A Systems Engineering Approach to Spacecraft Trajectory Optimisation

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Overview

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Speakers Bio

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Introduction

• Presenting a Systems Engineering (SE) approach in response to:
  – Global and rising use of miniaturised spacecraft
  – Availability of high fidelity software suites
  – Mitigate risks with space environment operations

• Motivated to objectively assist and benefit
  – Research organisations with scarce space engineering experience
  – Space industry development (SME’s)
Research Objectives & Motivations

• Miniatu...
Constellation Design Framework
Methodology – Conceptual Mission Architecture

- Specialised launch vehicle service; 12 co-planar miniaturised satellites
Constellation Design Framework
Methodology - Overview

• Automated process chain (originally developed at UNSW Canberra)
Constellation Design Framework
Methodology – *Evolutionary Algorithms*

- **MATLAB**

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**Evolutionary Algorithms**

*Decision variables* 
\{*Cluster initial state, Manoeuvres*\}

- **Evolutionary algorithms**
  - Elitist real-coded genetic algorithm inspired by biological evolution
  - A population with \(N\) individuals evolves for \(G\) generations via:
    - crossover
    - selection
    - reproduction
    - mutation

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Scenario Initialization

- Systems Tool-Kit MATLAB Application Programming Interface

- Decision Variables
  - Initial State (Keplerian, or other elements)
    \[ Orbital \ State = \{ n, i, e, \Omega, u \}, \ Epoch \]
  - Spacecraft Parameters
    \[ Dry \ Mass, C_D, C_R, C_K, Exposed \ Areas \]
  - Manoeuvre requirements (to achieve desired state)
    \[ \Delta H_1, \ldots, \Delta H_{11} \] (Reference satellite does not perform a manoeuvre)
Constellation Design Framework
Methodology – Numerical integration

- High Precision Orbit Propagation (HPOP)

- Mission architecture
  - Mission Control Sequence (MCS) graphically programmed
  - Converges on objectives (Delta V) according to:
    - HPOP capabilities
    - Atmospheric Model (F10.7): MSISE
    - Solar Radiation Pressure: Spherical SRP
    - Geopotential Model: WGS84EGM96
    - Third-body Model: Gravity Fields
    - Numerical Integration & Error Control: Upto 9\textsuperscript{th} order Runge-Kutta-Verna with 8\textsuperscript{th} order error control
Constellation Design Framework
Methodology – Post Processing

• MATLAB Programming Interface

• Solution
  – Objective Function
    \[ f_1 = \min \left( \sum_{i=1}^{12} |\Delta V_{x,y,z}| \right) \text{ [km/s]} \] (1)
  – Objective Function
    \[ f_2 = \min \left( \max (\Delta t_{phase}) \right) \text{ [s]} \] (2)
  – Objective Function
    \[ f_3 = \min (E_{Ref}) \text{ [rads]} \] (3)
  – Constraint Functions
• Surrogate modelling
  – In-lieu of computationally demanding numerical integration
  – Predicts objective functions for given input parameters
    – Response surface models
    – Radial basis functions (Artificial Neural Network)
    – Kriging approximation if:
      – Prediction error (Sq. Mean Error) < 5 %
        (best performing surrogate chosen)
Constellation Design

Results – *Double Transfer Co-Planar Phase*

**J2 Perturbations**

- Generation = 50

<table>
<thead>
<tr>
<th>HPOP Candidate</th>
<th>Delta V</th>
<th>Time</th>
<th>Rads</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.47 km/s</td>
<td>~70 hrs</td>
<td>~0.03</td>
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</tbody>
</table>

**HPOP model**

- Generation = 30
• Mean motion (Altitude) most pronounced effect on Delta-V and Radiation Dose

• Eccentricity most pronounced effect on phasing time, 2nd most on Rad Dose

• Varying Delta-H affects phasing time more so than Delta V
Research Output
RASC-AL 2016 & RASC-AL 2017

• Revolutionary Aerospace Systems Concepts – Academic Linkage
  – Full-scale space mission architecture design competition
  – Presenting ‘ELITE’ in Florida, May 2017
Research Output

GTOC 9

- European Space Agency - Global Trajectory Optimization Competition 9
  - Catastrophic LEO debris scenario
  - Highly constrained design space
Research Output

- MDO of Mini Cusped Field Thruster
  - ASRC 2016 (Muffatti & Ogawa)

- Multi-objective Trajectory & Control Optimisation for Multi-Asset Deployment
  - Rocket-Based Combined Cycle (RBCC) Two-Stage-to-Orbit Launch Vehicle AIAA 2014 (Ogawa)
Future Work (Cont.)

- Multi-asset, multi-plane orbital strategies – 31 ISTS (Japan)
  - RAAN Phasing by J2 perturbations
  - Utilizing optimal CFT model derived by Muffatti & Ogawa
- Uncertainty Quantification (UQ) – IAC 2017
  - Multiple simulators
  - Many modelling inputs

**UQ Framework**

- Scenario initialization
- Mission architecture
- Multiple Simulators
- Solution
- Post processing
- Decision variables
- Surrogate-assisted EA
- Evaluated objectives
Acknowledgements

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