Instituto Nacional de Técnica Aeroespacial

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DEVELOPMENT OF CONTROL CONTRACTION METRIC BASED METHODS ON NON-CONVENTIONAL AIRCRAFT CONFIGURATION

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INTA

EXAELIA
Flying Testbeds for Novel Long-Range Aircraft

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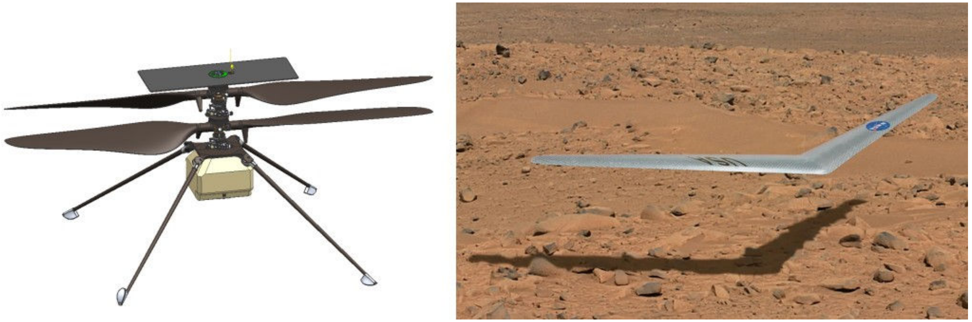
Motivation



Left: NASA’s Ingenuity [1] is up to date the only Remotely Piloted Aircraft System (RPAS) able to fly atmospheric missions on another planet. Right: Different configurations have been proposed as planetary exploration RPAS, for instance, Prandtl-m concept [2]

- Uncrewed Airborne Vehicles (UAVs) missions both in Earth and Space could benefit from power consumption reductions.
- New and non-conventional configurations could deliver this as long as control is possible.
- The case for a Blended Wing Body (BWB) may serve as initial work: EXAELIA.
- Control Contraction Metrics (CCMs) are the non-linear control alternative choosen.

[1] H. F. Grip, D. P. Scharf, C. Malpica, W. Johnson, M. Mandic, G. Singh, and L. A. Young, “**Guidance and control for a Mars helicopter,”** in 2018 AIAA Guidance, Navigation, and Control Conference, p. 1849, 2018.
[2] Nancy J. Pekar. **Could this be the first Mars Air-plane?** https://www.nasa.gov/aeronautics/could-this-become-the-first-mars-airplane/, note = [Accessed 1st June 2025].

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EXAELIA in a nutshell

- EXAELIA stands for '**EX**perimental **A**ircraft for **E**uropean **L**eadership **I**n **A**viation'
- It is an Horizon Europe project in response to HORIZON-CL5-2024-D5-01-10 "Towards a flying testbed for European leadership in aviation". Major European aviation research centers form the consortium.
- One of the objectives is '*to evaluate flying test beds that are needed for de-risking the development of disruptive future long-range aircraft. Novel flying test beds will thus help to accelerate the reduction of all aviation emissions and its climate and environmental impacts by 2050*' [3].
- For this purpose, UAV scale demonstrators are about to be flown and tested by 2028.

[3] EXAELIA Consortium. EU-Project EXAELIA: To-wards flying testbeds for novel long- range aircraft. https://exaelia.eu/, 2025. [Accessed 1st June 2025].

EXAELIA's family photo at NLR (Amsterdam), during Kick-off meeting on January 2025

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EXAELIA in a nutshell

- INTA's activities:
  - To measure Flight Test Data of test beds using SPOT system.
  - To compare and find the best testing site for a future real-scale demonstrator.
  - To develop control laws for 'Hazardous Flight Conditions' (HFCs)
- In this context, CCMs are the expected mean to achieve control during said HFCs

INTA's three contributions to EXAELIA. Selection of a suitable flight test site for project next phases (left). SPOT system for on-ground measurements (center) of flight testing demonstrators. HFC control is the third contribution. Preliminary insight was obtained thanks to modifications on CC0 Michael Krueger's model [4], while we obtain EXAELIA's final model.

[4] Michael Kruger. **Blended wing body on OpenAirshow.** https://airshow.openvsp.org/vsp/uGjWQekFe6IobbfZrymO, 2025. [Online; accessed2025-06-01].

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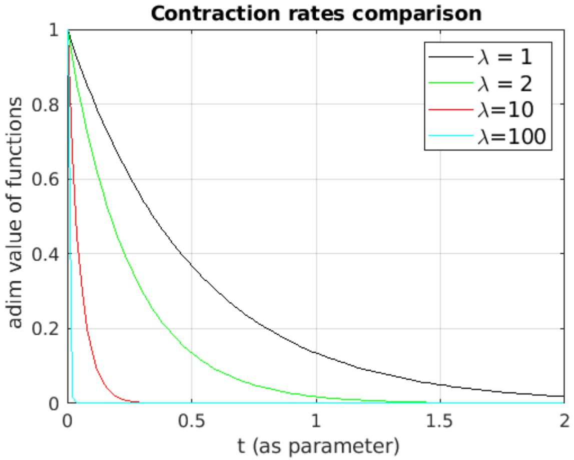
CCMs in a nutshell



$$\dot{x} = f(x,t) + B(x,t)u$$

$$A = \left(\frac{\partial f}{\partial x} + \sum_{i=1}^{m} \frac{\partial b_i}{\partial x} u_i \right)$$

$$u(t) = u^*(t) - \frac{1}{2} \int_0^1 \rho(\gamma(s),t)\ B(t)^T\ M(\gamma(s),t) \frac{\partial \gamma}{\partial s} ds$$

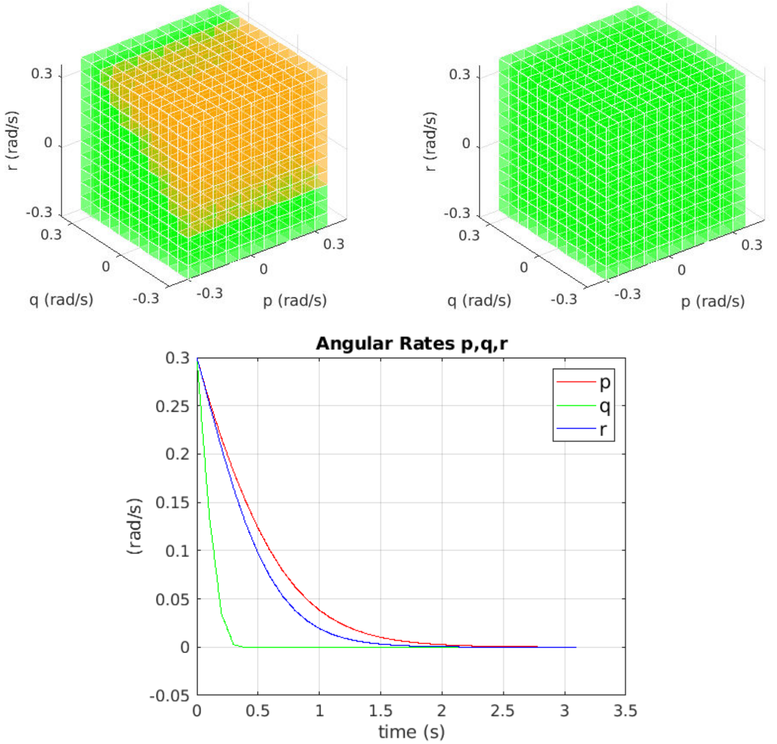
$$-\frac{\partial M}{\partial t} - \sum_i \frac{\partial M}{\partial x_i} \dot{x}_i + \sum_j \frac{\partial M}{\partial u_j} + AM + MA^T + 2\lambda M - \rho BB^T \prec 0$$

- *Control Contraction Metric* uses contraction analysis for:
  - Ensure contraction is possible by means of defining a metric with the right characteristics. [5]
  - To generate control laws through the integration of the metric geodesics. [6]
  - As a result, system can be steered through trajectories without the need for classic stability to be present.

[5] I. R. Manchester and J.-J. E. Slotine, **“Control contraction metrics: Convex and intrinsic criteria for nonlinear feedback design,”** IEEE transactions on automatic control, vol. 62, no. 6, 2017.
[6] Karen Leung and Ian R Manchester. “**Nonlinear stabilization via control contraction metrics: A pseudospectral approach for computing geodesics”.** In 2017 American Control Conference (ACC), pages 1284–1289. IEEE,2017.

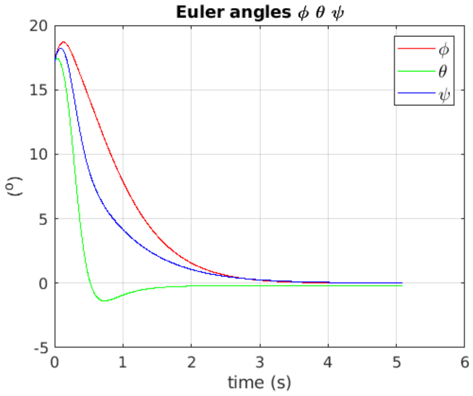
Work done

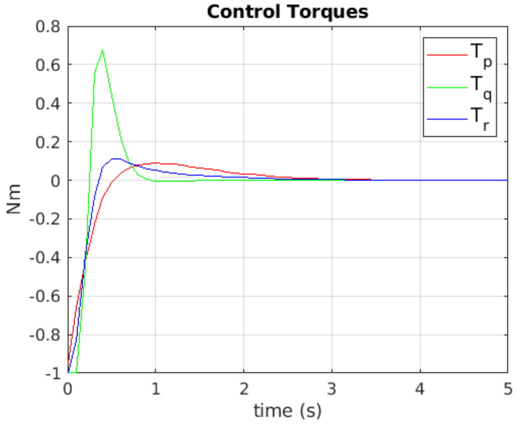
- A study on contraction has been performed by state space domain checks in a pure rotational system.
- A comparison of metrics performance has also been done, studying a baseline identity metric, an exponential metric and an angular quadratic rates metric.
- While exponential metric improves results a little, identity metric as baseline remains as a very attractive alternative.



Angular rate contraction domain for identity metric (up). Each big cube represents a discrete set of angular rate values (p,q,r) from -0.3 to 0.3 rad/s. Orange cubes are (p,q,r) values that can't guarantee contraction. Green cubes are angular rates which on the contrary, guarantee contraction. At the bottom, angular rates evolution from -0.3 rad/s to 0 rad/s using an exponential metric as CCM in the control.

Work done





Variable		Value	Unit
Max roll torque needed	L_{max}	$0-2$	Nm
Available roll($\delta_a = -30^o$)	L	up to 10	Nm
Max pitch torque	M_{max}	$8-10$	Nm
Available pitch($\delta_e = -30^o$)	M	up to 6	Nm
Max yaw torque	N_{max}	$8-10$	Nm
Available yaw($\delta_r = -45^o$)	N	about 1	Nm

Euler angles evolution and torques needed to steer the aircraft from HFCs to zero with the identity as CCM (up). A satisfactory response was found possible in under 4 seconds with this simplified model (left). Needed torques to control from available aircraft models were compared with needed control predicted by CCM method. Yaw control was not up to the task

- Attitude control was then added to angular rates control, obtaining reasonable responses with a simplified model of BWB aircraft.
- Identity CCM for attitude angles. Angular rates comparison between identity and exponential.
- Finally, a comparison between available and needed torques in the model was performed.

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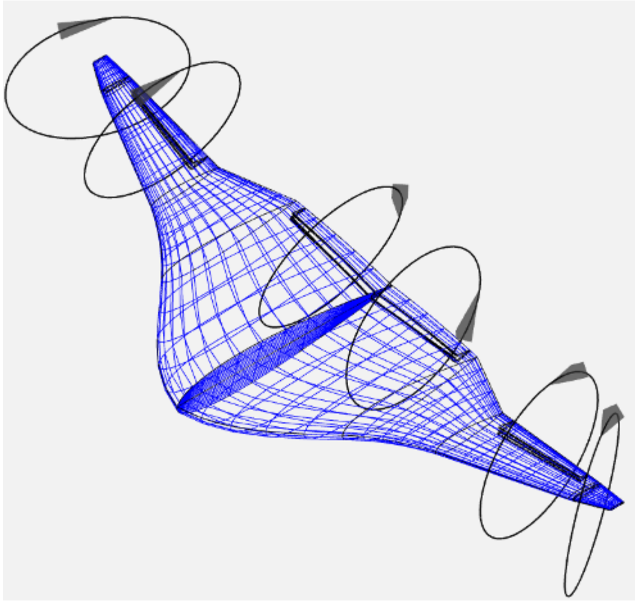
Discussion and Results

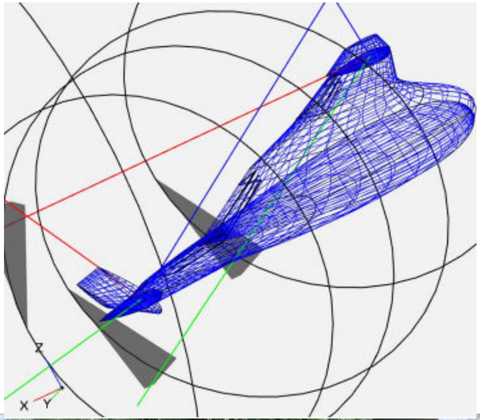
- Baseline metric offers consistent control (probably due the nature of the equations selected). Exponential metric improves little.
- It is theoretically possible to steer the dynamical system from hazardous initial conditions to safe state vector values (where linear control can return), in a reasonable time (about 3 to 4 seconds)
- This includes both angular rates and aircraft attitude.
- From the analysis it can be concluded that a more powerful directional control is needed, better than conventional drag-rudders: this can be critical in BWB configurations.



After accounting for control effectiveness reduction mainly due low Reynolds, it was concluded drag-rudders were not enough Instead, a wing tip all-surface will be tested to improve yaw control authority. A model from scratch was designed with OpenVSP [7] and currently is being tested at INTA.

[7] Rob McDonald J.R. Gloudemans et al. **Open Vehicle Sketch Pad,** 2025.

Conclusions and future works



A wingtip rudder solution is currently being simulated at INTA (up). This solution comes with trade-offs, but it is the preferred option once different conventional rudders configurations were tested with scaled 3D printed models (down). Preliminary data gathering with these models allowed fast checks on what theory already had predicted.

- As conclusions:
  - On pure rotational dynamics, the technique works fine (so far) up to attitude control.
  - Identity metric is a good baseline, although once sign changes are present, could be improved.
  - Yaw control authority requires novel solutions beyond conventional rudders.

- As future works:
  - A complete model with flight and initial conditions influence should be implemented and tested.
  - Adaptive solutions shall be added if possible due model uncertainty.
  - A real demonstrator for experimental data gathering shall be constructed and tested, prior to final test-beds flight testing in 2028.

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Questions?

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- [2] Nancy J. Pekar. Could this be the first Mars Air-plane? https://www.nasa.gov/aeronautics/could-this-become-the-first-mars-airplane/, note = [Accessed 1st June 2025].
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