Probabilistic modelling of space object controlled reentry and ground risk estimation

Francois Sanson (Inria)
Charles Bertorello (ArianeGroup)
Jean-Marc Bouilly (ArianeGroup)
Pietro Marco Congedo (Inria)
Initial conditions ?
Fragmentation criteria ?
Debris release conditions ?
Material behaviour to ablation ?
System of solvers for reentry trajectory predictions

- Initial conditions
- Material characteristics
- Mesh
- Range of flight conditions
- Debris characteristics

Many uncertain parameters that need to be propagated

Brute force Monte Carlo propagation is out of reach
Probabilistic modeling of breakup

$p_{abl}$ and $T_{frag}$ are additional uncertainties

fragmentation range

$t_{init}$ and $t_{end}$

mass

temperature

$T_{frag}$

$p_{abl}$
- Breakup occurs at random between $t_{\text{init}}$ and $t_{\text{end}}$
- Pre-computed fragments are released at breakup
Cases under investigation

GTO Reentry:

- Slope: -9 degrees
- Velocity: 9600 m/s
- Equatorial orbit

Object characteristics:

- Mass: 7000 kg
- Material: aluminium

Scenario:

- Controlled reentry
Uncertainties characterization:

Initial conditions:
- Boost time
- Boost orientation
- Orbital elements
- Upper Stage orientation: uniform

Material uncertainties: for Aluminium, Steel, Inconel, Titanium
- Density
- Emissivity
- $T_{\text{fusion}}$
- $H_{\text{fusion}}$

Atmosphere conditions:
- Solar flux: [65:240]
- Magnetic index: [2:75]
- Time: [0:365]

Fragmentation model parameters:
- $T_{\text{frag}}$: [400,700] K
- $P_{\text{abl}}$: [0.7, 0.9]

Total 38 uncertainties
Challenges with Uncertainty Quantification and probabilistic modelling

- Explore the potential outputs of a given probabilistic scenario → requires a lot of simulations
- Sensitivity Analysis: quantify the variation in the output due to variations in the inputs → requires a lot of simulations
Architecture of the system of surrogate models

- Initial conditions
- Material characteristics
- Mesh
- Range of flight conditions
- Debris characteristics

Allow very efficient uncertainty propagation

Breakup predictions
Altitude and velocity at breakup:
Altitude and velocity at breakup:
Identifying sources of uncertainties:

![Graph showing deorbiting properties and breakup model parameter]
Survivability predictions
Survivability probability

What is the probability for a given object to reach the ground?
Sensitivity Analysis on the residual mass

Initial conditions

Breakup model parameter

Fragment temperature at breakup
Impact location
Impact zone using Minimum Volume Sets

- Generalization of confidence intervals
  \[ \min_{\Omega} \text{Vol}(\Omega) \text{ subject to } P(X \in \Omega) \geq 1 - \epsilon \]

- Also defined in multivariate case
  - Confidence intervals do not generalize easily in 2D
  - They do not seem optimal for disjoint distributions

- Under mild assumptions it is a level set of the pdf
Impact zone using Minimum Volume Sets

\[
\min_{\Omega} \text{Vol}(\Omega) \text{ subject to } P(X \in \Omega) \geq 1 - \epsilon
\]

Impact zone at 99.99 %

Impact zone at 99.998 % [99.9985;99.9975] %

( using 3.3e6 samples, 3 sigmas)

Conclusions:

- Developed a robust reentry predictor using simple models

- The use of advanced uncertainty quantification tools cut down computational cost (millions of samples generated in a 2 hours on single core)

- Mathematical definition of impact zone

- More advanced probabilistic models are under development

- Uncertainty Quantification can provide quick and robust answers to complex problems
Related work:

- F. Sanson, C. Bertorello, J-M. Bouilly, P.M. Congedo, *Breakup prediction under uncertainty: application to upper stage controlled reentries from GTO orbit*, Aerospace Science and Technology, 2018, submitted: https://hal.archives-ouvertes.fr/hal-01898010v1


- F. Sanson, C. Bertorello, C. Finzi, J.M. Bouilly, P.M. Congedo, Robust Ground footprint estimation for reentering space objects, 4th International Space Debris Workshop, Darmstadt, Germany, April 2018

- F. Sanson, J.M. Bouilly, P.M. Congedo, *Uncertainty Quantification in Orbital Debris Reentry for Reliable Ground Footprint Estimation*, ESA Space Debris conference 2017 - 7th European Conference on Space Debris, Darmstadt, Germany, April 2017
Thank you

François Sanson : francois.sanson@inria.fr

Jean-Marc Bouilly : jean-marc.bouilly@ariane.group
Uncertainty quantification tools:

**Gaussian Processes**

Surrogate model construction with predictive error estimation

Used to generate Aerodynamic table with less than 0.2% error:

Computational cost with surrogate: 1500
Computational cost without surrogate: 10 000
Difficulty for survivability prediction: building a surrogate model on the discontinuity

Survivability

Burn up

yes → Burn up altitude

no → Impact position
Approach: use a Support Vector Machine classifier

SVM separates the uncertainty space between objects that burn and objects that do not.