Implementation of a Landing Footprint Algorithm for the HTV-2 and Trajectory Simulations

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Overview

• Landing Footprint Generation
  • Motivation
  • Problem Set-Up
  • Explanation of the Algorithm
  • Results
• OTIS Trajectory Simulations
  • MIPCC F-15 Performance Estimation
  • HTV-2
• Two week tour in the Engine Shop
Task 1:
Landing Footprint Generation
Motivation

- A landing footprint provides an estimate of the flyable boundary for a vehicle given initial conditions.
- Current research for re-entry guidance is moving towards onboard trajectory generation.
- Generation of a landing footprint will clearly define possible landing sites in the event of a vehicle malfunction.
- It is critical for the algorithm to be executable in near real-time and provide a realistic estimate of the footprint, taking into account vehicle limitations.
Problem Set-Up

- **Entry Dynamics**
  - \( \theta' = -\frac{\cos(\gamma) \cos(\psi)}{r \cos(\phi)} \left( \frac{1}{D} \right) \)
  - \( \phi' = -\frac{\cos(\gamma) \sin(\psi)}{r} \left( \frac{1}{D} \right) \)
  - \( r' = -\sin(\gamma) \left( \frac{1}{D} \right) \)
  - \( \psi' = \frac{\cos(\psi) \tan(\phi) \cos(\gamma)}{r} + \left( \frac{1}{V^2 \cos(\gamma)} \right) \left( \frac{L \sin(\sigma)}{D} \right) + C_\psi \)
  - \( \gamma' = \left( g - \frac{V^2}{r} \right) \left( \frac{\cos(\gamma)}{V^2} \right) \left( \frac{1}{D} \right) - \left( \frac{1}{V^2} \right) \left( \frac{L}{D} \cos(\sigma) \right) + C_\gamma \)

- Derivatives taken with respect to energy, \( E = \frac{V^2}{2} - \frac{mu}{r} \)
- Control variables are angle of attack and bank angle

Problem Set-Up

• Lift and Drag

\[
L = \frac{1}{2} \rho(r)V^2 \left( \frac{S}{m} \right) C_L(\alpha, M)
\]

\[
D = \frac{1}{2} \rho(r)V^2 \left( \frac{S}{m} \right) C_D(\alpha, M)
\]

• Taking the derivative of Drag twice yields:

\[
\frac{L}{D} \cos \sigma = \frac{1}{b} (D'' - a)
\]

\[
a = D \left( \frac{C''_D}{C_D} - \frac{C'^2_D}{C_D^2} \right) + D' \left( \frac{C'_b}{C_D} + \frac{2}{V^2} \right) - \frac{4D}{DV^4} + \frac{1}{DV^2} \left( \frac{1}{h_s} + \frac{2g}{V^2} \right) \left( g - \frac{V^2}{r} \right) + \left( \frac{1}{h_s} + \frac{2g}{V^2} \right) C_y
\]

\[
b = -\frac{1}{V^2} \left( \frac{1}{h_s} + \frac{2g}{V^2} \right)
\]

• Re-arrange and solve for bank angle

\[
|\sigma| = \cos^{-1} \left( \frac{D}{bL} (D'' - a) \right)
\]
The Algorithm

- Method the algorithm employs requires the computation of upper, lower, and intermediate drag profiles
- These drag profiles are used to create the boundary points of the footprint
- To do this, a nominal angle of attack profile is required

\[
\tilde{E} = \frac{E_{\text{current}} - E_i}{E_f - E_i}
\]
The Algorithm

- Computing the Flyable Upper Drag Boundary:
  - Path Constraints:
    - Dynamic Pressure:
      \[ D < Q_{max} \left( \frac{S}{m} \right) C_D \]
    - Normal Acceleration:
      \[ D < \frac{A_{max}}{\sin \alpha + \frac{L}{D} \cos \alpha} \]
    - Heating:
      \[ D < \frac{1}{2} \left( \frac{Q_{max}}{cV^k} \right)^2 V^2 S C_D \]
The Algorithm

- Flyable lower drag boundary
  - Determined by the equilibrium glide condition: \( \gamma' = 0 \) and \( \sigma = 0 \)

\[
\gamma' = \left( g - \frac{V^2}{r} \right) \left( \frac{\cos(\gamma)}{V^2} \right) \left( \frac{1}{D} \right) - \left( \frac{1}{V^2} \right) \left( \frac{L}{D} \cos(\sigma) \right) + C_\gamma
\]

\[
0 = \left( g - \frac{V^2}{r} \right) \left( \frac{1}{V^2} \right) \left( \frac{1}{D} \right) - \left( \frac{1}{V^2} \right) \left( \frac{L}{D} \right)
\]

\[
L = \left( g - \frac{V^2}{r} \right) \Rightarrow D_{\text{min}} = \frac{C_D}{C_L} \left( g - \frac{V^2}{r} \right)
\]

- Intermediate drag values are interpolated from the maximum and minimum drag profiles
  - \( D(E) = D_{\text{max}}(E) + c(D_{\text{min}}(E) - D_{\text{max}}(E)) \)
Simulated HTV-2 Data

Angle of Attack Profile

Altitude Profile
Simulated HTV-2 Data

Velocity Profile

Velocity vs. Energy for the HTV-2
Drag Profile Results

Sample Drag Profile from the Paper

Drag Profile Result
Further Results
Resulting Footprint
Future Work

- The lower drag boundary can be improved upon by adding the constraint that $\gamma \leq 0.01$ to reduce phugoid motion
  - A feedback linearization based flight path controller is used:
    \[
    \frac{L}{D} \cos \sigma = \frac{K_{\gamma} V}{D} (\gamma_{\text{ref}} - \gamma) + \frac{1}{D} \left( g - \frac{V^2}{r} \right) \cos \gamma - \frac{2 \omega V}{D} \cos \psi \cos \phi
    \]
- Obtain the correct constraint parameters to obtain an accurate drag curve, and thus a more accurate footprint
- Improve the speed of the algorithm
  - Paper claims 2 seconds, written in C
  - My result: 39.5 seconds for the footprint presented, 8.48 seconds to compute the drag profiles presented
Task 2:

OTIS Trajectory Simulations
OTIS Overview

- OTIS: Optimal Trajectories by Implicit Simulation
- Largely 3DOF Simulation software that treats the inputted vehicle as a point-mass
- Aerodynamics, propulsion, and reference area data are inputted to define the vehicle
- Capable of explicit and implicit integration, as well as multi-phase trajectory problems
- Implicit integration techniques are used to optimize a user-specified parameter along a chosen trajectory
F-15 MIPCC Modeling

- MIPPC: Mass Injected Pre-Compressor Cooling
  - A mixture of LOX and water are injected into the engine at high altitudes and Mach numbers,
  - Theoretically provides increased performance by cooling the compressor face and providing increased mass flow
Engine data for the Pratt & Whitney F100-100 was obtained from the Status Engine Estimated Steady State Performance Deck:
  - Data extracted was for maximum throttle over a wide range of altitudes.

Aerodynamic data was obtained from flight test data presented in graphs provided in the paper by Haering and Burcham for a range of Mach and altitudes:
  - Data was extracted from graphs using the MATLAB program Ascribe by David Berger.
  - Data was formatted and placed in an external file called by the main OTIS input file.
OTIS Calibration to F15 Streak Eagle

Min Time to Climb Results
MIPCC Modified F-15 OTIS Simulation

- Thrust and ISP data was inputted in accordance with predicted apparent Mach and Altitude
- MIPCC model was then run up to Mach 4 at a variety of altitudes
  - Explicit path used to verify Implicit integration
  - Energy was the chosen parameter to be optimized
    - \( e = \frac{v^2}{2g_0} + alt \)
- From OTIS, specific power curves and sample trajectories were outputted

Projected MIPCC Results (Carter, P.H.)
MIPCC Modified F-15 Sim: Results

• The study has been completed and the results are projected to appear in a NASA Technical Memorandum publication:
HTV-2 OTIS Simulation

- Work in progress…
- Explicit OTIS simulation complete
  - Trajectory begins at specified velocity, altitude, and weight and completes in the inputted time
- Implicit OTIS simulation still left to finish
  - Boundary conditions need to be added so that final energy state matches known data
Task 3:

Tour in the Engine Shop
The Engine Shop

- Provided hands-on experience
- During my two weeks...
  - Removed a mixer, A/B liner, pilot valves, distributor valves, spray bars, nozzle flaps, and a damaged flame holder, from an F404 engine
  - Aided in boroscopying 850, 852, and SOFIA
  - Watched an engine test run
Questions?


