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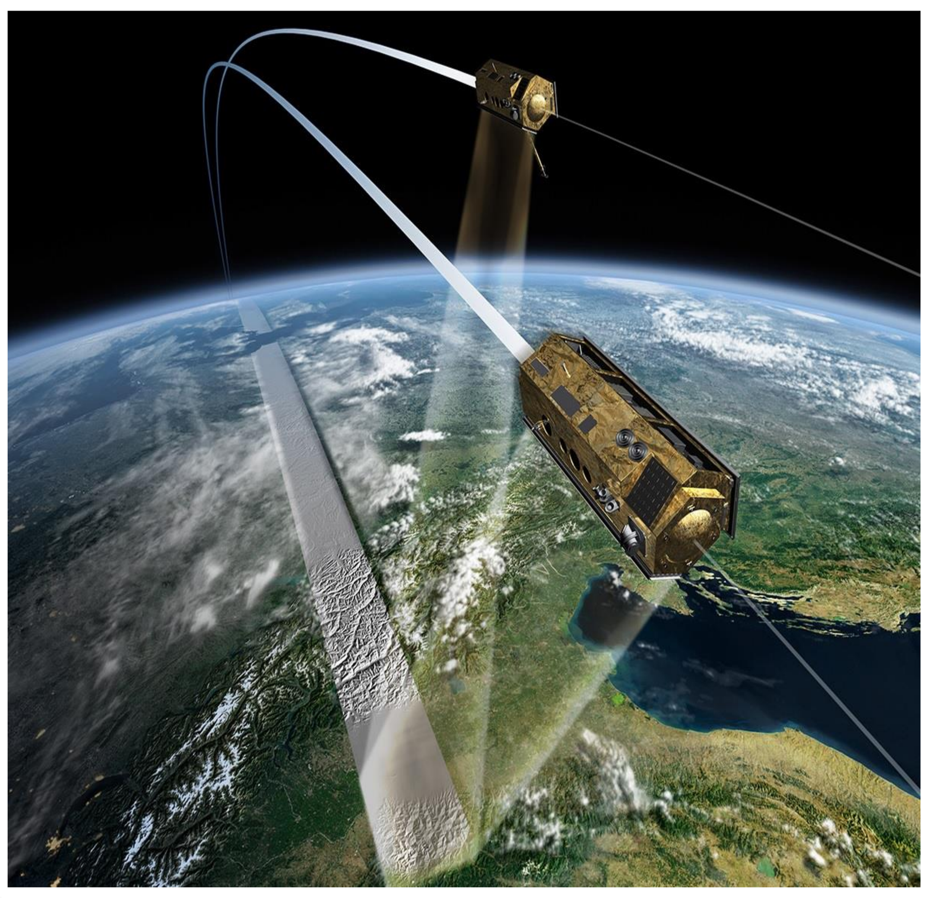
Robust Satellite Rendezvous Maneuver using Aerodynamic Forces

Motivation & Challenges



[1]

Motivation:

Satellite Formation Flight (FF):

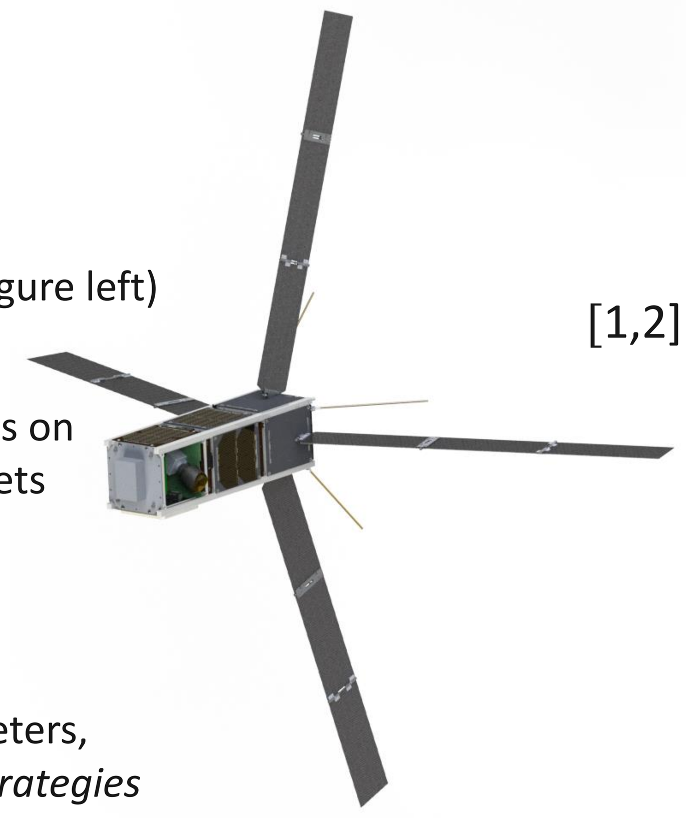
- Enhanced redundancy, flexibility and robustness
- Renders new scientific missions possible
- Enhanced resolution for EO via synthetic apertures (figure left)

Differential Aerodynamic Forces:

- Utilization of chemical thrusters has detrimental effects on small satellites' limited mass, volume and power budgets
- Propellant-less option: Intentionally creating differential aerodynamic forces between two satellites

Challenges:

- Highly variable control forces: interdependent parameters, uncertainties, dynamic variations → *Robust control strategies*



[1,2]

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Environment & Satellite Aerodynamics

Environmental Model:

- NRLMSISE-00 environment model [3]
- Moderate solar and magnetic activity

$$F_{10.7(avg)} = 140$$
$$A_p = 15$$

Satellite Aerodynamics:

C_L/C_D: *Sentman's* [4] *Gas-Surface Interaction (GSI) model*

- Diffuse reemission of particles ($\sigma = \sigma' = 1$)
- Varying degree of energy accommodation (α)

$$\alpha = \frac{E_I - E_R}{E_I - E_W}$$

α: *Semi-empirical satellite accommodation model (SESAM)* [5]

- n_O = number density of atomic oxygen [1/m³]
- T_i = neutral temperature of medium [K]

$$\alpha = \frac{7.50 \times 10^{-17} n_O T_i}{1.00 + 7.50 \times 10^{-17} n_O T_i}$$

Guidance & Control

Goal: *Guide a chaser spacecraft (deputy) within close proximity of a reference spacecraft (chief)*

Robust control approach:

- *Lyapunov* based DD controller for the in-plane control from Pérez and Bevilacqua [7] (*phase one*)
- Used for the out-of-plane relative motion control using DL (*phase two*)
- Tracks the desired trajectory $\boldsymbol{x_d}$ which is designed by regulating the *Schweighardt-Sedwig* model [6] using a *Linear-Quadratic Regulator* (LQR) ($\underline{\boldsymbol{A}}_{\boldsymbol{d}} = \underline{\boldsymbol{A}} - \underline{\boldsymbol{BK}}$)

Lyapunov function: $V = \boldsymbol{e}^T \underline{\boldsymbol{P}} \boldsymbol{e}$ *Tracking error:* $\boldsymbol{e} = \boldsymbol{x} - \boldsymbol{x_d}$

Lyapunov equation: $-\underline{\boldsymbol{Q}} = \underline{\boldsymbol{A}}_d^T \underline{\boldsymbol{P}} + \underline{\boldsymbol{P}}\underline{\boldsymbol{A}}_d$

Time derivative: $\dot{V} = \boldsymbol{e}^T(\underline{\boldsymbol{A}}_d^T \underline{\boldsymbol{P}} + \underline{\boldsymbol{P}}\underline{\boldsymbol{A}}_d)\boldsymbol{e} + 2\boldsymbol{e}^T \underline{\boldsymbol{P}}\,(\boldsymbol{f}(\boldsymbol{x}) - \underline{\boldsymbol{A}}_d \boldsymbol{x} + \underline{\boldsymbol{B}}\boldsymbol{u} - \underline{\boldsymbol{B}}\boldsymbol{u}_d)$

$\dot{V} = -\boldsymbol{e}^T \underline{\boldsymbol{Q}} \boldsymbol{e} + 2\Delta$ with: $\Delta = \beta\hat{u} - \delta$

$\delta = \boldsymbol{e}^T \underline{\boldsymbol{P}}\,(\underline{\boldsymbol{A}}_d \boldsymbol{x} - \boldsymbol{f}(\boldsymbol{x}) + \underline{\boldsymbol{B}}\boldsymbol{u}_d)$

$\beta = \boldsymbol{e}^T \underline{\boldsymbol{PB}} a_{aero}$

and: $\hat{u} = \begin{cases} 1 \\ 0 \\ -1 \end{cases}$

Final control strategy: $\hat{u} = -sign(\beta)$

Simulation Setup

Propagator: *In-house built, MATLAB® based including:*

- Harmonics of Earth's gravitational potential up to J_6
- Third-body perturbations of Sun and Moon
- Solar-Radiation Pressure

Table 1: Initial orbital parameters of the chief spacecraft

Parameter:	Chief:
Semi-major axis:	6778.137 km
Eccentricity:	0 °
Inclination:	10 °
RAAN:	45 °
Argument of periapsis:	130 °
True anomaly:	45 °

Table 2: Initial relative pos. and vel. of the deputy (LVLH)

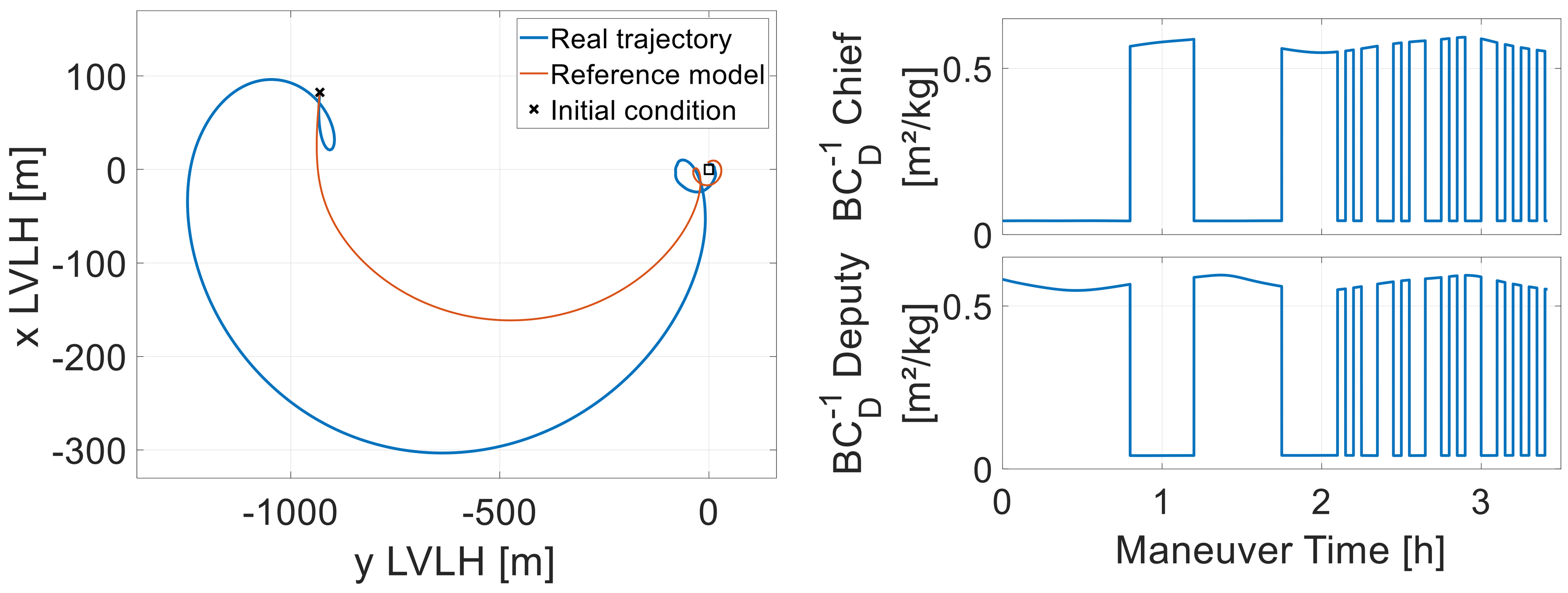
Parameter:	Deputy:
$x_0/y_0/z_0$ [m]	82.50/-930.46/55.27
$\dot{x}_0/\dot{y}_0/\dot{z}_0$ [m/s]	-0.17/-0.04/0.29

Table 3: Spacecraft design

Parameter:	Chief:	Deputy:
Mass	10 kg	10 kg
Area ⊥ (body)	0.09 m²	0.09 m²
Area ⊥ (panels) @ 90° AOA	2.2 m²	2.2 m²
Area ⊥ (panels) @ 0° AOA	0 m²	0 m²
Area ⊥ (panels) @ 45° AOA	1.556 m²	1.556 m²
S/C wall temperature	300 K	300 K

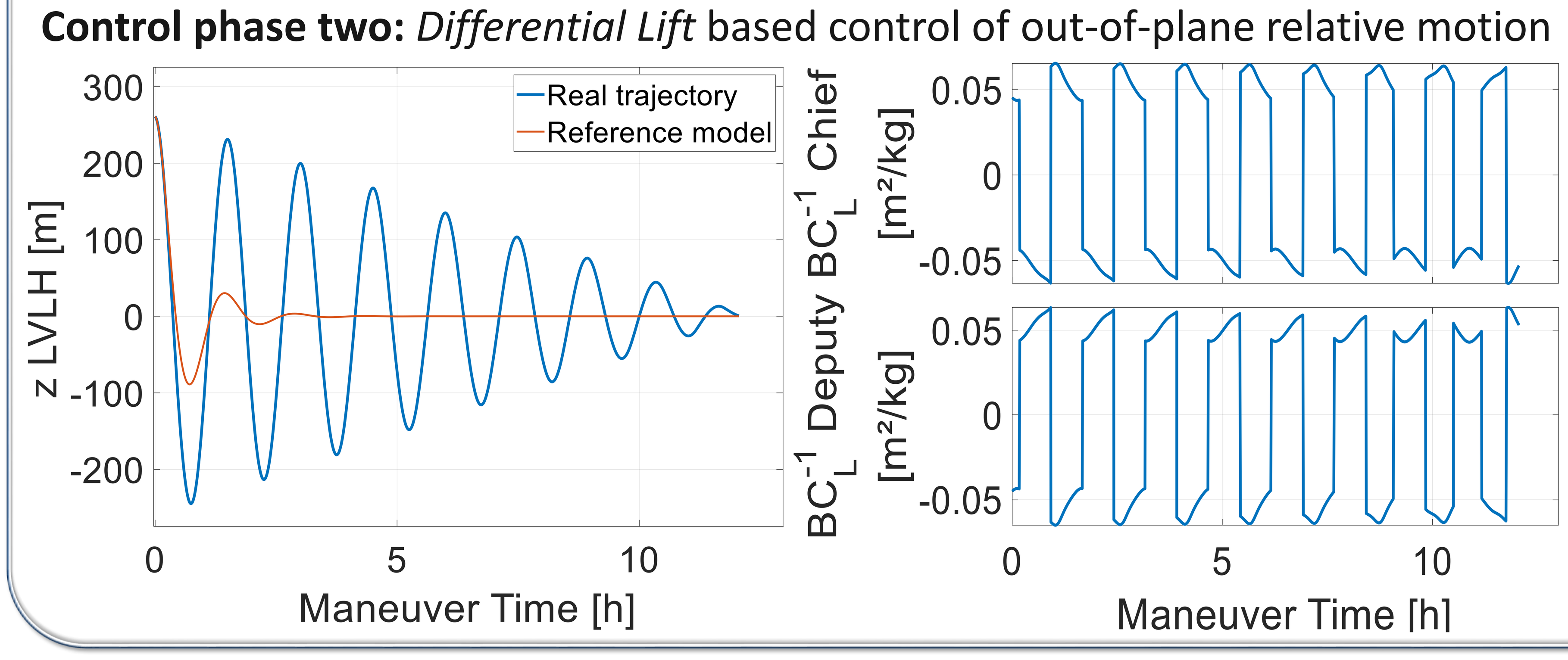
Results

Control phase one: *Differential Drag* based control of in-plane relative motion



Maneuver time:	3.41 h
# Panel switches:	24
Fin. rel. position: (Δx/Δy/Δz) [m]	4.8/-1.4/-261
Fin. rel. velocity: ($\Delta\dot{x}/\Delta\dot{y}/\Delta\dot{z}$) [cm/s]	-0.4/1.08/-1.4
$\bar{\alpha}$	0.913
$\bar{a}_y$ [m/s²]	6.89e-5

Control phase two: *Differential Lift* based control of out-of-plane relative motion



Maneuver time:	12.06 h
# Panel switches:	17
Fin. rel. position: (Δx/Δy/Δz) [m]	5.3/37.8/0.7
Fin. rel. velocity: ($\Delta\dot{x}/\Delta\dot{y}/\Delta\dot{z}$) [cm/s]	0.3/-0.1/0.5
$\bar{\alpha}$ [-]	0.913
$\bar{a}_z$ [m/s²]	1.4e-5

LVLH = local vertical, local horizontal coordinate system centered at the chief

Conclusion & Future Work

Conclusion:

- The proposed control strategy is able to guide the deputy into close proximity of the chief despite dynamic variations and perturbations.
- The maneuver time of control phase two is strongly dependent on the magnitude of the available differential lift acceleration.

Future work:

- Analysis of the influence of energy accommodation on the maneuver sequence → possible benefits from DISCOVERER findings [2].

References

[1] *DISCOVERER.* [Online] Available: https://discoverer.space/. **[2]** Roberts, P.C.E., Crisp, N.H., Edmondson, S., Haigh, S.J., Lyons, R.E., Oiko, V.T.A., Macario Rojas, A., Smith, K.L., Becedas, J., González, G., Vázquez, I., Braña, Á., Antonini, K., Bay, K., Ghizoni, L., Jungnell, V., Morsbøl, J., Binder, T., Boxberger, A., Herdrich, G.H., Romano, F., Fasoulas, S., Garcia-Almiñana, D., Rodriguez-Donaire, S., Kataria, D., Davidson, M., Outlaw, R., Belkouchi, B., Conte, A., Perez, J.S., Villain, R., Heißerer, B., Schwalber, A.:"DISCOVERER - Radical Redesign of Earth Observation Satellites for Suistained Operation at Significantly Lower Altitudes," *68th International Astronautical Congress (IAC)*, 2017. **[3]** J. M. Picone, A. E. Hedin, D. P. Drob, and A. C. Aikin, "NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues," *J. Geophys. Res.*, vol. 107, no. A12, SIA 15-1-SIA 15-16, 2002. **[4]** L. H. Sentman, "Free molecule flow theory and its application to the determination of aerodynamic forces," *Technical Report, Lockheed Aircraft Corporation*, 1961. **[5]** M. D. Pilinski, B. M. Argrow, and S. E. Palo, "Semiempirical Model for Satellite Energy-Accommodation Coefficients," *Journal of Spacecraft and Rockets*, vol. 47, no. 6, pp. 951–956, 2010. **[6]** S. A. Schweighart and R. J. Sedwick, "High-Fidelity Linearized J2 Model for Satellite Formation Flight," *Journal of Guidance, Control, and Dynamics*, vol. 25, no. 6, pp. 1073–1080, 2002. **[7]** D. Pérez and R. Bevilacqua, "Lyapunov-Based Spacecraft Rendezvous Maneuvers using Differential Drag," *AIAA Guidance, Navigation and Control Conference*, 2011.