Optimal Power Harness Routing for Small-Scale Satellites

Eirini Komninou, Dr. Massimiliano Vasile, Dr. Edmondo Minisci

eirini.komninou@strath.ac.uk
massimiliano.vasile@strath.ac.uk
Edmondo.Minisci@glasgow.ac.uk
Cheaper – Faster – Better philosophy

Nowadays the space industry triptych* ( & challenge) is:

- Cheaper – Lower the mission cost
- Faster – Lower the design & implementation time
- Better – Keep a high quality standard & achieve most mission targets

How to achieve this triptych:

- Scale down satellites
- Optimise their design

How can a small-scale satellite design be optimised?

*triptych /ˈtrɪptɪk/ noun: a picture or carving on three panels, typically hinged together vertically and used as an altarpiece.
Satellite subsystem modelling

- Develop high-fidelity subsystem models
- Develop an optimisation approach to perform subsystem optimisation

**Aim:** Complete optimised system design

- The Harness subsystem is usually designed based on integration convenience (e.g. available inner satellite volume, ease of integration). Therefore, the first subsystem that was chosen to be optimised is the **Harness**.
Harness simulator

- 3D representation of a generic satellite configuration
- Discretised satellite space (currently 1998 nodes)
- Collision detection feature – avoid solids
- Automatic interfacing between subsystems
Ant Colony Optimisation

- Nature inspired discrete optimisation metaheuristic
- Extensively used for solving complex 2D problems (e.g. TSP, QAP, VRP, JSP)
- Few 3D instances focused on generic pipe routing
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 $q \leq q_0$
  \[
p_{ij} = \frac{[\tau_{ij}]^\alpha \cdot [\eta_{ij}]^\beta}{\sum_{l \in J_i^k} [\tau_{il}]^\alpha \cdot [\eta_{il}]^\beta}
  \quad \text{if } q \geq q_0
\]

- Pheromone update
  - Local $\tau_{ij}(t) \leftarrow (1 - \xi) \cdot \tau_{ij}(t) + \xi \cdot \tau_0(t)$
  - Global $\tau_{ij}(t) \leftarrow (1 - \rho) \cdot \tau_{ij}(t) + \rho \cdot \Delta \tau_{ij}(t)$
  \[
  \Delta \tau_{ij} = \frac{1}{L^+}
  \]

- Candidate list $J_i^k$ representing the closest cities
3D Ant Colony Optimisation HARNess optimiser is loosely based on the Ant Colony System

**Objective function**

\[
\min \{ L_{\text{total}}^c \}
\]

- **Transition rule** using stochastic sampling
  \[
p_{ij} = \frac{[\tau_{ij}]^\alpha \cdot ([\eta_{\text{loc}}]^{(\beta+1)} + [\eta_{\text{glob}}]^{\beta})}{\sum_{l \in J_i^k} [\tau_{il}]^\alpha \cdot ([\eta_{\text{loc}}]^{(\beta+1)} + [\eta_{\text{glob}}]^{\beta})}
\]
  \[
  \tau_0 = \frac{1}{L_{\text{eucl}}}
\]

- **Pheromone update**
  \[
  \tau_{ij}(t) \leftarrow (1 - \xi_{ad}) \cdot \tau_{ij}(t) + \xi_{ad} \cdot \tau_0(t)
  \]
  \[
  \tau_{ij}(t) \leftarrow (1 - \rho_{ad}) \cdot \tau_{ij}(t) + \rho_{ad} \cdot \Delta \tau_{ij}(t)
  \]
  \[
  \Delta \tau_{ij} = \frac{1}{L^+}
  \]

- **Candidate list** \( J_i^k \) representing the ants’ field of view

- **Evaporation parameter adaptation** depending on maturity state of optimisation cycle
  \[
  \xi_{ad}, \rho_{ad}
  \]
Optimiser validation

How do we know that 3D ACOHARN works well?

- 3D ACOHARN is based on the well known and widely used ACS. This gives a solid foundation to the new algorithm developed.

- 3D ACOHARN was used on a 2D search space without obstacles, finding the shortest route possible.

- Likewise, the same test was conducted on a 3D search space and successfully passed.
Results (single cable optimisation)

Cable after first iteration
Results (single cable optimisation)

Cable after first iteration

Cable after second iteration
Results (single cable optimisation)

Cable after second iteration

Cable after first iteration

Cable after twenty-two iterations
Results (single cable optimisation)

Cable after second iteration

Cable after first iteration

Cable after twenty-two iterations

Optimised cable (forty-three iterations)
Results (multiple cable optimisation)

3-cable optimisation using length-only heuristics
Results (multiple cable optimisation)

- 3-cable optimisation using length and loose bundling heuristics
- 3-cable optimisation using length-only heuristics
Results (multiple cable optimisation)

3-cable optimisation using length-only heuristics and common waypoint

3-cable optimisation using length and loose bundling heuristics

Problem formulation
Suggested solution
Harness simulator
Discrete optimisation
Ant Colony System
3D ACOHARN
Optimiser validation
Results
Remarks
Conclusions
Future work
Results (Length only heuristics)

Sample of 100 runs, optimising 3 cables:

- Median cable total length: 1796 [mm]
- Interquartile range: 81.14 [mm]
- Mean total processing time: 0.64 [min]

Maximum inter-cable distance using the length only heuristics with no local pheromone step:

- Median max. cable distance: 156 [mm]
- Interquartile range: 43.89 [mm]
Results (Length only heuristics)

Minimum length case
Total cable length: 1705.8 [mm]
Results (Length only heuristics)

Minimum length case
Total cable length: 1705.8 [mm]

Maximum length case
Total cable length: 1942.3 [mm]

October 4th, 2011
E. Komninou, M. Vasile and E. Minisci
Results (Forced bundling)

Sample of 100 runs, optimising 3 cables:
Length-only heuristics used without applying the local pheromone step. Forcing cables to pass by a common waypoint (midpoint)

- Median cable total length: 2635 [mm]
- Interquartile range: 4.5e-13 [mm]
- Mean total processing time: 0.25 [min]

Maximum inter-cable distance using the length only heuristics with no local pheromone step. Forcing cables to pass by a common waypoint (midpoint)

- Median max. cable distance: 72.6 [mm]
- Interquartile range: 6.03 [mm]
**Results (Forced bundling)**

Minimum length case
Total cable length: 2635.4 [mm]
Results (Forced bundling)

Minimum length case
Total cable length: 2635.4 [mm]

Maximum length case
Total cable length: 1942.3 [mm]
Results (Loose bundling)

Sample of 100 runs, optimising 3 cables:
Length and bundling heuristics used without applying the local pheromone step

- Median cable total length: 2110 [mm]
- Interquartile range: 136.96 [mm]
- Mean total processing time: 93.84 [min]

Sample of 100 runs, optimising 3 cables:
Length and bundling heuristics used with local pheromone step applied

- Median cable total length: 1839 [mm]
- Interquartile range: 81.05 [mm]
- Mean total processing time: 77.03 [min]
Results (Loose bundling)

Maximum inter-cable distance using the length and bundling heuristics with no local pheromone step

- Median max. cable distance: 234.3 [mm]
- Interquartile range: 70.24 [mm]

Maximum inter-cable distance using the length and bundling heuristics with local pheromone step

- Median max. cable distance: 124.8 [mm]
- Interquartile range: 80.12 [mm]
Results (Loose bundling– no local update)

Minimum length case
Total cable length: 1910.4 [mm]

Maximum length case
Total cable length: 3453.6 [mm]
Results (Loose bundling– with local update)

Minimum length case
Total cable length: 1717.9 [mm]

Maximum length case
Total cable length: 2042.1 [mm]
Conclusions

- Novel approach to 3D routing problems based on discrete optimisation nature-inspired metaheuristics
- Optimisation considering length-only heuristics can achieve high quality results without the use of local pheromone updating, thus greatly speeding up the process.
- Optimisation considering bundling heuristics can be achieved, with local pheromone updating offering superior results. – This phenomenon needs to be further investigated.
Future work

- Implementing more constraints (e.g. avoid specified areas)
- Implementing more objectives (e.g. Electro-Magnetic Compatibility objective function)
- Use optimiser for simulating a real full harness design project
- Apply optimiser to other routing problems (e.g. optimal vehicle/building pipe routing, optimal vehicle harness routing)
frontier research on visionary space systems

Thank you for your attention!
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