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Machine Learning in Science Colloquium, 27th May 2020

Artificial Neural Network For Preliminary Multiple NEA Rendezvous Mission Using Low Thrust

Giulia Viavattene

Outline

1. Introduction
2. Neural Network Design
3. Sequence Search
4. Sequence Optimisation
5. Optimised NEA Sequences
6. Conclusions

Introduction

Artificial Neural Network For Multiple NEA Rendezvous Mission Using Low Thrust

Near-Earth asteroids

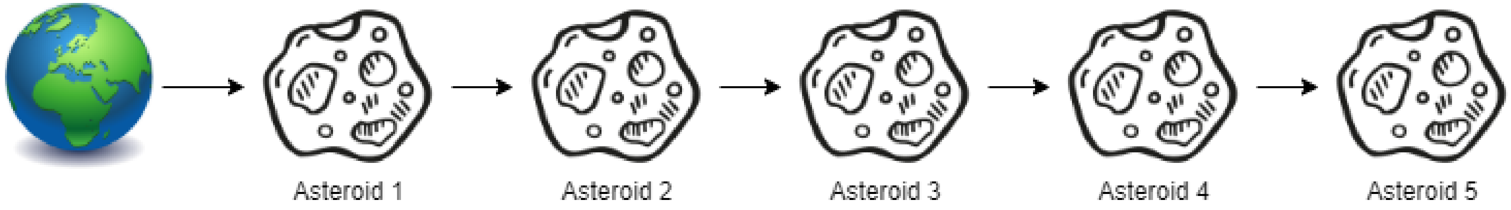
- Science
- Earth protection
- Resource exploitation

- Reduced cost per transfer
- Increased range of possibilities to visit NEAs of interest

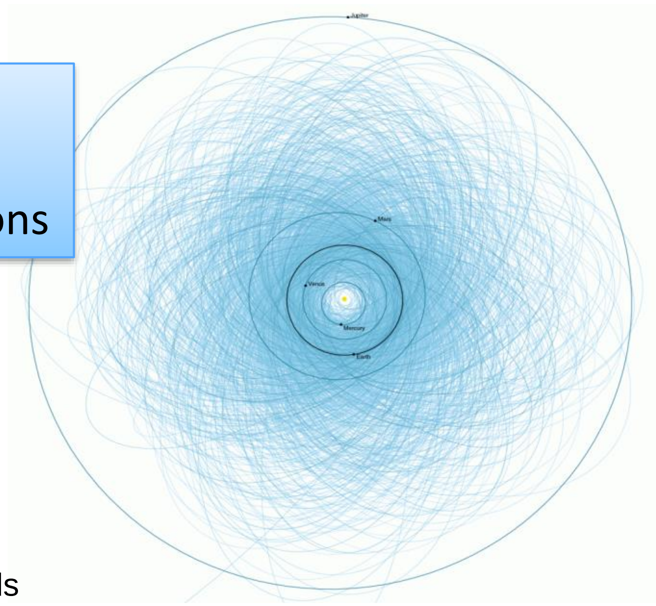
- High energy interplanetary missions
- Less propellant required

Introduction

Artificial Neural Network For Multiple NEA Rendezvous Mission Using Low Thrust

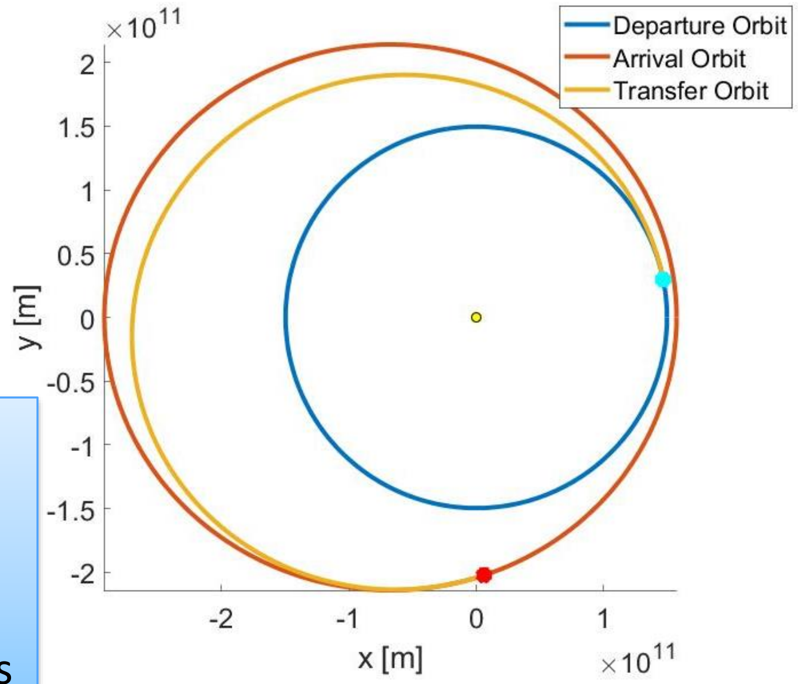


22,000 NEAs
↓
Trillions of permutations



NEA: Near-Earth asteroids

Optimisation problem
↓
1. Optimal trajectory
2. Control history
3. Mission requirements



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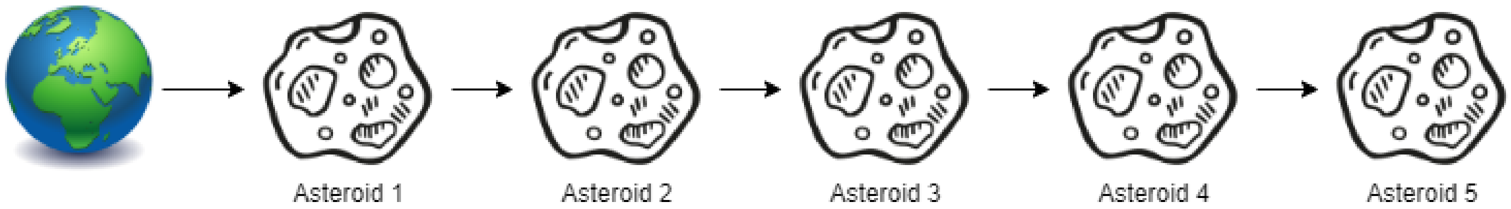

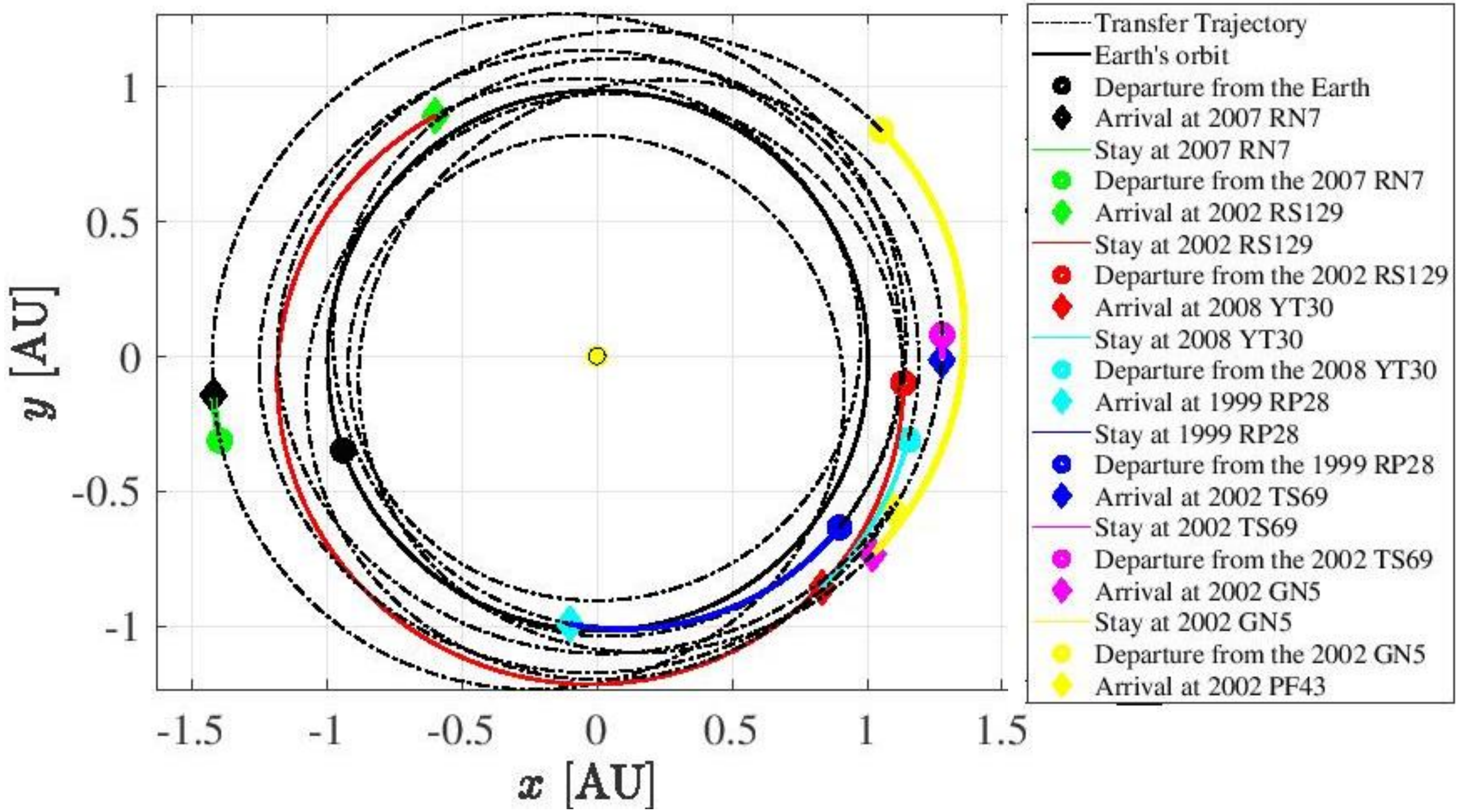

Identify the best sequences of asteroids

Solution to the optimisation problem

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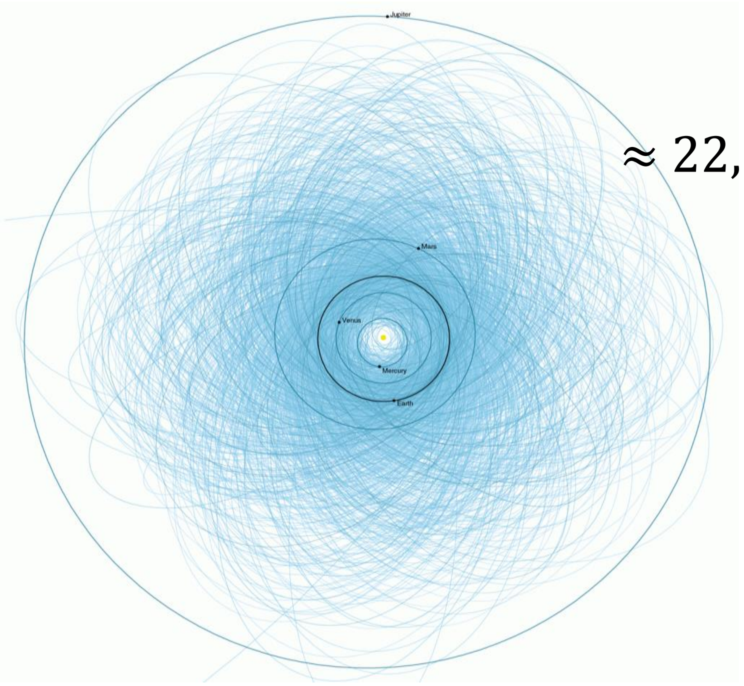
Multiple NEA rendezvous mission

Large combinatorial part
Selection of the asteroid sequences

Continuous part
Solution of optimal control problem (OCP)



$\approx$ 22,000 NEAs

Need

Quick estimation of the cost ΔV and time of flight (TOF) of a transfer between NEAs

Artificial Neural Network

Neural Network Design

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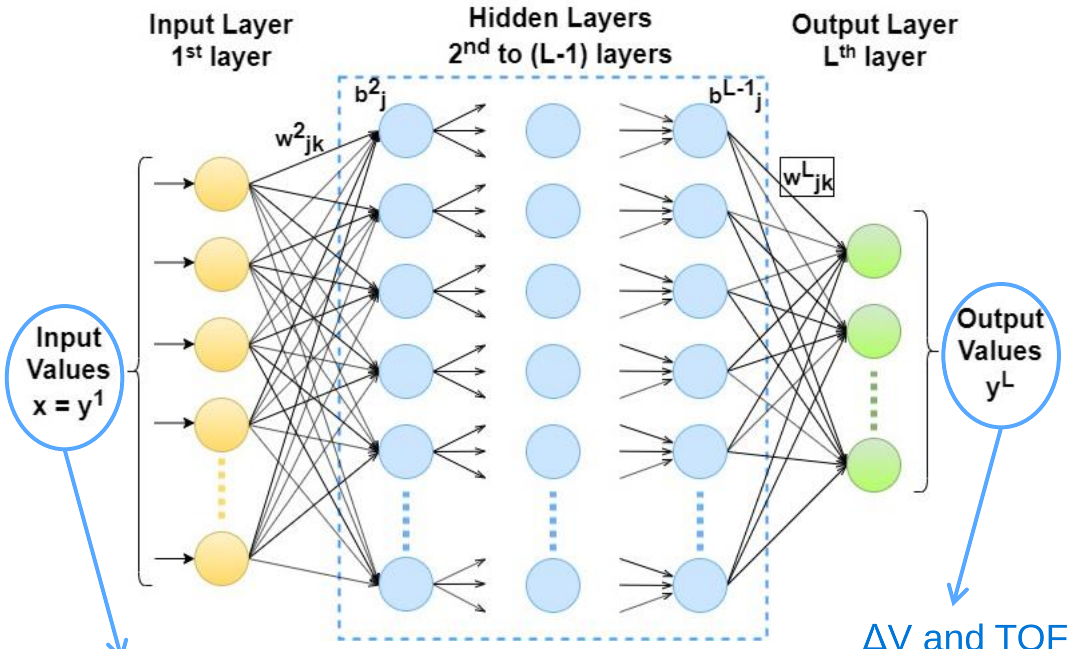
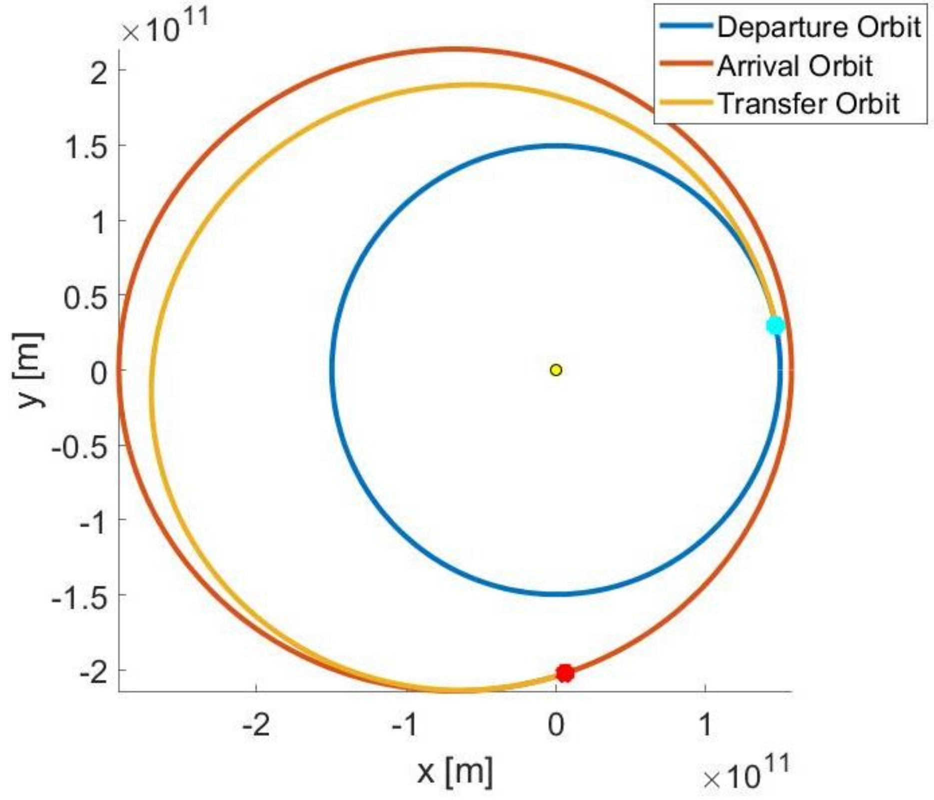


ΔV and TOF

Orbital parameters of
departure and arrival orbits



Neural Network Design

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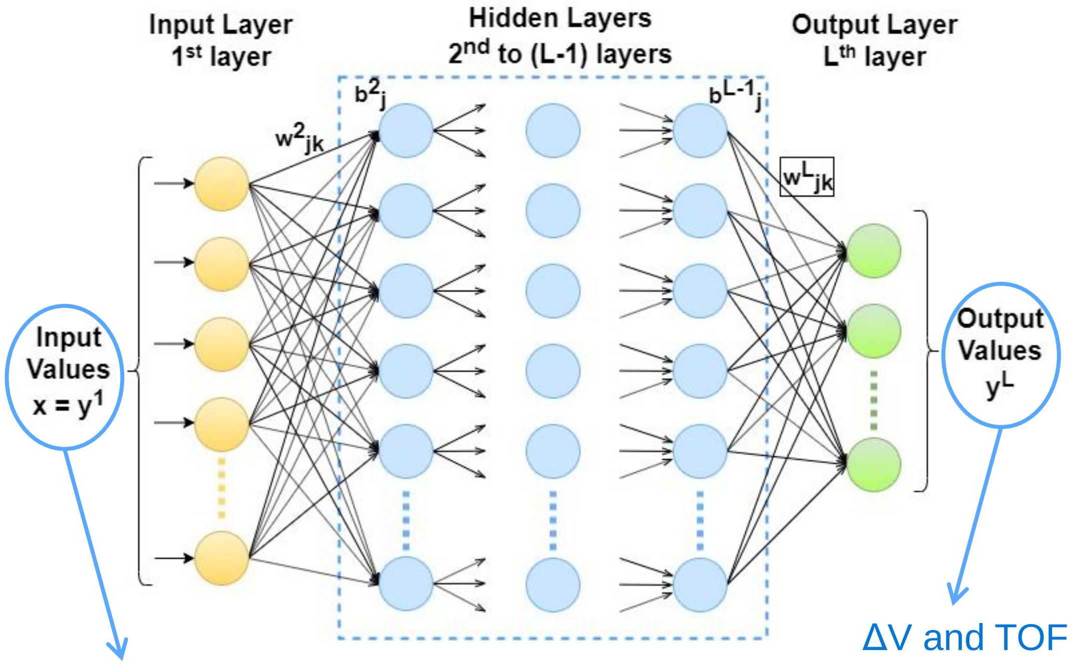


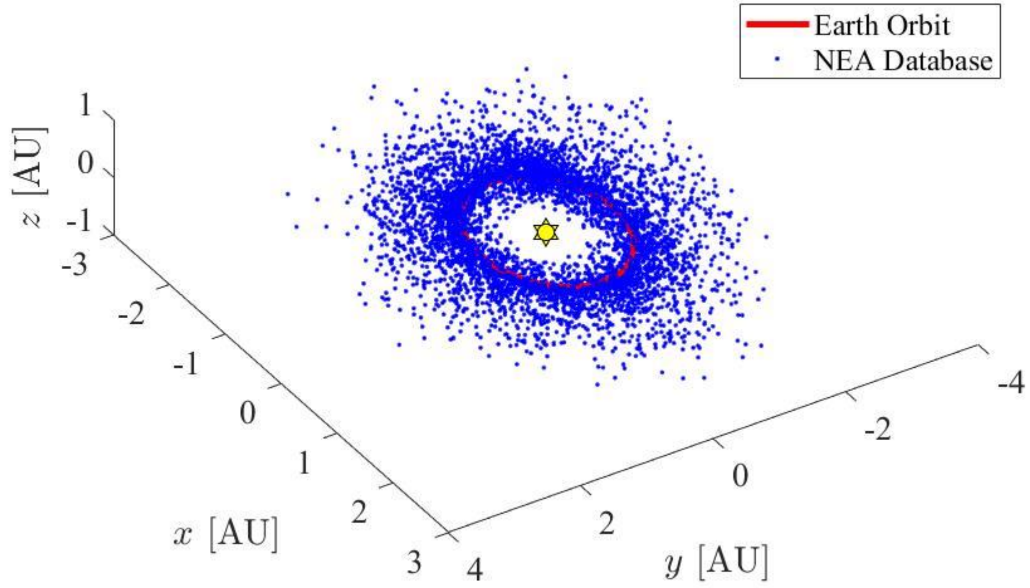
ΔV and TOF

Orbital parameters of departure and arrival orbits

TRAINING

→ Define w_{jk}^{l} and b_{j}^{l} so that MSE is minimised

$$MSE = \frac{1}{N}\sum_{i=1}^{N}\|\boldsymbol{y}_i - \boldsymbol{t}_i\|$$



TRAINING DATABASE

→ Collection of $(\mathbf{x}, \mathbf{t})_i$ with $i \in [1, N]$

→ Shape-based method

MSE: Mean-Squared Error
SEP: Solar Electric Propulsion

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Architecture & Parameter Tuning

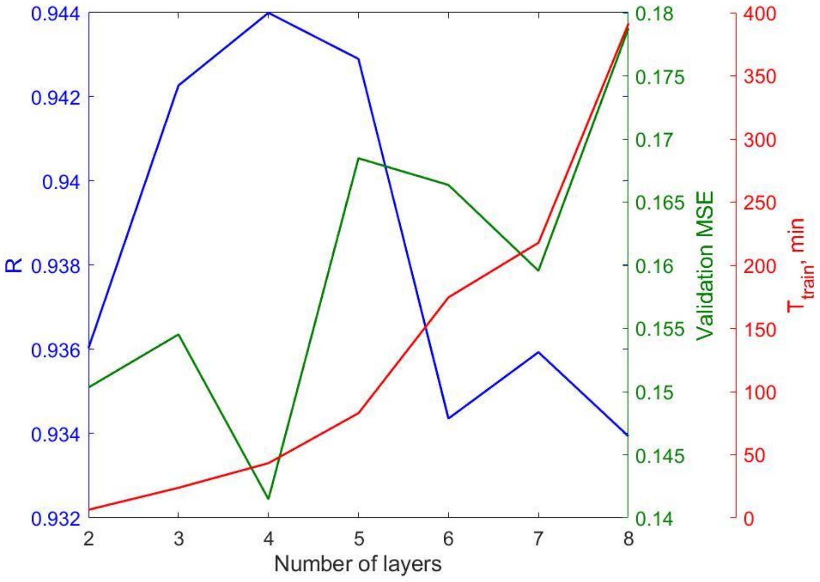
1) NETWORK INPUT:

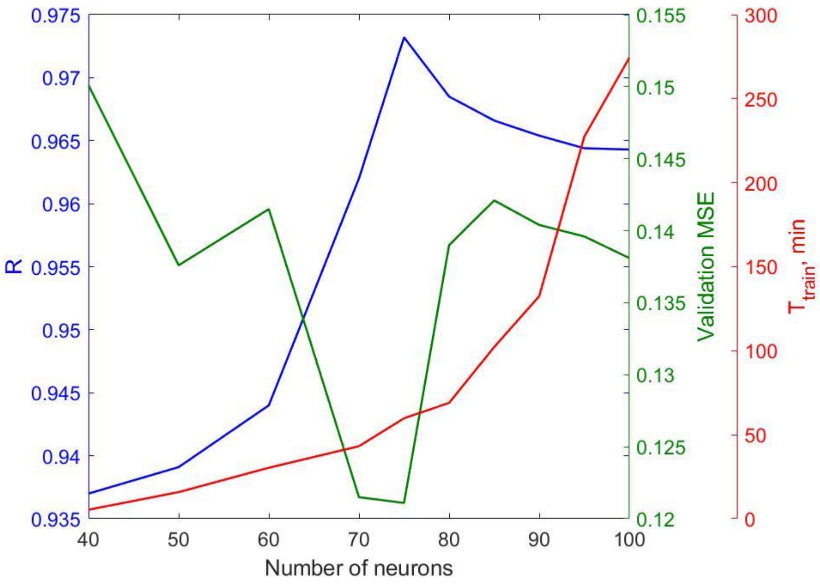
		Correlation	Validation-Set Error
Classical Orbital Elements	COE	0.855	0.530
Equinoctial Elements	EE	0.856	0.487
Modified Equinoctial Elements	MEE	0.925	0.236
Cartesian Coordinates	Cartesian	0.551	0.761
Delaunay Elements	Delaunay	0.694	0.862
Eccentricity and angular momentum vector	eH	0.908	0.221

Best Performance:
R = 0.9732
MSE = 0.1211

2) STRUCTURE:

- Learning algorithm
- Activation function
- Gradient constant
- Decrease factor
- Dataset division





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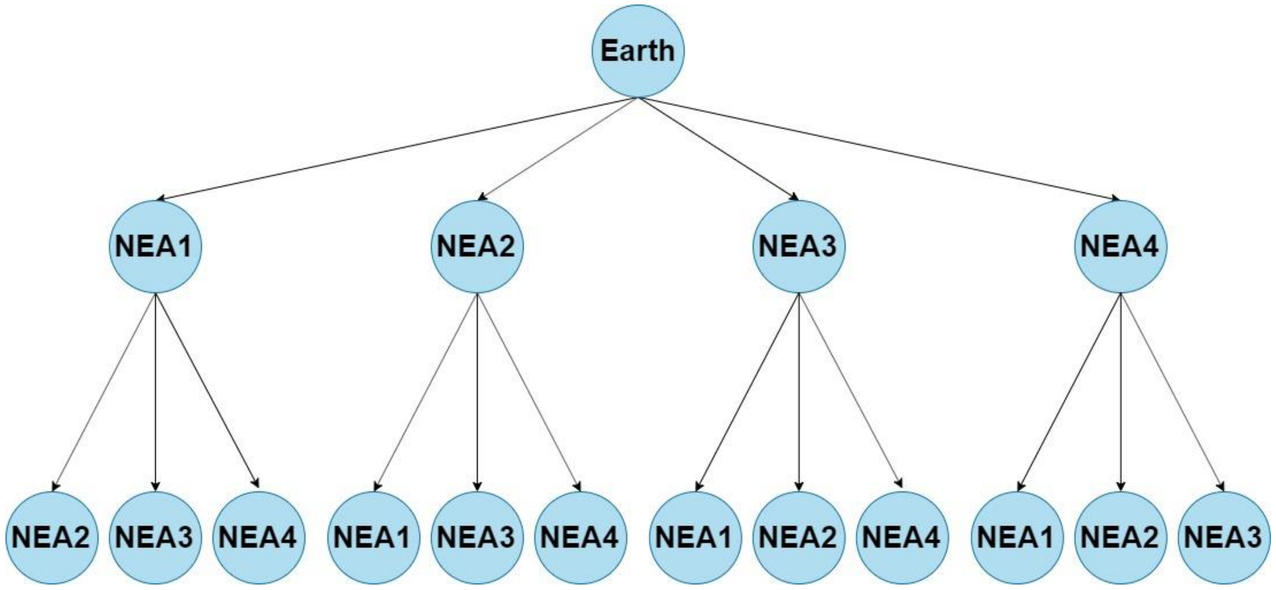
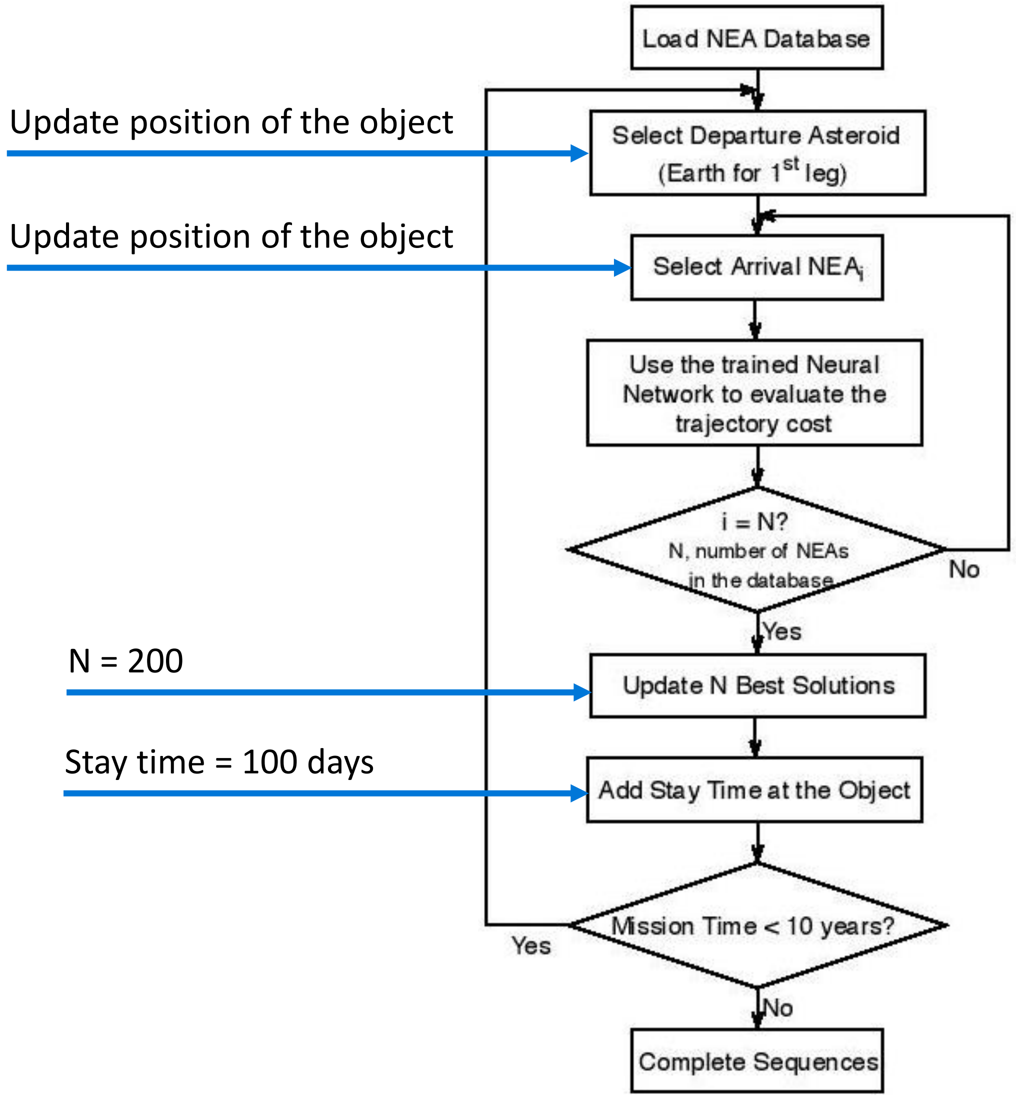
Tree-search method





Sequence Optimisation

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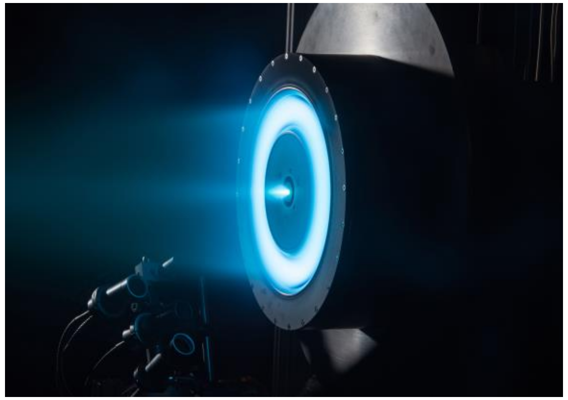
→ Obtain the optimal flight trajectory and control history

- State vector: $\boldsymbol{x} = (p, f, g, h, k, L, m)$
- Control vector: $\boldsymbol{u} = \boldsymbol{N} = (N_r, N_\theta, N_h)$

Dynamics:
$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}(\boldsymbol{x})\boldsymbol{a} + \boldsymbol{b}(\boldsymbol{x})$$

➢ Solar Electric Propulsion (SEP)

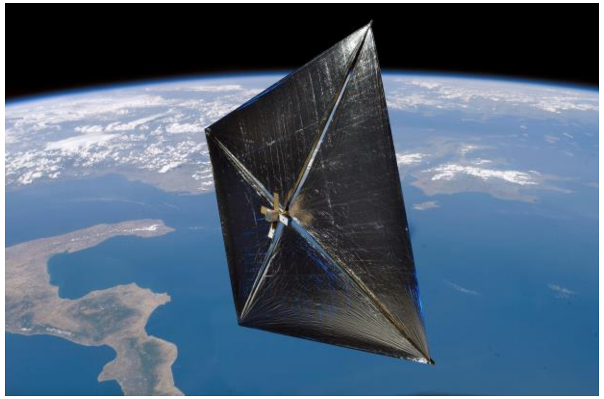
$$\boldsymbol{a} = \frac{T_{max}}{m}\boldsymbol{N}$$



- Electric power by onboard solar arrays
- Use 10 times less propellant

➢ Solar Sailing (SS)

$$\boldsymbol{a} = a_c\left(\frac{r_\oplus}{r}\right)^2 cos^2\alpha\ \widehat{\boldsymbol{N}}$$



- Radiation pressure
- No propellant

Sequence Optimisation

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➢ Solar Electric Propulsion (SEP)

$$\boldsymbol{a} = \frac{T_{max}}{m}\boldsymbol{N}$$

➢ Solar Sailing (SS)

$$\boldsymbol{a} = a_c \left(\frac{r_\oplus}{r}\right)^2 cos^2\alpha\, \widehat{\boldsymbol{N}}$$

→ Optimal Control Problem:

determine $\boldsymbol{u}$ so that propellant mass expenditure (or TOF for SS) is minimized.

1. Dynamic constraint
2. Path constraint: $0 \leq \|\boldsymbol{N}\| \leq 1$ for SEP

   $\|\widehat{\boldsymbol{N}}\| = 1$ for SS

Optimised NEA Sequences

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SEP: I_{sp}= 3000 s, a_{max}= 0.2 mm/s^2

Total TOF = 4292 days (11.7 years)

Total ΔV = 51.95 km/s

SS: a_c= 0.3 mm/s^2

Total TOF = 4406 days (12.1 years)

⇩

142 days more than SEP, but zero propellant

Transfer	Stay Time [days]	Departure	Arrival	TOF [days]	ΔV [km/s]
Earth	–				
⇓		2035/01/01 • 2035/01/01	2036/11/15 • 2037/03/12	684 (553) • 801	7.8 (7.04) • -
2011 AM24*	196 • 158				
⇓		2037/05/30 • 2037/08/17	2039/07/30 • 2039/11/10	791 (675) • 815	8.05 (6.9) • -
2003 MM	83 • 114				
⇓		2039/10/21 • 2040/03/03	2040/12/25 • 2041/04/27	431 (414) • 420	6.11 (6.25) • -
2006 SF6	134 • 184				
⇓		2041/05/08 • 2041/10/28	2043/04/15 • 2044/04/28	707 (524) • 913	9.04 (8.28) • -
2008 YT30	271 • 110				
⇓		2044/01/11 • 2044/08/16	2045/05/11 • 2045/11/21	486 (503) • 462	6.92 (5.24) • -
1999 FA	68 • 45				
⇓		2045/07/18 • 2046/01/05	2046/10/02 • 2047/01/24	441 (502) • 384	6.21 (4.67) • -
2019 FU2**	–				

* PHA
** NHATS
• Results using solar sailing.
(.) ANN results

Conclusions

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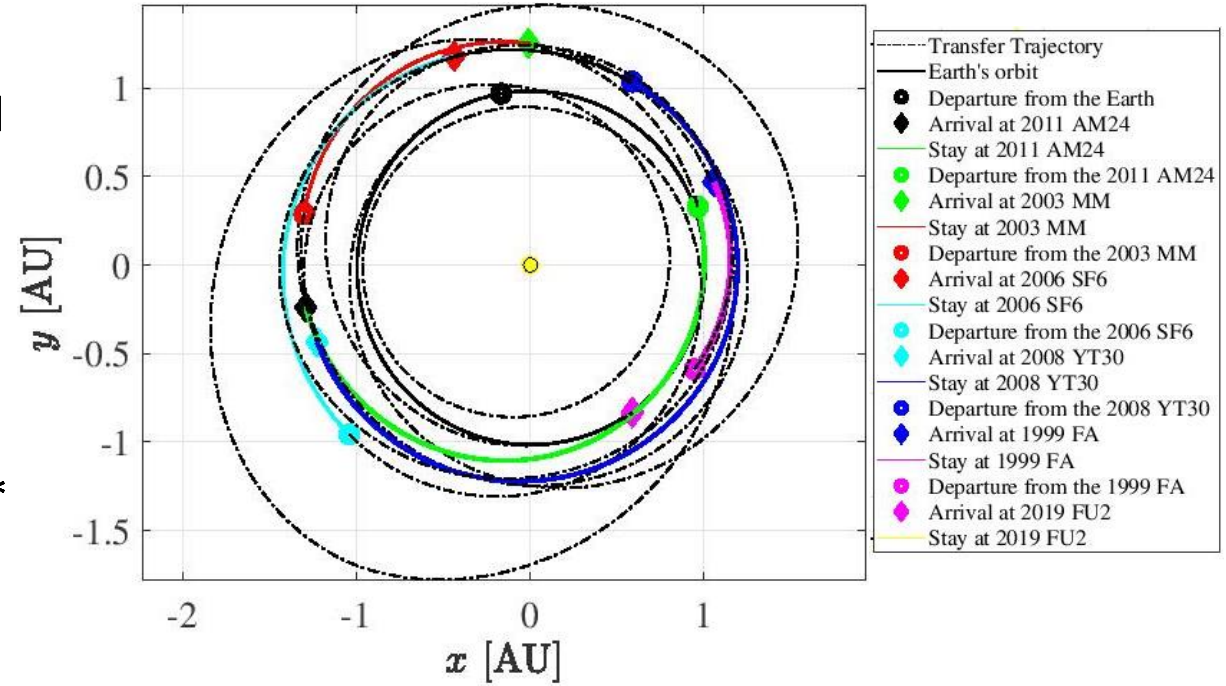
- ✓ ANN can provide a quick estimation of the cost of a transfer
- ✓ ANN architecture and parameters can be optimised for this application

ANN vs. Optimisation

- Sequence search algorithm using ANN results to be 25 times faster compared to others methods*
- Difference in TOF and ΔV generally limited
- Average percentage error for ΔV and TOF < 10 %



*A. Peloni, M. Ceriotti, and B. Dachwald. Solar-Sail Trajectory Design for a Multiple Near-Earth-Asteroid Rendezvous Mission. Journal of Guidance, Control, and Dynamics, 39(12):2712–2724, Sep 2016

Any questions?

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Thank you!

Giulia Viavattene

g.viavattene.1@research.gla.ac.uk