Development of a MonteCarlo Flight Simulation Suite

Team 58 Project Technical Presentation to the 2017 IREC

Roshan C. Doddanavar

Texas A&M University, College Station, TX, 77840

INTRODUCTION

To fulfill the requirements of the 2017 IREC Competition, the Texas A&M University Sounding Rocketry Team (TAMU SRT) must strive to reach an altitude of 10,000 ft AGL with its SRAD Hybrid entry *Daedalus*. In order to meet this metric, the team must have the capability to accurately predict the trajectory of the rocket, given knowledge of the rocket's properties and a realistic assumption of flight conditions.

Free, readily available flight simulation software already exists: OpenRocket[a], a 6 Degree-of-Freedom (6-DOF) software package, and RASAero[b], a 3-DOF package with advanced aerodynamic analysis, are well respected and used throughout the amateur rocketry community. However, both of these programs are missing key capabilities, such as hybrid engine modeling, advanced atmospheric modeling, and landing zone analysis. Additionally, they only produce *nominal* flights, without any consideration for uncertainty in rocket properties and flight conditions.

This creates the need for a flexible, easily extensible flight simulation that can quantify the uncertainty in a trajectory through the MonteCarlo method. The *SRT Flight Sim* (SRT FS), a 3-DOF simulation suite implemented in MATLAB®, has been developed to fufill this need.

MODELING

Equations of Motion (EOM)

The motion of the rocket is analyzed in two distinct phases, ascent and descent. During its ascent, the rocket is modeled as a rigid body with 3 degrees-of-freedom, two translational (inertial x & y) and one rotational (pitch θ). Second-order nonlinear ordinary differential equations (ODE) are built to model the motion and attitude as a function of time; these ODE's are then solved numerically using an integration scheme. After reaching apogee, the rocket is then idealized as a point-mass with three translational degrees-of-freedom (inertial x, y, z); this is done with the assumption of a fixed attitude under parachute descent. In a similar fashion as the ascent phase, an ODE for this motion is constructed and solved numerically.

Propulsion & Mass

The thrust profile of the hybrid engine as a function of temperature, pressure, and oxidizer mass is found through a separate software package, also developed internally by TAMU SRT (see *Hybrid Rocket Engine Thrust Prediction and Verification*, Alexander E. Pages[c]). Using the mass flow rates produced by this model, the mass properties of the rocket (weight, center-of-gravity, & longitudinal moment-of-inertia) are found as a function of time during the course of the engine's burn.

Aerodynamic

An aerodynamic database is generated using RASAero's analysis tool; drag coefficient (C_L), lift coefficient (C_D), & center of pressure position (x_{cp}) are found as a function of mach number and angle-of-attack. Distinct databases are built for the boost and coast phases of the rocket's flight. An average skin roughness across the rocket's body is used, approximated from profilometer measurements.

[a]Developed by Sampo Niskanen, licensed under the GNU GPL
[b]Developed by Charles E. Rogers and David Cooper
[c]Team 58 Project Technical Presentation to the 2017 IREC

Atmospheric

An atmospheric model is built using the Standard Atmosphere assumptions for isothermal and gradient regions, up to ~280,000 ft above sea level (ASL); this model takes in launch site temperature, pressure, humidity, and elevation, and outputs temperature, pressure, & density as a function of altitude. Using the dry lapse rate of each atmospheric region, the partial pressure of water vapor is found as a function of altitude, and a density correction for humidity is applied.

Wind turbulence is modeled as a 1-D velocity signal, derived from the stochastic von Kármán wind turbulence model. Discrete pink noise samples are generated from white noise using a digital filter. By prescribing an average windspeed (U_{avg}) and a turbulent intensity (I_U), a 1-D wind velocity time-series is then built from the pink noise signal.[1]

SIMULATION & ANALYSIS

MonteCarlo Method

In order to quantify uncertainty in the rocket's trajectory, several hundred random flights are simulated; the initial conditions of each flight are unique, and are assigned based on user-specified random distributions. The Runge-Kutta-Fehlberg Method (RKF45) is used to numerically solve the ODE's of motion, with a constant step size of 0.01 s. At every time step, random error is inserted into rocket and atmospheric properties; the random error is derived from Uniform, Gaussian (Normal), or Wiener distributions, with parameters (μ, σ, etc.) defined by the user.

Post-Processing

For the rocket's ascent, the time history of every flight variable (position, velocity, acceleration, etc.) is processed across the entire set of random flights, yielding a mean behavior. This mean behavior, in addition to the standard deviation and maximum/minimum values associated with each variable, allows the user to make quantitative assessments about the uncertainty in the nominal trajectory.

For the rocket's descent, the Circular Error Probable (CEP) of the set of landing points is used as the primary analysis tool. A radial zone centered on the mean landing point includes several sub-zones, each of which captures a different percentage of landings (CEP25 ≡ 25%, CEP50 ≡ 50%, etc.). This metric allows the user quantify the error in the predicted landing point, and understand how the landings are distributed. This landing zone is then projected onto a Google™Earth rendering of the launch site and surrounding areas, allowing the user to see how it interacts with local geographic features. This process can be repeated for a range of wind headings & speeds, and launch rail elevation/azimuth. In this fashion, rail pointing can be optimized to minimize recovery hazards.

VERIFICATION & FURTHER WORK

On October 29th, 2016 *Daedalus* was launched in Asa, TX under the power of a CTI N2500 motor[d]. As reported by the on-board flight computers, the vehicle reached an altitude of 8777 ft AGL. The SRT FS predicted an apogee of 8656 ft ± 315 ft ($\pm 2\sigma$), fully capturing the flight data within its error bounds.

In the future, aerodynamic databases need to be augmented by high-fidelity CFD simulation, and refined through additional wind tunnel testing. Considerations for pitch damping and other neglected forces/moments need to be made. The capability to model multi-stage vehicles is a necessity as TAMU SRT attempts larger projects.

REFERENCES

[1]Niskanen, S., "Development of an Open Source model rocket simulation software," Helsinki University of Technology, 2009.

[d]COTS, manufactured by Cesaroni Technology Incorporated