European Space Agency
Directorate of Technical and Quality Management

ACTIVITY DESCRIPTION

PhD on

“ Active Engine Control for Re-Usable Rocket Systems ”

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PhD on

Active Engine Control for Re-Usable Rocket Systems

Purpose and scope of activity

This document describes the PhD activity **Active Engine Control for Re-Usable Rocket Systems the European Space Agency and Polytehnica Bucharest.**

Background & Motivation

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.

In Europe current launcher engines operate in open-loop cycles. As a consequence, during ground tests one needs to calibrate a number of valves which control the mass flow rates of the propellants in order to obtain a desired thrust and mixing ratio. These remain in a fixed open-section throughout the flight duration. There are some engines using binary valve position to allow in flight adjustment, however, the precise regulated control over the operating point. Most European rocket engines work in open-loop. This means that during ground tests valve calibration is needed to set the desired propellant mass flow rates leading to the desired thrust and mixing ratio set points. These remain with a fixed open-section throughout the flight duration. There are some engines using a binary valve position to allow in flight adjustment, however, the precise regulated control over the operating point during flight is not yet there. During ascent phase there is both, an increase in temperature of the stocked fuel and non-negligible variations of the inlet pressure with the acceleration of the launcher.

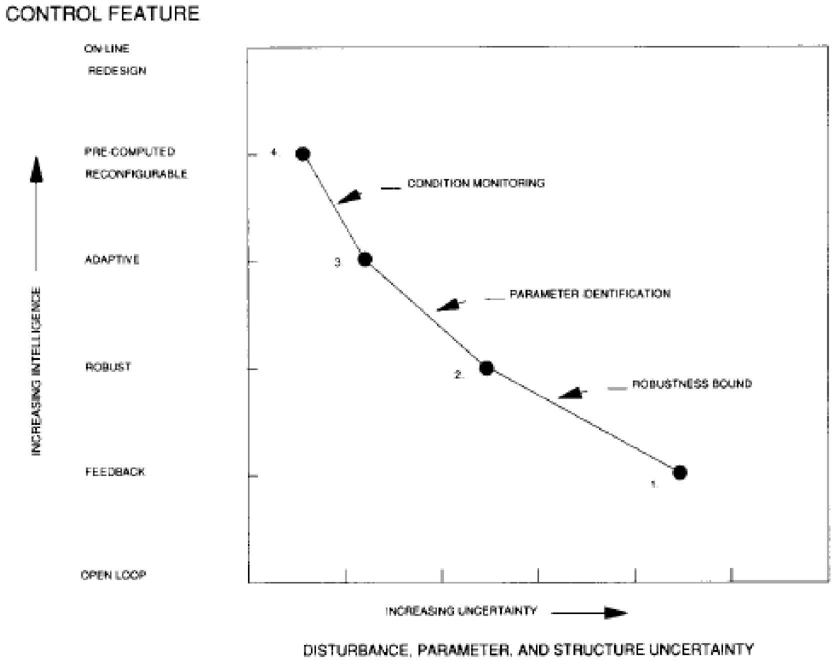
Notice that vehicle and engine conditions vary rapidly due to changes in atmospheric and external conditions, in internal engine adiabatic conditions as well as tank fuel and level conditions. As open-loop engines cannot cope robustly with varying operating point conditions pre-flight operation involve the need of substantial calibration activities.

The need of controlling both the mixing ratio and the thrust (or, equivalently, the pressure in the combustion chamber) can be justified for many reasons besides rapid deep throttling, optima fuel consumption etc. there are also operational advantages.

From a performance's point of view, the use of a closed-loop would not only allow us to suppress a great deal of ground testing effort but would allow also to maintain via regulation a steady optimal operating point throughout the whole flight. Furthermore, deep throttling would allow to decelerate flight to avoid exceeding Max Dynamic pressure limits. Further accurate flight predictions can be obtained via active disturbance rejection and biases correction. Specifically, a good knowledge of the total mass flow and the mixing ratio behaviour allows to optimise the fuel reserve tanking strategy.

In the setting of reusable launchers, controlling these two quantities would not only allow us to limit the mechanical and thermal stresses, but are fundamental in preserving structural integrity for subsequent launches to manage characteristics as ageing. In other words, the control system should be robust to parameter uncertainties seen from an ageing perspective in the context of reusability.

Finally, soft landing of a rocket stage requires well fast, large range (20/80) and well damped deep throttling transient control, and this over a wide thrust range.



These are the most important reasons why we seek to control the mixing ratio and the thrust of a launcher's engine. Figure 1, shows how feedback can increasingly manage uncertainty.

The importance of making a technological step forward is clear, and it is important to equip European rocket engines with digitally controlled valve systems to reach high bandwidth and precision closed-loop engine control. For a complete overview of rocket engine control we refer to [A survey of automatic control methods for liquid-propellant rocket engines - Archive ouverte HAL (archives-ouvertes.fr)]

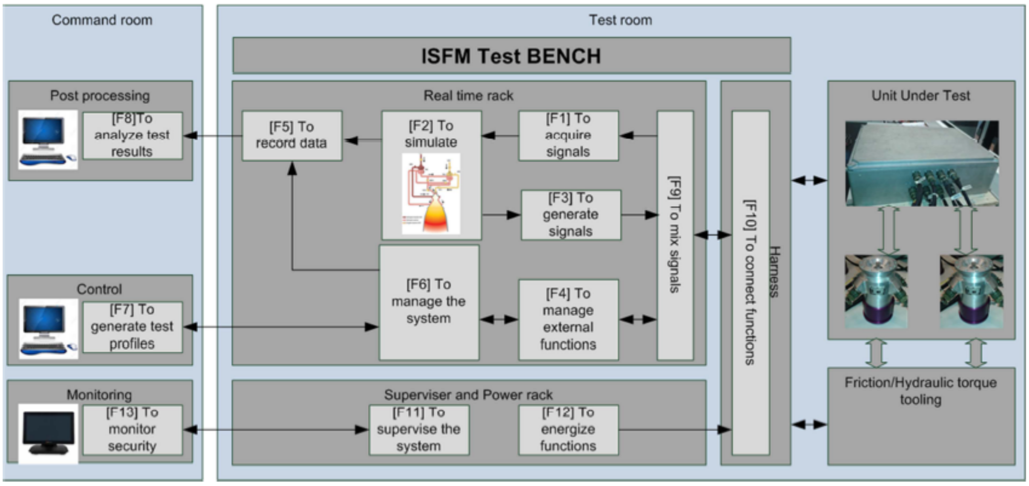


Figure 2: functional architecture of the real time test bench

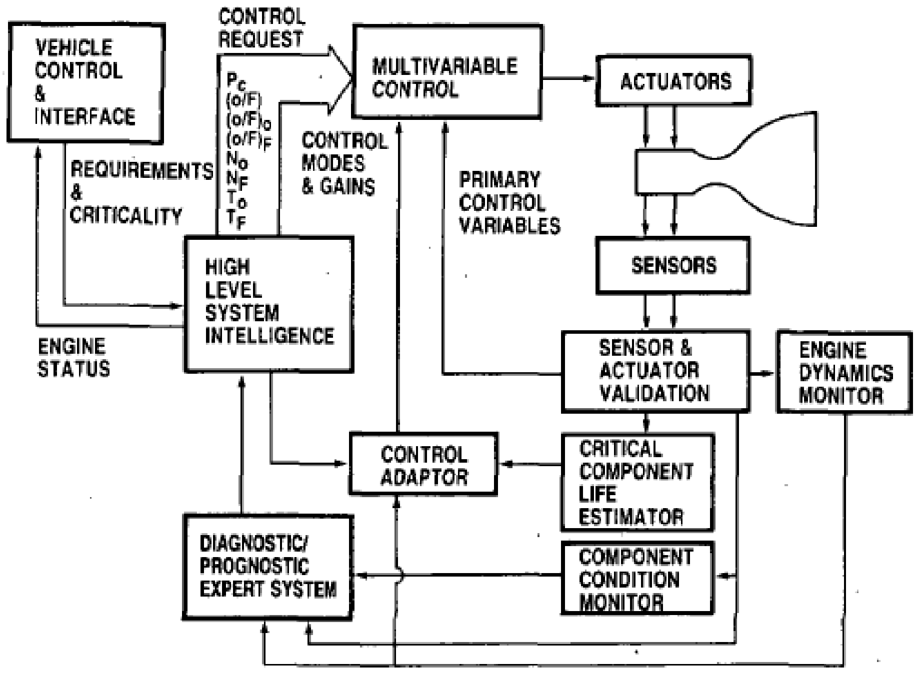


FIGURE 2. - REUSEABLE SPACE PROPULSION INTELLIGENT CONTROL SYSTEM FRAMEWORK.

Programme outline

The high-level goal of this activity is to develop and validate a suite of Multi-physics GNC SW tools for active engine control. This work will include the modelling of transients as it is of relevance to deep throttling technology.

The activity consists of the development of modelling, analysis and control tools for the next generation reusable launchers for which the ADAMPII test case shall be investigated.

Advanced model based engineering tools are to be exploited in order to generate digital twins as well as to manage the design process in a seamless computational infrastructure. This ranges from requirements, documentation, design and analysis up to hardware implementations.

A set of reference missions are to be studied that cover various flight regimes for which throttling can be employed for ascent as well descent and landing phases.

Objectives of this Thesis

This thesis shall addresses several challenges concerning the control in closed-loop of thrust and mixture ratio of a liquid-propellant rocket engine:

1. **Modelling:**
    - obtaining a low order physical linear model of the engine constitutes one of the critical aspects of this thesis; an analytic explicit form of a state-space model will be sought out. These models shall be developed from experimental data. Physical modelling shall be used to reflect reliably every component of the engine. The physical model shall be used as High Fidelity framework for design, analysis and testing.

2. **Model Analysis:**
    - Developed models shall be subjected to model validation over the operating domain;
    - Determination and validation of each engine's component and integration. Sensitivity analysis at component level to assess system level impacts
    - Analysis of the effects of parametric and dynamics uncertainties;
    - List the engine design parameters constraining the implementation of a control law;

3. **Control Law Implementation & Validation:**
    - implementing and validating a robust control law capable of maintaining with precision a desired equilibrium point and of transitioning towards a low-thrust equilibrium point while respecting the established requirements;
    - Above all, the main goal is to establish a methodology easily applicable to various actively controlled rocket engines.
    - The starting point of the research shall be based on a scaled version of the ADAMP engine as a study-case.

Thesis Outline & Work Logic

Step 1

Requirement Capture

- Review and lay down the necessary propulsion fundamentals to understand the work principle of a liquid-propellant rocket engine.
- Subsequently main engine subsystems are described and analysed.

Step 2 Active Engine Controls

- Describes some elements of control theory that are required in the implementation and analysis of the engine models as well as in the control of the future reusable ADAMP II engine.

Modelling for Control

- Formalise the physical laws driving the engine dynamics of the system.
- Develop a nonlinear physical simulation model of the entire engine. Use advanced multi-physics modelling tools. Typically, EcoSimPro, SimScape etc.. as well as other physical modelling tools are to be assessed in order to allow seamless integration with system simulation tools. Take into account transient phenomena into account.
- The engine model will be further augmented with relevant subsystems in order to make realistic predictions wrt to component sizing.
- Develop linearization and model reductions tools for the generation of efficient state-space models to be used for local analysis and control design.
- Study system identification methods starting from least-squares method to characterise engine dynamics from test data stemming from CFD Code as well as later on from test benches. Subsequently, refine these data based modelling techniques for the realisation of more accurate engine dynamics.
- Study the concepts of controllability and observability for the study optimal sensing and actuation placement.
- Study the concept of singular values to describe the behaviour of multiple-input multiple-output (MIMO) systems in the frequency domain as well as a brief account of some considerations regarding robustness analysis. Establish interaction metrics provide insights optimal mixing strategies.

Step 3 Architectural Design (Actuation and Sensing and Control Layout / and preliminary design)

- Study in depth the engine characteristics of the ADAMP II system, especially its thermodynamic cycle and of the available mechanisms (actuators) needed to control the mixture ratio and the chamber pressure.
- Develop and present the analytic linear model of that same engine and its corresponding state-space formulation to allow a preliminary control design
- Develop detailed control design specifications to be met by the closed-loop system. These are to be established in terms of multi-loop stability indicators and relevant performance metrics. These metric, will be characterise in the time domain as well as in the frequency domain.
- Develop a test bench architecture for real time testing of the actuation system
- Develop a target control computer
- Develop the integration plan to go from a SW in the Loop test bench toward a processor and actuator in the loop test bench.

Step 4 Detailed Design

- Address the implementation and analysis of the complete and reduced analytic linear models.
- Perform reduced order modelling from identification.
- Obtain full linear model as well as reduced order models
- Perform model validation
- Describe the baseline control approach for rapid implementation and validation. Develop a subsequent robust control design
- Study various control concepts for engine control

Step 5 Test Plan

- Develop a test plan
- Perform full validation on nonlinear simulation model
- Perform a robustness study against parametric uncertainties and failure events.

Step 6 Validation

- Experimental validation on test bench
- Make a new design loop with Engine test data
- Perform Hardware in the loop testing

Step 7 Synthesis

- Synthesis & Way Forward.
- Thesis delivery
- Redaction of Journal publication

Schedule and Activities

Work Logic

The work logic shall be established to cover the outlined activity steps.

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.

Output

Reports

- Definition Report 1st Year report
  This deliverable describes the work performed in Task 1
- Design Report 2nd Year report
  This deliverable describes the work performed in Task 2
- 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

The developed SW tools and models shall be delivered to the Agency.

SW1	SW Tools	PM1
SW2	SW Tools	PM2
SW3	SW Tools	FP