An Integrated System-Operations Approach to the Optimal Design of Small-Scale Satellites

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UNOOSA United Nations Office for Outer Space Affairs
Problem formulation

- Cheaper/Faster/Better

Methodology

- Integrated System/Operations design
  - Inner loop
  - Outer loop
- Generic satellite EPS – TTC – Payload

Conclusions

Future work
Cheaper/Faster/Better

- Spacecraft design is a complex concurrent distributed task involving numerous risk factors
  
  - Approx. 43% of failures may be attributed to human error

Also

- The “cheaper, faster, better” triptych aims at making space accessible to institutions with lower budgets

Therefore:

- Making space mission design more robust and affordable is important
Cheaper/Faster/Better

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Integrated System-Operations Design Approach

Integrated approach comprising two nested loops:

**Inner loop:** Optimal operations schedule
Integrated System-Operations Design Approach

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**Inner loop:** Optimal operations schedule

**Outer loop:** Pareto set of optimal satellite designs
Integrated System-Operations Design Approach

Integrated approach comprising two nested loops:

**Inner loop:** Optimal operations schedule

**Outer loop:** Pareto set of optimal satellite designs

Aim:
- Maximise satellite usage
- Optimise satellite design
- Enhance overall design robustness
- Alleviate designer workload by automating the process
Integrated System-Operations Design Approach

Modular flexible approach

Consisting of enclosed loops

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Modular flexible approach

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- Future work
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Inner Loop

- Orbit calculation
- Useful Operation
- Incident Solar Radiation
- Subsystem modelling
- Search space creation
- Schedule Optimiser
Integrated System-Operations Design Approach

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Classical orbital elements: $a, e, i, RAAN, \omega, Mo$
Integrated System-Operations Design Approach

**Inner Loop**

- Orbit calculation
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Integrated System-Operations Design Approach

- Subsystem analytical modelling
  - ACS (Attitude Control System)
  - CDH (Command and Data Handling)
  - EPS (Electrical Power System)
  - HARN (Harness)
  - PROP (Propulsion)
  - TTC (Telemetry, Tracking and Command)
  - SM (Structures and Mechanisms)

All models implemented in MATLAB®
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All models implemented in MATLAB®

- ESA LISA Pathfinder used as test case
Integrated System-Operations Design Approach

Each model’s *main outputs* are:
- Expected mass (kg)
- Expected power consumption (W)

*Additional outputs* can be:
- Battery capacity (Power system)
- Solar array area (Power system)
- Downlink data rate (TT&C system)

and more

Models can be used as
- Standalone for preliminary budget design
- In conjunction with optimisers for optimal satellite design
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Full satellite analytical model

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Table: Subsystem States

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Ant Colony Optimisation

- Nature inspired discrete optimisation metaheuristic
- Extensively used for solving complex 2D problems (e.g. TSP, VRP, JSP)
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Integrated System-Operations Design Approach

Ant Colony System
Originally invented by Dorigo & Gambardella (1997), based on Ant System

- Transition rule \( j = \arg \max_{u \in J_i^k} \{ [\tau_{iu}(t)]^\alpha \cdot [\eta_{iu}]^\beta \} \) if \( q \leq q_0 \)

\[ p_{ij} = \frac{[\tau_{ij}]^\alpha \cdot [\eta_{ij}]^\beta}{\sum_{l \in J_i^k} [\tau_{il}]^\alpha \cdot [\eta_{il}]^\beta} \] if \( q \geq q_0 \)

- Pheromone update

- Candidate list \( J_i^k \)

representing the closest cities
Integrated System-Operations Design Approach

Schedule Optimiser
Ant Colony Optimisation based

Objective function: \( \max\{Q\}, Q = T \cap OP_{\text{max}} \)

- **Transition rule:**
  \[
p_{ij} = \frac{[\tau_{ij}]^\alpha}{\sum_{l \in J_i^k} [\tau_{il}]^\alpha}
\]
  \[
  \tau_0 = \frac{1}{C}
\]

- **Pheromone update:**
  \[
  \tau_{ij}(t) \leftarrow (1 - \xi) \cdot \tau_{ij}(t) + \xi \cdot \tau_0(t)
  \]
  \[
  \tau_{ij}(t) \leftarrow (1 - \rho) \cdot \tau_{ij}(t) + \rho \cdot \Delta \tau_{ij}(t)
  \]

- **Solution quality:**
  \[
  \Delta \tau_{ij} = \frac{Q^+}{10^{|\text{Magn}_0| + |\text{Magn}_p|} \cdot P_{\text{peak}}}
  \]

- **Candidate list:**
  \[
  J_i^k, \quad \forall J \in (t + 1)
  \]
Integrated System-Operations Design Approach

Schedule Optimiser

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Schedule Optimiser

- Prioritisation of jobs
- Respect of constraints
- Maximisation of subsystem operation
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Schedule Optimiser
Global pheromone influence: 10 Ants, $\rho = 0.01$
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Schedule Optimiser

Global pheromone influence: 10 Ants, $\rho = 0.02$

![Graph showing probability density function vs. tour quality.](image)

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Global pheromone influence: 10 Ants, $\rho = 0.05$
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Global pheromone influence: 10 Ants, ρ = 0.1
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Schedule Optimiser
Global pheromone influence: 10 Ants, $\rho = 0.2$

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Cost as a function of global pheromone evaporation rate

Average useful operation [time steps]

Processing time [min]

Global pheromone evaporation constant

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Schedule Optimiser
Local pheromone influence: 10 Ants, $\xi = 0.1$
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Schedule Optimiser
Local pheromone influence: 10 Ants, $\xi = 0.2$

![Graph showing tour quality distribution with different density functions.](image)
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Schedule Optimiser
Local pheromone influence: 10 Ants, $\xi = 0.3$

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Schedule Optimiser
Local pheromone influence: 10 Ants, $\xi = 0.4$

10 Ants, $\xi=0.4$ using pheromone only (no local heuristic).

Probability Density Function

Tour quality

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Schedule Optimiser
Local pheromone influence: 10 Ants, $\xi = 0.5$

10 Ants, $\xi=0.5$ using pheromone only (no local heuristic).

Probability Density Function

Tour quality

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Schedule Optimiser
Ant number influence: 10 Ants

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Schedule Optimiser

Ant number influence: 20 Ants

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Schedule Optimiser
Ant number influence: 30 Ants

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Operation quality vs ant number in colony

Average useful operation [timesteps]

Processing time [min]

Ant number in colony

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Outer Loop

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Outer Loop

Agent-based multi-objective stochastic optimisation

3 objectives:

- \( \min(M_{\text{Total}}) \)
- \( \max(D_{\text{RATE}}) \)
- \( \max(Q) \)

Output:

- Pareto set of optimal satellite designs
Integrated System-Operations Design Approach

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Integrated System-Operations Design Approach

Outer Loop

- Output: Pareto set of optimal satellite design vectors
Integrated System-Operations Design Approach

Optimal design vectors

Each column represents one Pareto point

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<td>3.53</td>
<td>4.02</td>
</tr>
</tbody>
</table>
Integrated System-Operations Design Approach

Outer Loop

- Output: Pareto set of optimal satellite designs

The TTC design parameters correspond to:

- **f** – Transmission Frequency [GHz]
- **Ant** – Antenna Type [1- Horn, 2 - Parabolic reflector]
- **Mod** – Modulation
- **T** – Amplifier
- **Te** – Amplifier noise [K]
- **F** – Receiver Noise Figure [dB]
- **Tet** – Amplifier noise [K]
- **Ft** – Transmitter Noise Figure [dB]
- **Tant** – Antenna Noise Temperature [K]
- **nt** – Antenna efficiency [%]
- **Lc** – Antenna characteristic length [m]
Integrated System-Operations Design Approach

Outer Loop

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The *EPS* design parameters correspond to:

- **SAT** – solar cell efficiency [%]
- **XE** – Energy transfer during eclipse [%]
- **XD** – Energy transfer during daylight [%]
- **ID** – Inherent degradation [%]
- **SM** – Array specific mass [kg/m²]
- **NPCU** – PCU efficiency [%]
- **SED** – Battery pack specific energy density [Wh/kg]
- **Vdrop** – Maximum permissible bus voltage drop [%]
## Optimal design vectors

Each column represents one Pareto point

<table>
<thead>
<tr>
<th>TTC design parameters</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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</thead>
<tbody>
<tr>
<td>f [GHz]</td>
<td>4</td>
<td>3.87</td>
<td>4.21</td>
<td>4</td>
<td>5.15</td>
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<tr>
<td>Ant</td>
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<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Mod</td>
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<td>0.46</td>
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<td>T</td>
<td>0.44</td>
<td>0.53</td>
<td>0.56</td>
<td>0.44</td>
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<tr>
<td>Te [K]</td>
<td>91.49</td>
<td>91</td>
<td>86.91</td>
<td>91.49</td>
<td>93.77</td>
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<tr>
<td>Tet [K]</td>
<td>49.62</td>
<td>53.57</td>
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<tr>
<td>Ft [dB]</td>
<td>12.79</td>
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<td>12.21</td>
<td>12.79</td>
<td>13.78</td>
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<tr>
<td>Tant [K]</td>
<td>50.98</td>
<td>66.1</td>
<td>62.66</td>
<td>62.45</td>
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<td>nt</td>
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<td>0.75</td>
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<tr>
<td>Lc [m]</td>
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<td>0.3</td>
<td>0.3</td>
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<table>
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<tr>
<td>SAt</td>
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<td>0.29</td>
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<td>0.32</td>
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<tr>
<td>Xe</td>
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<td>Xd</td>
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<tr>
<td>S_Ed [Wh/kg]</td>
<td>123.3</td>
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<td>63.81</td>
<td>123.3</td>
<td>183.5</td>
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<tr>
<td>V_drop</td>
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<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
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<tr>
<td>M_tot [kg]</td>
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<td>3.45</td>
<td>3.52</td>
<td>3.53</td>
<td>4.02</td>
</tr>
</tbody>
</table>
Integrated System-Operations Design Approach

Outer Loop

- Output: Pareto set of optimal satellite designs

![3D scatter plot showing data rate vs. total satellite mass vs. useful operation in timesteps. The plot includes a blue arrow pointing to the Pareto set.]
Integrated System-Operations Design Approach

Conclusions

Modular tool aiming at:
- Maximising satellite usage
- Keeping physical and electrical characteristics minimal

Integrated approach offering:
- Optimisation of operations schedule
- Optimisation of full satellite design

Result:
- Optimisation of overall design
- Automation of early design stages
- Enhanced robustness of overall design
Integrated System-Operations Design Approach

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Future work

- Add efficient heuristics in Schedule Optimiser (currently in contact with the Strathclyde Planning Group, http://planning.cis.strath.ac.uk/).

- Parallelise Schedule Optimiser (GPU-based ACO design)

- Apply proposed technique to a real satellite
Special thanks

For their kind support!
Thank you for your attention!
Arigatou gozaimasu!