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

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Motivation

LAUNCHER PERFORMANCE IMPROVEMENT VIA G&C

Robust control techniques

Wind resilience

Load relief algorithms

Mission preparation reduction

Structural reduction

Booster reusability

Propellant reduction

Closed-loop recovery guidance
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  **Diego Navarro-Tapia**  Andrés Marcos  Christophe Roux

Funded by an **ESA NPI contract** 4000119571/17/NL/MH

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

Samir Bennani  **Pedro Simplicio**  Andrés Marcos  Stephan Theil  David Seelbinder
1. **Ascent Control**: robust $\rightarrow$ LPV $\rightarrow$ 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 $\rightarrow$ LPV $\rightarrow$ 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 (Vettore Europeo di Generazione Avanzata) is the new European Small Launch Vehicle

VEGA challenges:
VEGA launcher

VEGACONTROL nonlinear, high-fidelity simulator for atmospheric phase

Over 120 uncertain parameters

VEGA Soyuz Ariane 5 Saturn V

13 successful flights ... 14th this month
Four stages vehicle, all controlled by TVC thrust vectoring system

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

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

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

**Launcher model linearised at representative points along trajectory**

*For VEGA ~every 10 sec*

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

**Intensive V&V process using high-fidelity nonlinear simulator**

*For VEGA Monte Carlo & Vertex simulations*

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**VEGA TVC architecture**
**VEGA State-of-Practice:**
*Control objectives & design rationale*

<table>
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<th>Stability</th>
<th>Requirements</th>
<th>Metrics</th>
<th>Bounds</th>
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**Pure Attitude Control**

Vehicle tracks guidance

**Pure Load Relief Control**

Vehicle turns into wind to relieve aerodynamic load

**Optimized Control**

Wind
Ascent Control: robust → LPV → Adaptive
VEGA Structured $H_\infty$ synthesis: Rigid-body robust design

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

Wind model defined by a Dryden filter for severe turbulence:

$$G_w(s) = \frac{v_w(s)}{n_w(s)} = \frac{\sqrt{\frac{2}{\pi}} \frac{V(h) - \nu_{w0}(h)}{L(h)} s^2(h)}{s + \frac{\sqrt{\frac{2}{\pi}} (V(h) - \nu_{w0}(h)}{L(h)}}$$
VEGA Structured $H_\infty$ synthesis: Rigid-body robust nonlinear Monte Carlo analysis

In total, 9 linear structured $H_\infty$ 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 $\infty$-norm and 2-norm for different performance indicators.
Results normalised wrt baseline controller
VEGA Structured $H_{\infty}$ synthesis: Flexible sequential bending filter design

Structured $H_{\infty}$

- 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)

$$H_3 = \prod_{i=1}^{2} \left( \frac{s^2 + 2\zeta_{ni}s + w_{ni}^2}{s^2 + 2\zeta_{di}s + w_{ni}^2} \right)^3 \left( \frac{s^2 + 2 \cdot 0.24 \cdot 25 \cdot s + 25^2}{s^2 + 2 \cdot 0.4 \cdot 25 \cdot s + 25^2} \right)^3$$
VEGA Structured $H_\infty$ synthesis:
Flexible sequential linear analysis

Structured $H_\infty$

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

Classical stability analysis
Robust stability analysis

Only 1 linear structured $H_\infty$ controllers is synthesized and analyzed

Potential for improvement with respect to baseline bending filter
VEGA Structured $H_\infty$ synthesis: Rigid+Flexible integrated design

Structured $H_\infty$

Nominal rigid-body design

Robust rigid-body design

Bending filter design

Robust joint design
Rigid-body controller and bending filter

- **Rigid+Flexible integrated design**

- **Structured $H_\infty$**

- **Tunable controller**

- **Bending filter**

- **Four tuneable flexible-body parameters**

- **Four tuneable rigid-body parameters**

- **Rigid-body controller**

- **Notch filter 1** [min 1$^{st}$ BM]

- **Notch filter 2** [nom 1$^{st}$ BM]

- **Notch filter 3** [max 1$^{st}$ BM]

- **Notch filter 4** [min 2$^{nd}$ BM]

- **Low-pass filter** [Upper BMs attenuation]

Equation:

$$H_3(s) = \frac{s^2 + \eta_1 s + (\omega_{q1}')^2}{s^2 + \eta_1/\epsilon_1 s + (\omega_{q1}')^2} \cdot \frac{s^2 + \eta_2 s + (\omega_{q2})^2}{s^2 + \eta_2/\epsilon_2 s + (\omega_{q2})^2} \cdot \frac{s^2 + \eta_3 s + (\omega_{q3})^2}{s^2 + \eta_3/\epsilon_3 s + (\omega_{q3})^2}$$
In total, 9 linear integrated structured $H_{\infty}$ controllers synthesized along the atmospheric phase.
Ascent Control:

robust $\rightarrow$ LPV $\rightarrow$ Adaptive
VEGA LPV synthesis: Design weighting functions

LPV synthesis

LPV grid: \( t = \{20, 40, 50, 60, 70, 90\} \text{s} \)

LPVTools1.0 toolbox from UMN

LPVTools object

Actuation weighting function

Magnitude (dB)

Frequency (rad/s)

\[
W_u^{-1}(s, \theta) = \frac{s^2 + 0.5s + (\omega_{q1}(\theta))^2}{s^2 + 70s + (\omega_{q1}(\theta))^2} \cdot \frac{s^2 + 0.5s + (\omega_{q1}(\theta))^2}{s^2 + 70s + (\omega_{q1}(\theta))^2} \cdot F(s, \theta)
\]

Notch 1

Notch 2

Low-pass filter
VEGA LPV synthesis:
Control design & linear analysis

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

Control problem formulated as:

\[
\min_{K(s, \rho)} \|T_{e' \nu'}(s, \rho)\|_{\mathcal{L}_2 \to \mathcal{L}_2}; \quad \text{subject to} \quad \rho(t) \in \mathcal{P}_{NGV} \\
\nu_{NGA} < \dot{\rho}(t) < \overline{\nu}_{NGA}
\]

**Quadratic basis functions** to constrain the rate variation of VNG:

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

Resultant controller (rigid-body and bending filter): **22 states**
VEGA LPV synthesis: Nonlinear MC analysis

Baseline

Integrated RigFlex Structured $H_\infty$

LPV

4 gains
23 states controller

4 gains
15 states controller

Full-order controller: 22 states
Structured $H_{\infty}$ design improves robustness & performance for same controller structure

- 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 $H_{\infty}$ controller including an identified internal model $H_{IM}(s)$

Structured $H_{\infty}$ with Internal Model
Ascent Control:
robust $\rightarrow$ LPV $\rightarrow$ Adaptive
LPV versus Adaptive control: NASA adaptive controllers description

Adaptive augmentation is based on a multiplicative law:

\[ k_T = k_0 + k_a \]

- Total loop gain
- Minimum total loop gain
- Adaptive gain

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

\[ \dot{k}_a = a e_r^2 - \frac{k_2}{k_{\text{max}}} a e_r^2 - \alpha k_a y_s - \beta (k_T - 1) \]

- Adaptive Error
- Logistic Damper
- Spectral Damper
- Leakage

LPV controller achieves 30% reduction of average \( Q_\alpha \) peaks

J. Orr and T.S. VanZwieten
LPV versus Adaptive control:
Test case #5⁺ – performance

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

- **Structured** $H_{\infty}$ (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 & $\mu$) 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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<tr>
<td>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</td>
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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
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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
Descend Guidance: Reusable launcher model

- MCI updated online based on LOX/RP-1 re-ignitable engine
- Descent Guidance: Reusable launcher model

Diagram showing:
- Guidance & control algorithms
- Sensors & actuators
- Vehicle dynamics
- Environment

Key components:
- Launch & Recovery Guidance
- Control Allocation
- Cold Gas Thrusters
- Equations of Motion
- Fins
- Gravity
- Atmosphere & Wind
- Vehicle Dynamics

Online updates based on LOX/RP-1 re-ignitable engine.
Descent Guidance: Mission profiles

**Downrange landing (DRL)**

1. Lift-off
2. Atmospheric flight, dispersions grow
3. Engine cut-off
4. Separation
5. Exo-atmospheric flight, dispersions constant
6. Recovery burn
7. Recovery guidance, dispersions shrink
8. Touchdown

**Return to launch site (RTLS)**

1. Lift-off
2. 2nd stage ignition
3. Engine cut-off
4. Separation
5. Booster burn
6. Boostback burn
7. Engine cut-off
8. Exo-atmospheric flight, dispersions constant
9. Recovery burn
10. Recovery guidance, dispersions shrink
11. Touchdown

Recovery: 5.5% of launch
Recovery: 10.6% of launch

Need to shrink dispersions for **pinpoint landing** requires closed-loop guidance algorithms
Constrained terminal velocity

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

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
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
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

Descent Guidance: The DESCENDO algorithm

\[
\begin{align*}
\text{SOCP 2} \\
\max_{\mathbf{w},\mathbf{z}} & \quad z[N] - w_{\text{opt}} \sum_{k=1}^{N} g_n[k] \\
\text{subject to:} \\
\text{Boundary conditions} \\
z[1] = \ln \hat{a}(\hat{t}), \quad r[1] = \hat{r}(\hat{t}), \quad v[1] = \hat{v}(\hat{t}), \quad w[1] = \hat{w}(\hat{t}) \\
r[N] = r_f, \quad v[N] = v_f, \quad w_{x_3}[N] = 0_{2\times1}, \quad w_{x_3}[N] \geq 0 \\
\text{Dynamics equations, } \forall k \in [1, \ldots, N-1] \\
r[k+1] = r[k] + T_S v[k] + \frac{T_S^2}{3} \left( a[k] + a[k+1] \right) \\
v[k+1] = v[k] + T_S \left( a[k] + a[k+1] \right) \\
z[k+1] = z[k] - \frac{T_S}{I_{q_0} \Omega_0^2} \left( \sigma[r[k] + \sigma[k+1]] \right) \\
\text{Surrogate variables, } \forall k \in [1, \ldots, N] \\
a[k] = w[k] + \hat{r}(\hat{t}) - \dot{a}_d[\hat{t}] \hat{v}[k] \\
\|w[k]\| \leq \sigma[r[k]] \\
\text{Trust region constraints, } \forall k \in [1, \ldots, N] \\
\|w[k] - w_{\text{opt}}[k]\| \leq \eta_w[k] \\
\text{Flight path constraints, } \forall k \in [1, \ldots, N-1] \\
r_2[k] \geq \frac{T_r(\hat{t})}{\|x_3[k]\|} \|x_3[k]\| \\
\text{Control constraints, } \forall k \in [1, \ldots, N-1] \\
\begin{cases} \\
\frac{w_x[k]}{\tan \theta_{\text{max}}} \leq \sigma[r[k]] \leq \frac{T_{\text{max}}}{\hat{a}(\hat{t})} & \text{if } T_S(k-1) \in T_F \\
\|w[k]\| = 0_{3\times1} & \text{otherwise} \\
\end{cases} \\
\text{Control rate constraints, } \forall k \in [1, \ldots, N-1] \\
\sigma[r[k]] - T_S \hat{a}(\hat{t}) \leq \sigma[r[k+1]] \leq \sigma[r[k]] + T_S \hat{a}(\hat{t})
\end{align*}
\]
Descent Guidance:
The DESCENDO algorithm – detailed DRL trajectory results
### References Descent Guidance


- **Simplício, P., Marcos, A., Bennani, S.** “Guidance of Reusable Launchers: Improving Descent and Landing Performance,” AIAA Journal of Guidance, Control, and Dynamics, accepted for publication January 2019

- **Simplício, P., Marcos, A., Joffre, E., Zamaro, M., Silva, N.** “Parameterised Laws for Robust Guidance and Control of Planetary Landers,” 4th CEAS Specialist Conference on Guidance, Navigation and Control (EuroGNC 2017), Warsaw, Poland, April 2017


- **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

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Ascent Load Relief: Achievable performance

Limits of performance for a given control structure

Underperforming control

Error minimisation

Load minimisation

Wind
Ascent Load Relief: Achievable performance

Robust control helps to stay close to the optimality front

Limits of performance for a given control structure
Ascent Load Relief:
Achievable performance

- 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

\[
\begin{bmatrix}
\dot{\theta} \\
\dot{\phi} \\
\dot{z}
\end{bmatrix}
= \begin{bmatrix}
0 & 1 & 0 & 0 \\
\mu_\alpha + \mu_f & 0 & 0 & \frac{\mu_\alpha + \mu_f}{V \cos \alpha_0} \\
0 & 0 & 0 & 1 \\
-g \sin \theta_0 - \frac{N_\alpha + N_f}{m} & 0 & 0 & -\frac{N_\alpha + N_f}{mV \cos \alpha_0}
\end{bmatrix}
\begin{bmatrix}
\theta \\
\phi \\
z
\end{bmatrix}
+ \begin{bmatrix}
0 & 0 & 0 & 0 \\
-\mu_c & -\mu_f & -\mu_j & \frac{\mu_\alpha + \mu_f}{V \cos \alpha_0} \\
0 & 0 & 0 & 0 \\
-\frac{T}{m} & \frac{N_f}{m} & \frac{T_j}{m} & \frac{N_\alpha + N_f}{mV \cos \alpha_0}
\end{bmatrix}
\begin{bmatrix}
\beta_{\text{TVC}} \\
\beta_{\text{thr}} \\
\beta_{\text{fin}}
\end{bmatrix}
\]
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)
→ 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 use of TVC/fins can further improve load relief