Advances in launcher guidance and control design: from robust control to convex optimization

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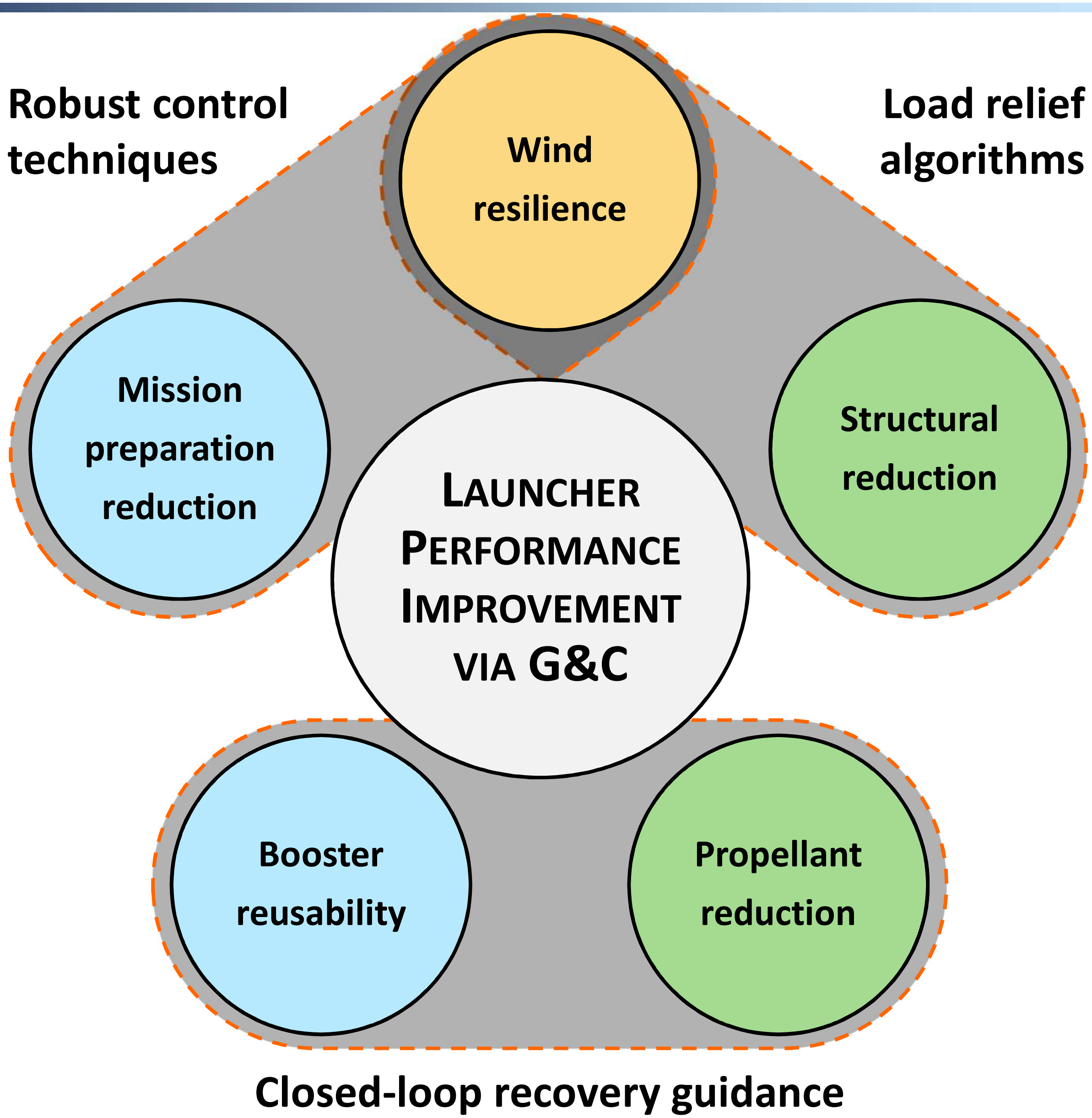
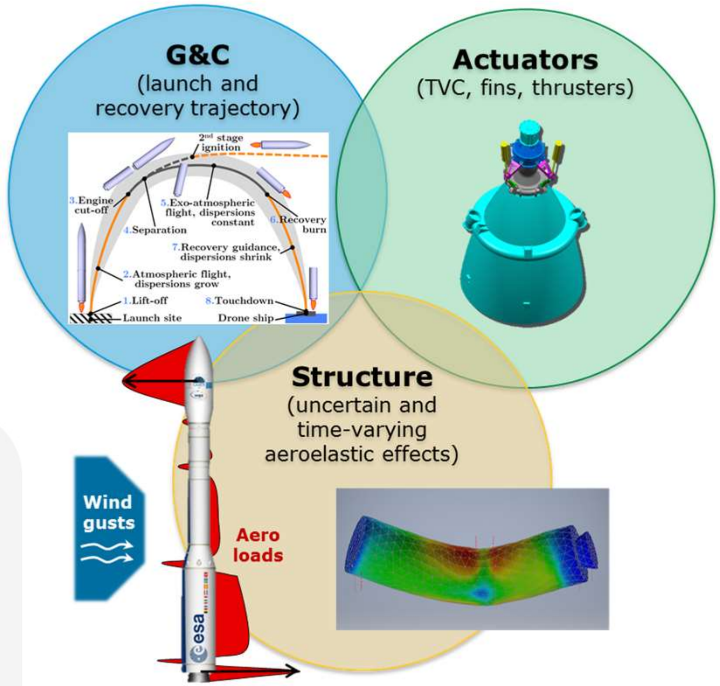
Motivation



Robust control techniques
Load relief algorithms
Wind resilience
Mission preparation reduction
Structural reduction
LAUNCHER PERFORMANCE IMPROVEMENT VIA G&C
Booster reusability
Propellant reduction
Closed-loop recovery guidance

Motivation

- Launcher G&C particularly **challenging** because:
  - Mission/aerothermal requirements tend to **compete** against each other
  - Strong **couplings** between trajectory, propulsion and flexible structure



Funded by an **ESA NPI contract** 4000114460/15/NL/MH/ats

"***Robust & Adaptable Launcher TVC Control Systems for the VEGA Evolution***"

Samir Bennani

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Christophe Roux

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"***Advanced Flight Control System Design With Active Load & Relief Capabilities***"

Samir Bennani

Pedro Simplício
Andrés Marcos

Stephan Theil
David Seelbinder

Layout

1. **Ascent Control: robust → LPV → adaptive**
    - VEGA launcher case
2. **Descent Guidance: convex pinpoint landing optimization**
    - VEGA-like reusable launch vehicle case
3. **Ascent Load Relief: wind disturbance observer + fins**
    - VEGA-like reusable launch vehicle case

Ascent Control:
robust → LPV → Adaptive

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"***Robust & Adaptable Launcher TVC Control Systems for the VEGA Evolution***"

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Diego Navarro-Tapia is also the recipient of a DTP award by the UK EPSRC

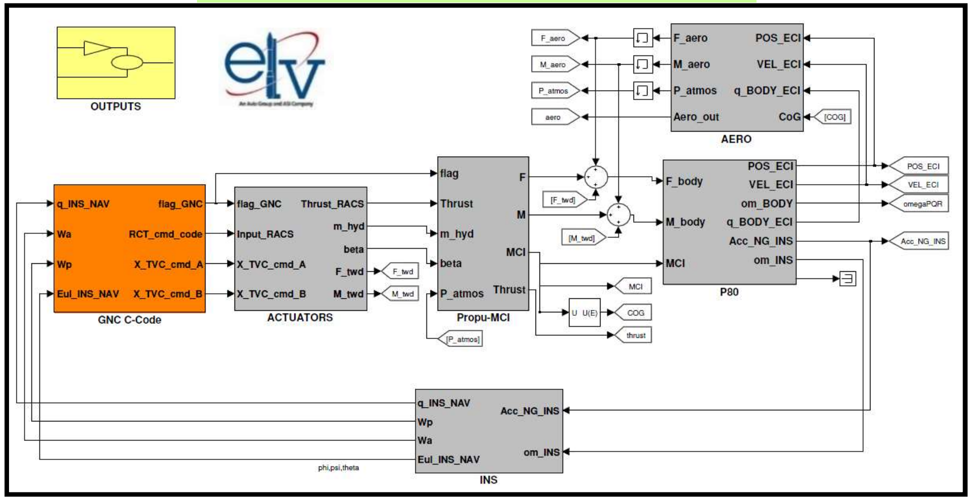
VEGA challenges:
VEGA launcher

VEGA (Vettore Europeo di Generazione Avanzata)

is the **new European Small Launch Vehicle**

13 successful flights … 14th this month

VEGACONTROL
nonlinear, high-fidelity simulator for atmospheric phase



Over 120 uncertain parameters

Type	Flag	Description
AEROELASTICITY	Flag.aeroelastic	aero-elasticity effect (+10% on CN coefficient)
AERODYNAMICS	Flag.disp_CA	Dispersion on 1st Stage Axial Coefficient
	Flag.unc_CA	Uncertainty on 1st Stage Axial Coefficient
	Flag.disp_CN	Dispersion on 1st Stage Normal Coefficient
	Flag.unc_CN	Uncertainty on 1st Stage Normal Coefficient
	Flag.disp_Xcp	Dispersion on 1st Stage Xcp
	Flag.unc_Xcp	Uncertainty on 1st Stage Xcp
	Flag.aero_roll	To enable Roll motion
WIND	Flag.azimuth_wind_angle	Wind azimuth direction [rad]
	Flag.h_wind	Synthetic wind gust altitude [Km]
IRS	Flag.IRSmountingX	IRS Mounting Error wrt X Body Axis
	Flag.IRSmountingY	IRS Mounting Error wrt Y Body Axis
	Flag.IRSmountingZ	IRS Mounting Error wrt Z Body Axis
THRUST PARAMETERS SCATTERING	Flag.dISP	1st stage impulse scattering
	Flag.dTc	Scattering on time burn
	Flag.SRM_roll	Scattering on P80 Roll Torque
MCI	Flag.stagedM	Structural mass scattering
	Flag.stagedM_Prop	Scattering on propellant mass
	Flag.stagedJx	Scattering on Stage XX MOI
	Flag.stagedJy	Scattering on Stage YY MOI
	Flag.stagedJz	Scattering on Stage ZZ MOI
	Flag. stagedxCOG	Scattering on X CoG
	Flag. stagedyCOG	Scattering on Y CoG
	Flag. stagedzCOG	Scattering on Z CoG
	Flag. stagedJx_S	Scattering on structural Stage XX MOI
	Flag. stagedJy_S	Scattering on structural Stage YY MOI
	Flag. stagedJz_S	Scattering on structural Stage ZZ MOI
	Flag. stagedxCOG_S	Scattering on structural X CoG
	Flag. stagedyCOG_S	Scattering on Y structural CoG

MCI	Flag.PLdM	Scattering on PL Mass
	Flag.PLdJx	Scattering on PL XX MOI
	Flag.PldJy	Scattering on PL YY MOI
	Flag.PLdJz	Scattering on PL ZZ MOI
	Flag.PLdxCOG	Scattering on PL X CoG
	Flag.PLdyCOG	Scattering on PL Y CoG
	Flag.PLdzCOG	Scattering on PL Z CoG
THRUST OFFSET & MISALIGNMENT	Flag.TVC_SF_A	Scattering on TVC gain Lane A
	Flag.TVC_bias_A_disp	Scattering on TVC Lane A (Gaussian)
	Flag.TVC_bias_A_unc	Scattering on TVC Lane A (uniform)
	Flag.TVC_SF_B	Scattering on TVC gain Lane B
	Flag.TVC_bias_B_disp	Scattering on TVC Lane B (Gaussian)
	Flag.TVC_bias_B_unc	Scattering on TVC Lane B (uniform)
	Flag.Thrust_misA_disp	Scattering on thrust misalignment first lane (Gaussian)
	Flag.Thrust_misB_disp	Scattering on thrust misalignment second lane (Gaussian)
	Flag.Thrust_misA_unc	Scattering on thrust misalignment first lane (uniform)
	Flag.Thrust_misB_unc	Scattering on thrust misalignment second lane (uniform)
	Flag.PvP_offsetX	Scattering on thrust offset in X
	Flag.PvP_offsetY_disp	Scattering on thrust offset in Y (Gaussian)
	Flag.PvP_offsetZ_disp	Scattering on thrust offset in Z (Gaussian)
	Flag.PvP_offsetY_unc	Scattering on thrust offset in Y (uniform)
	Flag.PvP_offsetZ_unc	Scattering on thrust offset in Z (uniform)
ATMOSPHERE	Flag.air_density_scat	Atmospheric Density
SEPARATION DISTURB	Flag.sep_dist_yz	

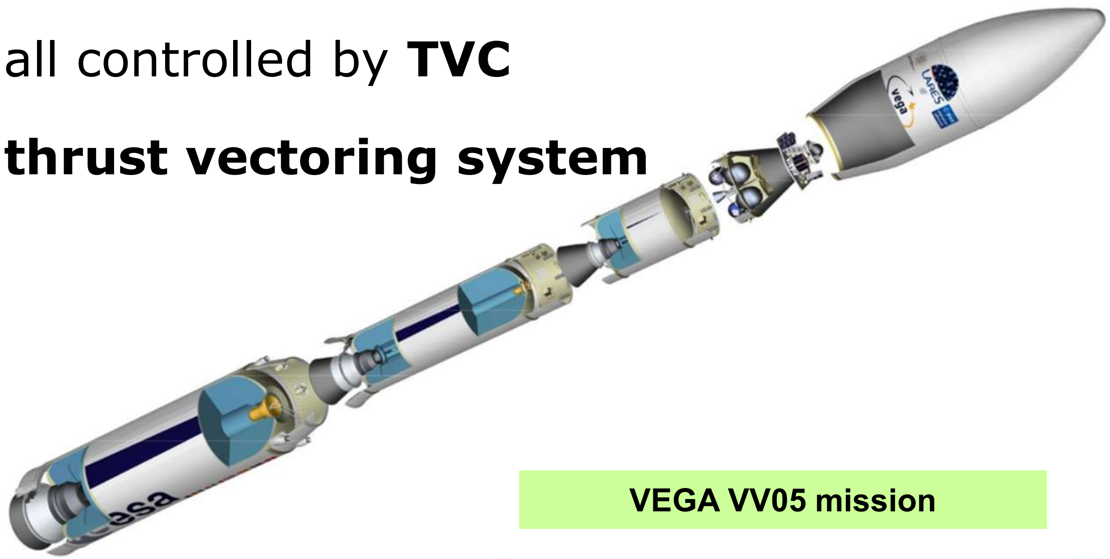
VEGA challenges:

Vehicle, mission and environment

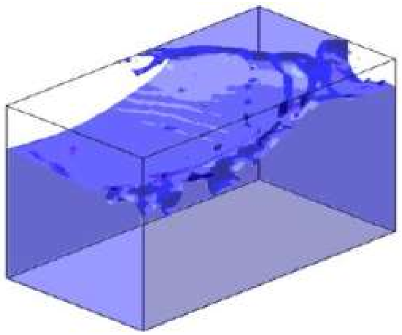
Four stages vehicle,

all controlled by **TVC**

thrust vectoring system



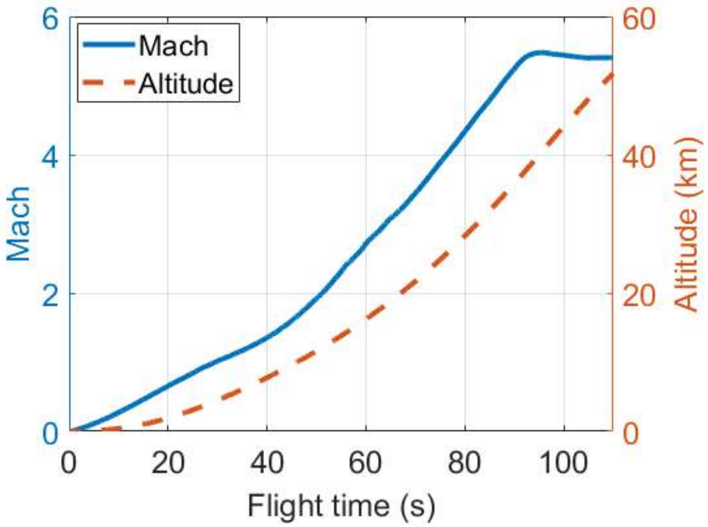
sloshing



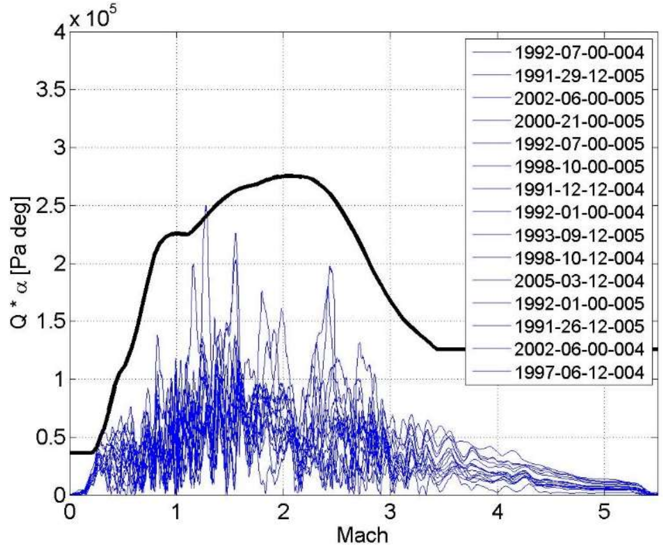
Atmospheric phase challenges

- ❑ **Launch vehicle:**
  - Unstable
  - Flexible structure
  - sloshing
- ❑ **High variation of flight parameters**
- ❑ **Challenging environment**:
  - Wind disturbances
  - Structural loads (Qalpha)

VEGA VV05 mission



VEGA Qalpha wind effect



VEGA State-of-Practice:
Control design process

Using nominal models | **Using perturbed models**

Modelling → **Design** → **Scheduling** → **V&V**

Modelling

Launcher model linearised at representative points along trajectory

For VEGA ~every 10 sec

Design

1. Rigid-body controller design
2. Bending filters design
3. Rigid- and flexible-body joint tuning

Scheduling

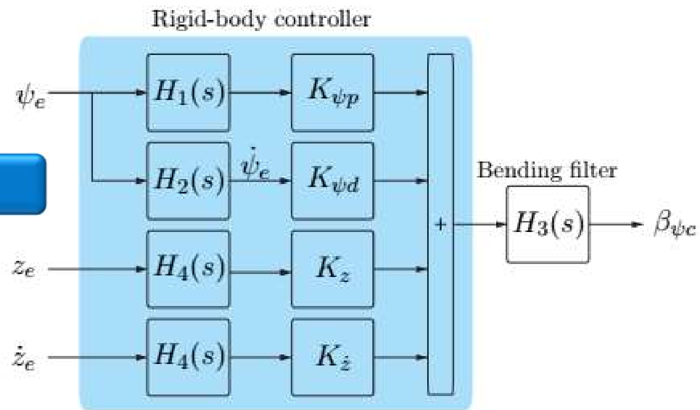
Ad-hoc scheduling based on some parameter (time, VNG)

V&V

Intensive V&V process using high-fidelity nonlinear simulator

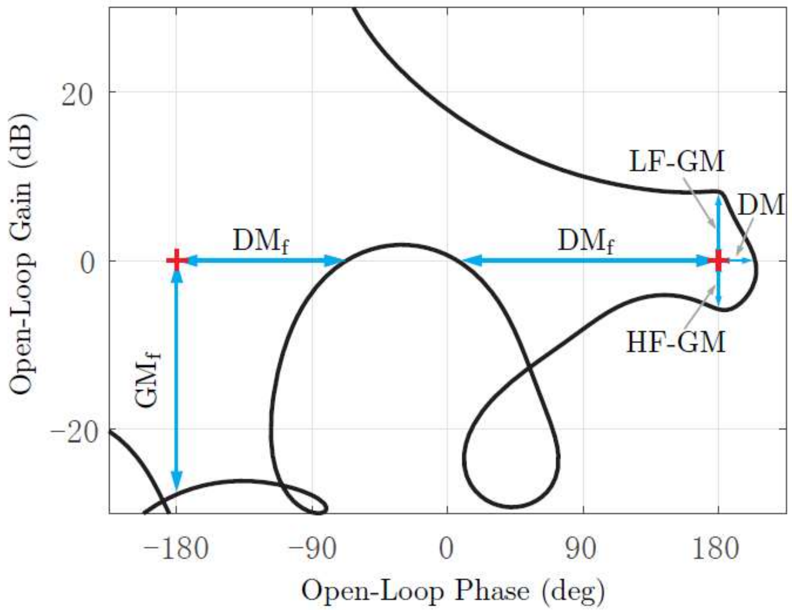
For VEGA Monte Carlo & Vertex simulations

VEGA TVC architecture

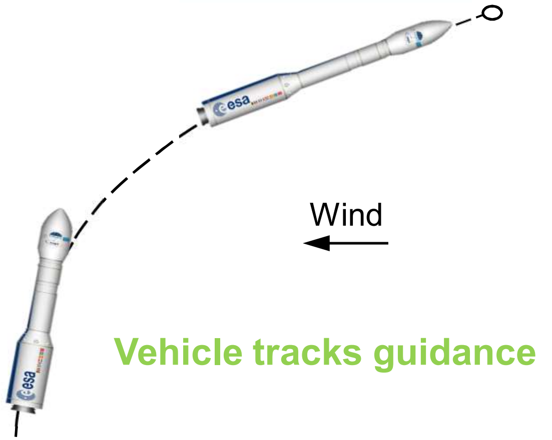


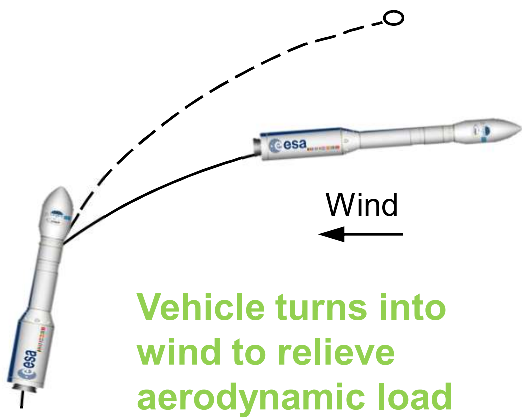
VEGA State-of-Practice:
Control objectives & design rationale

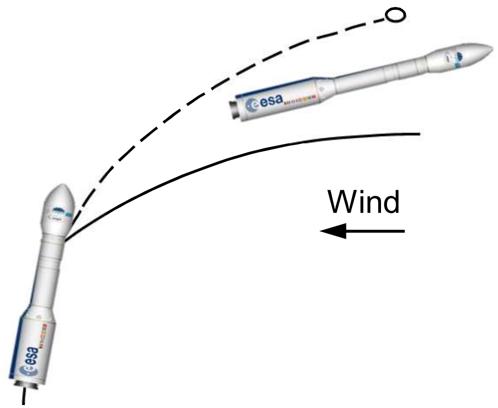
	Requirements	Metrics		Bounds
Stability	Rigid-body margins	LF-GM	Nominal	≥ 6 dB
			Dispersed	≥ 0.5 dB
		DM	Nominal	≥ 100 ms
			Dispersed	≥ 40 ms
		HF-GM	Nominal	≤ -6 dB
			Dispersed	≤ -3 dB
	Flexible-body margins	GM_f	Nominal	≤ -3 dB
			Dispersed	
		DM_f	Nominal	≥ 50 ms
			Dispersed	≥ 20 ms



Pure Attitude Control	Pure Load Relief Control	Optimized Control







Ascent Control:
robust → LPV → Adaptive

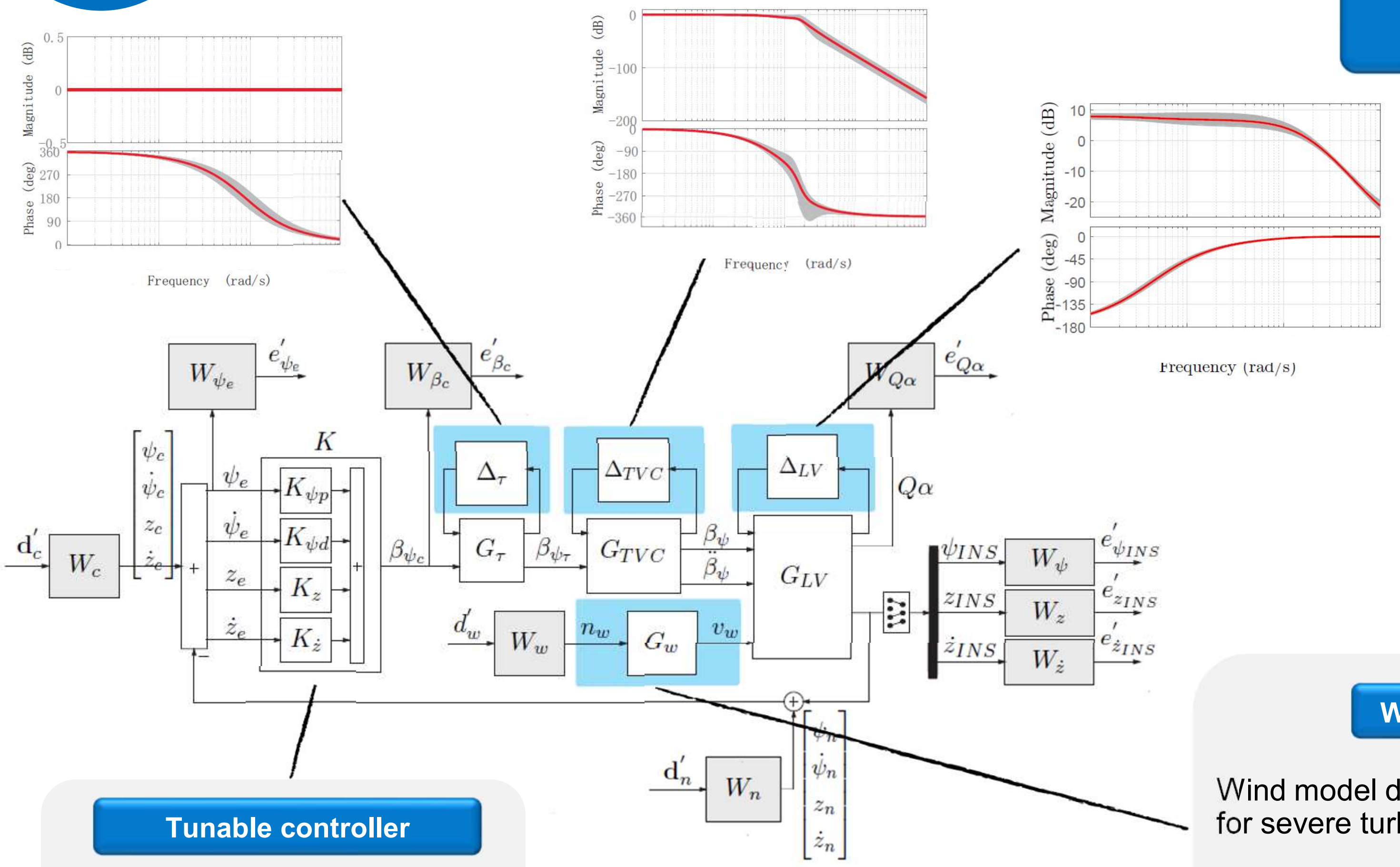
VEGA Structured H_∞ synthesis: Rigid-body robust design

Structured H_∞

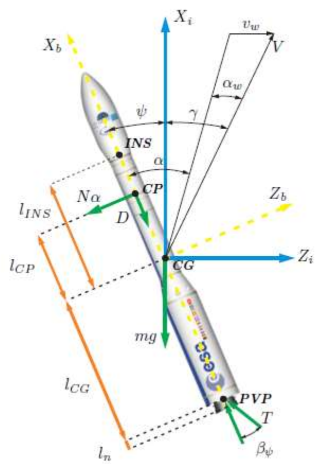
Nominal rigid-body design

Robust rigid-body design

Rigid-body design can be **augmented** to account for statistical **wind levels** and **parametric uncertainties (LFT modelling)**



Rigid-body Launch vehicle model



Tunable controller

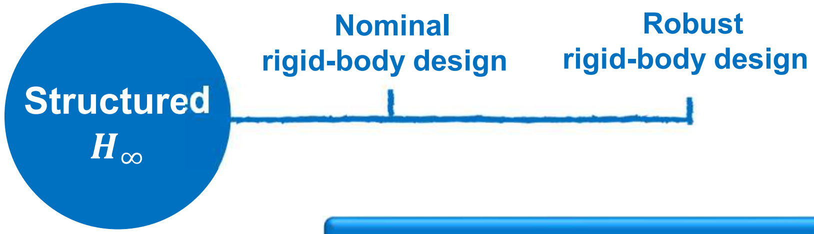
- ❑ Rigid-body controller four parameters

Wind generator

Wind model defined by a **Dryden filter** for severe turbulence:

$$G_w(s) = \frac{v_w(s)}{n_w(s)} = \frac{\sqrt{\frac{2}{\pi}\frac{V(h)-v_{wp}(h)}{L(h)}\sigma^2(h)}}{s + \frac{V(h)-v_{wp}(h)}{L(h)}}$$

VEGA Structured H_∞ synthesis:
Rigid-body robust nonlinear Monte Carlo analysis



In total, **9 linear structured H_∞ controllers** are synthesized along the atmospheric phase, and are scheduled using VNG (as in VEGA)

Nonlinear Monte Carlo analysis

4 MC campaigns of 500 runs:

Each MC used **same scattering flags**

but a **different wind profile**

MC quantitative assessment

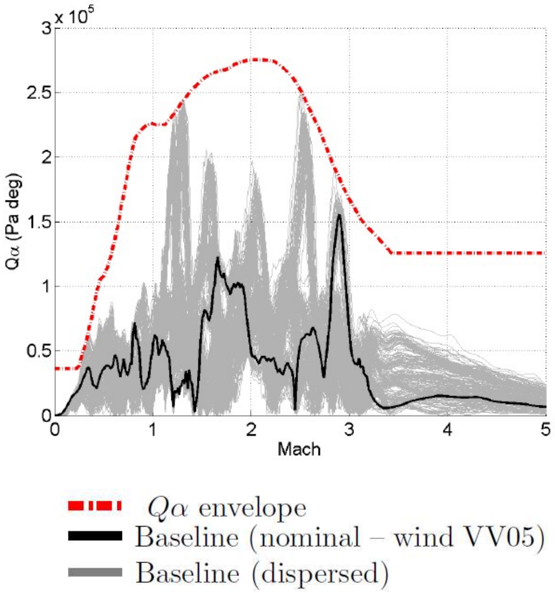
For each controller and each MC run,

get the **∞-norm** and **2-norm**

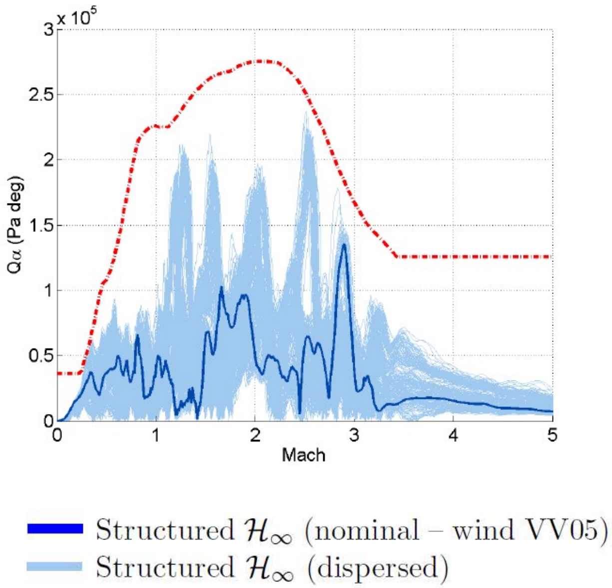
for different performance indicators.

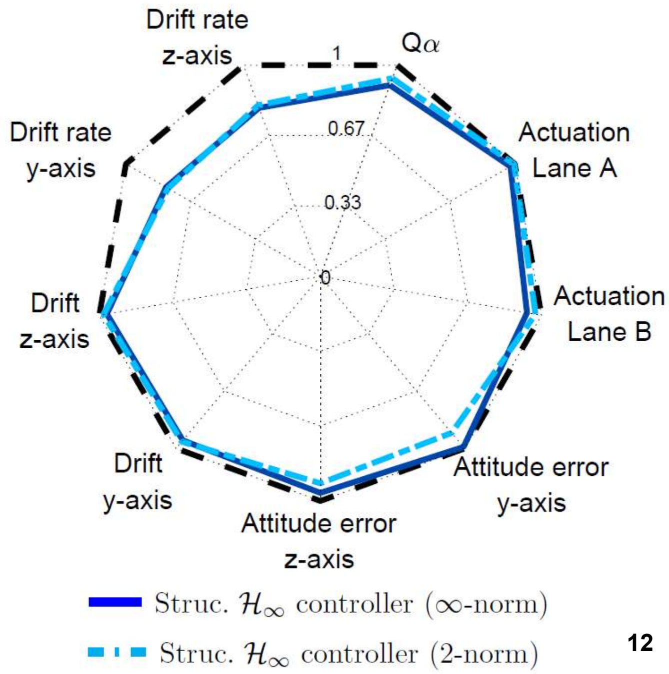
Results normalised wrt baseline controller

Baseline controller



Rigid-Body Structured H_∞ controller



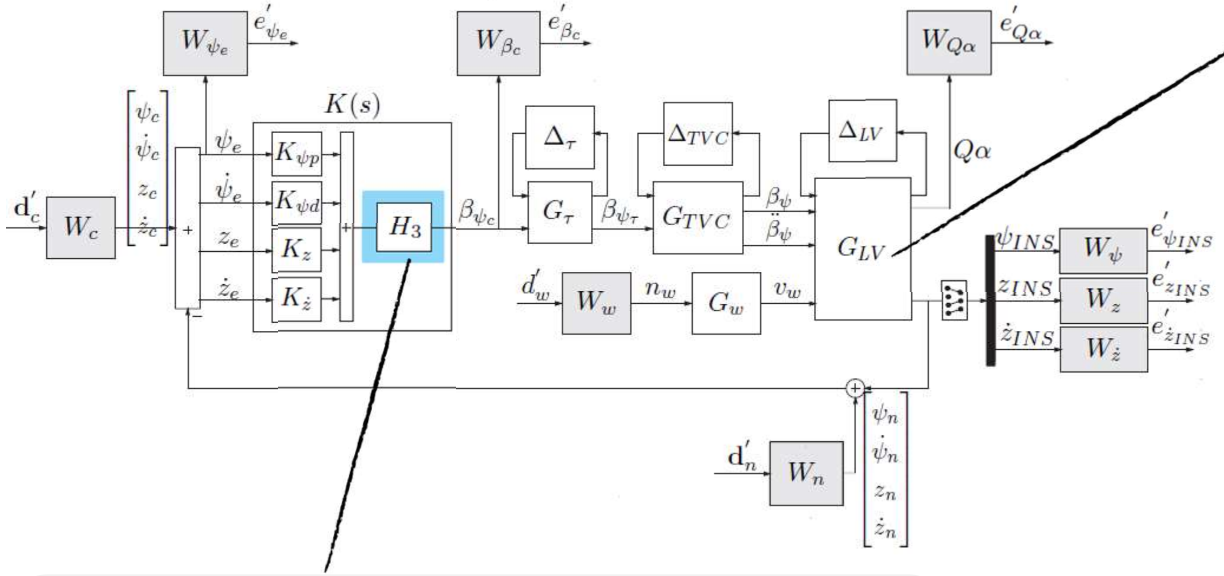


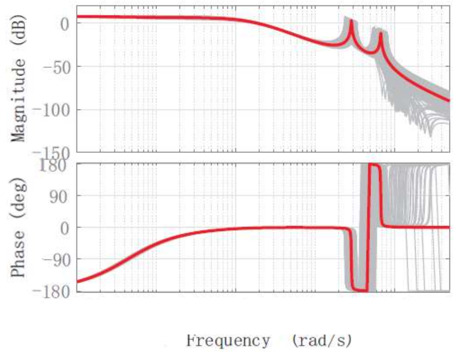
VEGA Structured H_∞ synthesis:
Flexible sequential bending filter design

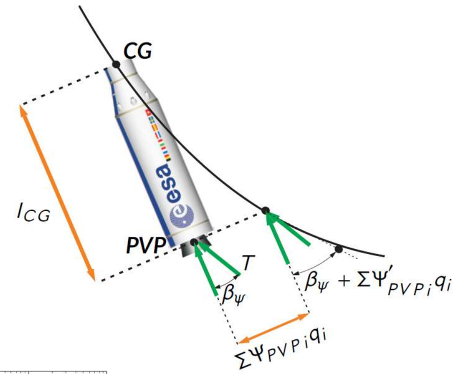
Structured H_∞

- Nominal rigid-body design
- Robust rigid-body design
- Bending filter design

LFT launch vehicle model
Rigid-body and flexible dynamics



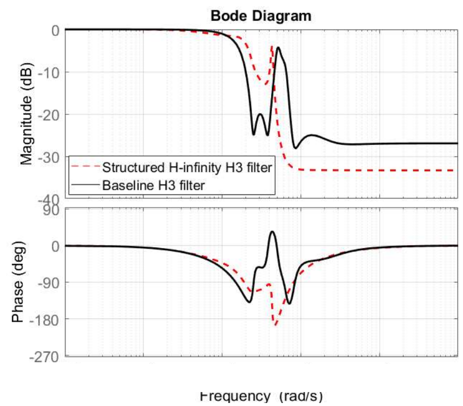




Tunable controller

- ❑ Rigid-body controller fixed as baseline controller
- ❑ Tunable bending filter (6 parameters)

$$H_3 = \prod_{i=1}^{2} \frac{s^2 + 2\zeta_{n_i} w_{n_i} s + {w_{n_i}}^2}{s^2 + 2\zeta_{d_i} w_{n_i} s + {w_{n_i}}^2} \left\{ \frac{s^2 + 2 \cdot 0.24 \cdot 25 \cdot s + 25^2}{s^2 + 2 \cdot 0.4 \cdot 25 \cdot s + 25^2} \right\}^3$$



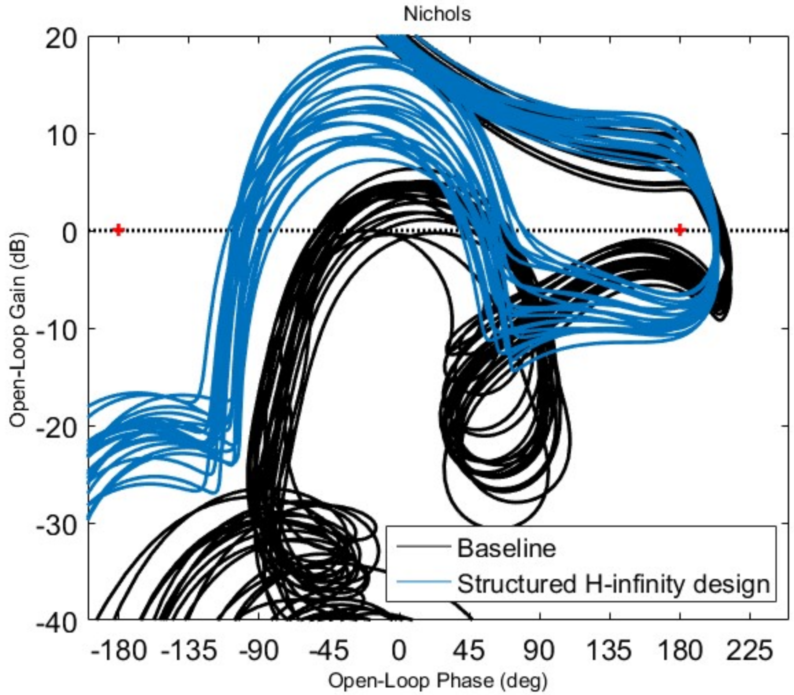
VEGA Structured H_∞ synthesis:
Flexible sequential linear analysis

Structured H_∞

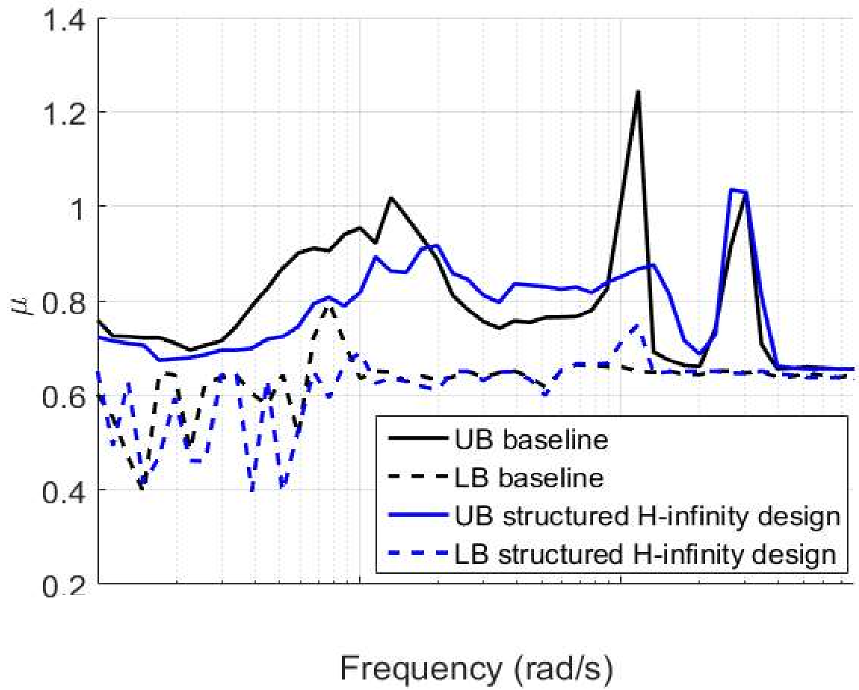
- **Nominal rigid-body design**
- **Robust rigid-body design**
- **Bending filter design**

Only **1 linear structured H_∞ controllers** is synthesized and analyzed

Classical stability analysis



Robust stability analysis

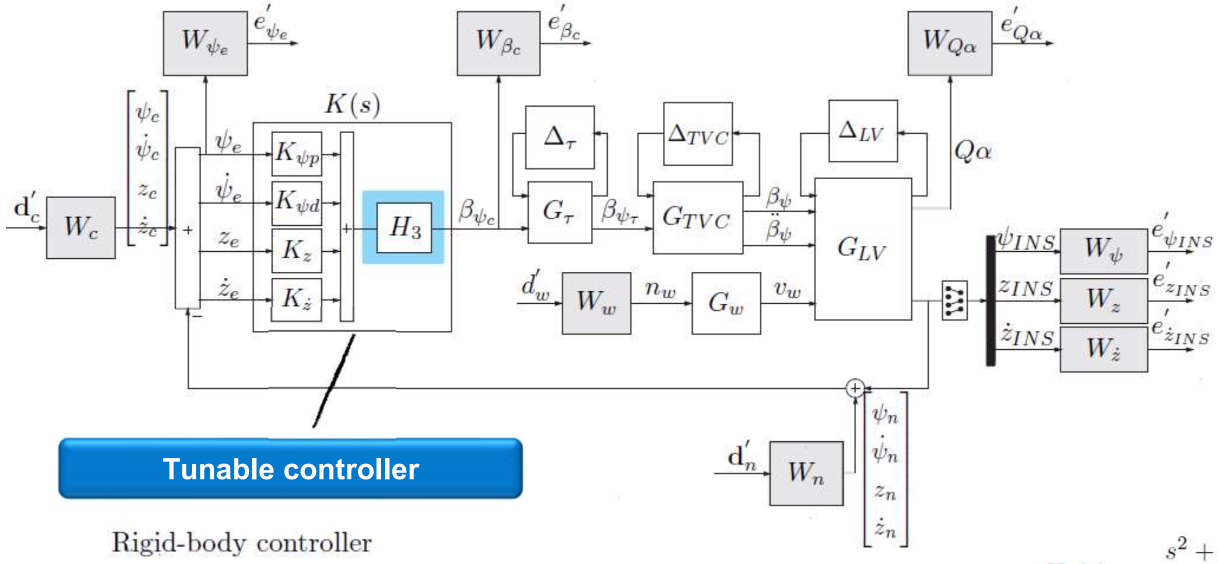


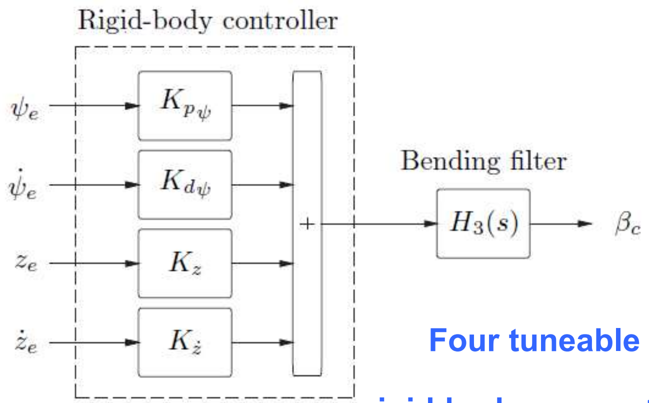
Potential for improvement
with respect to baseline bending filter

VEGA Structured H_∞ synthesis: Rigid+Flexible integrated design

Structured H_∞

- Nominal rigid-body design
- Robust rigid-body design
- Bending filter design
- Robust joint design Rigid-body controller and bending filter





Four tuneable rigid-body parameters

Four tuneable flexible-body parameters

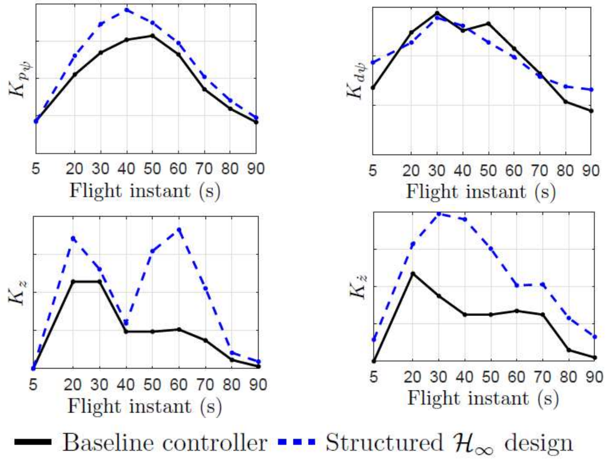
$$H_3(s) = \underbrace{\frac{s^2+\eta_1 s+(\omega_{q1}')^2}{s^2+\eta_1/\epsilon_1 s+(\omega_{q1}')^2}}_{\substack{\text{Notch filter 1}\\ [\min 1^{st} BM]}} \underbrace{\frac{s^2+\eta_2 s+(\omega_{q1})^2}{s^2+\eta_2/\epsilon_2 s+(\omega_{q1})^2}}_{\substack{\text{Notch filter 2}\\ [\text{nom}1^{st} BM]}} \underbrace{\frac{s^2+\eta_3 s+(\overline{\omega_{q1}}')^2}{s^2+\eta_3/\epsilon_3 s+(\overline{\omega_{q1}}')^2}}_{\substack{\text{Notch filter 3}\\ [\max 1^{st} BM]}}$$

$$\underbrace{\frac{s^2+\eta_4 s+(\omega_{q2}')^2}{s^2+\eta_4/\epsilon_4 s+(\omega_{q2}')^2}}_{\substack{\text{Notch filter 4}\\ [\min 2^{nd} BM]}} \underbrace{\left(\frac{\epsilon_{LP} s^2+\eta_{LP} s+(0.6\omega_{q2}')^2}{s^2+\eta_{LP} s+(0.6\omega_{q2}')^2}\right)^3}_{\substack{\text{Low-pass filter}\\ [\text{Upper BMs attenuation}]}}$$

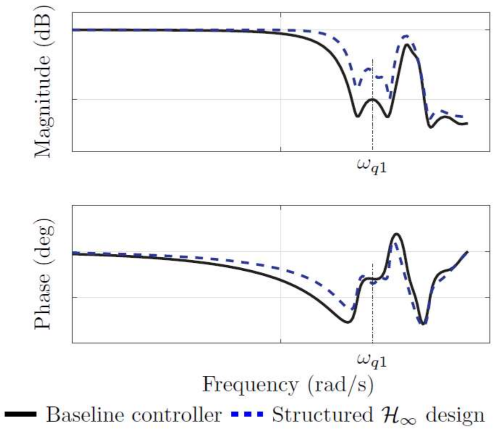
VEGA Structured H_∞ synthesis:
Rigid+Flexible integrated analysis

In total, **9 linear integrated structured H_∞ controllers** synthesized along the atmospheric phase

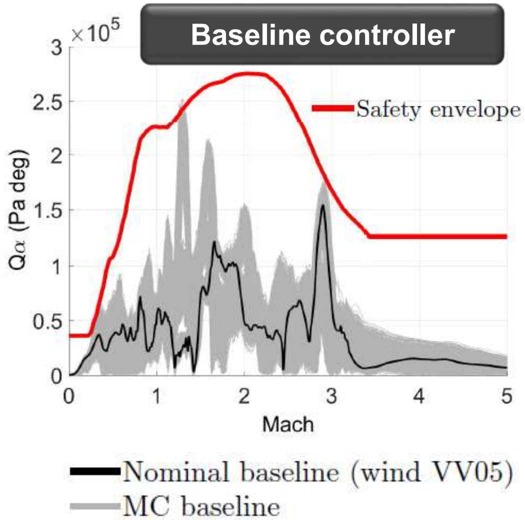
Rigid-body gains

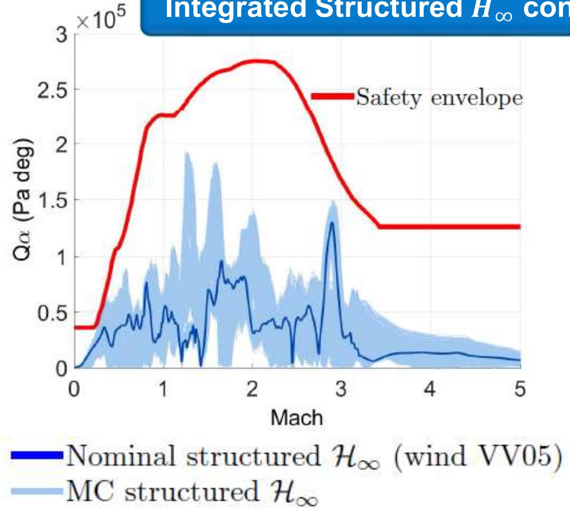


Bending filter comparison at t=50s

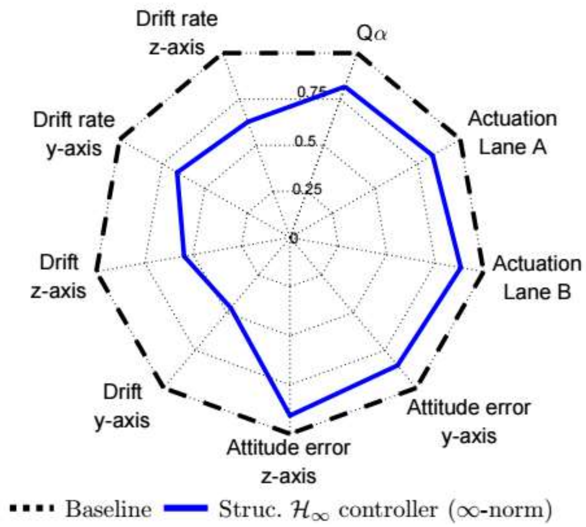


Nonlinear Monte Carlo analysis





MC quantitative assessment



Ascent Control:

robust → LPV → Adaptive

VEGA LPV synthesis:
Design weighting functions

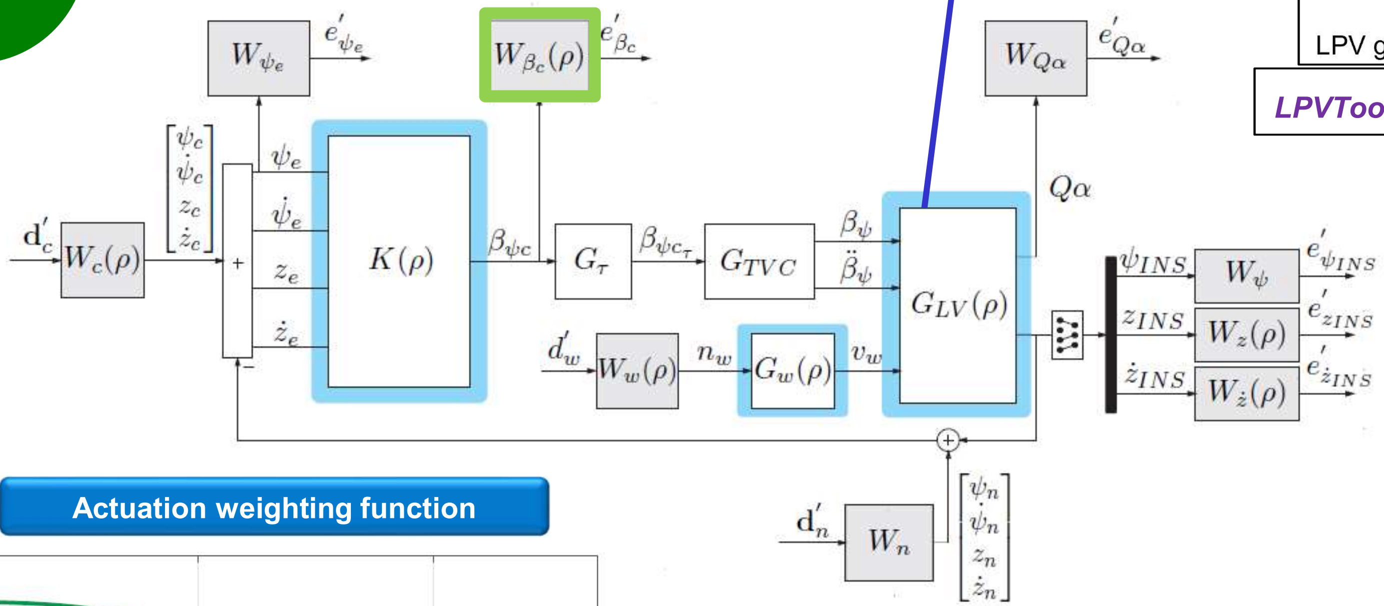
LPV synthesis

$$\begin{bmatrix}\dot{\mathbf{x}}_{\mathbf{LV}}\\ \mathbf{u}_{\mathbf{LV}}\end{bmatrix} = \underbrace{\begin{bmatrix}A_{LV}(\rho) & B_{LV}(\rho)\\ C_{LV}(\rho) & D_{LV}(\rho)\end{bmatrix}}_{G_{LV}(s,\rho)} \begin{bmatrix}\mathbf{x}_{\mathbf{LV}}\\ \mathbf{y}_{\mathbf{LV}}\end{bmatrix}; \quad \text{with} \quad \begin{matrix}\rho(t) \in \mathcal{P}_{NGV}\\ \underline{\nu_{NGA}} < \dot{\rho}(t) < \overline{\nu_{NGA}}\end{matrix}$$

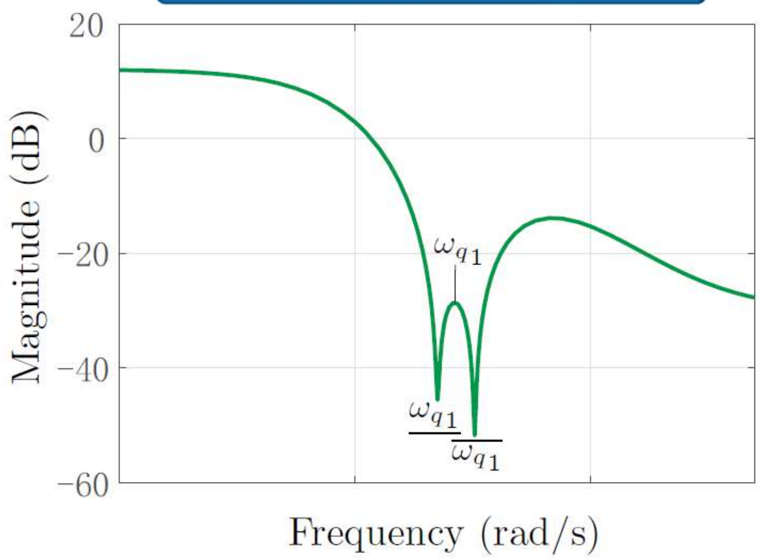
LPV grid: $t = [20\ 40\ 50\ 60\ 70\ 90]$s

LPVTools1.0 toolbox from UMN

LPVTools object



Actuation weighting function



$$W_u^{-1}(s,\theta) = \underbrace{\frac{s^2 + 0.5s + (\underline{\omega_{q1}}(\theta))^2}{s^2 + 70s + (\underline{\omega_{q1}}(\theta))^2}}_{\text{Notch 1}} \underbrace{\frac{s^2 + 0.5s + (\overline{\omega_{q1}}(\theta))^2}{s^2 + 70s + (\overline{\omega_{q1}}(\theta))^2}}_{\text{Notch 2}} \underbrace{F(s,\theta)}_{\text{Low-pass filter}}$$

LPV synthesis

LPV synthesis using ***LPVTools1.0 toolbox*** from UMN

Control problem formulated as: $\min_{K(s,\rho)} ||\mathcal{T}_{e'd'}(s,\rho)||_{\mathcal{L}_2 \to \mathcal{L}_2};$ subject to $\rho(t) \in \mathcal{P}_{NGV}$, $\underline{\nu_{NGA}} < \dot{\rho}(t) < \overline{\nu_{NGA}}$

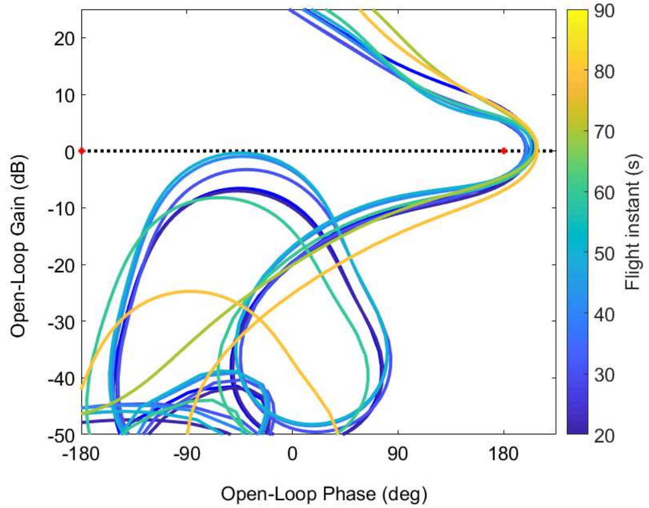
Quadratic basis functions to constrain the rate variation of VNG:

$$X_\rho = X_0 + X_1\rho + X_2\rho^2$$
$$Y_\rho = Y_0 + Y_1\rho + Y_2\rho^2$$

High computational complexity

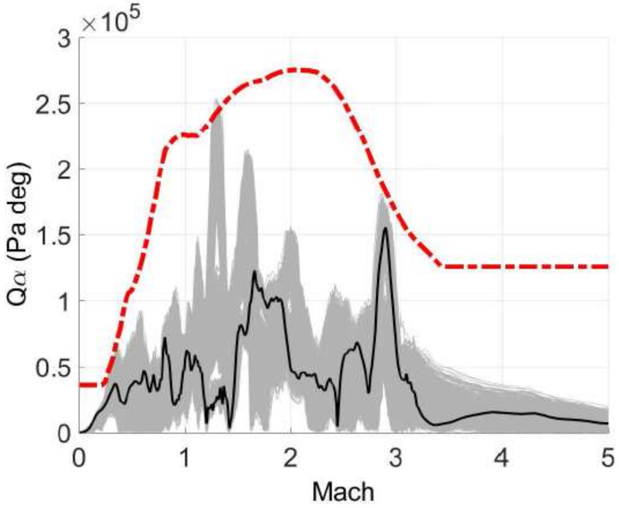
Resultant controller (rigid-body and bending filter): **22 states**

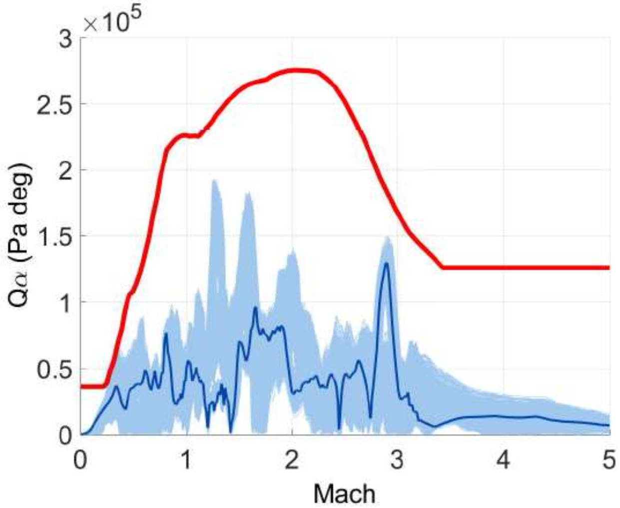
V&V Stability

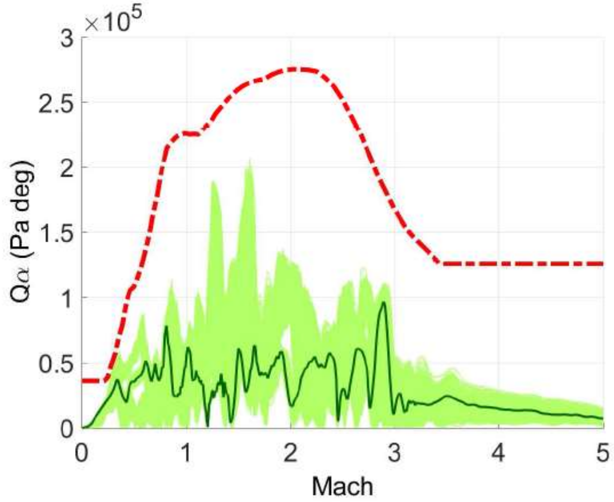


VEGA LPV synthesis:
Nonlinear MC analysis

Baseline | **Integrated RigFlex Structured H_∞** | **LPV**

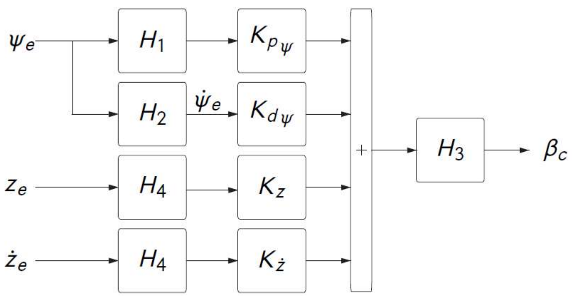






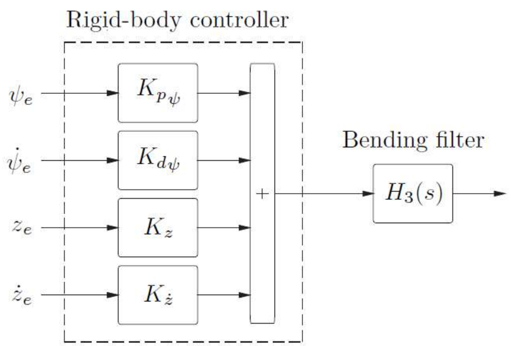
4 gains

23 states controller

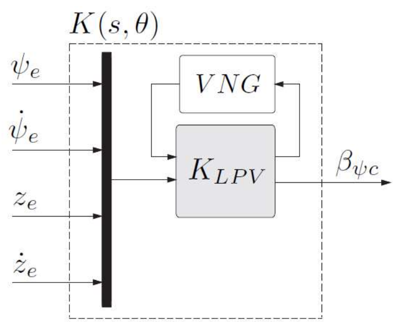


4 gains

15 states controller



Full-order controller: 22 states



VEGA Structured H_∞+IM synthesis:
Additional controller structure

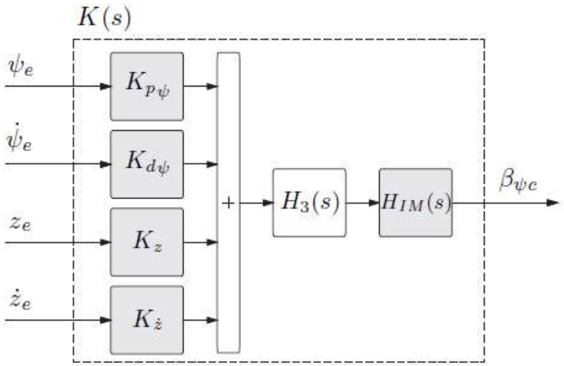
Structured H_∞ design improves robustness & performance for <u>same controller structure</u>

➔ **better gain-tunings are possible (and in an easier and more methodological manner)**

Non-Rate Bounded LPV design shows that there is room to improve robustness and performance

➔ **better controller architectures can, and should, be used**

Redesign the integrated structured H_∞ controller including an identified internal model **H_{IM}(s)**

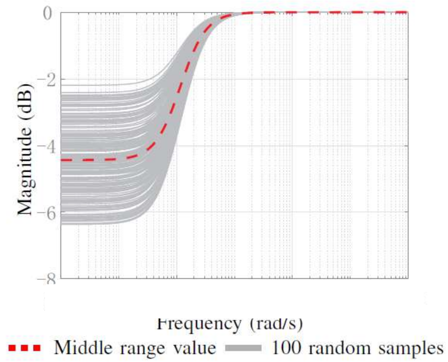


H_{IM}(s)

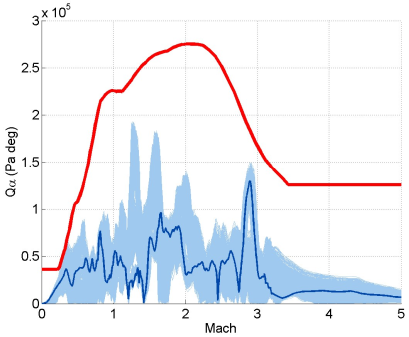
1[st]-order high-pass TF

with tuneable

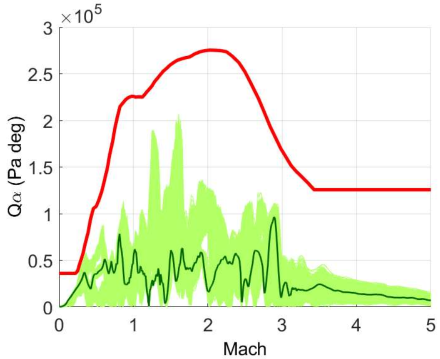
pole and zero parameters



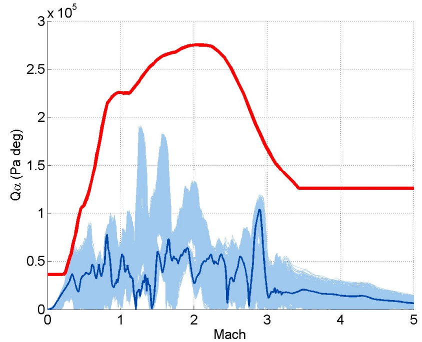
Structured H_∞



LPV



Structured H_∞ with Internal Model



Ascent Control:

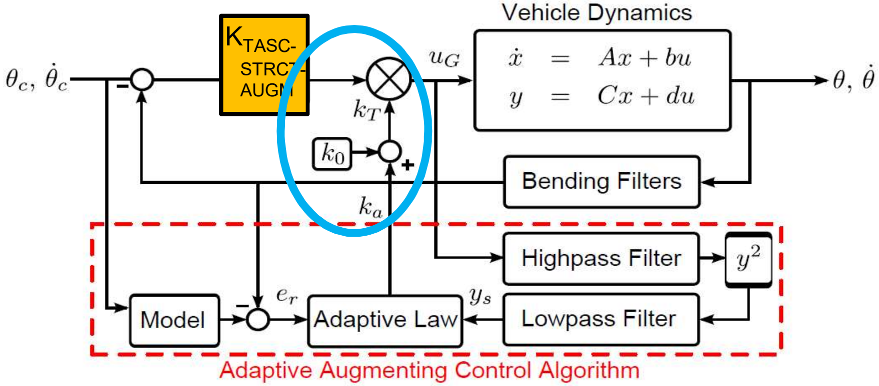
robust → LPV → Adaptive

LPV versus Adaptive control:
NASA adaptive controllers description

ADAPTIVE CONTROL LAW – A (2012)

J. Orr and T.S. VanZwieten
"**Robust, Practical Adaptive Control for Launch Vehicles**",
in AIAA Guidance, Navigation, and Control Conference, 2012

Adaptive augmentation is based on a multiplicative law:

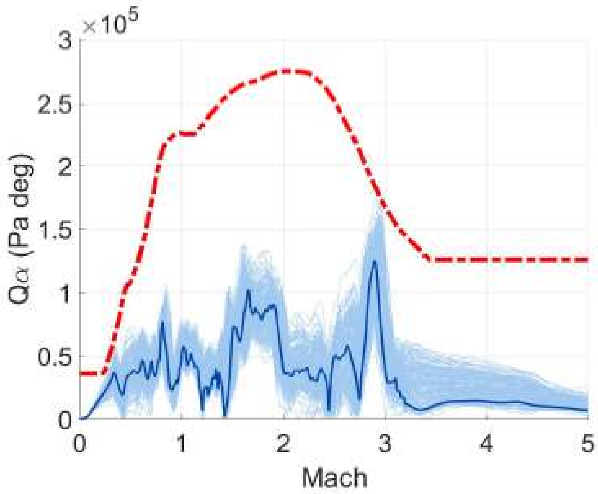


$$\underbrace{k_T}_{\text{Total loop gain}} = \underbrace{k_0}_{\text{Minimum total loop gain}} + \underbrace{k_a}_{\text{Adaptive gain}}$$

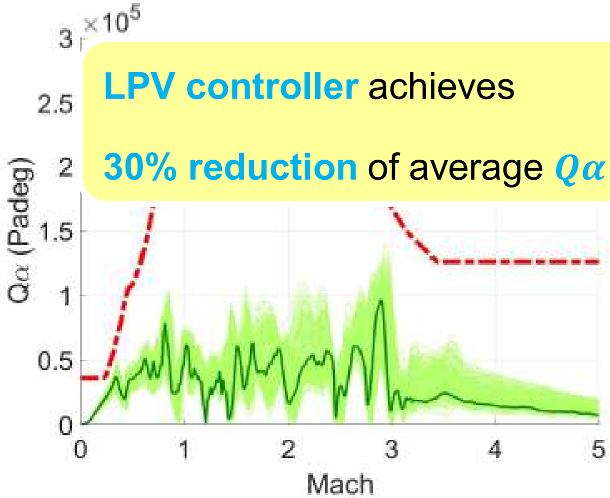
Adaptive gain k_a is given by a first order ODE equation:

$$\dot{k}_a = \underbrace{a e_r{}^2}_{\text{Adaptive Error}} - \underbrace{\frac{k_a}{k_{max}} a e_r{}^2}_{\text{Logistic Damper}} - \underbrace{\alpha k_a y_s}_{\text{Spectral Damper}} - \underbrace{\beta(k_T - 1)}_{\text{Leakage}}$$

Adaptive + integrated structured H_∞



LPV



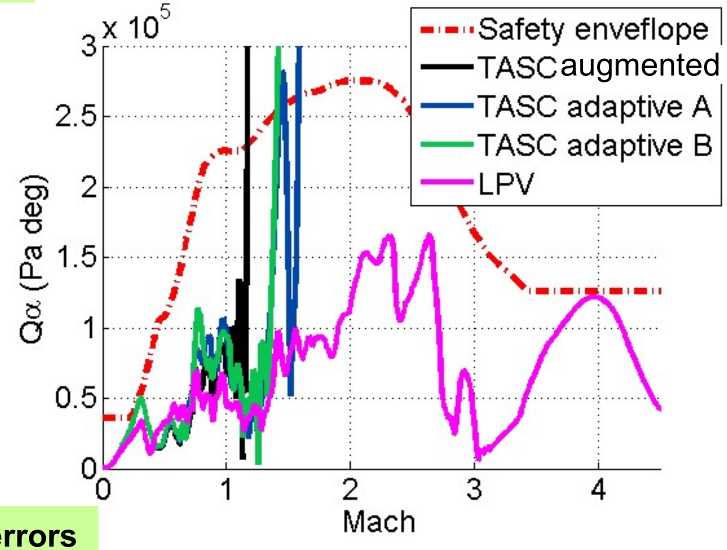
LPV controller achieves

30% reduction of average **$Q\alpha$ peaks**

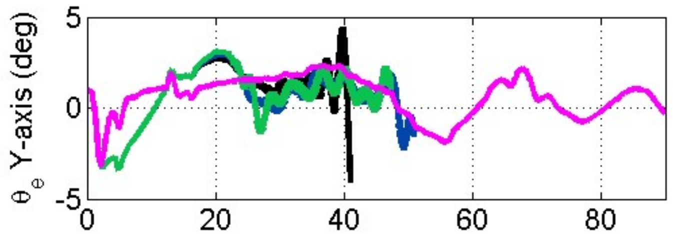
LPV versus Adaptive control:

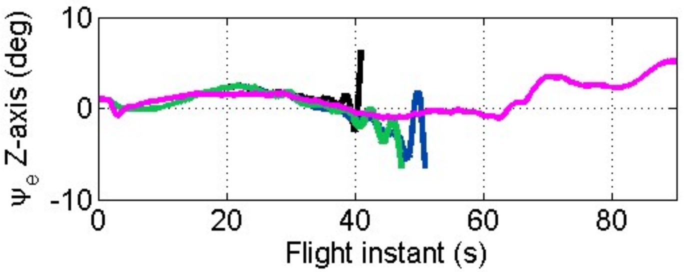
Test case #5⁺ – performance

Qalpha



Attitude errors





Test case #5⁺

- **VV05 wind**
- **All VEGACONTROL flags to +1.70**

None of adaptive control laws can avoid the loss of vehicle under such extreme conditions

The rate-bounded LPV design still capable of completing mission

Conclusions Ascent Control

→ The atmospheric phase ***VEGA launcher control design*** has been formulated as a robust control problem using

- **Structured H_∞** (incremental from robust rigid to rigid/flexible integrated design)
- **LPV**
- **Adaptive**

→ Clear benefits shown for each technique over traditional design

→ Use of robust modeling and analysis (LFT & μ) shown to be very advantageous

→ **LPV** shown to be best (for the presented case) in terms of:

- exploitation of robustness and performance domain
- methodological design approach
- ease of analysis (especially compared to adaptive)

References Ascent Control

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Marcos, A., Bennani, S., Roux, C., "**LPV modeling and LFT Uncertainty Identification for Robust Analysis: application to the VEGA Launcher during Atmospheric Phase**," 1st IFAC Workshop on Linear Parameter Varying Systems, Grenoble, France, October 2015

Navarro-Tapia, D., Marcos, A., Bennani, S., Roux, C., "**Structured H-infinity Control Based on Classical Control Parameters for the VEGA Launch Vehicle**," IEEE Multi-Conference on Systems and Control (MSC 2016), Buenos Aires, Argentina, September 2016

Navarro-Tapia, D., Marcos, A., Bennani, S., Roux, C., "**Structured H-infinity Control Design for the VEGA Launch Vehicle: Recovery of the Legacy Control Behaviour**," ESA Guidance, Navigation and Control Conference (ESAGNC 2017), Salzburg, Austria, May 2017

Navarro-Tapia, D., Marcos, A., Bennani, S., Roux, C., "**Structured H_∞ and Linear Parameter Varying control design for the VEGA Launch Vehicle**," 7th European Conference for Aeronautics and Space Sciences (EUCASS 2017), Milan, Italy, July 2017

Navarro-Tapia, D., Marcos, A., Bennani, S., Roux, C., "**Linear Parameter Varying Control Synthesis for the atmospheric phase VEGA launcher**," 2nd LPVS symposium, Florianopolis, Brazil, 2018

Navarro-Tapia, D., Marcos, A., Bennani, S., Roux, C., "**Structured H-infinity Control Design for the VEGA Launcher: Robust Control Design Augmentation**," International Astronautical Congress (IAC), Bremen, Germany, October 2018

Navarro-Tapia, D., Marcos, A., Bennani, S., Roux, C., "**Reconciling Full-Order LPV Design and Augmented Structured H_∞ via Internal Model Principle: A Launcher Application**," IEEE 7th International Conference on Systems and Control (ICSC), Valencia, Spain, October 2018

Navarro-Tapia, D., Marcos, A., Bennani, S., Roux, C., "**Robust-Control-Based Design and Comparison of an Adaptive Controller for the VEGA Launcher**," AIAA SciTech, San Diego, USA, Jan. 2019

Descent Guidance:
convex pinpoint landing optimization

ESA NPI contract 4000119571/17/NL/MH

"*Advanced Flight Control System Design With Active Load & Relief Capabilities*"

Samir Bennani

Pedro Simplício
Andrés Marcos

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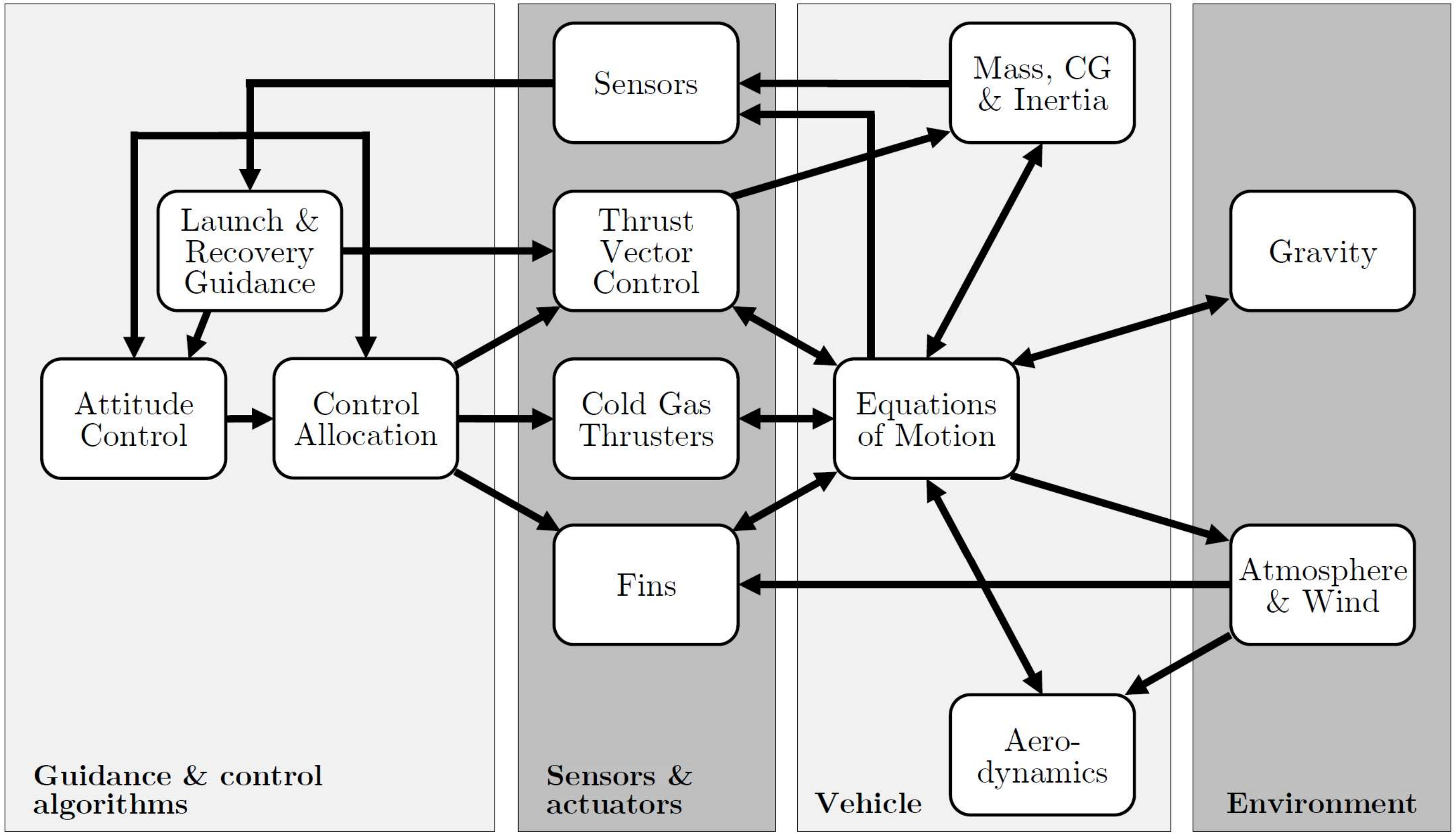
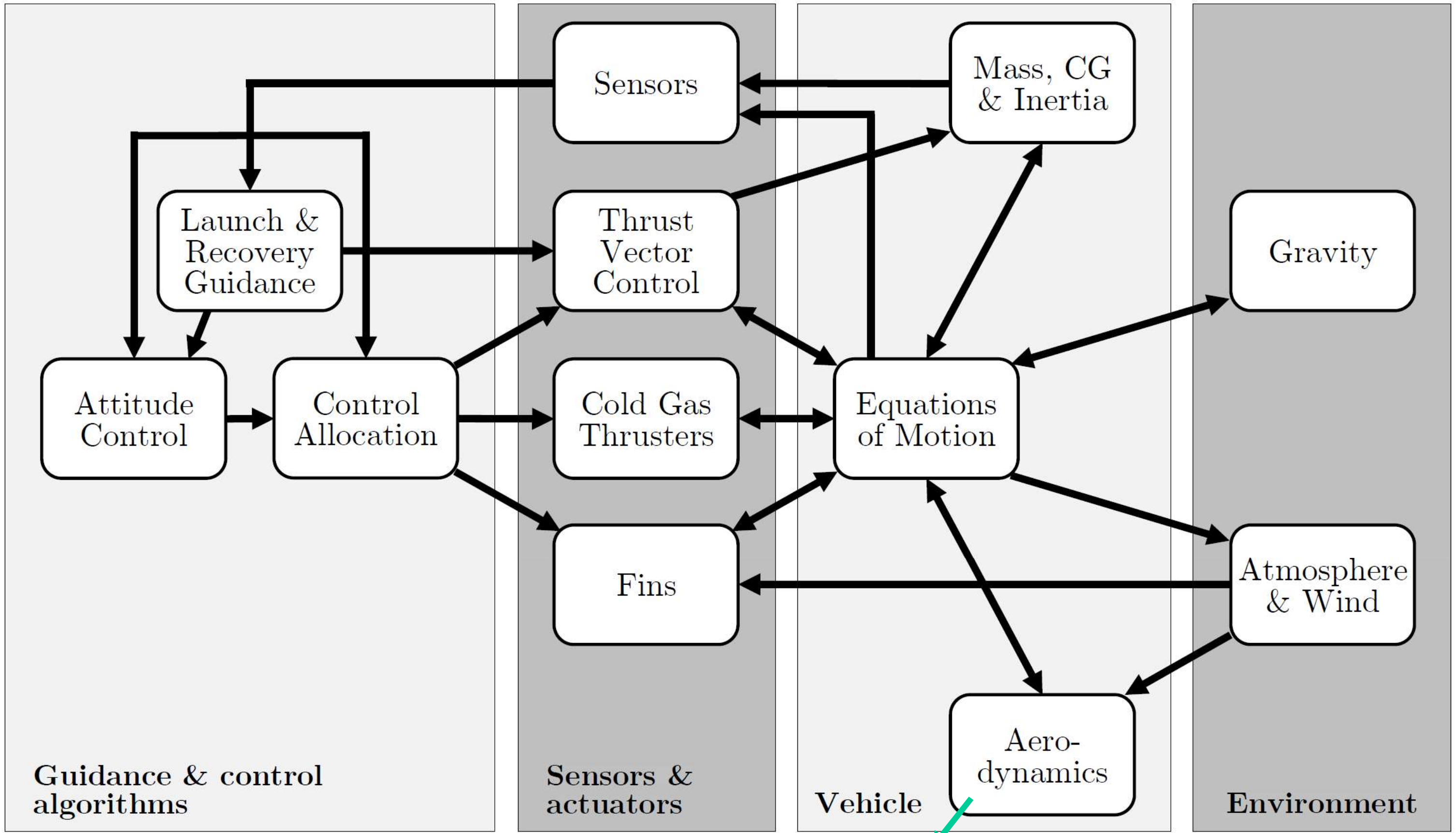
Descent Guidance:
Reusable launcher model

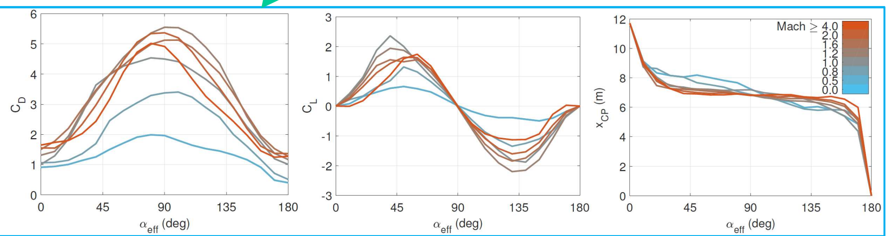


Descent Guidance:
Reusable launcher model

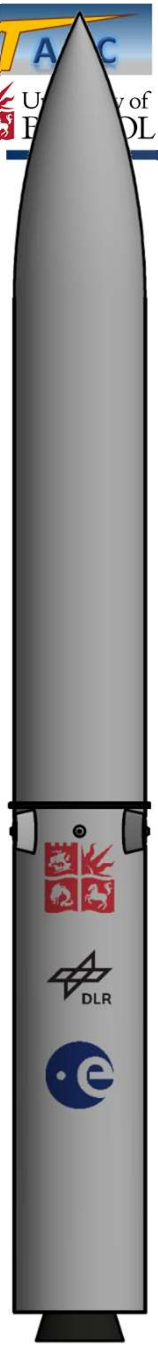


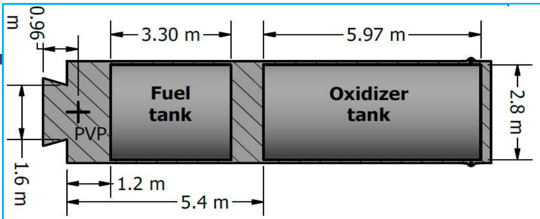
VEGA-like aerodynamics based on ascent and post-separation data*

*kindly provided by ELV/Avio

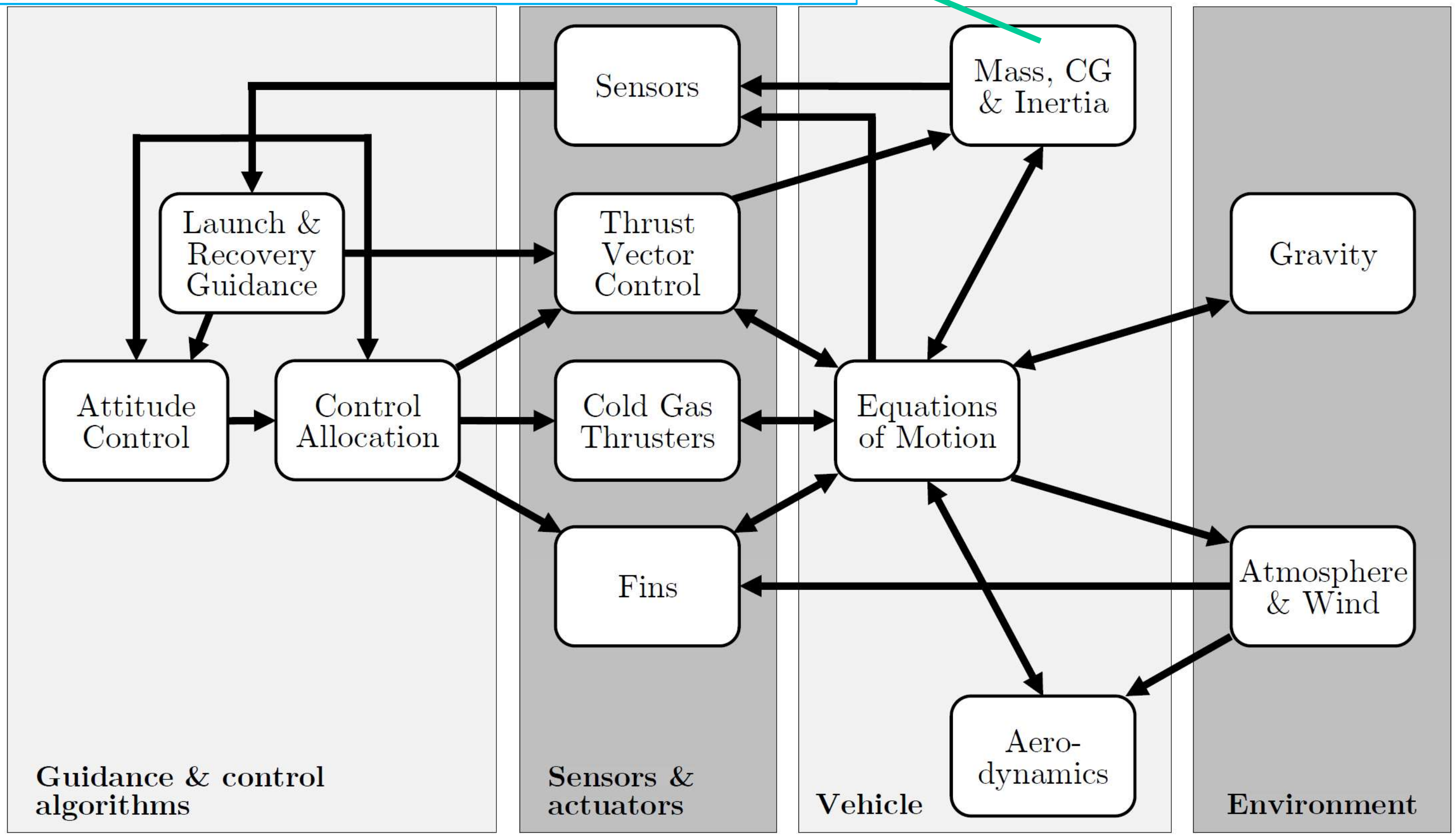


Descent Guidance:
Reusable launcher model



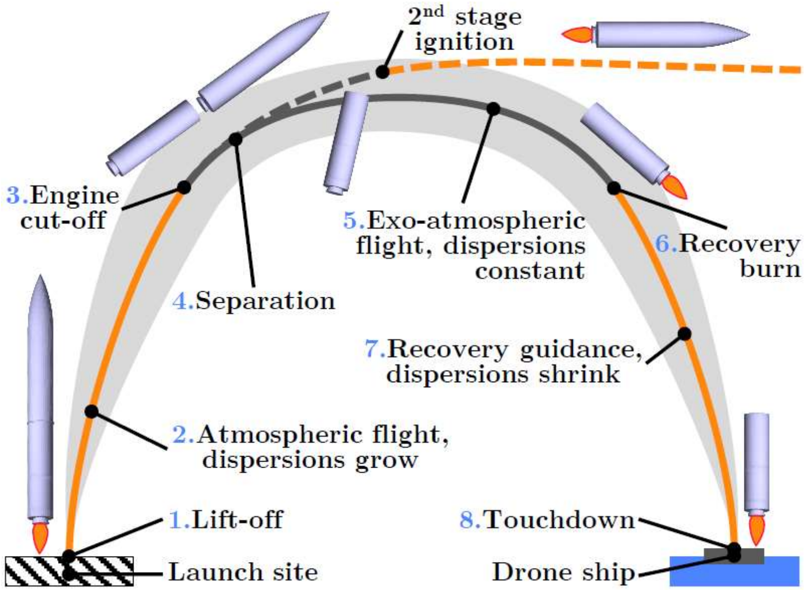


MCI updated online based on LOX/RP-1 re-ignitable engine



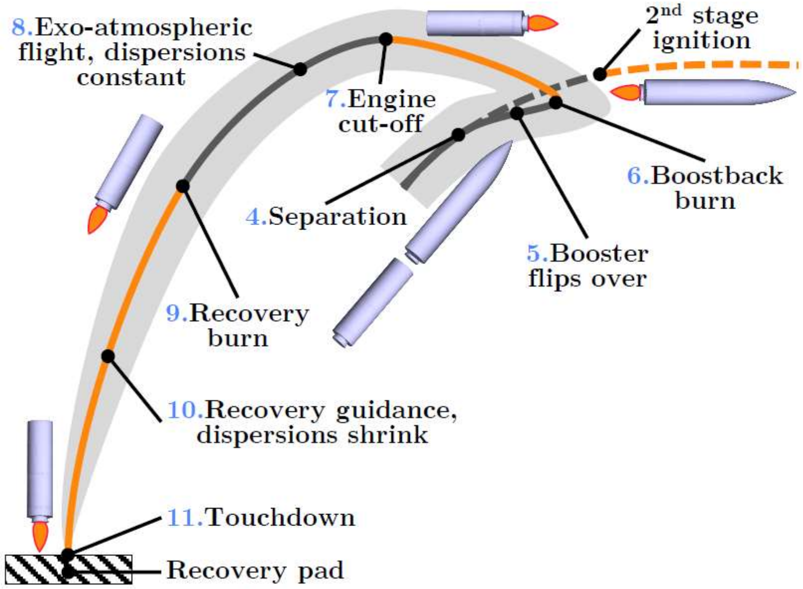
Descent Guidance:
Mission profiles

Downrange landing (DRL)



Recovery: **5.5%** of launch

Return to launch site (RTLS)



Recovery: **10.6%** of launch

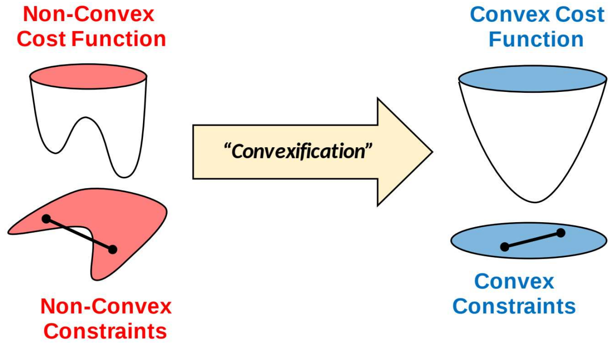
Need to shrink dispersions for pinpoint landing requires closed-loop guidance algorithms

Descent Guidance:
Recovery guidance techniques

- **Constrained terminal velocity**
  - Closed-form solution of a **simplified fuel-optimal** control problem
  - Simple but unable to enforce path constraints

$$\mathbf{T}_{\mathrm{CTV}}(t) = \hat{m}(t)\begin{bmatrix} k_r & k_v \end{bmatrix}\begin{bmatrix} \dfrac{\mathbf{ZEM}(t)}{(t_f - t)^2} \\ \dfrac{\mathbf{ZEV}(t)}{t_f - t} \end{bmatrix}$$

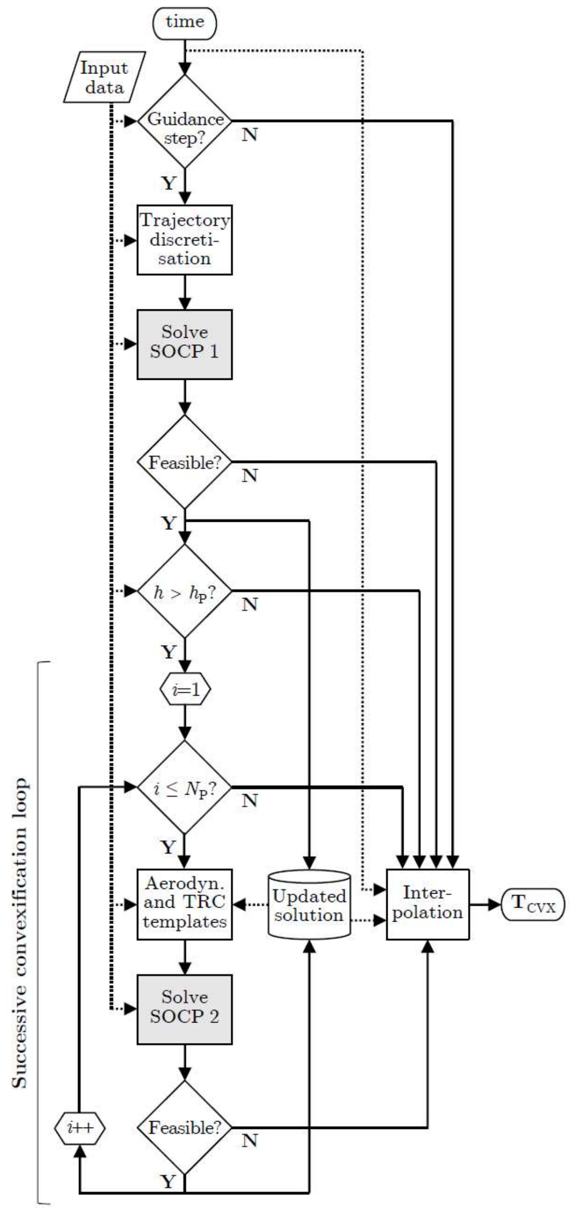
- **Convex optimisation-based**
  - Recovery trajectory and thrust commands updated on-board
  - Real-time **reliable** via convexification of the constrained optimal control problem
  - **Novel algorithm** developed to cope with the extended flight envelope of RLVs



Descent Guidance:
The DESCENDO algorithm

Descending over Extended Envelopes using Successive Convexification-based Optimisation

- **At each simulation instance**, commands are interpolated from most recent guidance solution
- Solution updated once a SOCP is triggered and feasible
- **SOCP 1** finds a **discrete trajectory** that does not account for aerodynamic forces
- **SOCP 2** applies **successive convexification** to approximate these forces



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SOCP 2

$$\max_{\mathbf{w},\sigma} \; z[N] - w_{\eta_w} \sum_{k=1}^{N} \eta_w[k], \quad \text{subject to:}$$

Boundary conditions

$$z[1] = \ln \hat{m}(t), \quad \mathbf{r}[1] = \hat{\mathbf{r}}(t), \quad \mathbf{v}[1] = \hat{\mathbf{v}}(t), \quad \mathbf{w}[1] = \hat{\mathbf{w}}(t)$$

$$\mathbf{r}[N] = \mathbf{r}_f, \quad \mathbf{v}[N] = \mathbf{v}_f, \quad \mathbf{w}_{x,y}[N] = 0_{2\times1}, \quad \mathbf{w}_z[N] \geq 0$$

Dynamics equations, $\forall k \in [1, \cdots, N-1]$

$$\mathbf{r}[k+1] = \mathbf{r}[k] + T_S\,\mathbf{v}[k] + \frac{T_S^2}{3}\left(\mathbf{a}[k] + \frac{\mathbf{a}[k+1]}{2}\right)$$

$$\mathbf{v}[k+1] = \mathbf{v}[k] + \frac{T_S}{2}\left(\mathbf{a}[k] + \mathbf{a}[k+1]\right)$$

$$z[k+1] = z[k] - \frac{1}{I_{sp} g_0}\frac{T_S}{2}\left(\sigma[k] + \sigma[k+1]\right)$$

Surrogate variables, $\forall k \in [1, \cdots, N]$

$$\mathbf{a}[k] = \mathbf{w}[k] + \hat{\mathbf{g}}(t) - d_i^*[k]\mathbf{v}[k]$$

$$\|\mathbf{w}[k]\| \leq \sigma[k]$$

Trust region constraints, $\forall k \in [1, \cdots, N]$

$$\|\mathbf{w}[k] - \mathbf{w}_i^*[k]\| \leq \eta_w[k]$$

Flight path constraints, $\forall k \in [1, \cdots, N-1]$

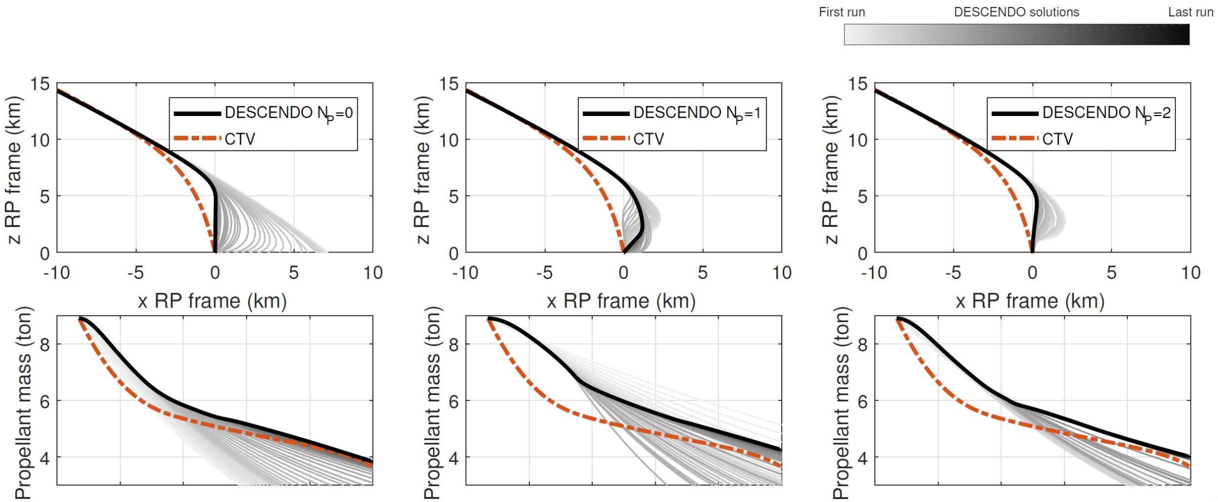
$$\mathbf{r}_z[k] \geq \frac{\hat{\mathbf{r}}_z(t)}{\|\hat{\mathbf{r}}_{x,y}(t)\|}\|\mathbf{r}_{x,y}[k]\|$$

Control constraints, $\forall k \in [1, \cdots, N-1]$

$$\begin{cases} \mathbf{w}_z[k] \geq \dfrac{\|\mathbf{w}_{x,y}[k]\|}{\tan\theta_{max}}, \quad \dfrac{T_{min}}{\hat{m}(t)} \leq \sigma[k] \leq \dfrac{T_{max}}{\hat{m}(t)}, & \text{if } T_S(k-1) \in \mathcal{T}_P \\ \mathbf{w}[k] = 0_{3\times1}, & \text{otherwise} \end{cases}$$

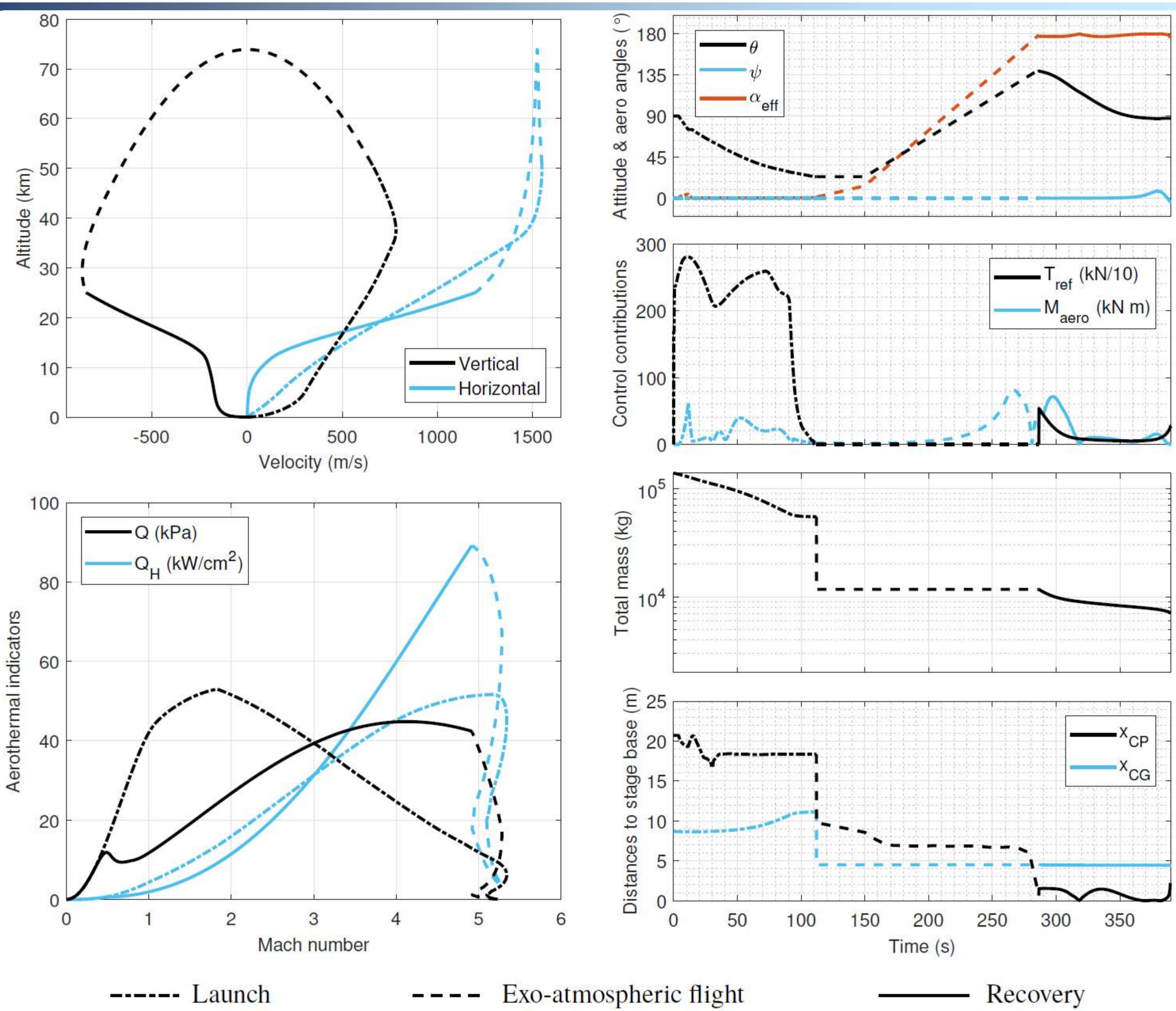
Control rate constraints, $\forall k \in [1, \cdots, N-1]$

$$\sigma[k] - T_S\frac{\dot{T}_{max}}{\hat{m}(t)} \leq \sigma[k+1] \leq \sigma[k] + T_S\frac{\dot{T}_{max}}{\hat{m}(t)}$$



Descent Guidance:

The DESCENDO algorithm – detailed DRL trajectory results



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Simplício, P., Marcos, A., Bennani, S., "**A Reusable Launcher Benchmark with Advanced Recovery Guidance**," 5th CEAS EuroGNC, Milan, Italy, April 2019

Ascent Load Relief:
Wind Disturbance Observer (WDO)

ESA NPI contract 4000119571/17/NL/MH

"***Advanced Flight Control System Design With Active Load & Relief Capabilities***"

Samir Bennani

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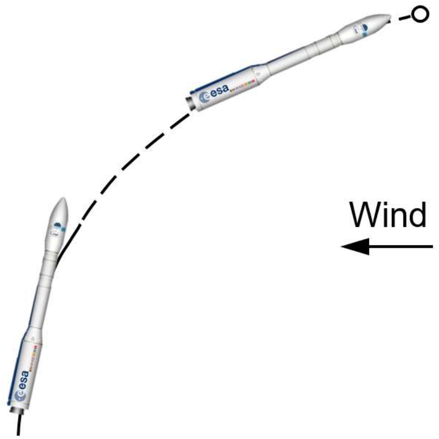
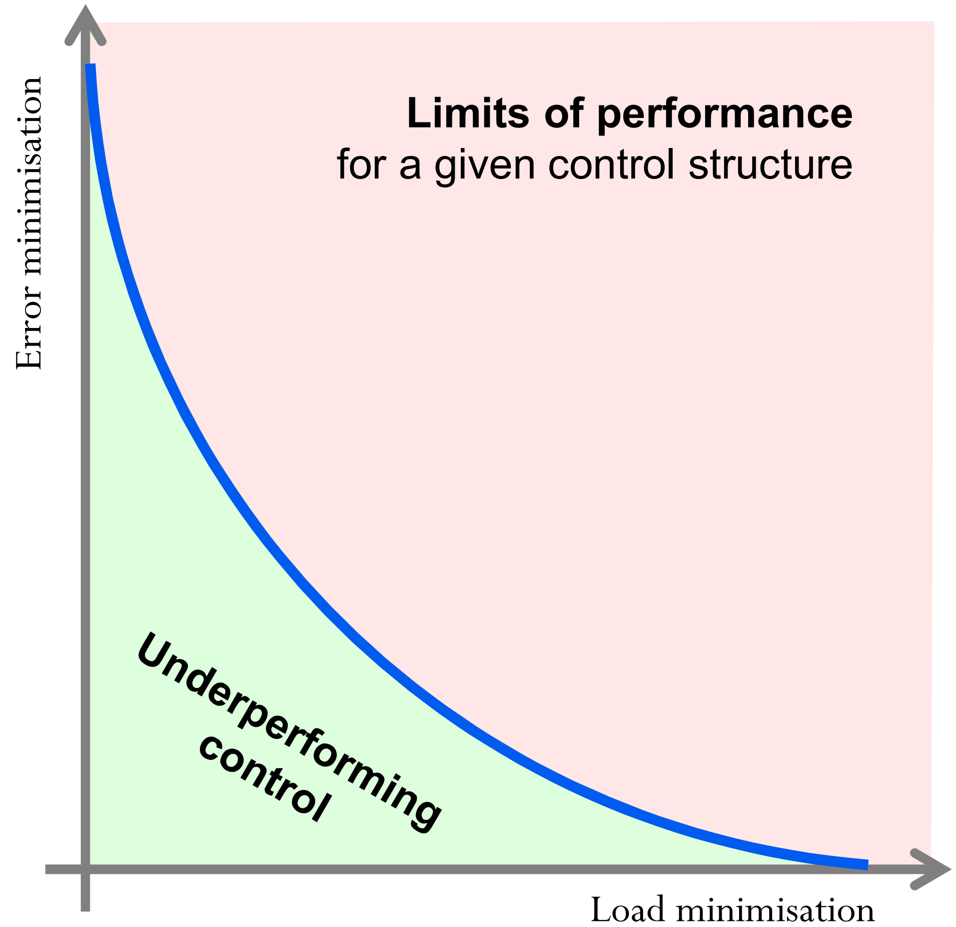
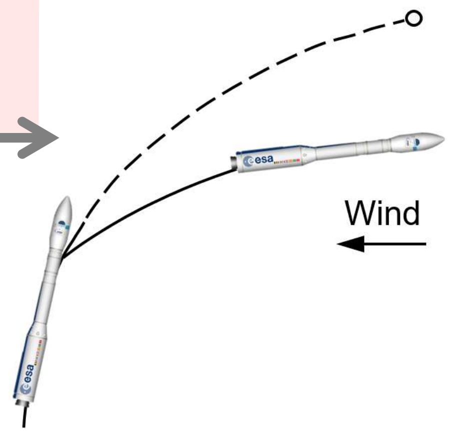
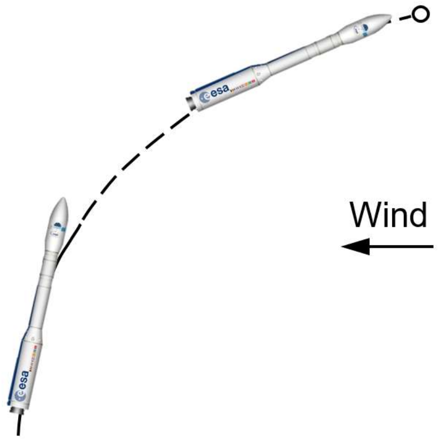
Ascent Load Relief:
Achievable performance

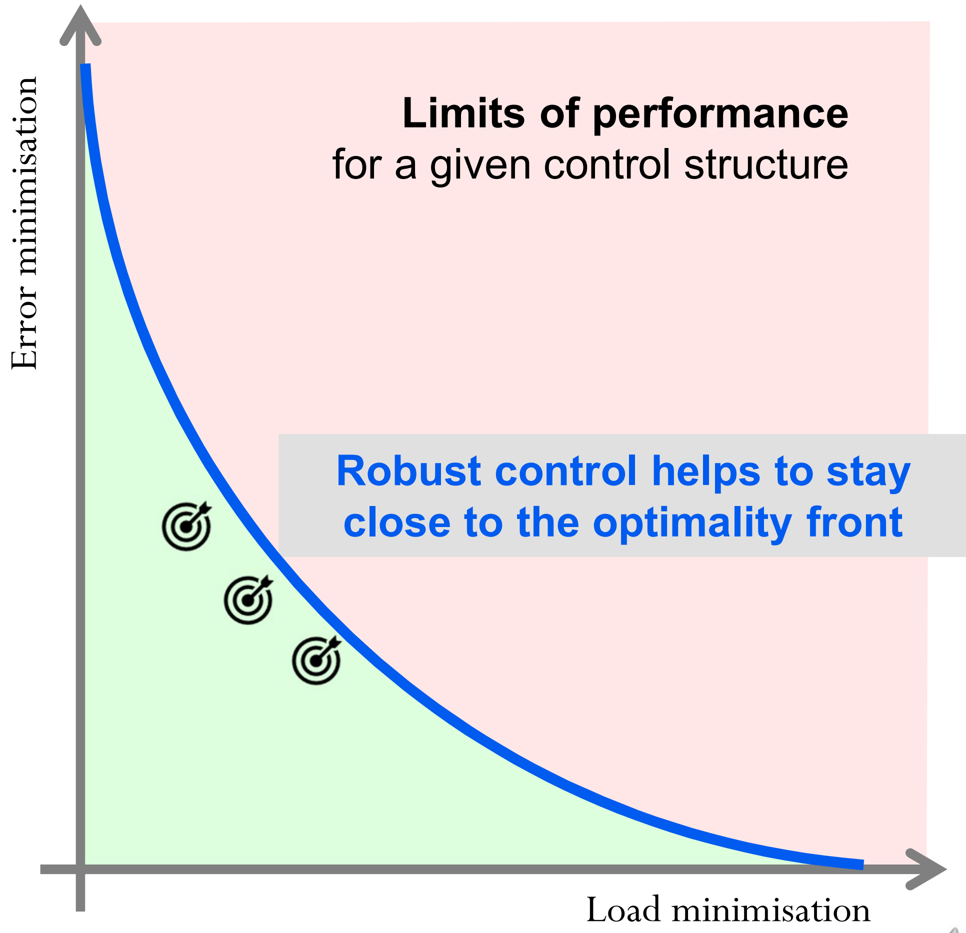


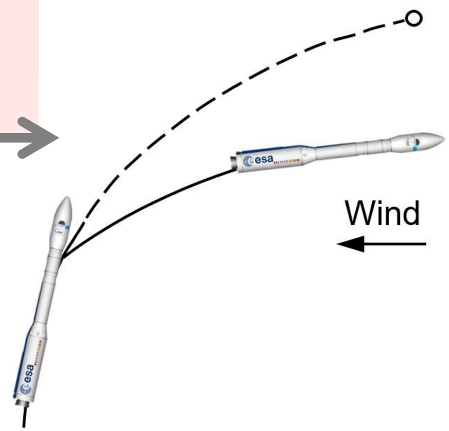




Ascent Load Relief:
Achievable performance







Ascent Load Relief:
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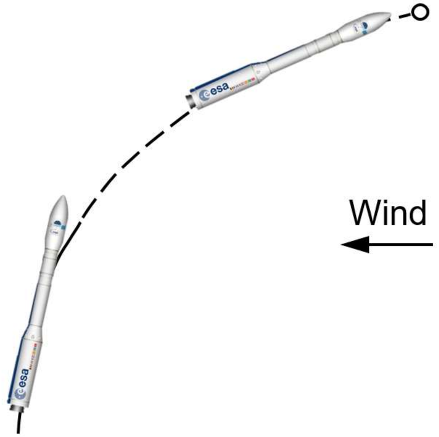
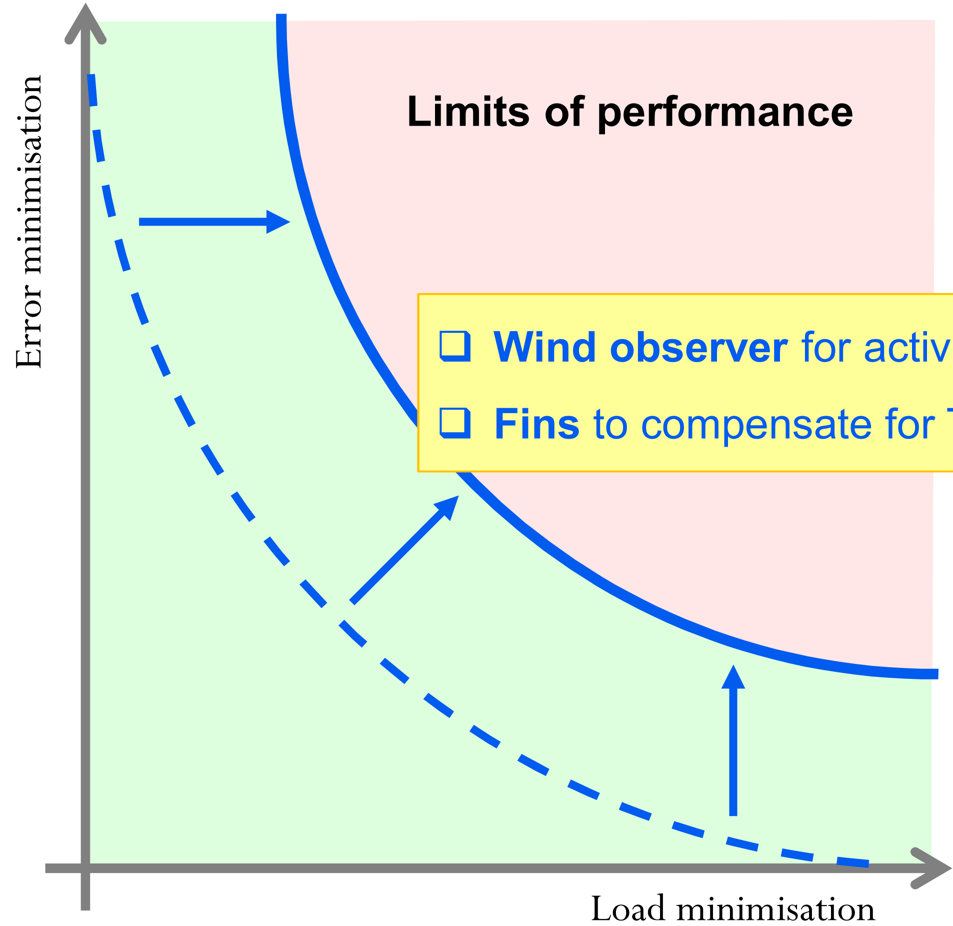
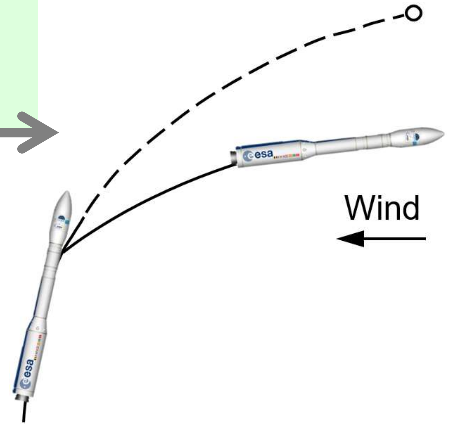




- **Wind observer** for active load relief
- **Fins** to compensate for TVC side-force



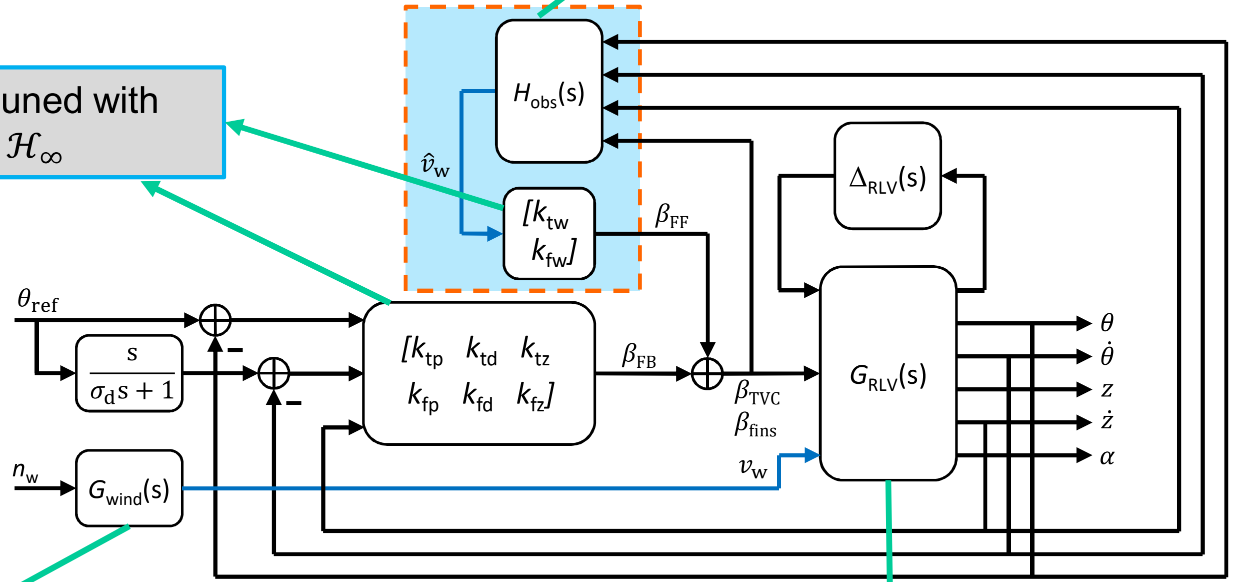
Ascent Load Relief:

Attitude control with WDO and fins - design

Only **1 linear design** is synthesized and analyzed

4th order MIMO observer designed with standard $\mathcal{H}_\infty$

8 control gains tuned with structured $\mathcal{H}_\infty$



Wind disturbances, with frequency-colouring filter

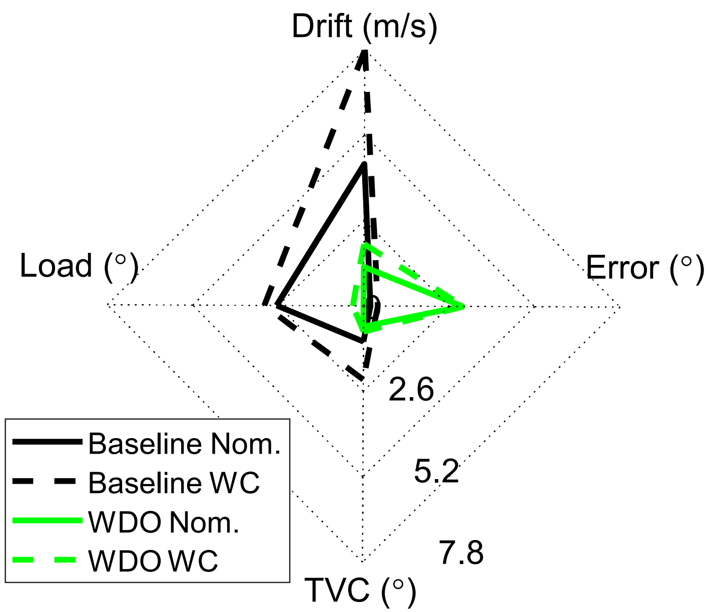
LTI model wrt. different points along trajectory

$$\begin{bmatrix}\dot{\theta}\\ \ddot{\theta}\\ \dot{z}\\ \ddot{z}\end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \mu_\alpha+\mu_f & 0 & 0 & \frac{\mu_\alpha+\mu_f}{V\cos\alpha_0} \\ 0 & 0 & 0 & 1 \\ -g\sin\theta_0-\frac{N_\alpha+N_f}{m} & 0 & 0 & -\frac{N_\alpha+N_f}{mV\cos\alpha_0}\end{bmatrix}\begin{bmatrix}\theta\\ \dot{\theta}\\ z\\ \dot{z}\end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\mu_c & -\mu_f & -\mu_j & -\frac{\mu_\alpha+\mu_f}{V\cos\alpha_0} \\ 0 & 0 & 0 & 0 \\ -\frac{T}{m} & \frac{N_f}{m} & \frac{T_j}{m} & \frac{N_\alpha+N_f}{mV\cos\alpha_0}\end{bmatrix}\begin{bmatrix}\beta_{TVC}\\ \beta_{fins}\\ \beta_{thr}\\ v_w\end{bmatrix}$$

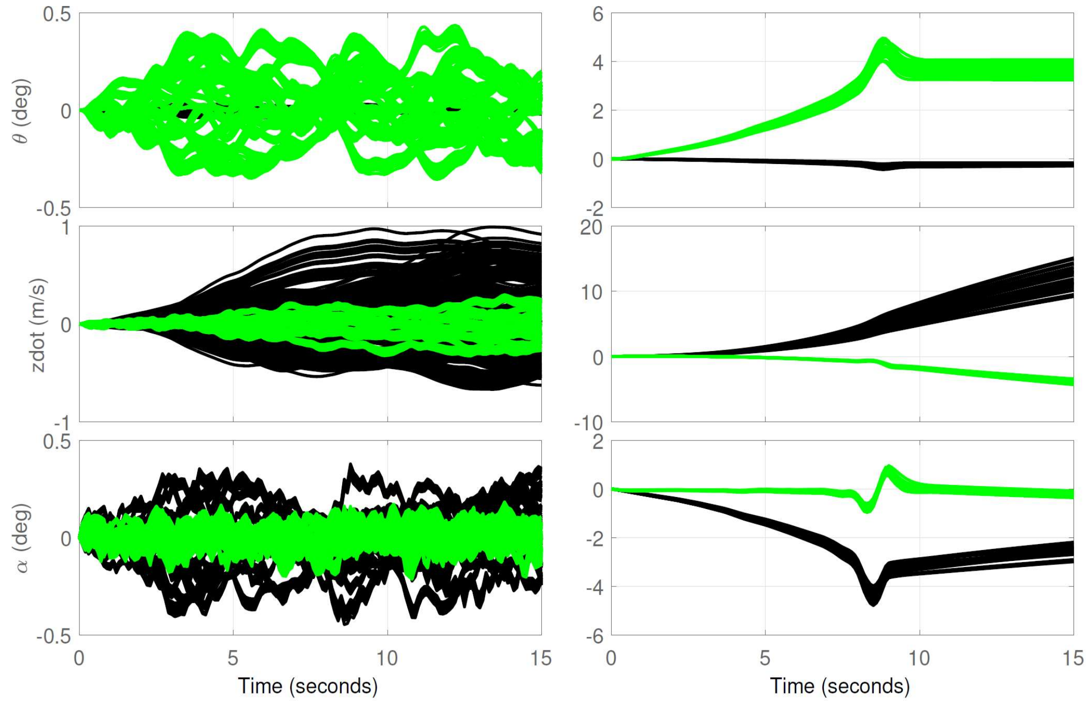
Ascent Load Relief:

Attitude control with WDO and fins - analysis

SS indicators for Dryden step



HF and LF gust responses



Notice that the Wind-Disturbance-Observer (WDO) results show a drastic reduction on:

[**ss indicators**] the load (°) and drift (m/s) & equivalently [**gust response**] the α (deg) and zdot (m/s)

Conclusions Descent Guidance & Ascent Load Relief

- **DESCENDO** provides a trade-off between computational efficiency and trajectory optimality which makes it suitable to the extended flight envelope of RLVs

- Earliest application of **robust wind disturbance observation (WDO)** for improved launcher load relief

- Shown that **combined used of TVC/fins** can further improve load relief