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Space and Exploration Technology Group

Advances in preliminary solar-sail trajectory design

Shape-Based Methods and Artificial Neural Networks

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Why preliminary trajectory design?

- Early mission design phase
 - Concept study, pre-phase A
- Fast preliminary trajectory design
- Interested in trajectory key figures of merit:
 - Δv, TOF, maximum thrust, propellant mass, feasibility
- Not interested in full control history (as long as feasible)
- Approximate solution
 - Design margins are high
- Fast to calculate
 - Can calculate hundreds to millions of options





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Multi-target missions

- Multi-target missions, wide launch window
 - Appealing for solar sailing: "infinite" Δv
- Multi-asteroid rendezvous mission
 - Complete database: *n* = ~13,000 NEAs
 - Near-Earth Object Human Space Flight Accessible Target Study (NHATS) (for a low-thrust return mission) Reduced database: n = ~1,800 objects



$$\mathbf{P}_q^n = \frac{m}{(n-q)!}$$

Database	п	q = 3	q = 4	q = 5
Complete database	12,840	2.1×10^{12}	2.7×10^{16}	3.5×10^{20}
Reduced database	1,801	5.8×10^{9}	1.0×10^{13}	1.9×10^{16}

NHATS criteria:

Peloni, A., Ceriotti, M. and Dachwald, B. (2016) Solar sail trajectory design for a multiple near-Earth asteroid rendezvous mission. Journal of Guidance, Control, and Dynamics, 39(12), pp. 2712-2724. (doi: 10.2514/1.G000470)



total Δv required ≤ 8 km/s total mission duration ≤ 450 days stay time at the object ≥ 8 days launch: 2015-2040 $H \leq 26$ magnitude OCC < 7

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Solar sailing vs. low thrust (EP)

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Continuous, low acceleration

Solar sailing

- Thrust direction and magnitude related
- Dependent on sun direction

$$\mathbf{a} = a_c \left(\frac{r_{\oplus}}{r}\right)^2 \cos^2 \alpha \,\hat{N} \qquad \hat{N} = \begin{bmatrix} N_r \\ N_g \\ N_h \end{bmatrix} = \begin{bmatrix} \cos \alpha \\ \sin \alpha \cos \delta \\ \sin \alpha \sin \delta \end{bmatrix}$$
$$a_c = 2P \frac{A}{M} \qquad \qquad \alpha = \angle \left(\mathbf{r}_{sun}, \hat{N}\right)$$
$$\alpha < 90^\circ$$

- Objective:
 - Time of flight

Low Thrust (EP)

- Free thrust direction
- Free magnitude (up to the max)

$$\mathbf{a} = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}, \qquad |\mathbf{a}| < a_{max}$$

- (Multi-) Objective:
 - Propellant mass
 - Time of flight

Solar sailing vs. low thrust (EP)

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Dachwald, B., "Low-Thrust Trajectory Optimization and Interplanetary Mission Analysis Using Evolutionary Neurocontrol", Institut fur Raumfahrttechnik, Universitaet der Bundeswehr Muenchen, 2004.

Trajectory models



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SHAPE-BASED TRAJECTORIES FOR SOLAR SAILING

Shape-based methods





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- Take the Equations of Motion: $\ddot{\mathbf{x}} = f(\mathbf{x}, t) + \mathbf{a}(t)$
- Assign a "shape", i.e. trajectory function of time: $\mathbf{x}(t) = \mathbf{x}^*(t, \mathbf{p}), \dot{\mathbf{x}}, \ddot{\mathbf{x}}$
- Set shape parameters **p** to meet the boundary conditions (e.g. rendezvous): $\mathbf{x}^*(t_0, \mathbf{p}) = \mathbf{x}_0, \ \mathbf{x}^*(t_f, \mathbf{p}) = \mathbf{x}_f$
- "Invert" the EoM to find the control (acceleration) profile: $\mathbf{a}(t) = \ddot{\mathbf{x}}^* f(\mathbf{x}^*, t)$

- Usually fast to calculate
- Provides a thrust profile
 - Can be used as initial guess for OPC

- Inversion of EoM only possible for specific shapes
- Does not always satisfy the constraints!

Shape-based methods

- Exponential sinusoid (Petropoulos & Longusky)
- Inverse polynomial (Wall & Conway)
- Pseudo-equinoctial (De Pascale & Vasile)
- Hodographic (Gondelach & Noomen)
- Finite Fourier series (Taheri & Abdelkhalik)

••••

Usually low-thrust (EP) with tangential acceleration

- Shape-based for solar sailing (Peloni et al.)
 - 2D
 - Sail magnitude/direction constraint not considered

	Shape-Based Algorithm	n for .	Auto	mated De	sign					
	of Low-Thrust, Grav	ity-As	sist '	Frajectori	es					
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	 zeroth order constant coefficient for out-of-plane a 	œ	- 6	rest angle, rad						
	 Itrst-order constant coefficient for out-of-plane a difference in inverse radii, m⁻¹ 	ΔV	- 10	locity change, m/s						
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							phase. The effectiveness of the proposed approach is de asteroid rendercous mission. The results show that it is po	monstrated t	dier o	h a fully optimized multiple near-Earth war-Earth asteroids within 10 years with
							near-term solar-sail technology.			
							Nomenclature	1.	-	selocity vector
					A	1	sail area, m ² matrix of the dynamics	4	-	state vector in modified equinoctial elements
					5	1	solar-sail acceleration, mm/n ² semimajor axis, astronomical unit		-	sail cone angle, deg
					#. #	-	solar-call characteristic acceleration, mm/e ¹ anxiliary tector of the dynamics	8	-	velocity increment, km/s sail clock angle, deg
					1		occustricity	5		longitude of pericenter variation, rad angle between two consecutive salicraft attitudes, deg
					1.8	-	in-plane modified equinoctial elements	:	-	in-plane transversal unit vector angle between angular momenta of two orbits, deg
					2	-	orbital avgalar momentum unit vector	4,	-	shaping parameter related to semilarus rectam, astronomical unit
					S	-	objective function for the genetic algorithm	A 10	-	shaping parameter related to in-plane modified
							out-of-plane modified equinoctial elements			and account of the second s
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2D shape for solar sailing

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EoM Modified Equinoctial Elements

 $k = \tan(i/2)\sin(\Omega)$

 $L = \Omega + \omega + \nu$

2D Shape

In-plane motion

$$p = a(1 - e^{2})$$

$$p = p_{I} \exp[p_{F}(L - L_{0})] + \lambda_{p} \sin(L + \varphi_{p})$$

$$f = e \cos(\Omega + \omega)$$

$$f = f_{I} + f_{F}(L - L_{0}) + \lambda_{fg} \sin(L + \varphi_{fg})$$

$$g = e \sin(\Omega + \omega)$$

$$g = g_{I} + g_{F}(L - L_{0}) - \lambda_{fg} \cos(L + \varphi_{fg})$$
Coplanar Earth-Mars
$$h = \tan(i/2) \cos(\Omega)$$

$$Coplanar = 0$$



Peloni, A., Ceriotti, M. and Dachwald, B. (2016) Solar sail trajectory design for a multiple near-Earth asteroid rendezvous mission. Journal of Guidance, Control, and Dynamics, 39(12), pp. 2712-2724. (doi: 10.2514/1.G000470)

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3D shape for solar sailing



EoM **3D Shape Modified Equinoctial Elements** $\begin{array}{l} \begin{array}{l} p = a(1-e^2) \\ f = e\cos(\Omega+\omega) \\ g = e\sin(\Omega+\omega) \end{array} \end{array}$ $p(L) = \tilde{p}_0 + \tilde{p}_f (L - L_0) + a_p (L - L_0)^2 + \lambda_p \sin(L - L_0 + \phi_p)$

 $g(L) = \tilde{g}_0 + \tilde{g}_f (L - L_0) - \lambda_{fg} \cos(L - L_0 + \phi_{fg})$ $\begin{cases} h = \tan(i/2)\cos(\Omega) \\ k = \tan(i/2)\sin(\Omega) \end{cases}$ $h(L) = \tilde{h}_0 + \tilde{h}_f (L - L_0) + a_h \exp[b_h (L - L_0)] + \lambda_{hk} \sin[2(L - L_0) + \phi_{hk}]$ $k(L) = \tilde{k}_0 + \tilde{k}_f (L - L_0) + a_k \exp[b_k (L - L_0)] - \lambda_{hk} \cos[2(L - L_0) + \phi_{hk}]$ $L = \Omega + \omega + \nu$ Free parameters

 $f(L) = \tilde{f}_0 + \tilde{f}_f (L - L_0) + \lambda_{fg} \sin(L - L_0 + \phi_{fg})$

Caruso, A., Quarta, A., Mengali, G. and Ceriotti, M. (2020) Shape-based approach for solar sail trajectory optimization. Aerospace Science and Technology, 107, 106363. (doi: 10.1016/j.ast.2020.106363)



Earth-1620 Geographos ($i = 13^{\circ}$), $a_c = 0.2 \text{ mm/s}^2$

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3D shape fitting

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Shape-based trajectory design for solar sailing

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$$\operatorname{min}\left\{\operatorname{Time of Flight} \quad T = \int_{L_0}^{L_f} \frac{dt}{dL} dL\right\}$$

$$a_p, \lambda_p, \phi_p, \lambda_{fg}, \phi_{fg}, a_h, b_h, a_k, b_k, \lambda_{hk}, \phi_{hk}, L_0 \text{ and } L_f$$

Boundary constraints (pos, vel)

$$\widetilde{p}_0, \widetilde{p}_f, \widetilde{f}_0, \widetilde{f}_f, \widetilde{g}_0, \widetilde{g}_f, \widetilde{h}_0, \widetilde{h}_f, \widetilde{k}_0, \text{ and } \widetilde{k}_f$$

$$1. : \max_t (\|\boldsymbol{a}\| - a_{\max}) < 0$$

$$2. : \min_t (a_r) > 0$$

$$3. : \max_t (|a_r - a_c(\frac{r_{\oplus}}{r})^2 \cos^3 \alpha|) < \epsilon$$

$$4. : \max_t (|a_t - a_c(\frac{r_{\oplus}}{r})^2 \cos^2 \alpha \sin \alpha|) < \epsilon$$

Constraint satisfaction

Shape-based trajectory design for solar sailing

- 1. Shape-based trajectory:
 - Genetic Algorithm + gradient-based
 - 3 methods:
 - 1. Solar sail shape + all constraints 1-4
 - 2. Solar sail shape + constraints 1-2
 - 3. Linear-trigonometric shape (LT, Pascale, Vasile) + constraint 1

- 2. Optimisation with full dynamics:
 - Multiple-shooting
 - Shape-based solution used as initial guess

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1. $: \max_{t}(\|\boldsymbol{a}\| - a_{\max}) < 0$ 2. $: \min_{t}(a_{r}) > 0$ 3. $: \max_{t}(|a_{r} - a_{c}(\frac{r_{\oplus}}{r})^{2}\cos^{3}\alpha|) < \epsilon$ 4. $: \max_{t}(|a_{t} - a_{c}(\frac{r_{\oplus}}{r})^{2}\cos^{2}\alpha\sin\alpha|) < \epsilon$

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Performance evaluation

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Earth - 2002 DU_3 $a_c = 0.3 \text{ mm/s}^2$



	Shape-	based	Multiple shooting			
	Success rate	Comp. time	Success rate	Comp. time		
Method 2:	93 %	58 s	38 %	104 s		
Method 3:	50 %	52 s	16 %	187 s		

Earth - 2007 MK₁₃ $a_c = 0.3 \text{ mm/s}^2$



Shape-	based	Multiple shooting		
Success rate	Comp. time	Success rate	Comp. time	
100 %	45 s	46 %	221 s	
100 %	16 s	2 %	284 s	

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Results

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SAIL TRAJECTORY DESIGN WITH ARTIFICIAL NEURAL NETWORKS

University

An even faster trajectory estimation



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• Can a machine to "learn" to estimate the "cost" of transfers between asteroids?



Artificial Neural Networks



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HOW DOES MACHINE LEARNING WORK?



Neural Network Design

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Neural Network Design



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Viavattene, G. and Ceriotti, M. (2020) Artificial Neural Network Design for Tours of Multiple Asteroids. In: 15th International Conference on Hybrid Artificial Intelligence Systems (HAIS 2020), Gijón, Spain, 11-13 Nov 2020, pp. 751-762. ISBN 9783030617042 (doi:10.1007/978-3-030-61705-9_63)

Additional challenges



Orbit parameterisation

		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

Dependence on time (phasing problem)

• Orbital transfer ≠ Rendezvous



ANN architecture design

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ANN param	eter	Search space	Optimal value		
No. hidden	layers	[2, 8]	4		
No. neurons	5	[40, 100]	80		
Learning alg	orithm	Levenberg-Marquardt Resilient back-propagation Scaled conjugate gradient Gradient descent	Levenberg-Marquardt		
Activation f	unction	tansig, sigmoid, ReLu	Sigmoid		

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Sequence search with ANN

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Multiple asteroid rendezvous

- 6,286 asteroids
 - ~300 PHAs, ~1,450 NHATS
 - Excluded highly inclined ($i \ge 20^\circ$) and eccentric ($e \ge 0.4$)
- Launch date fixed: 2035/01/01
 - Systematic scan of launch window could be done
- Stay time at asteroid: 100 days
- Only best 200 transfers with lowest ToF stored
 - Limits exponential growth
- 2 sequences selected for full optimisation
 - OPC solver GPOPS-II [Patterson, Rao]
 - Ideal solar sail with $a_c = 0.2 \text{ mm/s}^2$



Asteroid sequence tree graph

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Sequence

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Matteo Ceriotti

Earth (2035/01/01)

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7 June 2023



7 June 2023

Performance analysis



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Error in Time of Flight estimation

$$\mathcal{E}_{TOF} = \frac{1}{N} \sum_{i=1}^{N} \left(\frac{|TOF_{i,opt} - TOF_{i,ANN}|}{TOF_{i,opt}} \right) = 13.4 \%$$

ANN within sequence search algorithm

200 best sequences in less than 8 hours

~100x faster than using shape-based trajectories*

ANN **not** trained on fullyoptimal solar sail trajectories

*compared to the method used in: 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

Conclusions



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Shape-based methods can provide an approximate thrust profile

- Still require optimisation
- Trade-off between accuracy of solution and computational time
- A better shape-based solution eases the follow-up optimisation, but takes longer
- Artificial neural networks can provide a very fast estimate of transfer "cost"
 - Require training
 - The position-time problem (phasing of bodies) is not fully solved
- Future work
 - Train ANN with full solar sail trajectory model

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Thank you!

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