Automated Design Improvement of a Crossbow Arrow Vane with HEEDS and STAR-CCM+

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Arrow Vanes Have Significant Impact on Stability and Accuracy

- Lift and drag on arrow vanes shift center of pressure aftward
  - Produce a stabilizing moment to counter the destabilizing moment produced by lift/drag on arrow tip
- Offset vanes produce an axial moment on the arrow that creates spin stabilization

Variety of Bohning Archery arrow vanes

- Arrow vane design has traditionally been based on experience and tribal knowledge
- Due to time and cost, R&D is limited to a sparse parametric design space using a traditional design/prototype/test workflow
- Automated, multi-disciplinary optimization can be used to increase arrow vane performance by investigating a broad and full parameter space

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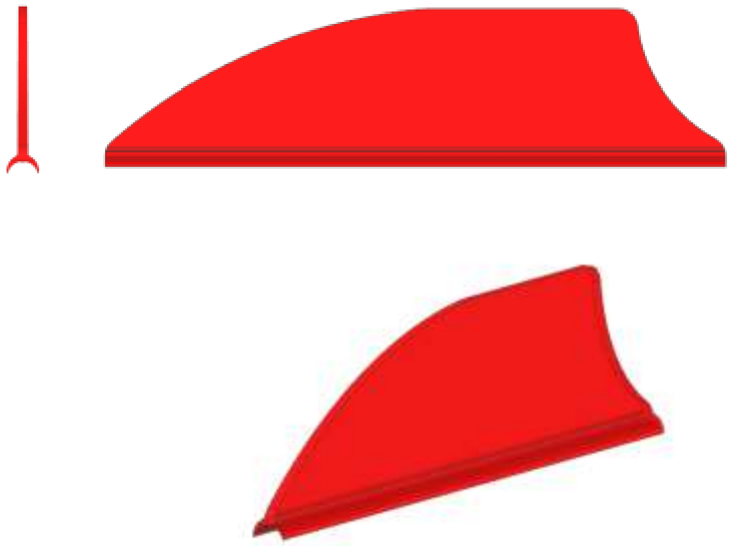
HEEDS Used to Improve Performance of Existing Bohning Crossbow Vane

- The Bohning Company, Ltd. manufactures high performance archery equipment
- Desire to accelerate the design cycle by using computational approach early in the process
- HEEDS orchestrated automated intelligent design space exploration
  - Four high-fidelity parallel CFD simulations per design iteration
  - Approximate 6-DOF trajectory analysis to assess crossbow arrow accuracy



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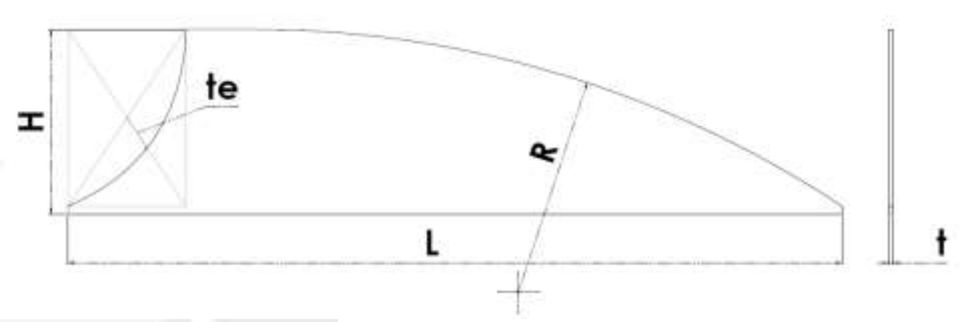
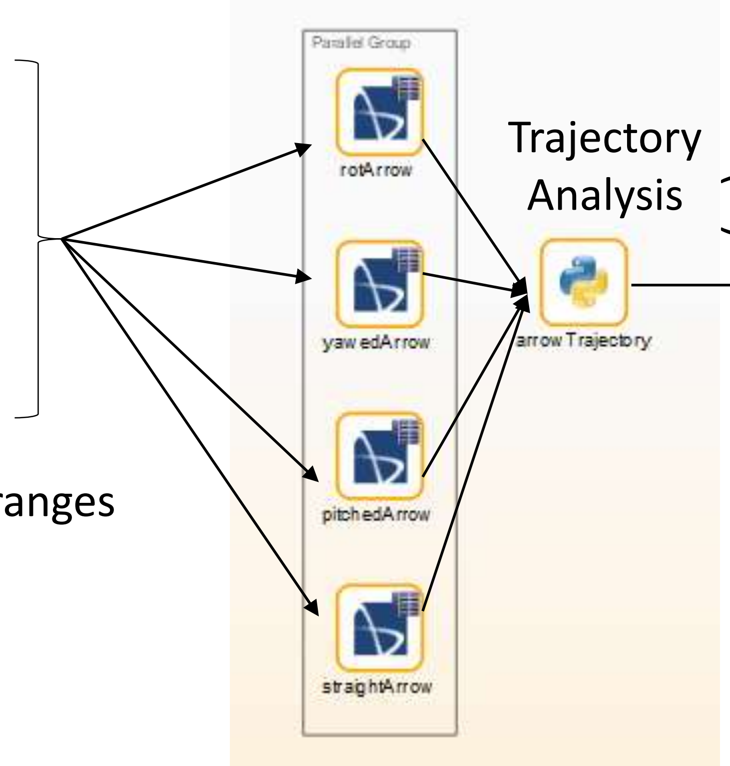
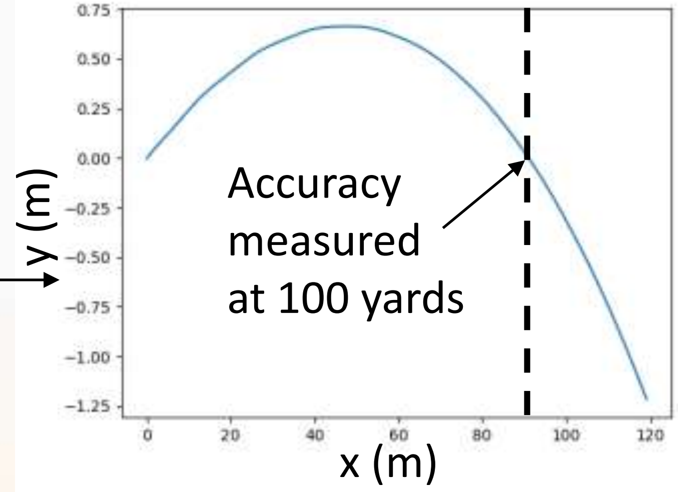
HEEDS Crossbow Vane Optimization Process







Parametric Vane

- Parameterized by 5 variables over continuous ranges

Parameter	Baseline (in.)	Minimum (in.)	Maximum (in.)
H	0.45	0.125	0.5
L	2.0	0.5	6.0
R	1.7	0.25	6.0
te	0.16	-0.29	0.29
t	2.47×10^{-2}	1×10^{-2}	0.1

- Vane geometry added to 20" shaft with vented broadhead geometry
- Vane given a 1° left offset to induce axial rotation

STAR-CCM+ CFD Simulations

- Four steady CFD simulations
- Generate aerodynamic coefficients on design iteration

Design Result

- Mass properties and aerodynamic coefficients sent to trajectory analysis

CG	Center of gravity
m	Mass
I_1	Transverse moment of inertia
I_2	Vertical moment of inertia
I_3	Axial moment of inertia
$C_{L\alpha}$	Lift curve slope
C_{D0}	Drag coefficient at 0° AoA
$C_{D\alpha}$	Drag curve slope
CP	Center of pressure
C_{R0}	Roll-moment coefficient at 0 RPM
C_{R12000}	Roll-moment coefficient at 12,000 RPM

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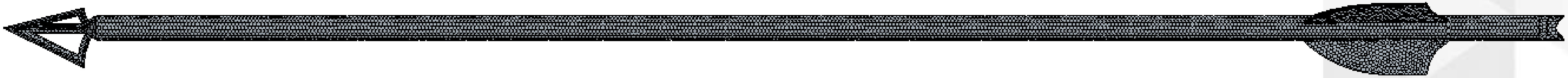
Mass Property Calculation Performed Within STAR-CCM+

- Although not a full CAD tool, STAR-CCM+ is able to do all CAD operations needed in for the arrow vane design study
- Geometry modifications performed within native 3D-CAD tool
- Mass properties calculated via arrow mesh and field functions
  - Solid portion of arrow assembly meshed and assigned to inactive regions for each design iteration
  - Volume integral report and field functions used to numerically integrate mass, CG, and moments of inertia

$$mass = \sum_{i}^{nCell} \rho_i v_i \qquad \mathrm{CG} = \frac{1}{mass} \sum_{i}^{nCell} \vec{r}_i \rho_i v_i \qquad I_j = \sum_{i}^{nCell} x_{j,i}^2 \rho_i v_i$$



STAR-CCM+ and Python Computational Models

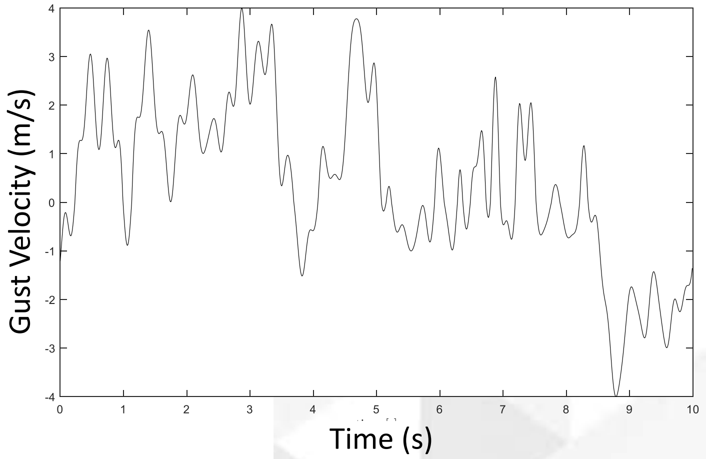
- STAR-CCM+ Simulation Setup
  - Coupled solver
  - Menter SST turbulence model
  - Moving reference frame (for rotating arrow case)
  - Steady solution
- Mesh
  - Polyhedral with prism layers
  - 12 M finite volume cells
  - $Y^+<5$ on arrow surface

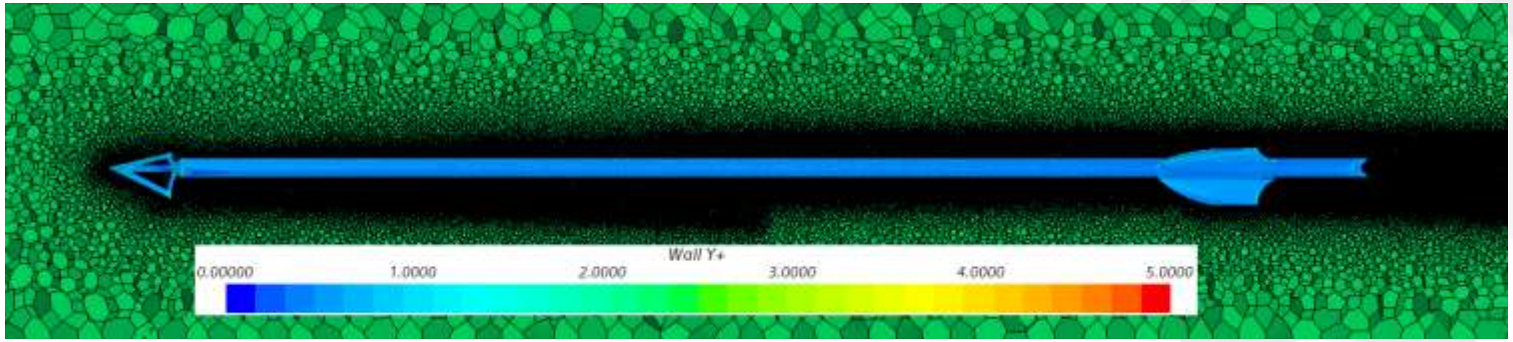
- Trajectory analysis
  - RK4 used to integrate

$$\dot{x}(t) = f(x(t), v_{gust})$$

$$x(t) = [\alpha\ \beta\ \dot{\alpha}\ \dot{\beta}\ u_2\ u_3\ x_2\ x_3\ u_1\ \omega]$$

  - v_{gust} is a lateral gust profile
  - Initial conditions: u_1=400 ft/s, u_2=3.75 ft/s
  - Result reported at x=100 yards





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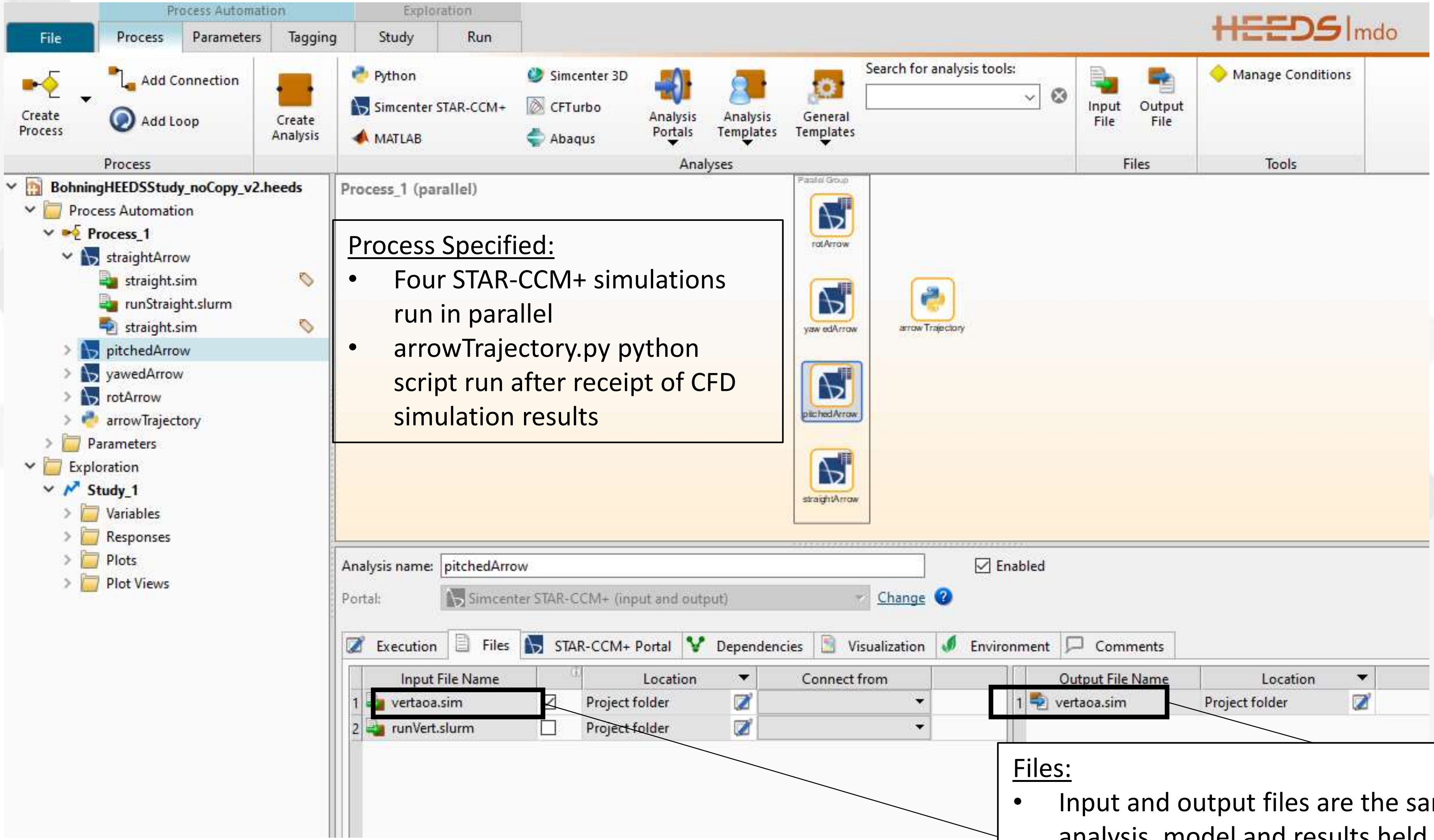
HEEDS Setup is Easy with the STAR-CCM+ and Python Analysis Portals



Process Specified:

- Four STAR-CCM+ simulations run in parallel
- arrowTrajectory.py python script run after receipt of CFD simulation results

Files:

- Input and output files are the same in this analysis, model and results held in .sim file
- A custom Slurm submission script is included to run on HPC cluster

HEEDS Intelligent Design Space Exploration Drives Towards Optimal Result

- HEEDS SHERPA design space exploration intelligently searches parameter ranges to determine the most accurate design
- Objectives to maximize roll rate and minimize distance from bullseye

Parameter	Range (in)		Resolution
	Minimum	Maximum	
Height	0.125	0.5	101
Length	0.5	6	101
Thickness	0.001	0.1	101
Leading Edge Radius	0.25	6	101
Trailing Edge Concavity	-0.29	0.29	101

Response	
Variable	Objective
Final Roll Rate (rpm)	Maximize
Distance from Bullseye (in)	Minimize

- Exhaustive search of this design space: 10.5 billion simulations
- SHERPA finds a better design after just 32 iterations

Three design variants compared with baseline

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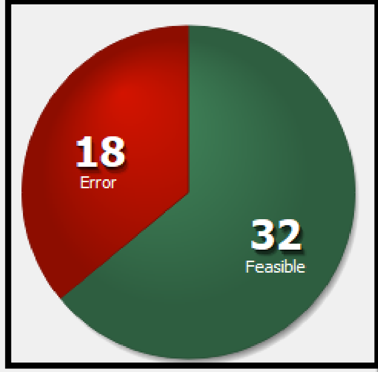
HEEDS Keeps You Updated on Progress

Keeps track of simulations and skips simulations with errors

Optimization problem definition

Study_1



Status: Completed
Type: Parameter Optimization
Method: SHERPA
Version: 2020.1.1.11291
Started: May 13, 2021 @ 17:46
Elapsed: 2 d 21 hr 28 min 24 sec

Study Details
Completed 50 designs

Study Details

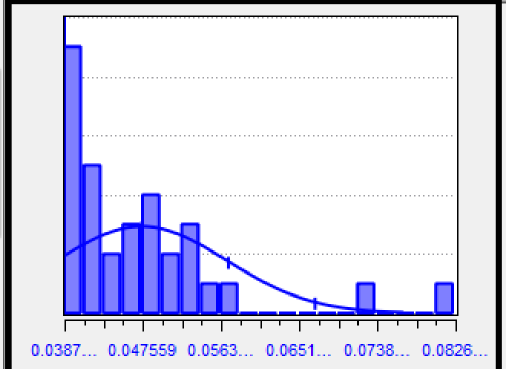
Location: S:/Bohning/Arrow_Sims/BohningHEEDSStudy_noCopy_v2_Study_1
Designs completed: 50
Error designs: 18
Best design: 33

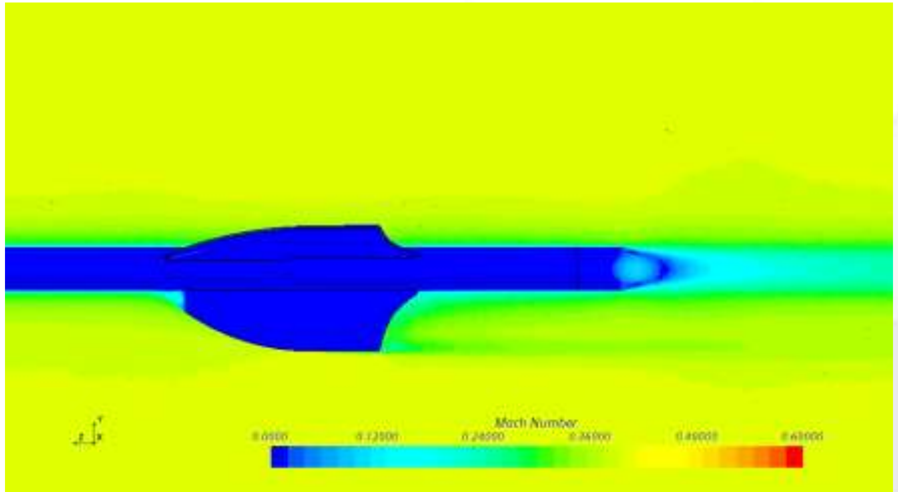
Optimization Statement

Objective: Minimize distOut_out
Maximize rpmOut_out

Name	Min	Max	Best Valu
distOut_out	0.0387883	0.0826421	0.0387883
rpmOut_out	1,118.32	1,710.53	1,582.27
cg_z	0.0232819	0.0838454	0.0822942
Total_IX_aboutCG	0.000933277	0.00134443	0.000943987
Total_IY_aboutCG	0.000933267	0.00134358	0.000943968
Total_IZ_aboutCG	4.10605e-07	1.29068e-06	4.20489e-07
mass_total	0.0261469	0.03429	0.026302
Pitched_PitchMom	-6.8171	0.38057	-1.74672
Pitched_Lift	-1.91462	-0.448468	-0.752401
Pitched_Drag	0.375576	0.70733	0.437223
Yawed_Side	0.450492	1.63571	0.693337

distOut_out





Range of parameters and responses vs. baseline

Histogram showing distribution of designs evaluated

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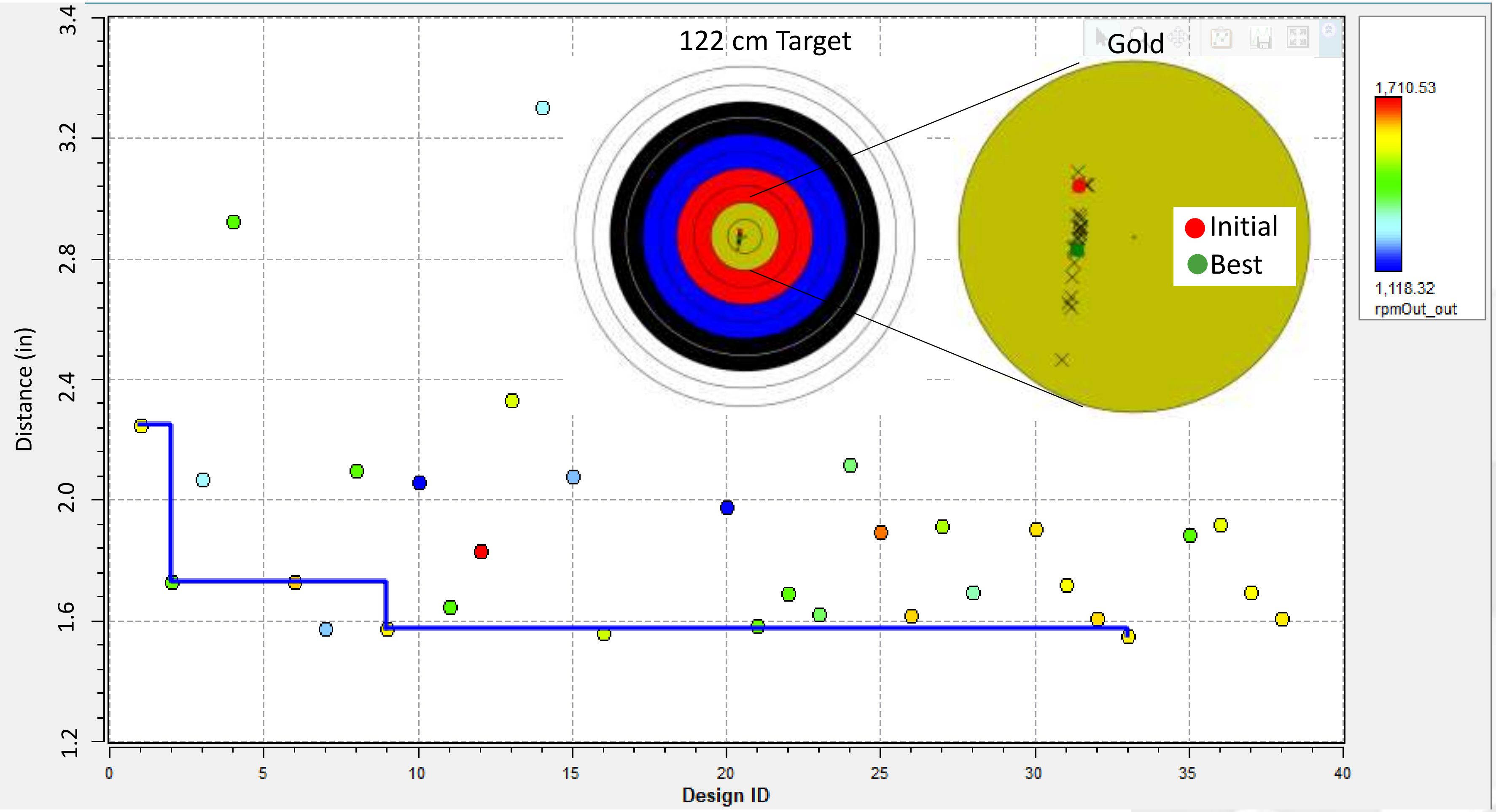
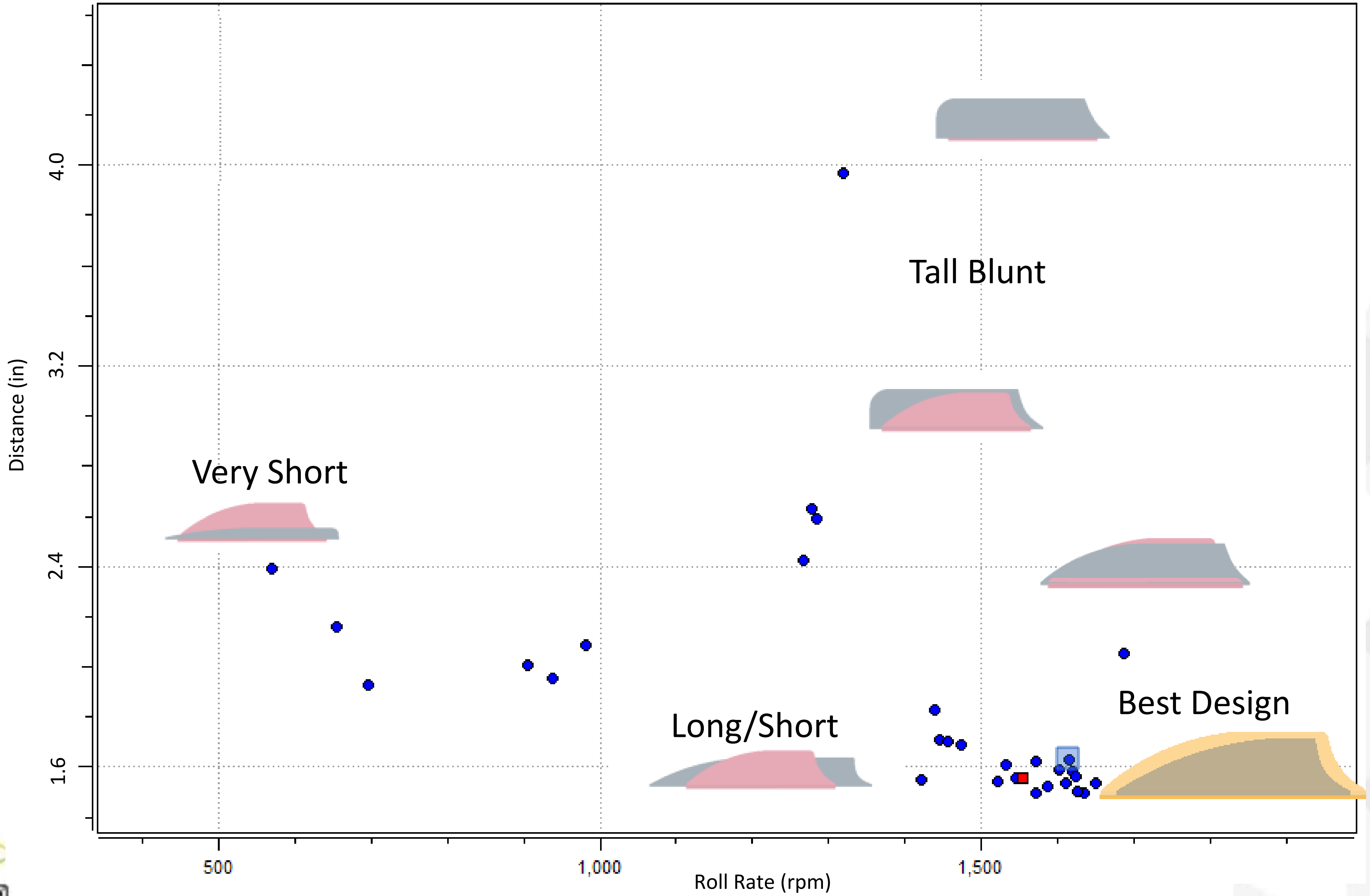
HEEDS Design Optimization History Shows Quick Improvement

- HEEDS SHERPA algorithm explores design space to drive towards objective
- In first 9 evaluations, accuracy improved **30%**
- After 32 evaluations, **31%** accuracy increase

Objective History

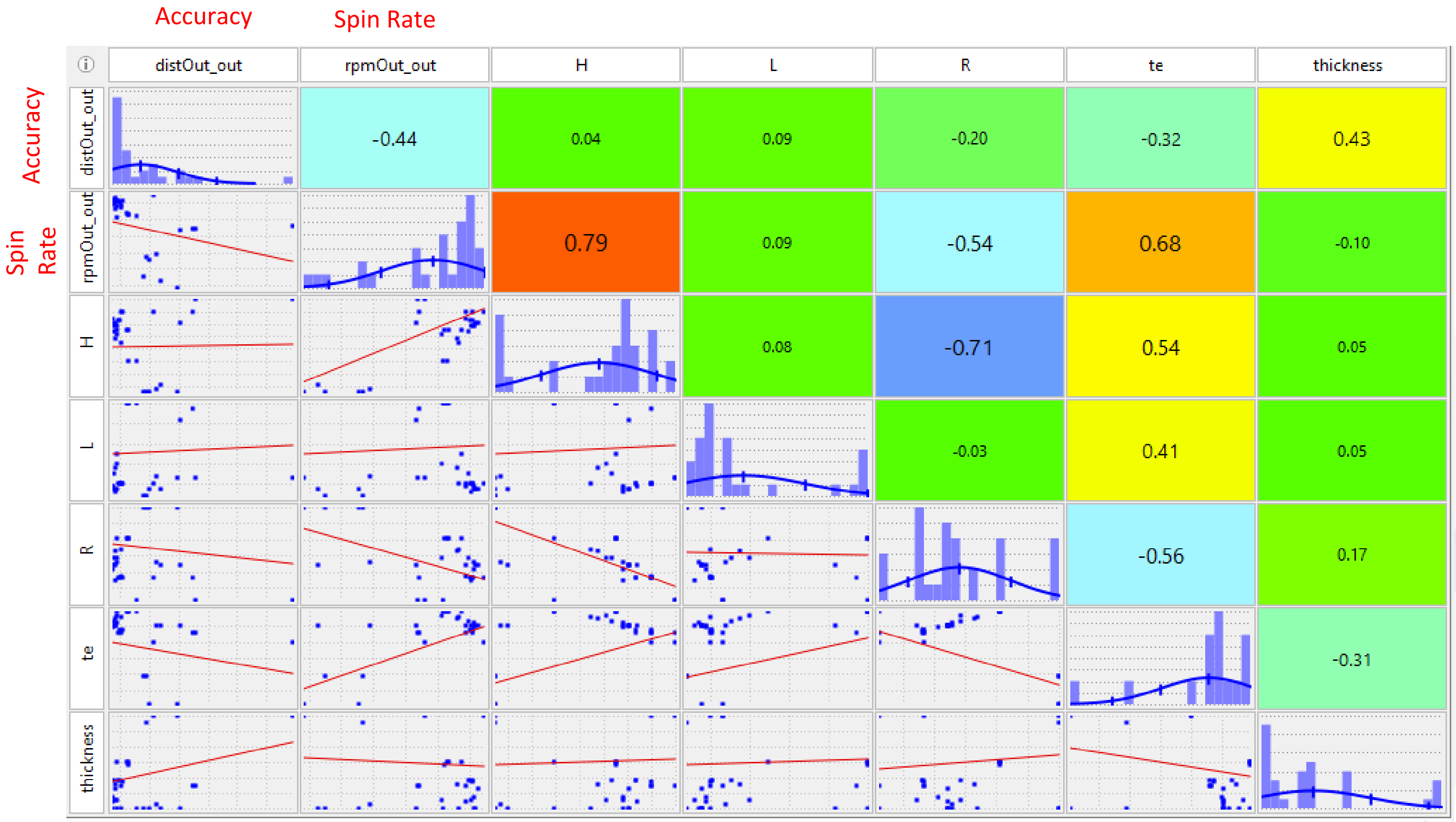


HEEDS Provides Insight into Successful Design Features



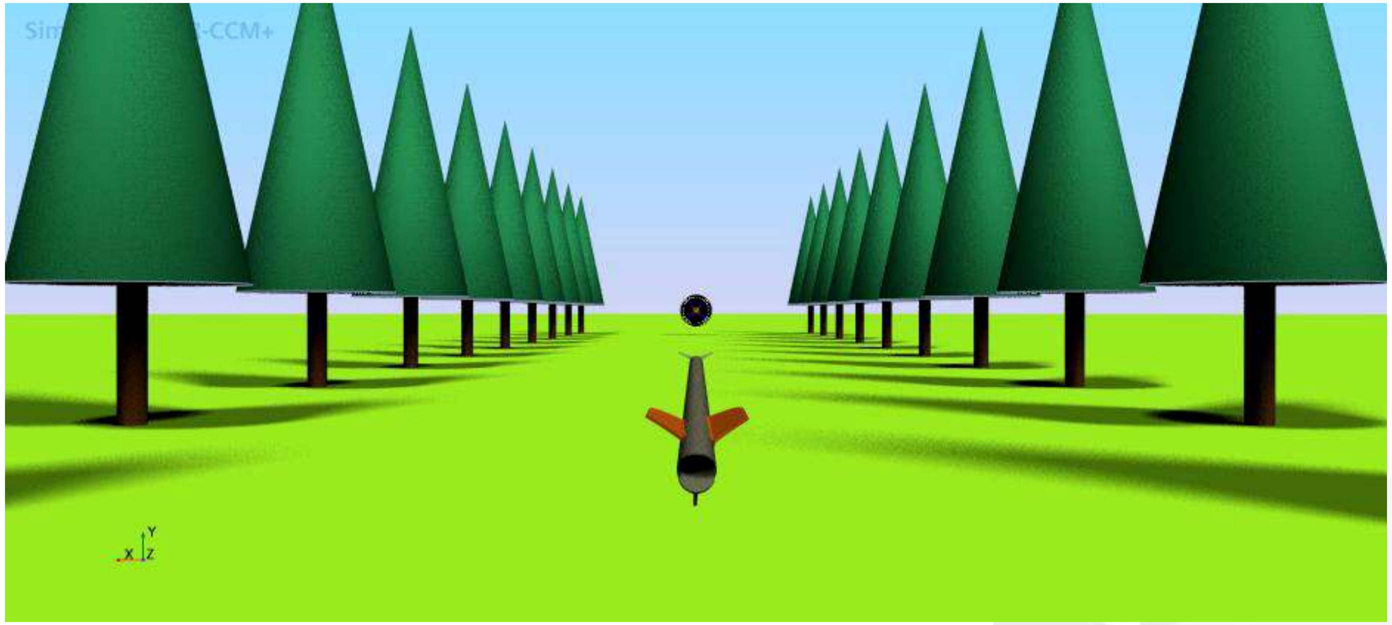
HEEDS Can Help Identify Important Design Parameter Correlations

- Correlation table exposes relationships between parameters and responses
- Example: Spin rate is strongly correlated with vane height



*Accuracy corresponds to low distOut

Summary



Created with STAR-CCM+ screenplay

- Need: More accurate crossbow vane
- Method: Employed HEEDS Design Space Exploration software with STAR-CCM+ and an approximate trajectory analysis to find a better design automatically
- Results: The automated method produced a design with a 31% increase in accuracy
- Conclusion: HEEDS directed STAR-CCM+ and Python to produce an improved crossbow arrow vane on an HPC cluster with minimal effort from the analyst

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HEEDS Results in Engineering Time Savings

- Prior to use of HEEDS, manual performance analysis of 4 arrow variants took about two weeks of engineering analyst time
- Model setup for use with HEEDS took 20 hours
- After initial setup, HEEDS managed analysis and design of 32 arrow variants over the weekend on cluster

$$Speedup = \frac{\left(\frac{80\ hours}{4\ designs}\right)}{\left(\frac{20\ hours}{32\ designs}\right)} = 64$$

HEEDS resulted in 64 times gain in efficiency
Engineers can spend less time submitting and monitoring simulations, more time engineering

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