Robust Control Design
for the VEGA Launch Vehicle
during atmospheric flight

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Motivation

- Study **robust control** laws to improve VEGA missions
  - (i) Improve safety and performance capabilities
  - (ii) Improve GNC robustness
  - (iii) Reduce the need for intensive mission-dependent control tuning before each flight

- Explore **adaptive** features of the VEGA GNC functions

- Transfer the techniques to industry
  - (i) Reconcile classical control with robust control techniques

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

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

Samir Bennani  
Andrés Marcos  
Christophe Roux

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

1. VEGA mission & vehicle
2. Structured H-infinity synthesis
3. LPV (Linear Parameter Varying) synthesis
4. Conclusions
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VEGA mission and vehicle:
VEGA mission

VEGA (Vettore Europeo di Generazione Avanzata)
is the new European Small Launch Vehicle

10 successful flights

1st flight on 13th February 2012 (Multi payload)
2nd flight on 7th May 2013 (Multi payload)
3rd flight on 30th April 2014 (KazEOSAT-1)
4th flight on 11th February 2015 (IXV)
5th flight on 23rd June 2015 (Sentinel-2A)
6th flight on 3rd December 2015 (LISA Pathfinder)
7th flight on 16th September 2016 (Multi payload)
8th flight on 5th December 2016 (Göktürk-1A)
9th flight on 7th March 2017 (Sentinel 2B)
10th flight on 1st August 2017 (Multi payload)

and more to come:

11th flight on 11th November 2017 (MN35-13)
VEGA mission and vehicle: Challenges – Vehicle, Environment and Dynamics

Four stages vehicle, all controlled by thrust vectoring system (TVC)

Atmospheric phase challenges

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

VEGA P80 atmospheric phase

VEGA Qalpha wind effects
**VEGA mission and vehicle:** Challenges – Uncertainties


**120 uncertain and dispersion parameters:** MCI, bending modes characteristics …

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The model used is a **6 degrees-of-freedom nonlinear simulator of the VEGA launcher** set up to perform simulations in the atmospheric flight phase P80, **VEGACONTROL**.

It is developed in Simulink with S-Function written in C-code and includes:
VEGA mission and vehicle:
Industrial state-of-the-practice for control design

1. Launcher **model linearized** at representative points
   
   \[ \text{time} = [10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110] \text{ seconds} \]

2. For each point, **independent design first & then joint tuning** of:
   
   - Rigid-body control design
   - Flexible bending filter design
   - Rigid- and flexible-body joint tuning

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

4. **Intensive V&V process** using high fidelity nonlinear simulation
VEGA mission and vehicle: Industrial state-of-the-practice for control design

Control design task

- Achieve stability
VEGA mission and vehicle: Industrial state-of-the-practice for control design

Control design task

- Achieve stability

- Optimize performance

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<td>Vehicle turns into wind to relieve aerodynamic load</td>
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<td>System achieves balance for best performance</td>
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Vehicle tracks guidance

Wind

Wind

Wind
VEGA mission and vehicle: Industrial state-of-the-practice for control design

Control design task

- Achieve **stability**

- Optimize **performance**

- Provide **robustness**

  Stability and performance must be ensured in presence of:
  - Uncertainties
  - Disturbances
Outline

1. VEGA mission & vehicle

2. Structured H-infinity synthesis

3. LPV (Linear Parameter Varying) synthesis

4. Conclusions
Structured \(H\)-infinity synthesis: Closed-loop for design: TVC controller structure

VEGA controller structure

- PD in attitude
- Lateral control (drift and drift-rate)
- \(H\) filters
Structured H-infinity synthesis:
Closed-loop for design: delay and TVC actuator

LFT representation for parametric uncertainties

Delay block

TVC actuator

International Workshop on Robust Modeling, Design & Analysis – Robust-MDA 2017 – Bristol, UK
Structured H-infinity synthesis: Closed-loop for design: launch vehicle model

The launcher dynamics described by:
Rotational motion (yaw $\psi$ or pitch $\theta$)
Translational motion ($y$ or $z$)

Yaw and pitch planes are identical if the roll rate is considered negligible.
Structured H-infinity synthesis:
Augmented closed-loop for design

Standard $H_\infty$ interconnection

Structured H-infinity Control problem
\[
\min_K \| F_t(M, K) \|_\infty
\]

Requirements expressed as input/output weighting functions
Structured H-infinity synthesis:
Legacy recovery: linear design @ t=50s

The baseline controller frequency response is successfully recovered at t=50s

VEGACONTROL verification
Structured H-infinity design recovers baseline controller nonlinear, time behavior
Structured H-infinity synthesis: Closed-loop for design: wind generator (i)

Wind generator

Modelled by a **Dryden filter** for [light, moderate, severe] turbulence

\[
G_{\text{wind}}(s, h) = \frac{v_w}{n_w} = \frac{\sqrt{2 \pi \frac{V(h)-v_{wp}(h)}{L(h)}} \sigma^2(h)}{s + \frac{V(h)-v_{wp}(h)}{L(h)}}
\]
Structured H-infinity synthesis:
Closed-loop for design: wind generator (ii)

Wind VV05: '07_2015_23_12_005.wind'

- Controller [K1]: No wind channel in the design
- Controller [K2]: Wind generator: moderate wind
- Controller [K3]: Wind generator: severe wind

![Graph showing various wind scenarios]
Structured H-infinity synthesis: Robust rigid-body design

Robust rigid-body design

Robust rigid- and flexible-body design
Structured H-infinity synthesis:
Robust rigid-body design: robust stability

Robust rigid-body design

Robust rigid- and flexible-body design
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LPV design technique: Introduction

Family LTI/LFT models

LPV model

LPV synthesis

LPV modelling and design using LPVToolsv1.0 from UMN

Same design interconnection as before used for LPV synthesis
LPV design technique: Nominal nonlinear simulations using VEGACONTROL

Wind VV05: '07_2015_23_12_005.wind'
LPV design technique: Monte-Carlo analysis 1000 runs using VEGACONTROL

- Baseline controller
- Structured $H_{\infty}$ controller
- LPV controller
Outline

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Conclusions

- The atmospheric phase **VEGA launcher control problem** has been presented.

- **Classical control** has a rich heritage but several **limitations** are recognized.

- **Two robust control design techniques have been presented:**
  - Structured $H_\infty$ infinity synthesis
  - LPV synthesis

  - A very important achievement is the demonstration of the recovery of legacy controller!!!!

Project aims towards a **robust control design and analysis framework**:

- More suitable for **multivariable** control problems
- Incorporating **wind disturbance estimation** in the design
- Guaranteeing **robustness and performance by design**
- Allowing to perform **RS/RP, WC and TV/NL analyses**
Thank you for your attention

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