European Space Agency
Directorate of Technical and Quality Management

ACTIVITY DESCRIPTION

PhD on

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

Date: 10 May 2021

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PhD on

Advanced Flight Control System Design with Active Load & Relief Capabilities

Purpose and scope of activity

This document describes the PhD activity **Advanced Flight Control System Design with Active Load & Relief Capabilities between the European Space Agency and Polytehnica Bucharest.**

Background

In rocket design, the accurate understanding of the interplay between control-induced loads, dynamical wind perturbations and their propagation through the flexible launcher body towards the payload is critical, not only to guarantee that all flight safety requirements are fulfilled, but also to allow launcher integrity and flight performance.

In rocket design, the accurate understanding of the interplay between control-induced loads, dynamical wind perturbations and their propagation through the flexible launcher body towards the payload is critical, not only to guarantee that all flight safety requirements are fulfilled, but also to allow the achievement of extended performance envelopes.

Due to the multi-disciplinary and aero-elastic properties of the next generation of launchers, traditional dynamics models are no longer sufficient for the purposes of stability and load assessment for unsteady flight. This is particularly applicable to non-symmetric and multi-actuated configurations or simply rockets with an extremely light and flexible structure (targeting low-cost and reusability).

Currently, the Agency has implemented within GSTP the ADAMP project. The objective is to develop a series of reusable flying demonstrator launch vehicles in order to maturate various technology components. In relation to this work, flight control concepts involving autonomous flight, precision flight and landing using retro-propulsion are key elements which have not yet been extensively studied in Europe at physical demonstrator level.

The current activity shall concentrate on the design of future flight control system sfor and ADAMP II version taking into account structural deformation under flight and external loads. These elements must be studied together, this in order to give the vehicle the desired structural shape and performance envelopes.

With this in mind, it is necessary to provide an integrated load modelling methodology for the purpose of active load attenuation for a next generation of launchers.

Structural deformation due to wind effects need to be characterised through modelling strategies that couple FEM (Finite Element Models) and CFD (Computational Fluid Dynamics). These strategies to be relevant need to be validated through flight testing.

Efficient and realistic multi-physics aero-elastic model can be represented as partial differential equations as well as differential algebraic equations.

Both formalisms are suitable for a detailed analysis over the flight, but still intractably complex for a compact description of the system, although new machine learning concepts are available to overcome the current limitations.

Reduction as well as surrogate modelling techniques such as Polynomial Chaos, Proper Orthogonal Projection techniques etc. can provide compact and low order model realisations for real-time flight control implementation. These low order reduction techniques are fundamental for any engineering implementation and efficient design and analysis activities.

Finally, state of the art launcher control techniques enabling real time augmented adaptation as well as forward looking predictive algorithms for in-flight load relief must elaborated to provide improved load vs. drift management at reduced GNC sensitivity to the wind.

Indeed, recent tests on US launchers (NASA SLS, Blue Origin, SpaceX F9 and Grasshopper Demonstrators, SN_x, and many others) have clearly demonstrated that the benefits of novel control methods are not only radical, but also the only way to meet the needs for future launch vehicles.

In the face of new launch vehicle flight paradigm it is necessary to understand existing solutions as well to elaborate on novel alternative flight control concepts to meet reusability constraints.

In the face of an innovative and revolutionising space transportation market, the inclusion of load management and relief methodologies is critical for the design and analysis of vehicles and control systems over an extended domain of configurations and flight envelopes.

Simulated wind-field reconstruction techniques using data fusion techniques shall be studied (Figure 1) and shall be matured at a later stage on the VTVL demonstrator is in place (Figure 2).

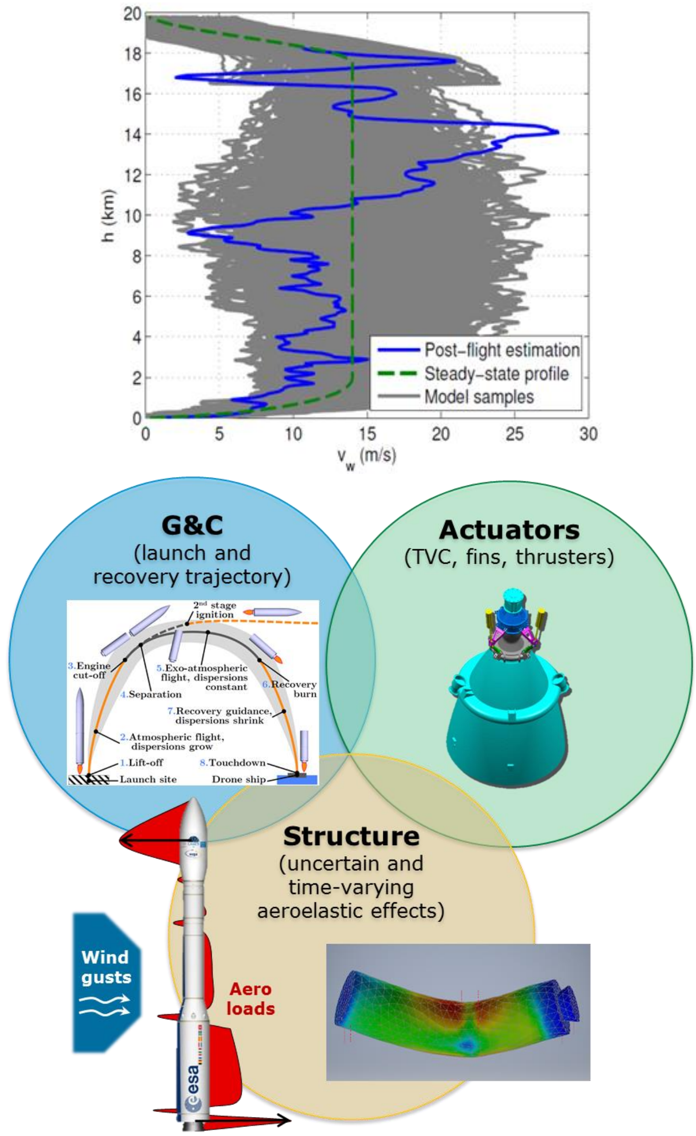

Figure 1: Wind field profiles & Associate Loads

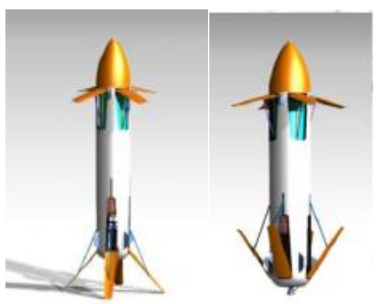

Figure 2: ADAMP II VTVL Demonstrator Concept

Programme outline

The high-level goal of this activity is to develop and validate a suite of Multi-physics GNC SW tools for the management of integrated aero-elastic loads for rockets in atmospheric flight.

The load management activity consists by the development of modelling, analysis and control tools for flexible launchers under forced motions from actuation and environment.

The type of reference mission to be studied at simulation level shall cover ascent up to landing for a variety of slender highly flexible launcher configurations under high load conditions from external winds, manoeuvres, aerothermodynamics and aerodynamics.

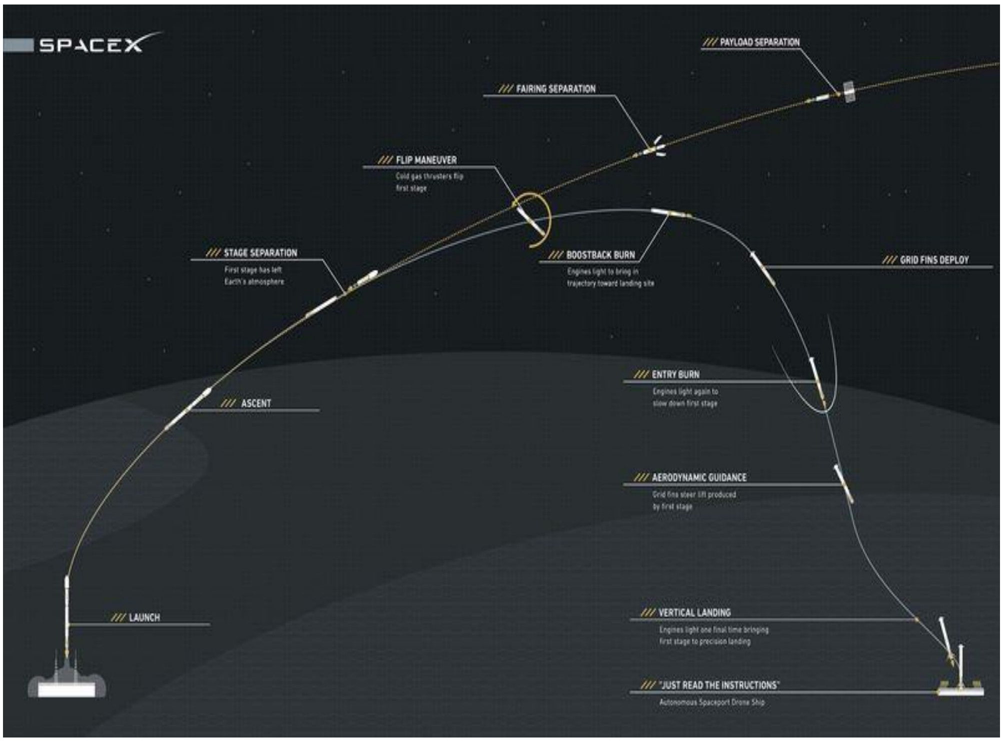

Figure 3: Space-X Falcon-9 Recovery Scenario (Courtesy SpaceX).

Re-usable and responsive rocket flight imposes the design of a high level of robustness and performance guidance and control system subject to external load impact.

Despite being absolutely critical (e.g., atmospheric loads generate forces that bend the launcher structure, which makes the unstable vehicle even more unstable), accurate modelling and analysis methods for complex configurations are not well addressed in the literature.

Development Integrated Aero-Elastic Modelling Techniques.

This task focuses on the development of mathematical representations that capture the interplay between control-induced loads, dynamical wind perturbations and their propagation through a flexible and asymmetric launcher body towards the payload. Such an integrated modelling is not yet readily available and not yet been performed in an end to end fashion.

Pre-scheduling techniques are the state of the art for load relief to meet safety envelope requirements. Due to the wind uncertainty at mission preparation stage, this results inevitably in an over-conservative control design, with the launcher operating far from its maximum performance envelope. In addition, this strategy is highly dependent on the configuration of vehicle and payload, which is translated into large mission preparation efforts.

Load Relief Design

This activity will exhibit a Conceptual Load-Relief Design demonstration using advanced multi-physics models and control design tools.

This will entail developing control-oriented model of reduced sized, design of a robust baseline flight controller featuring a classical load relief technique, and design of adaptive and predictive load relief algorithms in order to provide improved load vs. drift management and reduced GNC sensitivity to the wind.

The novel load-relief algorithms will strongly rely on the novel multi-physics/aero-elastic launcher models and will utilize advanced on-board information to adapt the control laws with load predictions while managing the subsequent trajectory drift. Indeed, in order to facilitate the required level of accuracy, the advanced on-board information must be derived from frequency-based estimation techniques (e.g., wavelet analysis), alternative sensor inputs (evt., from a LIDAR) and/or innovative control configurations (e.g. gyro blending, multiple actuation allocation).

Figure 4 shows a prototype candidate architecture for an on-line load relief strategy with preview upon which novel sensing, computation can be implemented with nowadays COTS technology.

It is expected that such technology shall be able to eliminate wind induced load impact with at least a factor 80% in the case of a relief system with preview and 50% in the case of wind estimation opening door towards 10% launch availability as well as improvement of tolerance to aero-elastic instabilities.

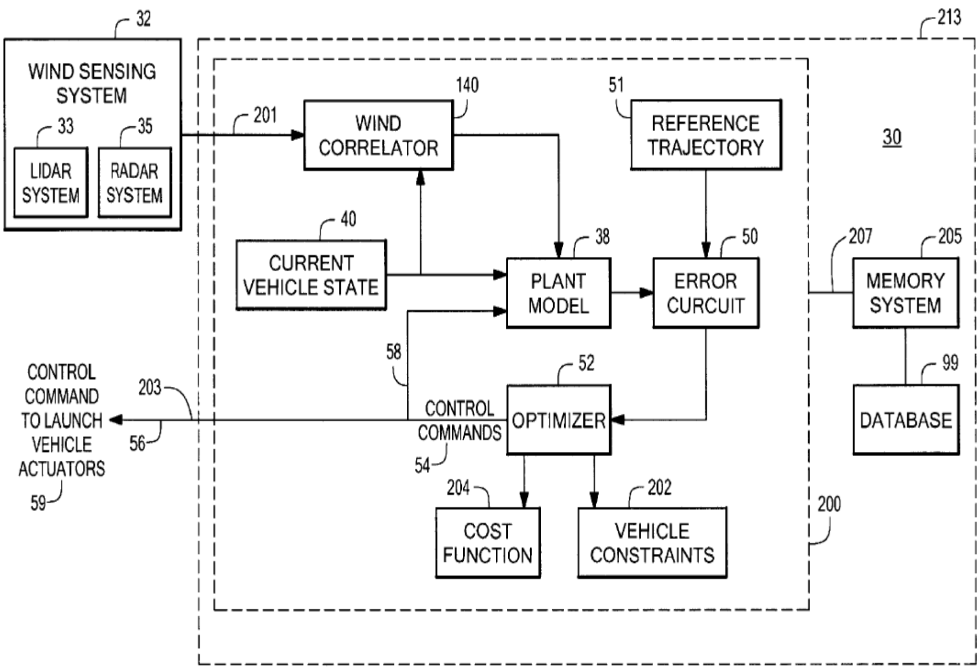

Figure 4: Load relief architecture with preview (US Patent #)

<u>This aim is decomposed into three main technical objectives</u> (and associated steps):

1. ***Critical Analysis Load Management Systems / Definition / Requirements***

- Investigation of modelling techniques for inhomogeneous flexible launcher and distributed wind fields
    a. Aero-Flex-Loads launcher modelling in stationary and non-stationary regime in FEM-CFD
    b. Aero-Flex-Loads-Controls interaction characterization in FEM-CFD

c. Wind field characterization / Wind intensity metrics
d. Wind-Flex-Loads characterisation and load intensity metrics
e. Flight mechanical studies of launcher in ascent and descent for controllability and manoeuvrability
f. Preliminary Guidance and Control strategies for RLV's with tight path and load constraints

- Preliminary integration of new flow-flex mode into launcher simulation, design and analysis infrastructure for impact studies.
    a. Development of multi granularity LV-dynamics models via equivalent modelling techniques (polynomial chaos, proper orthonormal decomposition, surrogate models, etc.)
- Study of measurement techniques including data fusion, filtering, estimation, and identification for wind preview
- Study of advanced robust, adaptive and preview control techniques.
- Requirement Capture
- Benchmark Development, experimental development plan, mission plan, test and validation plan

2. ***Architecture / Load-Relief Design / Development of Active and Predictive Load Relief System***

- Definition of an integrated flight controls, load management system with wind preview.
    a. In-flight wind model acquisition and preview architecture and techniques.
    b. Launcher sensor actuator configuration for flex management, definition GNC architecture and computational infrastructure
    c. Development of load management control concepts
    d. Development reduced wind acquisition techniques and aero-elastic models
    e. Development robust baseline classical control and load relief system
- Extended launcher configuration space design and validation
    a. Parameterised Launcher-PL Flex configuration including uncertainties
    b. Worst Case analysis Launcher Load Cases (Uncertainties/Controls/External Perturbations)
        - Analytical / Robust-modelling based (uncertainty/LFT models)

- Computational / Simulation based (Worst Case Simulation)

- Validation closed loop integrated simulation results with computational accurate FEM and CFD simulation model
- Development and assessment of distributed load metrics

3. *Validation adaptive augmented and predictive load relief algorithms (HWIL).*

- Demonstration basic load relief technology using in-flight simulation of wind acquisition and preview techniques (HWIL).
- Validation robust baseline flight controller featuring a classical load relief technique processor in the loop and eventually in flight
- Validation predictive load relief algorithms processor in the loop and eventually in flight
- Thesis redaction

Schedule and Activities

Work Logic

The activity objectives shall be attained according to the work logic shown in Figure 1.

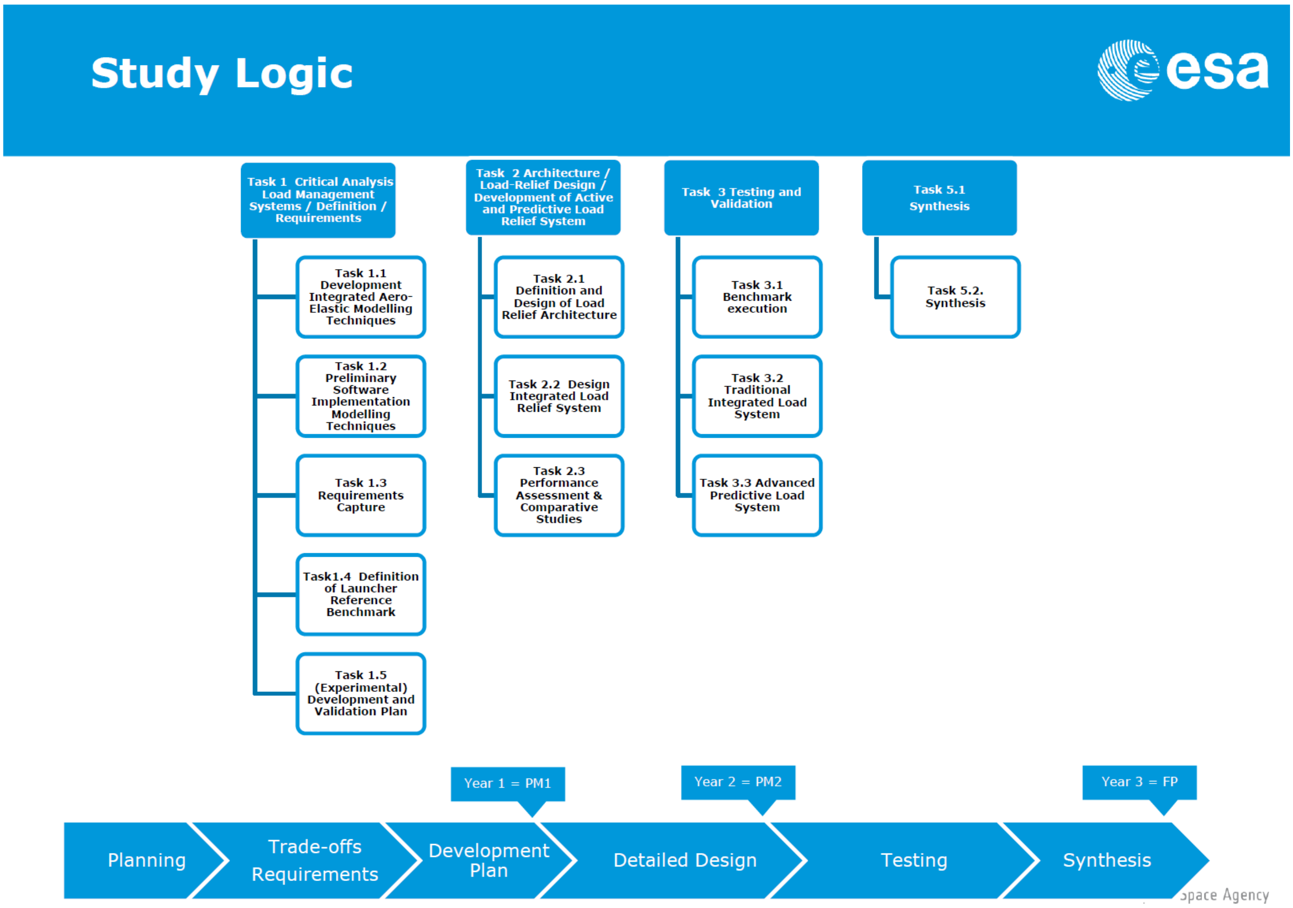

Figure 1 Work Logic

The work is organized according to the following steps:

- **Task-I: Critical Analysis Load Management Systems / Definition / Requirements**
- **Task-II: Architecture / Load-Relief Design / Development of Active and Predictive Load Relief System**
- **Task-III: Testing & Validation**

- **Task IV Study Synthesis**:

The schedule for following major reviews shall be held:

- **PM1 (Progress Meeting 1)**: after 12 month in year 1, ESA will review the results.
- **PM2 (Progress Meeting 2)**: after 24 month in year 2, ESA will review the results.
- **FP (Final Meeting)**: after 36 month final presentation will be held ESA will review the conclusions.

Tasks

As shown in Work Logic Figure 1, there are four main tasks, which are described next.

- ***Task 1: Critical Analysis Load Management Systems / Definition / Requirements***
- **Objective**

  Critical analysis, Requirements Capture: Study integrated aero-elastic launcher modelling, aerology methodologies and advanced control concept for load management. Benchmark Definition
- **Input**

  This SoW, the aforementioned reference documents/software.
- **Tasks description**

  Task 1.1 Development Integrated Aero-Elastic Modelling Techniques

  Task 1.2 Preliminary Software Implementation Modelling Techniques

  Task 1.3 Flight Mechanical Studies & Requirements Capture

  Task 1.4 Definition of Launcher Reference Benchmark

  Task 1.5 (Experimental) Development and Validation Plan
- **Output**

  D1: Integrated Launcher Load Management Techniques 1-st year report

  SW1: Preliminary Load-Relief & Management SW Tools

- ***Task 2: Architecture / Load-Relief Design / Development of Active and Predictive Load Relief System***
- **Objective**

  To define an evolvable load management architecture. Perform detailed design, development of integrated flight control system with load management system with and without wind preview. Study and design of adaptive and predictive algorithms for in-flight load relief.

- **Input**

  Inputs & Outcome from TASK 1

- **Tasks description**

  Task 2.1 Definition and Design of Load Relief Architecture

  Establish various aerologic sensing scenarios with full Information, Estimation, Lidar , Laser etc… address the feedback and preview configurations

  Task 2.2 Design Integrated Load Relief System Traditional (without preview / with observer, etc..) & Preview

  Task 2.3 Performance Assessment & Comparative Studies

- **Output**

  D2: Integrated Launcher Load Management Techniques 1-st year report

  SW2: Preliminary Load-Relief & Management SW Tools

- ***Task 3: Testing & Validation***
- ***Objective***

- **Input**

  Outcomes from TASK 2

- **Tasks description**
  - Definition of experimental setup for verification of developed methods for processor in the loop testing (trade-off between complexity, feasibility).
  - Definition of the processor in the loop test plan and procedures to be agreed with the Agency.
  - Design and integration of experimental add-ons for the demonstrator (basic control law – in flight simulation)considering the limitations of the demonstrator

- Preparation and execution of experimental tests (eventually with demonstrator) according to agreed test plan

- **Output**

  SW3: Active and predictive launcher load-relief designs

- ***Task 4: Study Synthesis***
- **Objective**

  Synthesis of Study
- **Input**

  Outcomes from TASK 2 and TASK 3
- **Tasks description**

  Critical assessment and synthesis of the study
- **Output**

  Final report and SW tools

Output

Reports

- Integrated Launcher Load Management Techniques (Definition Report) 1st Year report
  This deliverable describes the work performed in Task 1
- Integrated Launcher Load Management Techniques (Design Report) 2nd Year report
  This deliverable describes the work performed in Task 2
- Integrated Launcher Load Management Techniques Final (Thesis) Report (Validation & Results)
  This deliverable summarizes previous reports and describes the work in Task 3
- Summary in the form of Journal Publication

Software

In the frame of this activity developed SW tools and models shall be delivered to the Agency.

SW1	Preliminary Load-Relief & Management SW Tools	PM1
SW2	Consolidated Load-Relief & Management SW Tools	PM2
SW3	Load-Relief & Management SW Tools	FP