Evolved Artificial Intelligence for First-Order Conceptual Missile Design Optimization

Dr. Randal Allen

Lone Star Aerospace

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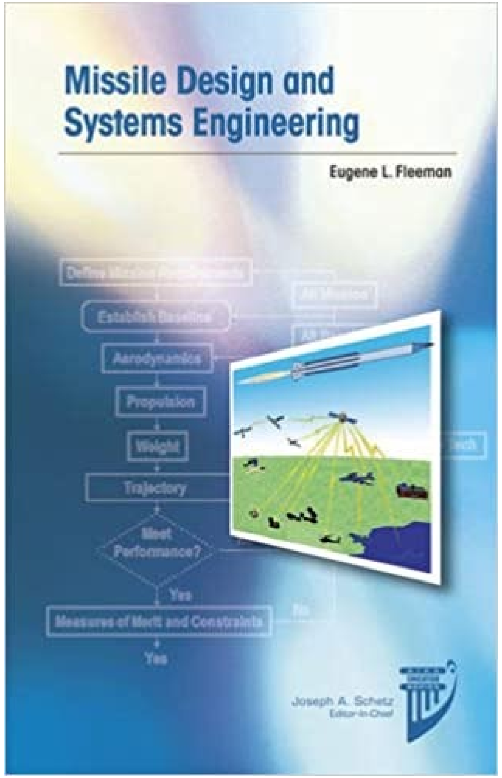
Agenda

- Background
- Conceptual Design → MBSE
- Model implementation
- Aerodynamics applications
- Results
- Conclusion

Background

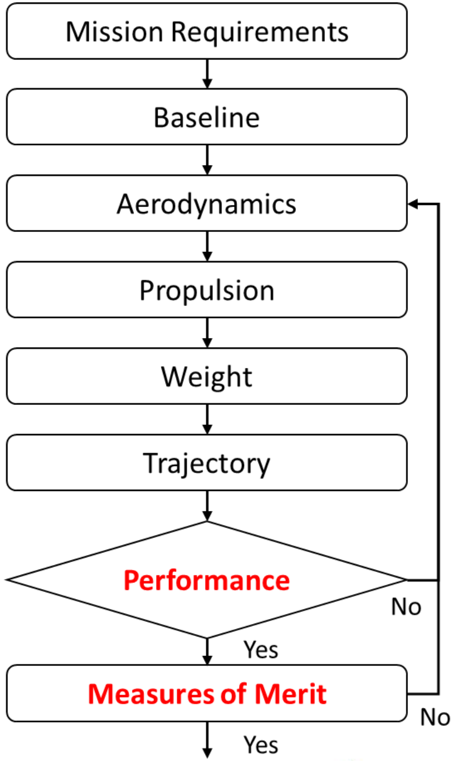
- ➢ Fleeman spreadsheet project*
  - ➢ Turbojet missiles and guided bombs
- ➢ Separate model built for V&V
  - ➢ Optimization capability
- ➢ All subsystems modeled
  - ➢ Aerodynamics focus or this presentation



*Spears, S., Allen, R., and Fleeman, E., “First-Order Conceptual Design for Turbojet Missiles and Guided Bombs,” AIAA SciTech Conference, San Diego, CA, 3-7 January 2022, AIAA-2022-0321

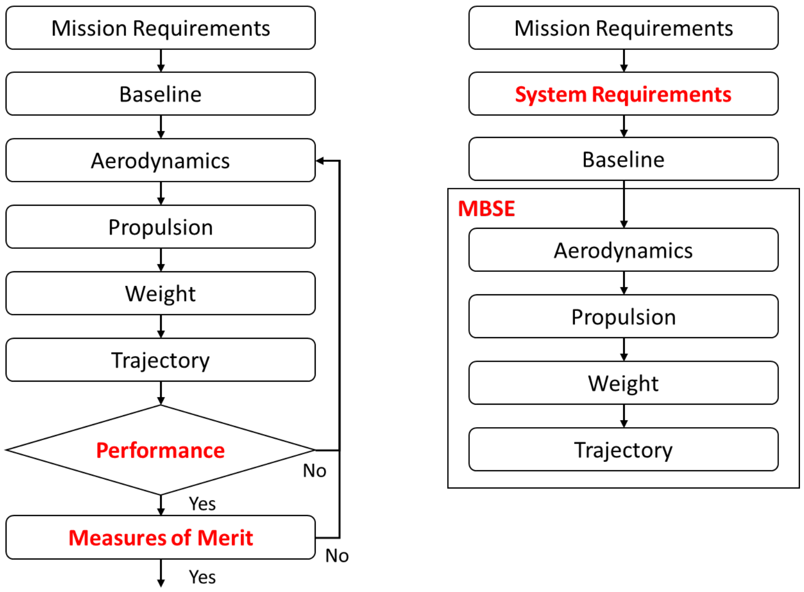
Conceptual Design and System Engineering

- In *Missile Design and System Engineering* (AIAA Education Series), Eugene Fleeman presents a comprehensive approach to first-order conceptual missile design and system engineering
- Two decisions (*Performance* and *Measures of Merit*) within an iterative process



Modified Conceptual Design for MBSE

- Instead of assessing *Performance* and *Measures of Merit* as decisions, move them to *System Requirements*, inserted after the mission requirements, before the baseline is established
- The modified process facilitates Model-Based Systems Engineering (MBSE)

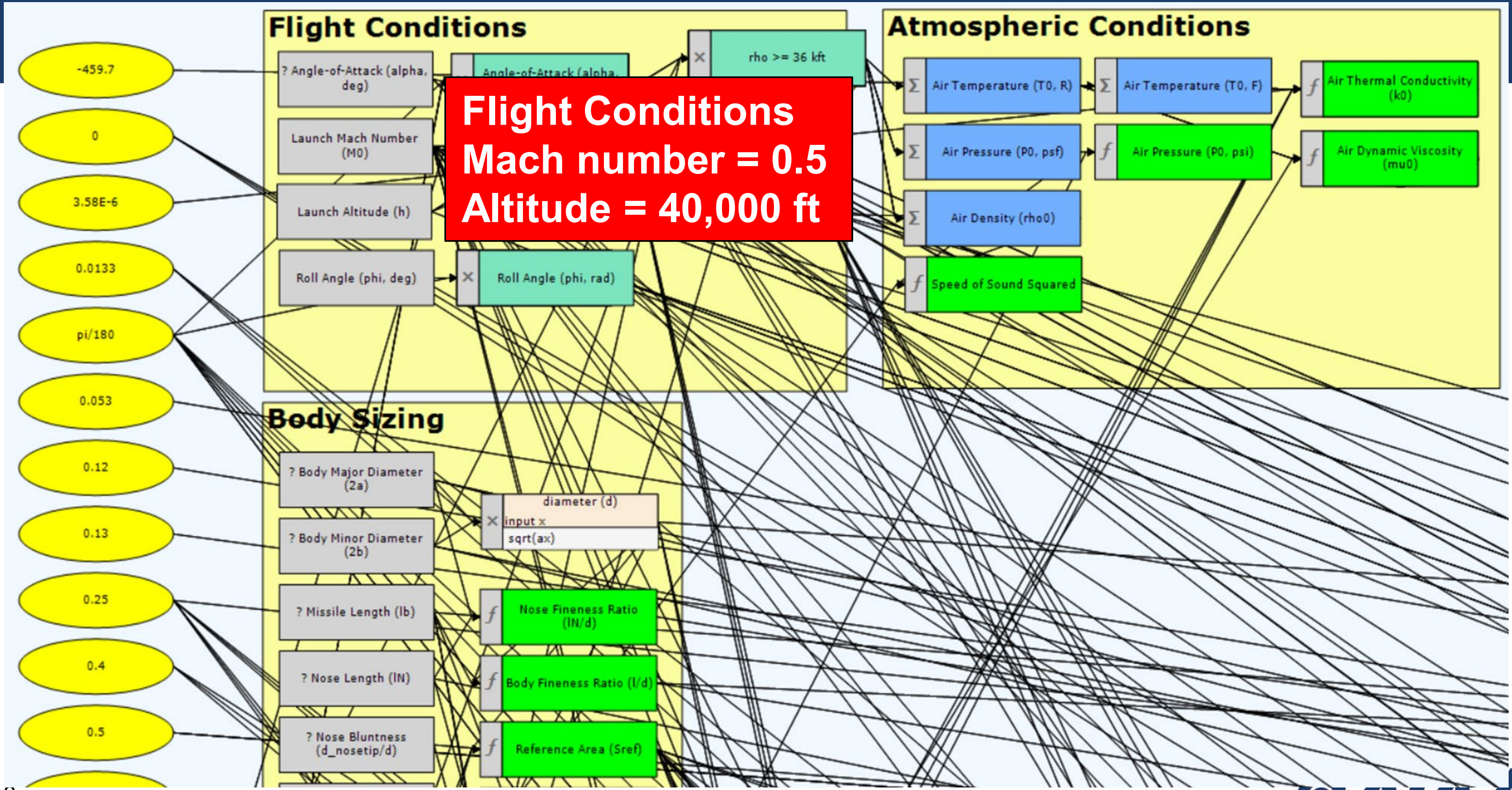


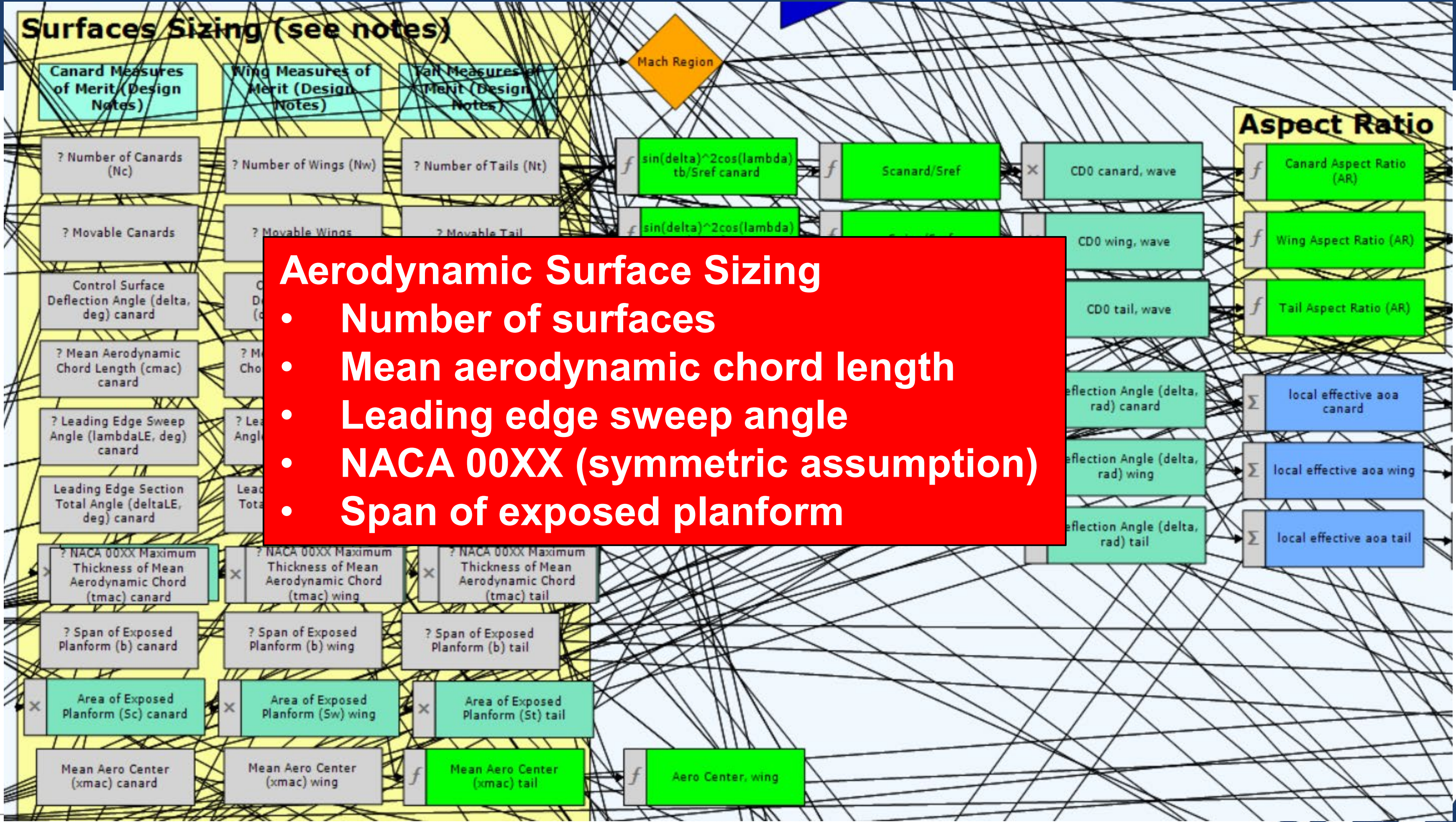
Model Implementation

- Digital twin generic missile model architected from the physics-based engineering equations found in Fleeman's text – implemented in *Evolved AI*™ capable of machine learning and optimization
- Model organized by subsystem, i.e., aerodynamics, propulsion, mass properties, flight performance, and measures of merit (robustness, lethality, miss distance, observables, and survivability)
- Equations verified and validated by checking each formula with sample calculations associated with the examples found in Fleeman's text, his course notes, or in some cases, direct correspondence
- *Evolved AI* and its capability of stochastic optimization allows the System Engineer to optimize the flight performance criteria or measures of merit and observe the influencing parameters

Aerodynamics Application

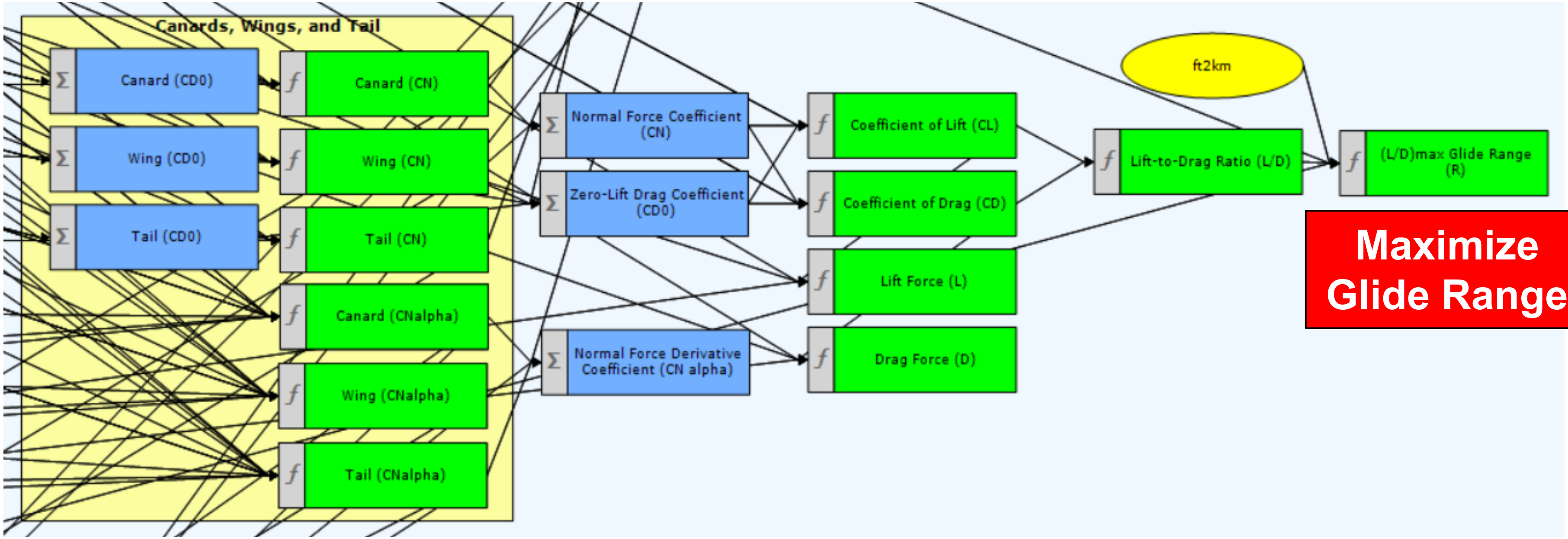
- For certain flight conditions (Mach, altitude, and angle-of-attack), the system engineer may maximize glide range by maximizing L/D
- L/D is based on body geometry (body diameter & length, nose bluntness & length) and aerodynamic surfaces (#canards, wings, and tails and airfoil characteristics)
- Parameters vary with constraints, e.g., body diameter and length may be constrained by the launch platform for which it will be integrated
- Optimal parameters are reported, including sensitivity analyses so the System Engineer can immediately identify the performance drivers


Flight Conditions
Atmospheric Conditions
Body Sizing
Flight Conditions
Mach number = 0.5
Altitude = 40,000 ft
-459.7
0
3.58E-6
0.0133
pi/180
0.053
0.12
0.13
0.25
0.4
0.5
? Angle-of-Attack (alpha, deg)
Launch Mach Number (M0)
Launch Altitude (h)
Roll Angle (phi, deg)
Roll Angle (phi, rad)
rho >= 36 kft
Air Temperature (T0, R)
Air Temperature (T0, F)
Air Thermal Conductivity (k0)
Air Pressure (P0, psf)
Air Pressure (P0, psi)
Air Dynamic Viscosity (mu0)
Air Density (rho0)
Speed of Sound Squared
? Body Major Diameter (2a)
? Body Minor Diameter (2b)
diameter (d)
input x
sqrt(ax)
? Missile Length (lb)
Nose Fineness Ratio (lN/d)
? Nose Length (lN)
Body Fineness Ratio (l/d)
? Nose Bluntness (d_nosetip/d)
Reference Area (Sref)

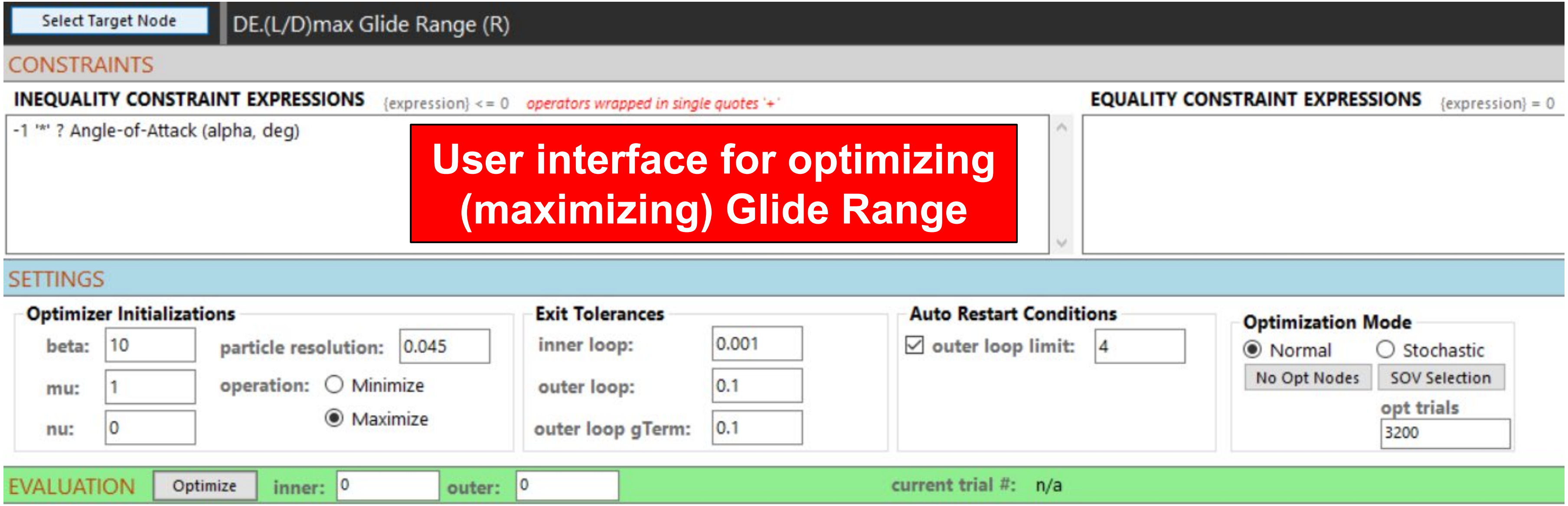


Aerodynamic Surface Sizing

- Number of surfaces
- Mean aerodynamic chord length
- Leading edge sweep angle
- NACA 00XX (symmetric assumption)
- Span of exposed planform



Maximize Glide Range


Select Target Node
DE.(L/D)max Glide Range (R)
CONSTRAINTS
INEQUALITY CONSTRAINT EXPRESSIONS
{expression} <= 0
operators wrapped in single quotes '+'
-1 '*' ? Angle-of-Attack (alpha, deg)
EQUALITY CONSTRAINT EXPRESSIONS
{expression} = 0
User interface for optimizing (maximizing) Glide Range
SETTINGS
Optimizer Initializations
beta: 10
mu: 1
nu: 0
particle resolution: 0.045
operation: Minimize Maximize
Exit Tolerances
inner loop: 0.001
outer loop: 0.1
outer loop gTerm: 0.1
Auto Restart Conditions
outer loop limit: 4
Optimization Mode
Normal
Stochastic
No Opt Nodes
SOV Selection
opt trials
3200
EVALUATION
Optimize
inner: 0
outer: 0
current trial #: n/a

Results with Loose Constraints

Results

- Glide Range = 149 km
- AoA = 1.74 deg

- Body Diameter = 1 in
- Body Length = 20 in

- 1 Canard Sweep = 2.1 deg
- 1 Canard Chord = 1.4 in
- 1 Canard Span = 6.2 in
- 1 Canard NACA 0021

- 2 Tail Sweep = 0.2 deg
- 2 Tail Chord = 1.0 in
- 2 Tail Span = 9.9 in
- 2 Tail NACA 0026

- 1 Wing Sweep = 1.2 deg
- 1 Wing Chord = 2.0 in
- 1 Wing Span = 30 in
- 1 Wing NACA 0028

Tail span half the body length.

Wingspan greater than body length.

The result is essentially an arrow, a little difficult to pack electronics.

Tighter Constraints: Excalibur

- Excalibur
  - M = 106 lb
  - L = 39.2 in
  - D = 155 mm
  - Glide Range = **28.6 km**

Variant 1a-1 has a range of **23 km**
https://en.wikipedia.org/wiki/M982_Excalibur

Results

- AoA = 10.5 deg

- 1 Canard Sweep = 0.3 deg
- 1 Canard Chord = 1.5 in
- 1 Canard Span = 5.4 in
- 1 Canard NACA 0020

- 2 Tail Sweep = 5.0 deg
- 2 Tail Chord = 1.4 in
- 2 Tail Span = 5.4 in
- 2 Tail NACA 0020

Results

- Applying first-order conceptual design optimization (with maximum glide range as an MBSE System Requirement) achieved reasonable results (**29 km**) with the M982 Excalibur (variant 1a-1) performance (**23 km**)

Conclusions

- While the example focused on aerodynamic performance, the digital twin has the capability to optimize parameters associated with propulsion alternatives (rocket, turbojet, ramjet); mass property alternatives and corresponding thermal properties; and other measures of merit (IR, RF, and SAL seekers, accelerometers, gyroscopes, accuracy, warhead lethality, observables, and launch platform integration)
- With the proposed two modifications to the conceptual design and system engineering process, the System Engineer can apply MBSE to optimize the design of a missile based on mission and system (performance/measure of merit) requirements

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Propulsion

- Given nozzle throat and exit diameter/area (expansion ratio)
  - Determine exit pressure, chamber pressure ratio
- Given a desired thrust (FOCD thrust = 10X launch weight)
  - Determine optimal chamber pressure
  - Determine burn area and hence the required volume
  - Determine the burn time
- All based on an assumed propellant
  - Density, characteristic velocity, burn rate, burn rate exponent, discharge efficiency coefficient