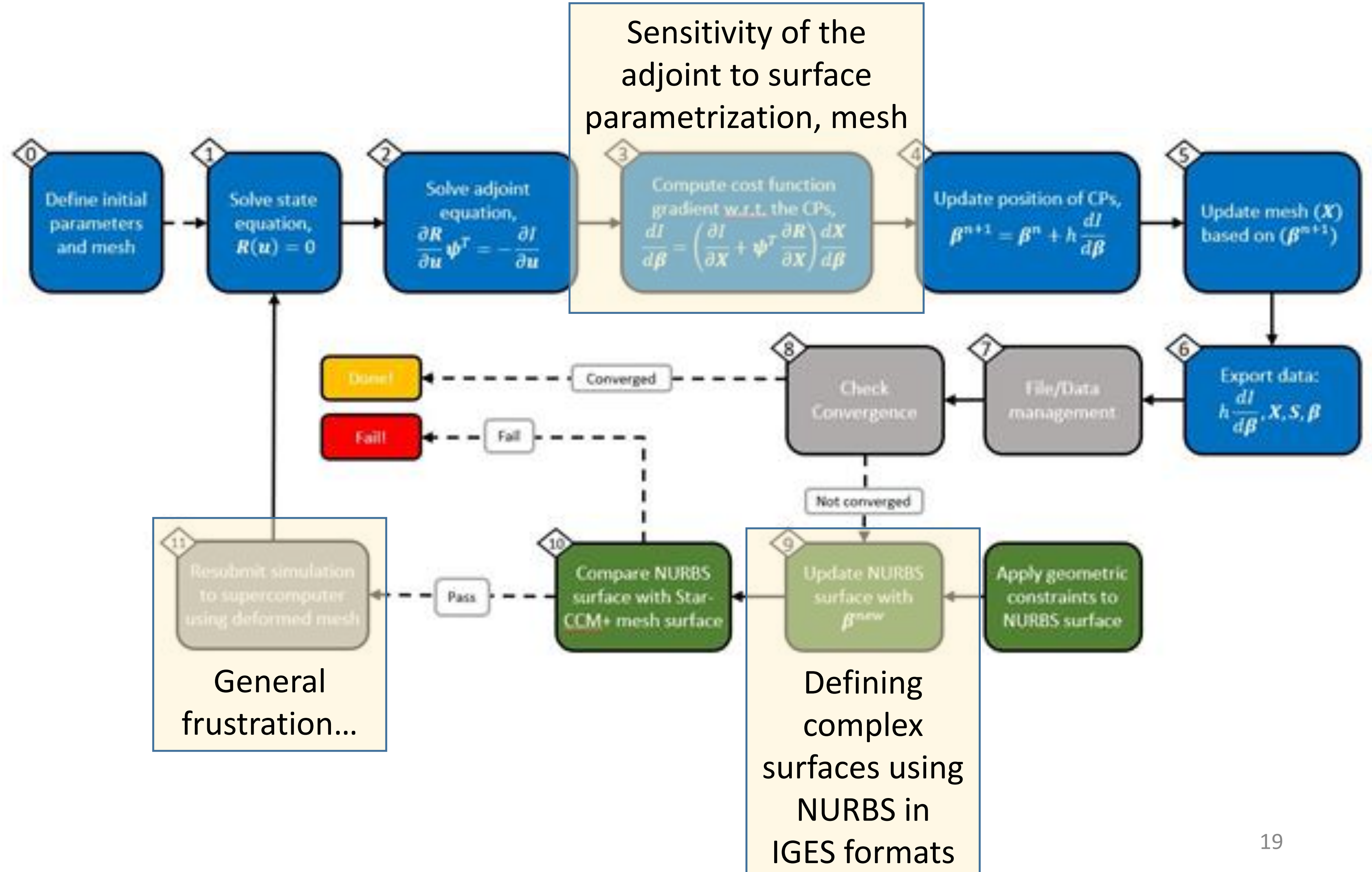
There are two technical “sticking points” we have addressed this year to ensure robust calculations

Sensitivity of the adjoint to surface parametrization, mesh



Defining complex surfaces using NURBS in IGES formats

Bonus battle: interfacing with a supercomputer system you have no administrative rights to…



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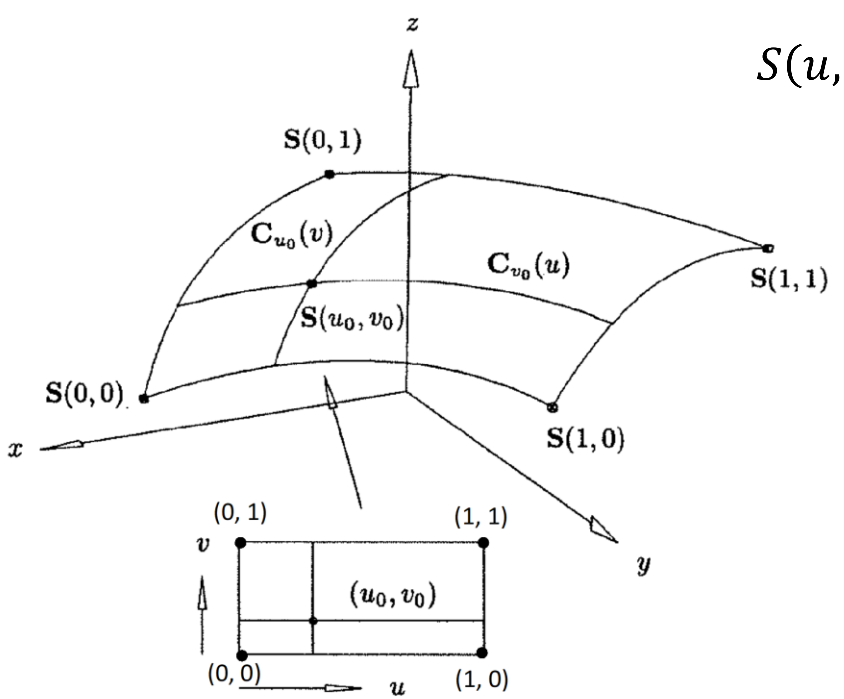
Injector surfaces are defined using NURBS to allow for precise shape quantification and flexibility in changing the shape

NURBS Surface:

Non-**U**niform **R**ational **B**asis **S**plines

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

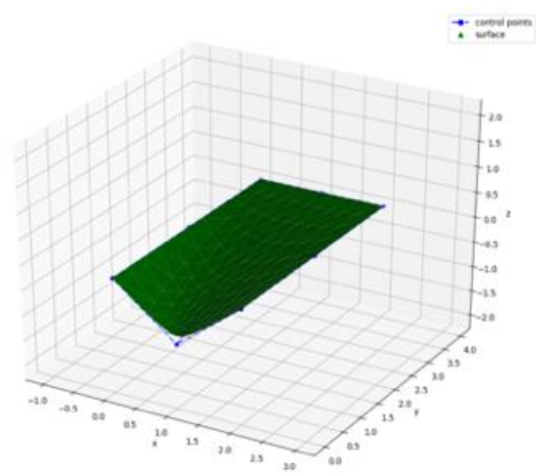
- Enable local control



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)

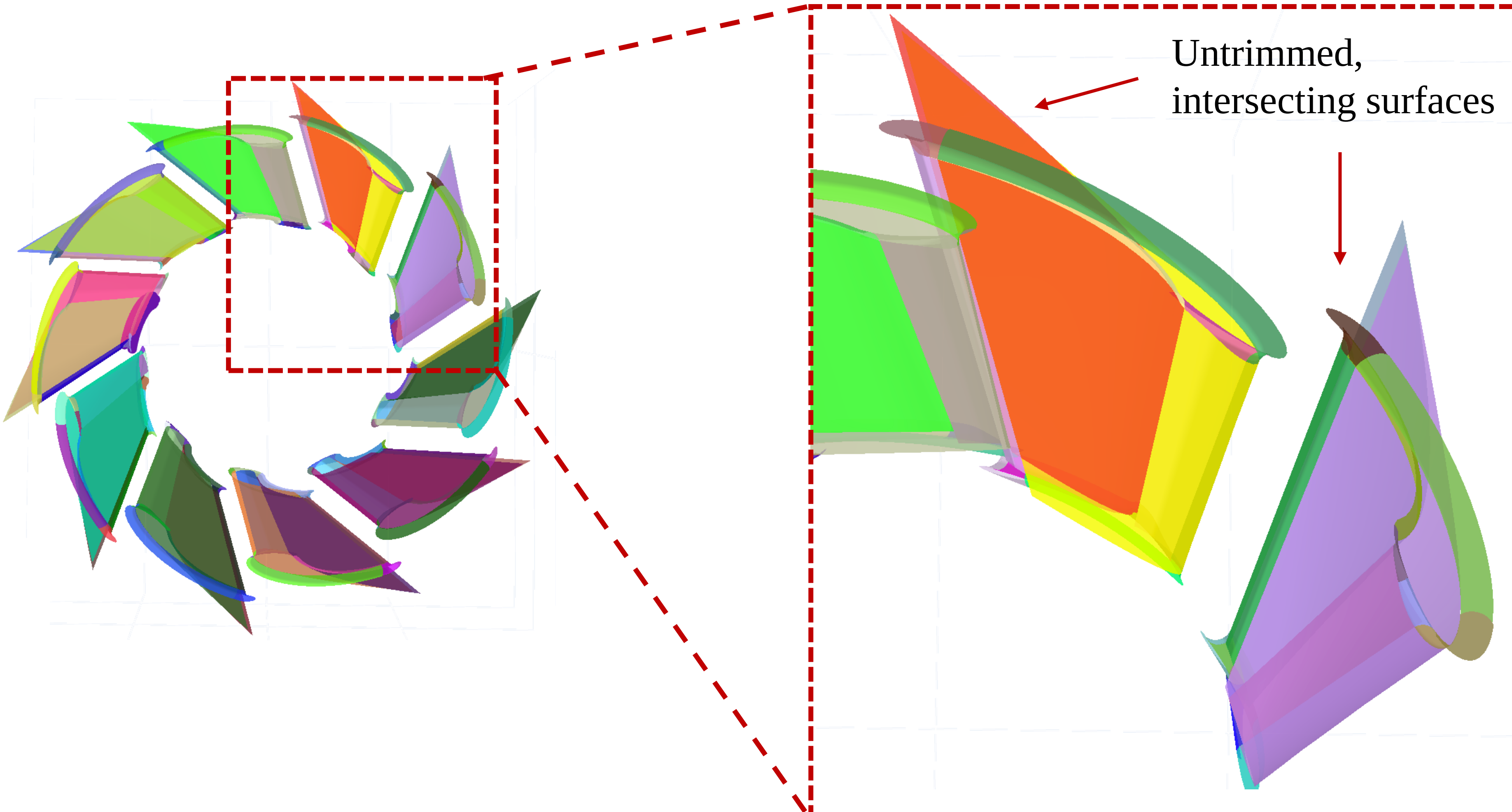
$$S(u,v) = \frac{\sum_{i=0}^{n}\sum_{j=0}^{m} N_{i,p}(u)N_{j,q}(v)w_{i,j}P_{i,j}}{\sum_{i=0}^{n}\sum_{j=0}^{m} N_{i,p}(u)N_{j,q}(v)w_{i,j}} \quad 0 \le u, v \le 1$$



NURBS Python (geomdl)

- Visualization
- Manipulation

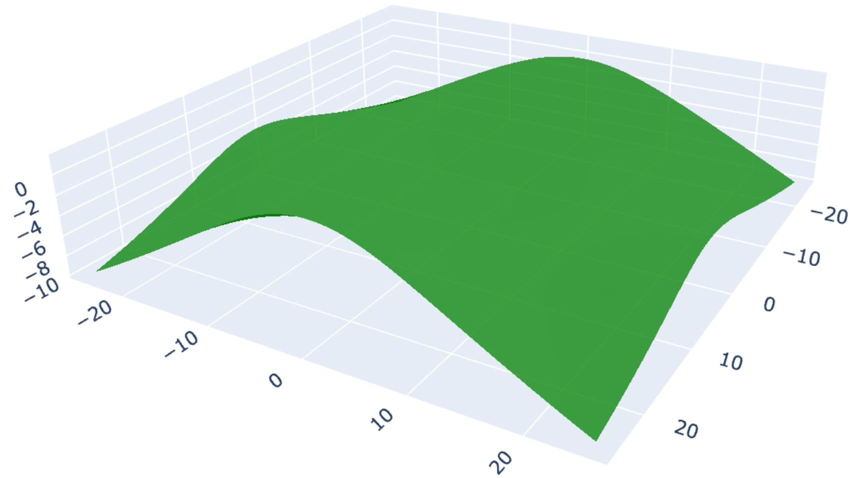
However, defining aerodynamic surfaces requires "trimmed" NURBS to account for interfaces, holes, etc.



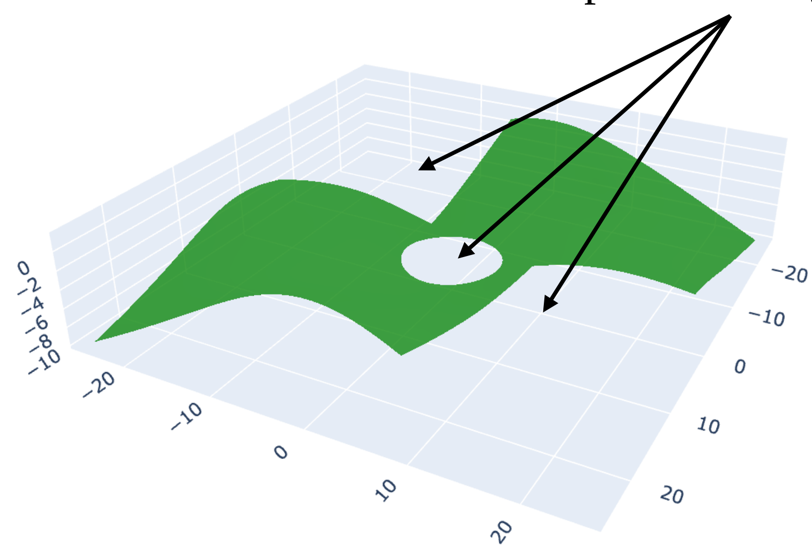
To accomplish trimming, the IGES files include different "types," which incorporate the trimming curves

IGES file types

- 124 – Transformation Matrix
- 408 – Singular subsurface instance
- 308 – Subfigure definition
- 186 – Manifold Solid B-Rep object
- 514 – Shell
- 510 – Face
- 508 – Loop
- 143 – Bounded surface
- 141 – Boundary
- 126 – B-Spline Curve
- 128 – B-Spline surface
- 502 – Vertex
- 504 – Edge
- 406 – Property
- 314 – Color



multiple trimming curves

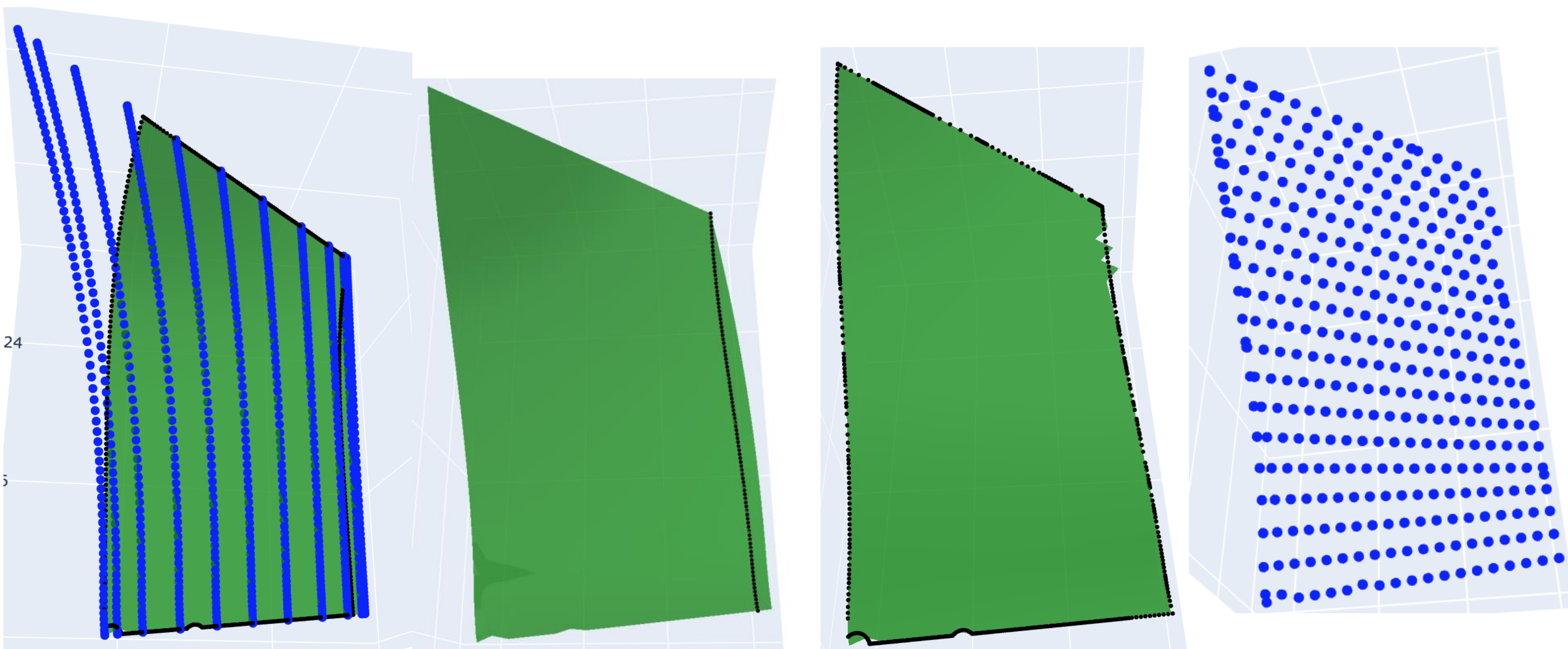


Current optimization methodology now incorporates trimming, is robust to geometry changes during optimization

Original NURBS on vane surface

Application of trimming curves…

Trimmed NURBS on vane surface



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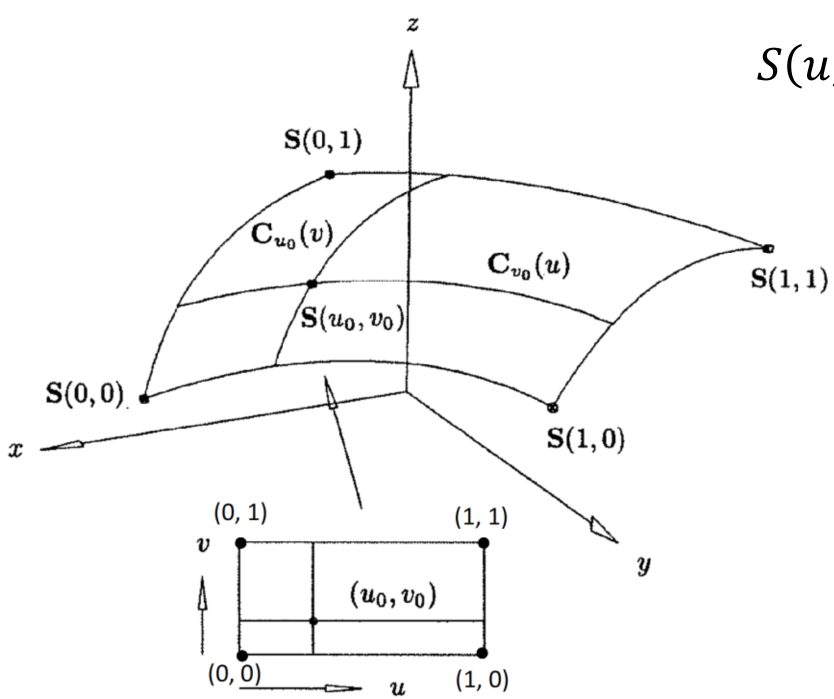

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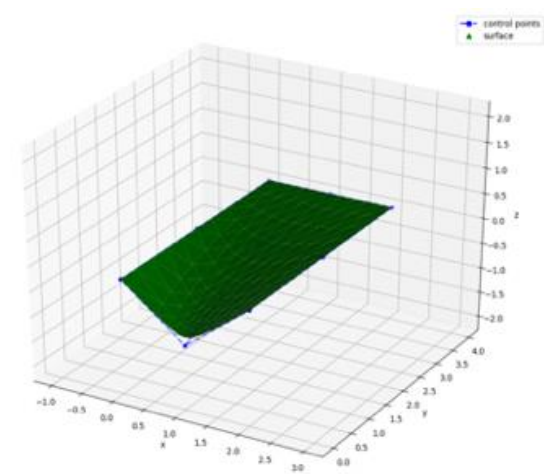

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However, STAR-CCM uses radial basis functions (RBF) for defining surfaces in the adjoint calculation – not optimal for AM

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

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

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

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

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

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

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

IF… $$\frac{\partial S}{\partial NURBS} = \frac{\partial S}{\partial RBF}$$ for small α

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

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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

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Publications

Published

— Li, J., Kwon, H., Seksinsky, D., Doleiden, D., O'Connor, J., Xuan, Y., Akiki, M., & Blust, J. (2021). “Describing the mechanism of instability suppression using a central pilot flame with coupled experiments and simulation.” *ASME Turbo Expo.*

In progress

— Seksinsky, D., Jalui, S., Manogharan, G., Xuan, Y., & O'Connor, J. (2022) “Mesh sensitivity of adjoint solutions for aerodynamic design optimization.” *AIAA Aerospace Sciences Meeting* → *will then be submitted to 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*

Outreach

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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