CAMELOT
Computational-Analytical Multi-fidelity Low-thrust Optimisation Toolbox

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Computational-Analytical Multi-fidelity Low-thrust Optimisation Toolbox (CAMELOT)

Preliminary design and optimisation of multiple-target low-thrust missions.

- **FABLE**: Fast Analytical Boundary-value Low-thrust Estimator
- **MP-AIDEA**: Multi-Population Adaptive Inflationary Differential Evolution Algorithm
- **AIDMAP**: Automatic Incremental Decision Making And Planning algorithm
Cost estimation of low-thrust orbital transfer using **multi-fidelity** analytical approach and **surrogate** models.

**Low-fidelity** fast analytical estimation of low-thrust transfer cost.

Analytical low-thrust control law:

| Transfer type | Reference |
|---------------|-----------|
| \(a_0 \rightarrow a_f\) | Ruggiero et al. (2011) |
| \((a_0, i_0) \rightarrow (a_f, i_f), e = 0\) | Edelbaum (1961) |
| \((a_0, i_0) \rightarrow (a_f, i_f), e = 0, a < \bar{a}\) | Kechichian (2010) |
| \((a_0, \Omega_0) \rightarrow (a_f, \Omega_f), e = 0\) | Kechichian (2010) |
| \((a_0, e_0, \omega_0) \rightarrow (a_f, e_f, \omega_f)\) | da Silva et al. (2015) |
| \(a_0 \rightarrow a_f, e_0 = e_f\) | Burt (1967) |
| \(e_0 \rightarrow e_f, a_f = a_0\) | Ruggiero et. al. (2011) |
| \((e_0, i_0) \rightarrow (e_f, i_f), a_f = a_0\) | Burt (1967) |
| \(i_0 \rightarrow i_f\) | Pollard (2000) |
| \(\omega_0 \rightarrow \omega_f\) | Ruggiero et al. (2011) |

Change of semimajor axis and inclination of circular orbit (Edelbaum):

- Semimajor axis [km] vs. Time [days]
- Inclination [deg] vs. Time [days]
- Velocity [km/s] vs. Time [days]
Higher-fidelity analytical model:

- **Osculating analytical propagator** based on analytical formulas for the perturbed Keplerian motion (first order expansion in the perturbing acceleration):
  - low-thrust acceleration
  - J2 zonal harmonic
  - atmospheric drag
  - solar radiation pressure (eclipses)

- **Averaged analytical propagator**
- Different control parametrisation can be implemented
Use of surrogate models to model the cost of the transfer to allow for fast evaluation of complex trajectories

Surrogate models:
- **Kriging**
- **Co-Kriging** (few samples from higher-fidelity model, many samples from low-fidelity model)
- **Tchebycheff** sparse grid

Multi-fidelity optimisation: maximisation of expected improvement associated to Co-Kriging
- Maximisation of expected improvement: point where the likelihood of achieving an improvement is maximised
Multi population single objective adaptive global optimiser based on the combination of Differential Evolution with Monotonic Basin Hopping

- Automatic adaptation of the parameters of Differential Evolution and Monotonic Basin Hopping
- **Local search** after Differential Evolution
- **Local restart**: transition from one local minimum to another
- Strategy to avoid multiple detection of the same local minima
  - Basin of attraction
  - **Global restart**
Single objective **incremental decision making algorithm** for the solution of complex **combinatorial optimisation problems** such as tasks planning and scheduling.

- **AIDMAP** decision making map based on **tree-like** topology:
  - Nodes: decisions made
  - Edges: cost associated to decision

- Tree built **incrementally with time** through **exploration** and **growth** by virtual agents

- Possible heuristics:
  - **Deterministic**: Branch-and-Cut algorithm
  - **Probabilistic**: bio-inspired Physarum algorithm
Applications

- Multiple Atira Asteroids Fly-by Mission
- Multiple Active Debris Removal Mission
Multiple Atira Asteroids Fly-by Mission

- $a < 1$ AU, $Q < 0.983$ AU
- 14 known Atira asteroids - many more IEOs are expected to exist
- Observation of the inner Solar System: limitations of ground-based survey (Sun in the instrument field of view)
- Fly-by at the nodal points of the asteroids’ orbit
Multiple Atira Asteroids Fly-by Mission

- AIDMAP
  - Identification of optimal:
    - sequence of asteroids
    - departure dates
    - times of flight
  - Impulsive model: Lambert arcs with departure dates at steps of 10 days.

133,761 solutions identified:
Multiple Atira Asteroids Fly-by Mission

- **AIDMAP**
  
  Best Solution: fly-by with 6 asteroids, $\Delta V = 3.77$ km/s

| Asteroid     | Departure Date | ToF [days] | $\Delta V$ [km/s] |
|--------------|----------------|------------|-------------------|
| 2013JX28     | 2020/09/29     | 205        | 0.87              |
| 2006WE4      | 2022/05/14     | 215        | 0.86              |
| 2004JG6      | 2023/06/14     | 235        | 0.61              |
| 2012VE46     | 2024/09/11     | 265        | 0.36              |
| 2004XZ130    | 2026/09/15     | 205        | 0.73              |
| 2008UL90     | 2028/07/31     | 195        | 0.34              |

**TOT.** | 3.77
Multiple Atira Asteroids Fly-by Mission

MP-AIDEA

- Identification of **new departure dates leading to reduced** $\Delta V$
- Global optimisation with search space defined allocating **time window of $\pm 10$ days** around previously identified departure dates

| Asteroid      | AIDMAP Dep. Date | MP-AIDEA Departure Date | AIDMAP $\Delta V$ [km/s] | MP-AIDEA $\Delta V$ [km/s] |
|---------------|------------------|-------------------------|--------------------------|----------------------------|
| 2013JX28      | 2020/09/29       | 2020/09/20              | 0.87                     | 0.95                       |
| 2006WE4       | 2022/05/14       | 2022/05/24              | 0.86                     | 0.69                       |
| 2004JG6       | 2023/06/14       | 2023/06/12              | 0.61                     | 0.61                       |
| 2012VE46      | 2024/09/11       | 2024/09/05              | 0.36                     | 0.34                       |
| 2004XZ130     | 2026/09/15       | 2026/09/18              | 0.73                     | 0.72                       |
| 2008UL90      | 2028/07/31       | 2028/08/10              | 0.34                     | 0.29                       |
| TOTAL         |                  |                         | **3.77**                 | **3.61**                   |
Multiple Atira Asteroids Fly-by Mission

- **FABLE**
  - Direct optimisation method and multiple shooting algorithm
  - Spacecraft injected into an hyperbolic escape orbit from Earth that encounters the first asteroids at its nodal point.
  - Low-thrust engine: $T = 0.07 \text{ N}, I_{sp} = 3000 \text{ s}$

| Asteroid      | $m_0$ [kg] | $m_f$ [kg] | $\Delta V$ [km/s] |
|---------------|------------|------------|-------------------|
| 2013JX28      | 700        | 700        | -                 |
| 2006WE4       | 700        | 673.45     | 1.12              |
| 2004JG6       | 673.45     | 642.07     | 1.37              |
| 2012VE46      | 642.07     | 633.47     | 0.39              |
| 2004XZ130     | 633.47     | 600.89     | 1.51              |
| 2008UL90      | 600.89     | 594.17     | 0.30              |
| **TOT.**      |            |            | **4.69**          |
Multiple Atira Asteroids Fly-by Mission

- **FABLE**
  - Transfer to a **reduced perihelion orbit (0.725 AU)** for observation of asteroids of the inner Solar System
  - Transfer: low-thrust propulsion or Earth gravity-assist
  - \( T_0 / T_{⊕} = 0.88 \)
  - \( T_f / T_{⊕} = 0.78 \)

| \( \Delta V \) [km/s] | ToF [days] |
|-----------------------|-----------|
| 1.79                  | 422       |

| \( \Delta V \) [km/s] | ToF [days] |
|-----------------------|-----------|
| 1.31                  | 565       |
Multiple Active Debris Removal Mission

- Deorbiting of **large satellites from LEO** (800 - 1400 km) using a **low-thrust servicing spacecraft** ($T = 0.1$ N, $I_{sp} = 1600$ s, $m = 1000$ kg)

- Two possible strategies:
  - multi-target delivery of **de-orbiting kits** (100 kg) to perform a controlled re-entry;
  - low-thrust **fetch and deorbit** using the single servicing spacecraft.

- Selected targets: 25 objects with high Criticality of Spacecraft Index and low inclination (J2 drift to change $\Omega$)

![Graph showing perigee and apogee altitude vs. inclination.](image)
Multiple Active Debris Removal Mission

- FABLE: transfer between two satellites (multi-target delivery of deorbiting kit)
Multiple Active Debris Removal Mission

- FABLE: transfer between two satellites (multi-target delivery of deorbiting kit)
- FABLE: deorbiting of objects (fetch and de-orbit)
  - Spiral with negative tangential acceleration: $\gamma = 0$ deg
  - Increase of eccentricity (negative thrust at apogee and positive thrust at perigee): $\gamma = 1.5$ deg
Multiple Active Debris Removal Mission

- **FABLE**: transfer between two satellites (multi-target delivery of deorbiting kit)

- **FABLE**: deorbiting of objects (fetch and de-orbit)
  - Spiral with negative tangential acceleration: $\gamma = 0 \text{ deg}$
  - Increase of eccentricity (negative thrust at apogee and positive thrust at perigee): $\gamma = 1.5 \text{ deg}$

- **FABLE**: surrogate model of the cost of the transfer for different possible initial mass of the spacecraft and time of flight of the transfer
Multiple Active Debris Removal Mission

- FABLE: transfer between two satellites (multi-target delivery of deorbiting kit)
- FABLE: deorbiting of objects (fetch and de-orbit)
  - Spiral with negative tangential acceleration: $\gamma = 0$ deg
  - Increase of eccentricity (negative thrust at apogee and positive thrust at perigee): $\gamma = 1.5$ deg
- FABLE: surrogate model of the cost of the transfer for different possible initial mass of the spacecraft and time of flight of the transfer
- AIDMAP: identification of the optimal sequence of targets to be removed using surrogate model
Multiple Active Debris Removal Mission

Multi-target delivery of de-orbiting kits:

| Departure Object | Arrival Object | $\Delta V$ [km/s] | $ToF$ [days] | $m_0$ [kg] | $m_f$ [kg] |
|------------------|----------------|-------------------|-------------|------------|------------|
| 1                | 39015          | 0.0628            | 30.43       | 1900.00    | 1892.40    |
| 2                | 40343          | 0.1128            | 65.75       | 1792.40    | 1779.55    |
| 3                | 40340          | 0.0595            | 33.14       | 1679.55    | 1673.19    |
| 4                | 39016          | 0.0429            | 29.73       | 1573.19    | 1568.89    |
| 5                | 40342          | 0.0339            | 42.28       | 1468.89    | 1465.72    |
| 6                | 40338          | 0.0013            | 7.05        | 1365.72    | 1365.60    |
| 7                | 40339          | 0.1116            | 44.55       | 1265.60    | 1256.63    |
| 8                | 39011          | 0.0035            | 14.19       | 1156.63    | 1156.37    |
| 9                | 39012          | 0.0448            | 28.04       | 1056.37    | 1053.34    |
| Total            | -              | -                 | 0.4731      | 294.17     | -          |

Fetch and deorbit:

| Departure Object | Arrival Object | $\Delta V$ [km/s] | $ToF$ [days] | $m_0$ [kg] | $m_f$ [kg] |
|------------------|----------------|-------------------|-------------|------------|------------|
| 1                | 39244          | 1.1307            | 159.91      | 3000.00    | 890.11     |
| 2                | 36413          | 0.9811            | 182.32      | 2890.11    | 802.79     |
| Total            | -              | -                 | 2.1118      | 373.23     | -          |

CAMELOT Applications
Conclusions

Multiple Atira Asteroids Fly-by Mission
Multiple Active Debris Removal Mission
Conclusions

CAMELOT, toolbox for the preliminary design of multi-target low-thrust missions:

- **FABLE**: low-thrust transfer estimator
- **MP-AIDEA**: single objective multi population adaptive global optimiser
- **AIDMAP**: single objective combinatorial optimiser

Applications:

- **Multiple Atira Asteroids Fly-By Mission**
  - Six asteroids fly-by in less than 10 years
  - Limited propellant consumption

- **Multiple Active Debris Removal Mission**
  - De-orbiting kits: 10 objects removed from LEO in less than 1 year
  - Fetch and deorbit: 3 objects removed from LEO
Thank you. Questions?