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Diagnosis and fault-tolerant control for a multi-engine cluster of a reusable launcher with sensor and actuator faults

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ABSTRACT

A possible way to increase the reliability and availability of a system is to apply an Active Fault Tolerant Control (AFTC) algorithm. This thesis aims to use this algorithm in a multi-engine propulsive cluster with sensor and actuator faults. First, a Health Monitoring System (HMS) will be developed to monitor the entire propulsive cluster. The HMS will use model-based fault diagnosis techniques. Then, in case of actuator faults, the cluster will be reconfigured to minimize its effects. The reconfiguration can be made by using control allocation or modifying the control law of the engine. A simulation model of the entire cluster is under development. The model simulates the whole system, including the propellant feeding system, engines, and mechanical system. It will be used to study the effect of different faults on the system and compare different reconfiguration strategies.
Keywords: Control allocation, propellant feeding system, system of systems, fault tolerance, recovery.

1. PROBLEM STATEMENT

Reusable rockets are an innovation in the aerospace industry. Complete or partial recovery of rockets appears to be a promising way to reduce operating costs and environmental impacts. The next generation of European launchers is being designed with a multi-engine propulsive cluster composed of multiple Liquid-Propellant Rocket Engines (LPRE), a Thrust Vector Control (TVC), and a propellant feeding system.

The multi-engine cluster offers more reliability and availability with respect to a unique engine (Colas et al., 2019). Ideally, even if a failure occurs in one engine, the mission can be completed thanks to the remaining healthy engines. However, several steps should be addressed to achieve such a goal. First, the system should be able to detect, isolate, and identify all faults that might significantly impact the multi-engine cluster. Then, the system has to be reconfigured to mitigate the fault effect.

To solve the problems cited above, this thesis aims to develop an Active Fault Tolerant Control (AFTC) (Castaldi, Mimmo, & Simani, 2016) algorithm capable of treating actuators and sensor faults. This strategy will be based on the signals produced by the sensors. It must identify outliers from data and be able to operate in real-time under actuator faults.

A possible functional architecture of the multi-engine cluster is illustrated in Figure 1. Each motor has its own control law and Health Monitoring System (HMS) at the engine level. The role of the global HMS at the bay level is to monitor the health state of shared resources (TVC and propellant feeding system). Combining information from both levels of HMS, the overall state of the propulsive cluster can be established. The control allocation module's main objective is to translate the reference coming from the trajectory management module into feasible instructions to each engine, taking into account the health state of the cluster.

Concretely, the development of an HMS and an allocation module is linked to numerous open issues:

- The fault detection can be made at the individual engine level via an HMS filter (Sarotte, Marzat, Piet-Lahanier, Ordonneau, & Galeotta, 2020). On the other hand, the faults could be detected using information from the shared resources, at the bay level.
- The system reconfiguration under actuators fault can be made at the bay level, using an optimal control allocation (Johansen & Fossen, 2013) (Abauzit & Marzat, 2013) strategy in the engine cluster. The reconfiguration can also be performed at the engine level, modifying its con-

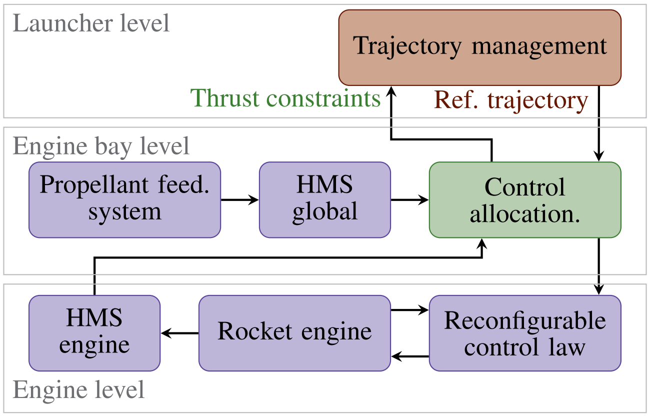

Figure 1. Possible functional architecture.

trol law.

- The consolidation of the sensor measurements is envisaged using analytical redundancy. The cluster can be seen as a system of systems: each engine shares its resources and capabilities, creating a highly interconnected system. This interdependency between systems can be used in favor of sensor measurement consolidation.
- If one actuator fault occurs, two different modules could make the trajectory reconfiguration. Either the trajectory module recalculates a feasible reference considering the degraded state, or the control allocation module generates its own optimal reference.

2. State of the art

Fault Detection and Diagnosis (FDD) techniques in rocket engines have been studied since the 1970s, and it is a vital part of an HMS. In the early years, the health monitoring of rocket engines was made by observing some important operational parameters with fixed redlines values(Wu, 2005). In the literature, the Space Shuttle program carried out by NASA is an important source of information concerning HMS in LPRE. In (Hawman, Galinaitis, Tulpule, & Mattedi, 1990), different fault detection techniques are tested, and an HMS is proposed. The HMS has one output: yes/no to shut down the engine. According to the report, about 900 Space Shuttle Main Engine (SSME) failure modes can be identified with the database available at that time. The HMS focused on a small group of faults that directly impact the engine safety, but at the same time, they can be detected and treated. The minimization of the impact of those faults was the target of the HMS. Data-driven algorithms such as pattern recognition and Autoregressive Moving Average (ARMA) models were tested for fault detection. Another data-driven method, using bivariate time-series analysis, has been implemented in (Tsutsumi et al., 2021). The algorithm is applied to the Reusable Sounding Rocket (RSR) was developed by the Japan Aerospace Exploration Agency (JAXA). In (Iannetti, Marzat, Piet-Lahanier, Ordonneau, & Vingert, 2015), model-based methods for fault diagnosis were tested in a rocket engine demonstrator. Under those circumstances, parameter identification and Kalman filter were applied. The modeling of LPREs can be made by describing the thermo-fluid and mechanical dynamics of the engine. Those models can be complex to simulate, requiring specific platforms. In (Pérez-Roca et al., 2019), an overview of modeling techniques of LPREs for control applications is given. The linearized version of the nonlinear thermodynamic model is often used to generate control laws. Control allocation algorithms can be used to control over-actuated mechanical systems. This algorithm can also be applied for the Fault Tolerant Control (FTC). In (Marks, Whidborne, & Yamamoto, 2012) an allocation scheme is used for FTC of an eight-rotor Unmanned Air Vehicle (UAV). If the UAV is exposed to rotor failures, the control allocation scheme maintains its stability and performance.

3. Expected contribution

There is very few open literature on the HMS in a multi-engine propulsive cluster. Despite the fact that the HMS implemented in the Space Shuttle is widely documented, the system was developed for each engine separately. The multi-engine characteristic of the cluster was not taken into account. An HMS using the measurements from the shared resources of the propulsive cluster has not been investigated yet. This thesis aims to investigate different solutions considering the specificity of the multi-engine propulsive cluster from an HMS and control reconfiguration point of view. In particular, the fault diagnosis techniques applied to shared resources of the cluster, like reservoirs and propellant feeding lines. In addition, we intend to compare different reconfiguration methods in case of actuator fault.

4. Research plan

The associated research plan can be divided into three main tasks:

1. Modeling and simulation: a first mandatory task is to build a representative model of the system studied. It should be composed of LPREs, TVC, and a propellant feeding system with reservoirs and feeding lines. Then, the chosen failure modes can be simulated.
2. Fault diagnosis: in this phase, we intend to use model-based algorithms for fault detection, isolation, and identification. Model-based algorithms were chosen because it does not rely on recorded data. Reusable launchers are relatively new. Therefore flight data are scarce, especially data recorded under faulty conditions.
3. System reconfiguration: As discussed before, the system reconfiguration can be made at the bay level , using control allocation techniques, or at the engine level. The comparison of those strategies will be part of the study.

4.1. Work performed and remaining work

The modeling task has been the main focus of the work carried out so far. A rocket with three engines is used as a reference to our model. The rocket is considered to be powered by three 1000kN class engines, which will use liquid oxygen and liquid methane propellants. The CNES developed one 0D model of the engine on the simulation software CARINS. The models of two subsystems have been derived: the plant dynamics and the propellant feeding lines. The plant dynamics inputs are the force and the position of each engine, and its output is the resulting force of the launcher. The propellant feeding lines are the system that connects the engines with the reservoirs. Its inputs are the inlet temperature and pressure of the propellant and the outlet mass flow. The outputs are the outlet temperature and pressure. A simplified diagram of the main models of the cluster is illustrated in figure 2.

We developed the propellant feeding system on Simulink® using the Simscape™ library. We simulated the model of the engine in nominal and faulty scenarios. Then, we recorded the evolution of the inlet mass flow of the engine. The mass flow is used as input to our feeding system, and we can study the impact of the simulated scenarios on the feeding system. The next step is to connect and validate the three existing models to the same platform. Then, steps 2 and 3 of the research plan will be studied.

5. Conclusion

Active fault-tolerant control is a promising way to increase the reliability and availability of a engine propulsive cluster. Mainly due to the hardware redundancy characteristics of the cluster. Different strategies to the reconfiguration problem can be considered, namely at the individual engine level or at the launcher level, and this thesis aims to implement and compare them. The steps that must be followed to study this problem were formulated. From the beginning, most of the effort is concentrated on building a representative model of the multi-engine cluster. Then after analyzing the subsystem models and the available measurements, dedicated methods will be selected and evaluated. It is foreseen that techniques relying on physics-based models would be better suited given the characteristics of the problems formulated in this paper.

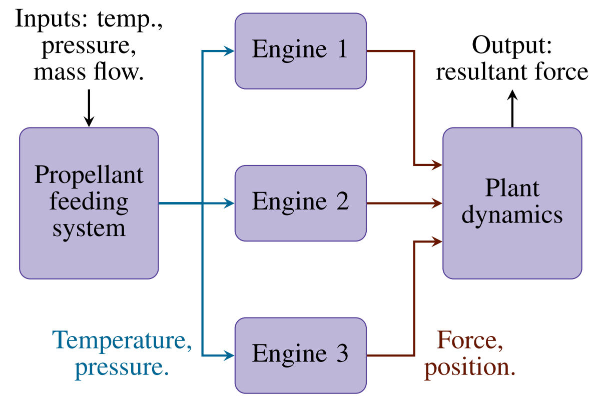

Figure 2. Simplified diagram of the multi-engine propulsive cluster model.

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