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A point of view about the control of a reusable engine cluster

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Abstract

In the framework of studies on reusable liquid propulsion engines and reusable launchers, some control problematics are highlighted. These questions open the field of possibilities to control a multi-engine bay under maintainability, controllability and safety constraints.

This complex new system imposes new needs such as for example high throttling capabilities, monitoring and maintenance tools.

The strong interaction between the launcher Guidance Navigation & Control (GNC) system on one hand and the Engine Control System (ECS) with its monitoring on the other hand, while introducing the challenges of cost, reliability and stability, may lead to the deployment of new functions.
These functions are either already evaluated but not deployed, or to be designed or even just imagined.
This article will illustrate the associated issues, seen from an automatic control perspective. Topics covered include:

- Engine cycle intrinsic dynamics vs. engine control performance
- Engine control performance vs. performance modulation dynamics
- Engine monitoring and interaction with engine control
- Engine monitoring and propulsive bay reliability
- Thrust Vector Control of the Bay
- Methods and tools for reusable engine cluster

The notion of reusability as well as that of multi-engine bay offers new needs and therefore new thought on control system architectures; that is what we are going to highlight in this paper.

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Abbreviations list

AI	Artificial Intelligence
AFTC	Active Fault Tolerant Control
EC	Electronic Controller (local loop power cards)
ECS	Engine Control System
EFF	Engine eFFiciency coefficient
EMCU	Engine Monitoring and Control Unit
FADEC	Full Authority Digital Engine Control
FDI(R)	Fault Detection, Isolation (and Recovery)
FLPP	Future Launcher Preparatory Program
FMECA	Failure Modes, Effects and Criticality Analysis
FTC	Fault Tolerant Control
FTF	Functional Test Facility
GNC	Guidance Navigation and Control
HCI	Health-Control Interaction
HIL	Hardware In the Loop
HMS	Health Monitoring System
HP	High Power (electrical)
HUMS	Health and Usage Monitoring System
ISFM	Engine Functional Simulation Facility
LP	Low Power (electrical)
MCAU	Measurement Conditioning and Acquisition Unit
MTBF	Mean Time Between Failures
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
LOBC	Launcher On Board Computer
LOSW	Launcher On board SoftWare
PAM	Propellant Active Management
PCCM	Propulsive Cluster Control Management
PMSM	Permanent Magnet Synchronous Motor
REEC	Rocket Engine Electronic Controller
SOBC	Stage On Board Computer
SOSW	Stage On board SoftWare
TMF	Thrust Management Function
ULA	Upper Level Authority

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1. Motivations and general Context

Today, the launcher market is becoming increasingly competitive and the challenge to reduce the cost of launchers is becoming more and more critical. Some studies were already performed on this topic [1][2]. One of the main ways to reduce those costs would be to recover at least parts of the rocket. As the recovered part needs to have suffered minimal damage in order to be reused with as little refurbishment as possible, the first stage is the most interesting part since it re-enters from a lower altitude and with a reduced speed. The capability to have a reusable launcher, and more particularly its multi-engine bay, depends on the capability to reuse the liquid rocket engines and to coordinate the engine cluster in all the flight phases.

After a quick engine cluster description, the article will introduce overall GNC problematics (§ 3), followed by the Engine Control System (§ 4) and consequently the Health Monitoring System (§ 5) – fundamental part in a reusable frame – and its interaction with the control. Then, after a focus on the Propellant Active Management (§ 0), the thrust vector control is treated with its potential imbrication with the thrust control (§ 7). An overview of the avionic architecture of a multi-engine propulsive bay is also provided with associated optimization opportunities (§ 8). Finally, the tools for reusable multi-engine cluster system evaluation and validation are discussed (§ 9) and synthesis including some perspectives provided in conclusion.

2. Engine cluster general presentation

An engine cluster is based on some identical or derivative engines aiming at reaching the full thrust at lift-off, reduced thrust in particular situations such as guidance nominal commands, Active Fault Tolerant Control (AFTC) recovery action or during specific phases of the mission (i.e. braking, re-entry or landing boosts) eventually requiring only few of the cluster engines.
The engine cluster and more generally speaking the whole propulsive bay is made off the following main systems, depending on the considered main function to be realized, and without forgetting some interactions existing between them:

- **The propulsion system**: to provide thrust to the launcher or the stage
- **The electrical and power system**: to provide, convert, distribute and control electrical energy for high and low power users
- **The command & control system**: to compute appropriate commands from input orders, measured or estimated data in order to manage the propulsive bay and each engine operating point (thrust, mixture ratio)
- **The thrust vector control system**: in association with the engine control, to generate the thrust orientation of each engine from a single upper thrust vector order and to apply it on each engine
- **The health monitoring system**: to perform at engine and cluster levels the in-line fault detection and autonomous recovery actions, as well as the off-line analysis of archived data for engine maintenance optimization between flights

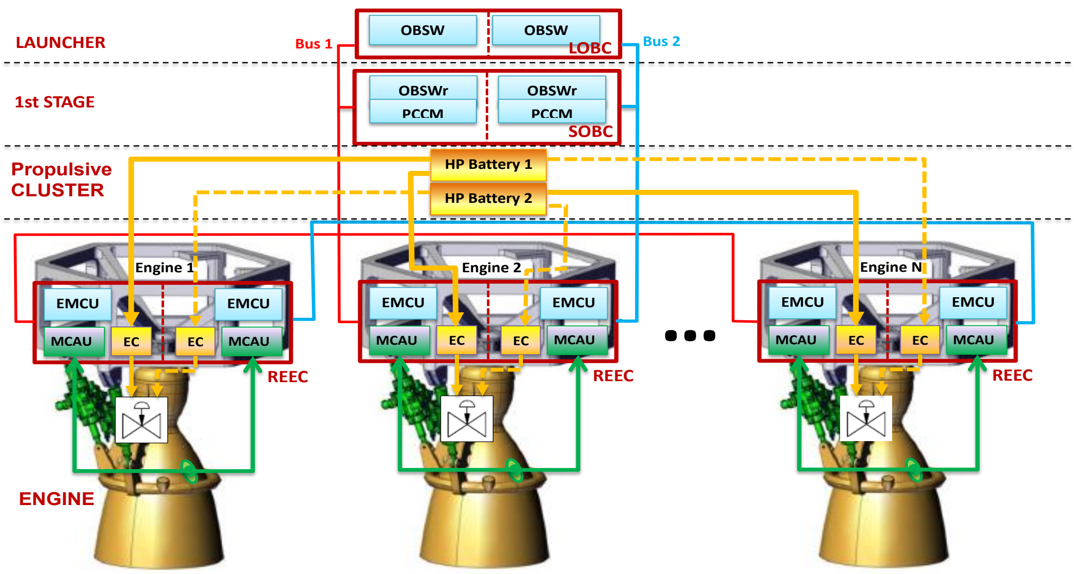

Figure 1 : an example of main functions repartition and interaction on a propulsive cluster

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2.1 Some problematics to solve and opportunities to catch

Some issues to be treated in the frame of a propulsive cluster of a reusable stage are linked to the merging of requirements and constraints of a usual propulsion system with those of the reusability on the one hand and of the engine multiplicity on the other hand.
Nevertheless, let's first list some opportunities offered by the engine clustering with respect to a unique engine:

- **Higher propulsion reliability** and availability as well as slower ageing due to the lower level of thermal and mechanical loads to be sustained by each engine, in comparison with a unique high thrust engine,
- **Higher mission reliability** thanks to the ability to complete a mission (totally or partially) despite an engine failure,
- **Ability to use only one or few engines** of the cluster in specific mission phases (such as landing), in comparison with developing a complex unique very deep throttling engine,
- **Ability to use the natural level arm associated to throttling** capability of external engines to contribute to the thrust vector control without gimbal angle losses,
- **Ability to reduce the overall recurring cost** of the system through both simplification of each engine and manufacturing serial effect.

Given those positive aspects brought by the cluster architecture, here are the main associated problematics to be handled for an efficient cluster design:

- **Engine dynamics versus engine control performance**: more linked to the reusability than to the multi-engine property, it consists in verifying that the thrust variation rate required by the GNC (mainly during landing phase) is coherent with the engine operating point variation intrinsic capability. This is mainly discussed in §4.
- **Engine control performance versus mission needs**: propulsive cluster operating point (overall thrust and inlet mixture ratio) control loop shall meet static and dynamic requirements from the GNC – for thrust modulation – and from the mission optimization – for coherent propellant depletion in tanks – while ensuring both the targets follow-up and the perturbations rejection. Interaction with GNC and notion of Propellant Active Management (PAM) are treated in §3 and §6. The necessity of a centralized cluster management function for distributing elementary operating point targets to the engines from a unique request from the GNC and PAM is treated in §7, commonly with thrust vector control centralized management.
- **Engine monitoring and interaction with the control**: the opportunity brought by the ability to throttle down or shut-down each engine independently from the others in the cluster generates a new functionality for synthesizing the individual engine health reports (and eventually rapid engine local autonomous jump to a degraded operating mode) in order to update the way to distribute the commands in the goal of maximizing the mission success. This strategy involving local and cluster HMS functions is depicted in §5.
- **Engine monitoring and propulsive bay reliability**: on-line real time as well as off-line pre-flight or post-flight differed time HMS shall contribute enhancing the overall system reliability and availability while optimizing recurring costs. This is also discussed mainly in §5. On the other hand, some avionics architecture optimization and simplifications could result from the increasing number of engines, as explained in §8.
- **Thrust vector control of a propulsive cluster**: several aspects are linked to the control of the torque applied to the launcher, from the optimization of the engines that are gimbaled and the choice of the gimballing axes per engine up to the optimal repartition of the commanded torque between thrust variation (using the lever arm effect) and gimballing for each engine, while considering the reliability and availability of the thrust vector control function.
- **Methods and tools for reusable engine cluster**: due to the number of functions, the software complexity should inevitably increase. A focus is provided on validation and qualification of such a complex system (§ 9). In addition, particular methodology has to be developed either for the demonstration and the qualification but also for automatic coding in the frame of high level of criticality. In another way, because the system has to be robust to the degradation, it is important to consider early in the reflection the Health Monitoring problematics. Not only in off-line for the maintenance need, but, of course also, for the real time with a decision making functionality.

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2.2 Overall functional architecture

Overall functional architecture naturally leads to three main levels of hierarchy from top to down:

- The launcher system level (functions of which are at stage authority level after separation)
- The propulsive cluster level
- The rocket engine level

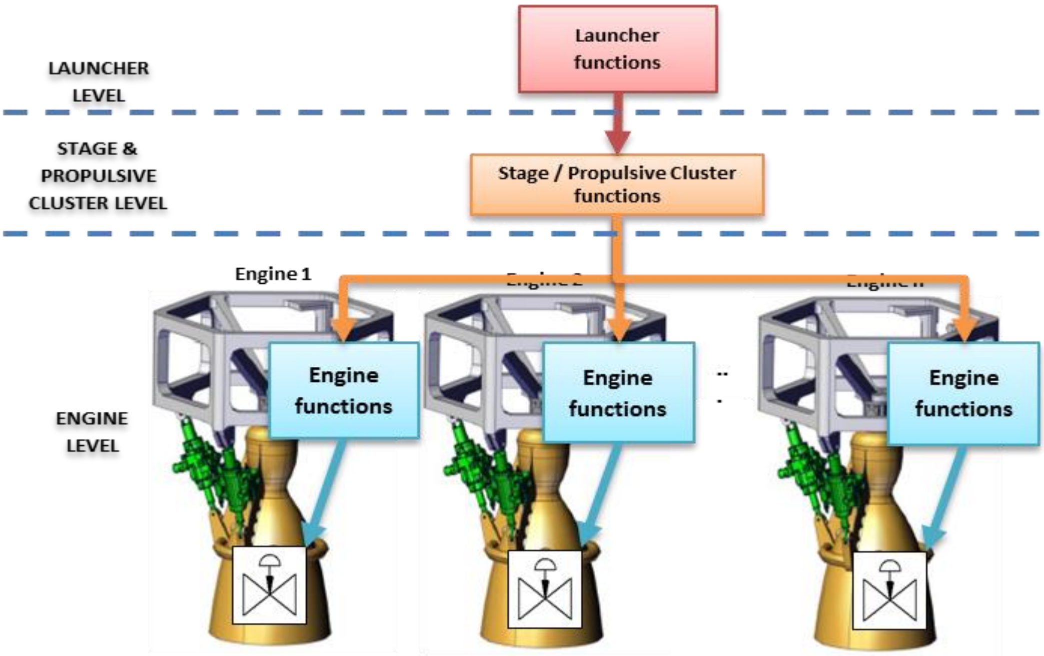

Figure 2 : Main cluster management functional hierarchy levels

The launcher system level mainly corresponds to the flight sequence management and GNC functions, responsible for generating commands of thrust and thrust orientation for a use by the cluster. At this level, an on-line correction of the commanded mixture ratio to be consumed by the engine cluster is performed in order to target an optimal propellant depletion (PAM). After 1st stage separation, these functions are handled by the stage itself based on its own on-board computer, as it is disconnected from the upper part.

The propulsion cluster level is mandatorily handled at stage level. It is mainly responsible for the splitting of global thrust vector (magnitude and orientation) command from the launcher level into elementary orders sent toward each Rocket Engine Electronic Controller (REEC) and each engine Thrust Vector Control (TVC), eventually taking into account some degraded configuration for an optimal repartition. At this level, the global mixture ratio target is also distributed between engines with potential adaptation due to specific degraded cases.

At engine level, the operating point control loop is performed, as well as the detection of anomalies and failures and the on-line rapid and local HMS treatment to avoid feared events and propagation. Indeed, some failures necessitate a high reactivity (for instance turbopump overspeed) and shall lead to rapid local recovery action before informing the upper levels. At this level the effective parameters are measured and treated for a use by all levels.

Trade-offs were performed in the frame of Prometheus project, aiming at optimizing the appropriate location level – launcher, cluster or engine – and the appropriate number of elementary hardware realizing these functions. The complexity and high computing need of on-line engine control and HMS functions, as well as the advantages brought by an autonomous rocket engine lead to the necessity for each engine to have its own REEC receiving operating point targets and orders from the stage computer and directly providing modulated high power to engine valve electrical actuators.

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3. Guidance, Navigation and Control aspects

From GNC point of view this leads directly to two main challenges and opportunities:

- **Mastering GNC for re-entry, descent and landing of the stages and their associated engines.**

  The possibilities include landing part of that stage like an airplane or a shuttle, as it was studied in the Adeline project from Ariane Group. The other possibility is to use remaining propellant to brake and land vertically on a barge or on a launch pad (toss-back). The first stage return and Toss-Back is the core part of CALLISTO and THEMIS European demonstrators [16].

  There are many challenges related to landing a launcher stage. For Guidance Navigation and Control (GNC) the main challenges are that the conditions at the landing must be precisely controlled, in terms of position and velocity accuracy, to ensure the safety of the rocket and the landing platform. Furthermore the fuel consumption must be kept to a minimum to maximize the mass of the payload that can be put into orbit. During years, the most famous approach for landing a stage was using a trajectory based on a quadratic polynomial in time as for the Apollo mission [15]. Even if it was not a fuel optimal solution, it was simple and satisfying initial and final boundary conditions. Today, approaches used for planetary landings and stage recovery are based on some low computer consuming on-line optimization algorithms for convexified problems in presence of constraints, allowing finding the best trajectory for lowering the propellants consumption.

- **Enhancement of ascent phase GNC to increase its reliability in front of degraded engine functioning mode and take advantage of engine cluster opportunities.**

  GNC functions for expendable launchers during ascent phases were widely developed since the first launches more than 50 years ago and methodology improvement were continuously searched, and published, in each field of Guidance Navigation and Control functions with focus on accuracy, performance or robustness improvement.

  Today with the development of reusable launchers new challenges appear with, on the one hand, increased level of risk of failure or degraded functioning conditions of re-used engines, and, on the other hand, new perspectives that are opened towards autonomy, with thrust modulation capacities of cluster of liquid engines.

  The key features would be a new concept with less robust design (nominal or reduced domain) and more adaptive and/or learning parts. This concept could be drastically **less expensive during the design phase** and **safer in case of failure**.

To face these challenges the main research direction is autonomous GNC that covers a complete new GNC strategy:

- In a first step, we shall **increase the level of adaptivity learning and FDIR** inside each Guidance Navigation Control and cluster functions. An example is the use of enhancement of sensor data fusion in Navigation function.
- Then we shall extend these evolutions to **multi-functions interactions** such as Guidance Control and Thrust Management Function (TMF) coupling for reusable launcher landing.
- Finally, we shall include on-board **the use of engine cluster in safe mode in case of failure. This safe mode should focus on ensuring the mission safety despite performance requirements.**

Figure 3 : *CALLISTO landing illustration*

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4. Description of engine control

The engine control appears necessary for throttling, disturbances rejection and performance optimization needs. The throttling capability leads to have a system that varies in term of dynamics and static gain. Moreover engine hardware dispersions lead also to variations of the system. These variations shall be taken into account in the design of the engine control law to permit to have a closed loop dynamics that respects requirements (from engine system, launcher, etc.). Moreover the throttling capability leads also to have a disturbance sensitivity that varies on the thrust range. This evolution of sensitivity shall also be taken into account. That is why non-linear approach with varying parameters shall be taken into account to counter these evolutions and to have the best performance. Specific studies about the non-linear control dedicated to the engine start-up transient are partially illustrated in [12] and an overall vision of the automatic control for liquid propellant rocket engine is synthesized in [11]. The other side of the performance is about the accuracy. The overall control accuracy is made off the accuracy of sensors and the resolution of actuators (in case of an engine, valves) on the system. Accuracy requirement is driven by needs coming both from mission performance (to maximize payload capability) and from safe landing related requirements.

In case of a reusable launcher, the problematic of the response time of the engine for landing is critical. Indeed a bad engine response time can lead to a loss of the launcher. In this way the engine control system shall deal with this specification. A trade-off between stress on the engine and response time for landing shall be conducted. Indeed in case of an engine that have a natural response time slower than the required response time, the engine and actuators will be more solicited to respect the specification for landing and reliability of such a critical phase is no more insured.

As explained before, the varying parameter is an important challenge of new rocket engine. Because the thrust range is wider and due to the needed reduced recurring costs, hardware dispersions are greater. So these two requirements lead to have a range of engine characteristic variation more important. The controlled system and consequently the control law shall deal with these variations. A classical linear control law does not necessarily deal with that and so the introduction of non-linear elements or the introduction of a fully non-linear control law can be a solution. These non-linearities permit compensating the variations exposed here by taking into account them thanks to model and/or tests.

Another topic is about the hybrid control that allows taking into account binary on-off actuators, within the control system (used for the most part during start-up phase and more generally during phases where the engine is not controlled in closed loop). This control permits merging all command and actuators and making all the cycle from the start to the end in close loop.

Finally in case of a smart engine, the control system can also be reconfigured with the status of the engine. Indeed in case of a damaged engine due to ageing of sub-systems, coefficient of control law can be adapted online with the online damage computation performed by the Health Monitoring System. This interaction is useful to optimize the performance and the reliability of the propulsive bay. This particular last point, the Health Control Interaction, also named AFTC “Active Fault Tolerant Control” is shown in the §5.

5. Monitoring and AFTC

The engines are progressively degraded with the duration of use and according to their solicitations. The availability of hardware in operation is associated with the probability of failure, which increases with the degradation of the hardware.

On a multi-engine bay, the objective is to guarantee the thrust function minimizing the probability of failure of the propulsion unit by distributing the thrust on the various engines.

However, on a reusable launcher, each engine of the propulsion bay can have a life cycle of its own, for example by having a particular reception time or a different solicitation on the occasion of the previous flights (specificities of certain launch mission).

The overall HMS architecture is based on some layers. In first approach one can consider the level 1 at the engine level and the level 2 at the cluster level.

Level 1 (engine):

At each engine, using the available information (operating time, pressure measurements, rotational speed, temperature or vibration), a damage indicator is calculated. The damage indicator can be established on the basis of the individual damages computation defined for each of the organs (or subsystems) of the engine considered.

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For each motor it could be defined an operating range that can be restricted. This area is referred to as "functional limitations".
Depending on the value of the damage counter, it is possible to maintain the reliability of the equipment constant or contained for the remaining time to work without having to work in a zone with rapid degradation to ensure the acceptable level of reliability.

In the case of propulsion system, this capability is possible as soon as this propulsion system is composed of several engines. Indeed, by constraining an engine, it may be possible to pass or divide the need on the other ones that are the healthiest.

The goal is to contain the operating point at "good" distance from the risk of failure. This function is all the more applicable as the system is subject to a large number of cycles. However, the function should have the ability to inhibit itself in case of an unusual or contingency management request, which may be seen in some avoidance situations.

For this, the engine control function can be based on 2 strategies:

- Top-down: the motor asks the higher-level function to lower its operating point to limit its reliability by sending a flag indicating its status.

- Bottom-Up: the motor self-restricts and informs the function of higher level by a flag indicating that the area of the engine has been restricted, and a second flag indicating its level of efficiency, ie the ratio between the thrust desired and the current one.

Thus an engine for which it is requested a thrust of 1000kN (100T) and whose ageing leads to prevent it from exceeding 80T, efficiency EFF = 80% is raised to the upper level management function of the propulsion system.

This function is composed of the following elements:

- F1n: n functions of calculation of the individual damages
- F2: Calculation of the global damage
- A function determining the operating limit of the motor by acting on the functional limitations (limit to a parameter not to be exceeded)
- An automatic control integrating the potentially varying limitations

Level 2 (propulsive cluster):

The second level of treatment is at engine cluster level. A function that will be called "floor thrust distribution system" receives:

- From the launcher level:
    - o The global order of thrust
    - o Possibly the thrust management constraints (in accordance with the flight management)
- From each of the engines:
    - o The EFF coefficient

This function aims at managing these data and assigning to each engine control its own thrust instruction.

5.1 The Engine HMS

The improvement of safety and availability of a system goes through the detection, the isolation and the correction or reconfiguration of its failures. A failure can be a total breakdown of an element of the system or a modification of its characteristics, sufficiently important to deteriorate the total operation of the system. Safety is thus affected when a failure occurs that is not detected (no-detection). In addition, a stop due to an unjustified alarm (false alarm) increases the unavailability of the system.

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In the case of structure malfunctions, faults or damage, we need to define when a structure is merely damaged and when a structure contains a fault. A coherent definition of faults, damage and defects [17] is given below:

- A **fault** is when the structure can no longer operate satisfactorily. If one defines the quality of a structure or system as its fitness for purpose or its ability to meet customer or user requirements, it suffices to define a fault as a change in the system that produces an unacceptable reduction in quality.
- **Damage** is when the structure is no longer operating in its ideal condition but can still function satisfactorily, i.e. in a sub-optimal manner.
- A **defect** is inherent in the material and statistically all materials will contain some unknown amount of defects; this means that the structure can operate at its design condition even if the constituent materials contain defects.

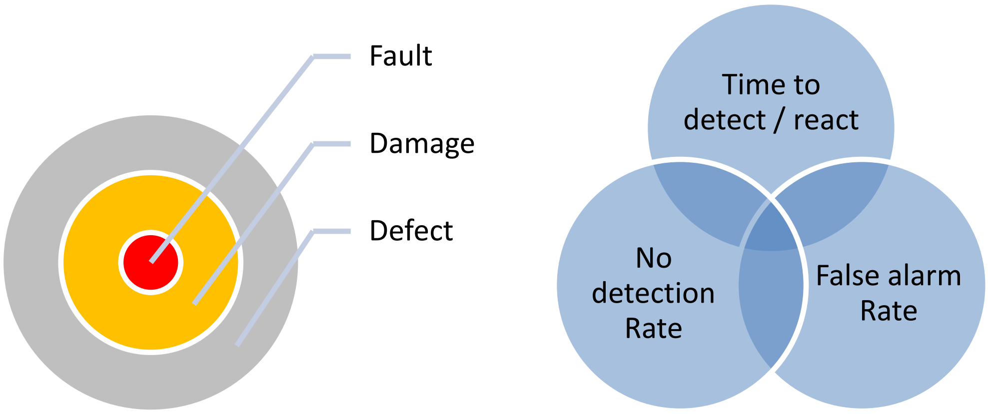

Figure 4 : Illustration of main definitions related to the HMS

The purpose of the monitoring systems are thus to detect, isolate and diagnose the failures (Fault Detection and Isolation, FDI) with a minimum of false alarms and as fast as possible.
The functional analysis of the HMS shows that this system can be broken down into the following functions:

- **To detect, isolate and reconfigure the instrumentation.** Indeed, it is necessary to have correct information for the upper functions.
- **To detect** consists in deciding if the system is or is not in normal working state. The result of the procedure of detection is an alarm meaning that the real operation of the system does not agree any more with the model of healthy operation.
- **To isolate or locate** comes down to assign the defect to the defective module of the system: sensors, actuators, process or control unit.
- **To diagnose** consists in carrying out classification defects according to certain parameters which characterize them: moment of appearance, amplitude. This stage also consists in envisaging the evolution of the defects and quantifying their degree of severity.
- **To prognose** consists in carrying out predictions of the evolution and consequences of the previous defects. In this process the remaining life time is computed and is used for the maintenance objective. (When we have to change any equipment)
- **To reconfigure** consists in applying new control orders or parameters or carrying out modification on some items such as the acquisition of the sensors with an aim of maintaining the objective of the mission while accepting degraded performances in the presence of known failures. We can also use the word term “**action”**.

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The following pyramidal structure illustrates the HMS data processing stages:

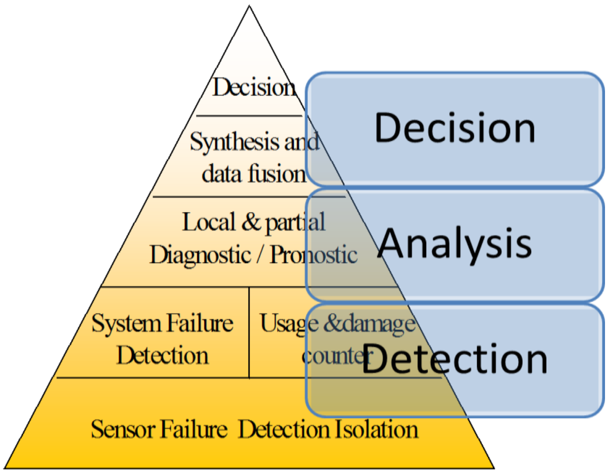

Figure 5 : HMS pyramidal structure

References [3], [4], [6], [8] and [13] illustrate some examples of algorithms dedicated to the failure detection either at sensor level or at subsystem and engine system levels.

The complexity of a HMS system development will depend on the value that will be allowed to 3 main factors:

- **Availability:** The ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided.
- **Reliability:** The ability of an item to perform a required function under given conditions for a given time interval. All parts of the system (hardware, firmware and software) contribute to the reliability.
- **Criticality:** The level of the damaging consequences to the system and to its environments in case of failure: risk of people casualty, loss of mission, damages to the ground facilities, etc.

To obtain a perfect HMS system without failures, the availability of the HMS system must be close to 100%, the reliability close to 100% and the criticality must be null. Of course no system could function without potential failures because the MTBF[1] of the hardware board, which contains the software code, is not infinite. The electronic components might have some failures (ageing or stress of component particularly in space environment) that might decrease the availability of the System.

[1] Mean Time Between Failures. MTBF is a measure of how reliable a product is. MTBF is usually given in units of hours; the higher the MTBF, the more reliable the product is. MTBF = MTTF + MTTR

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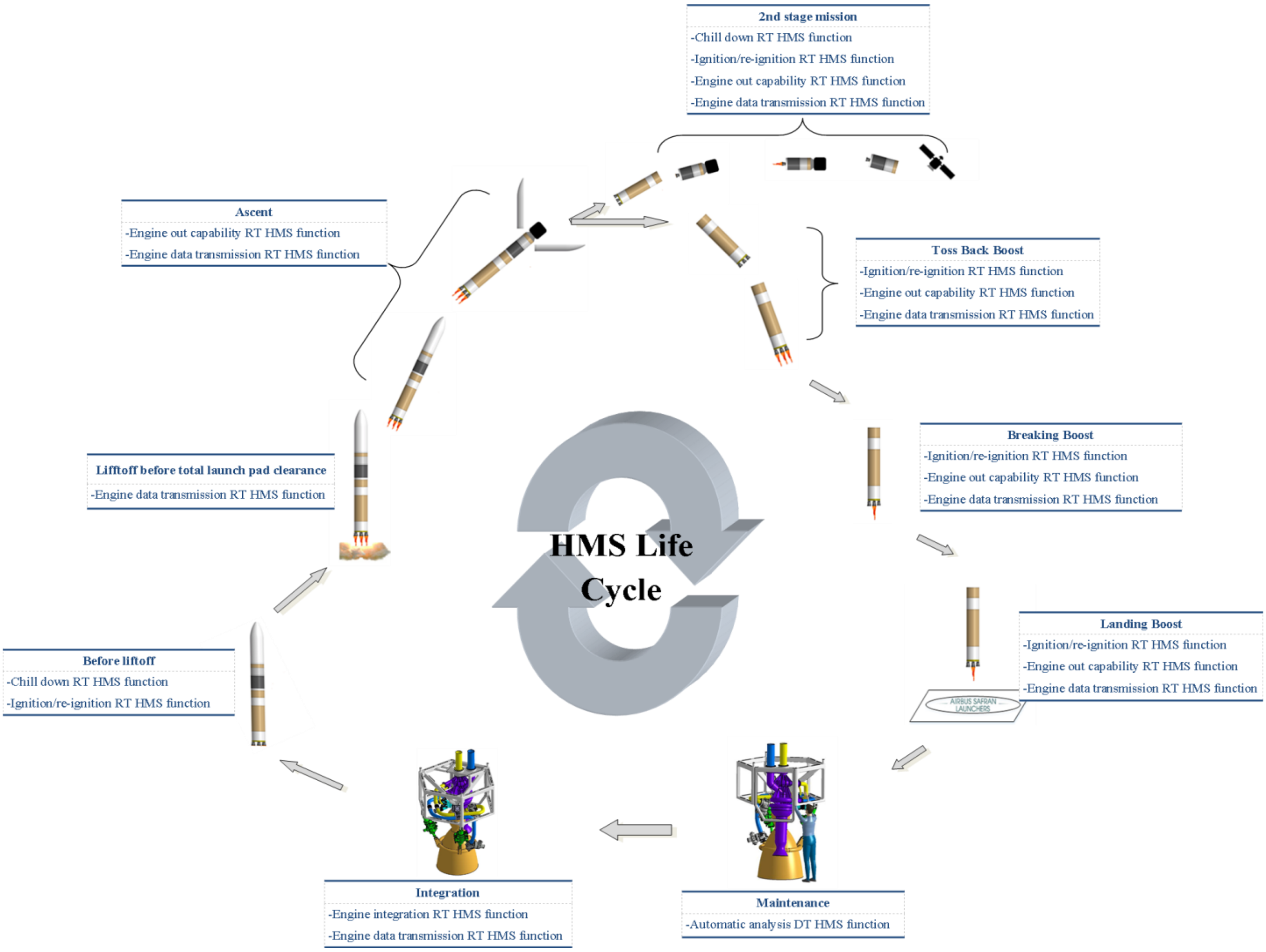

Figure 6 : The ON or OFF line HMS location according to the flight phase

5.2 Actions

The action can take different forms and be dependent on the system to be controlled. For example we can note:

- system shut-down
- reconfiguration of the system (using the hard redundancy)
- parameter adaptation of the control law
- accommodation (modification of the control law structure)
- new target of the system functioning
- adjustment of the operability threshold
- maintenance action

These strategies will be proposed based on system FMECA and in accordance with the overall launcher safety philosophy.

In any cases the HMS activities will consist in evaluating:

- Abnormal behaviour with its level (fault, damage, defect)
- System/Sub-system impacted
- Criticality
- Severity
- Probability
- Symptom

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HMS activities shall then also drive the design based on:

- Best location for detection
- Sensor used
- Algorithm(s) chosen

The automatic and manual checks, helped by an expert system, should alert the maintenance team for either complementary tests or for exchange of any equipment.

5.3 The Health - Control Interaction

Based on generic architecture of HMS-Control, the following figure provides an overview of a typical interaction:

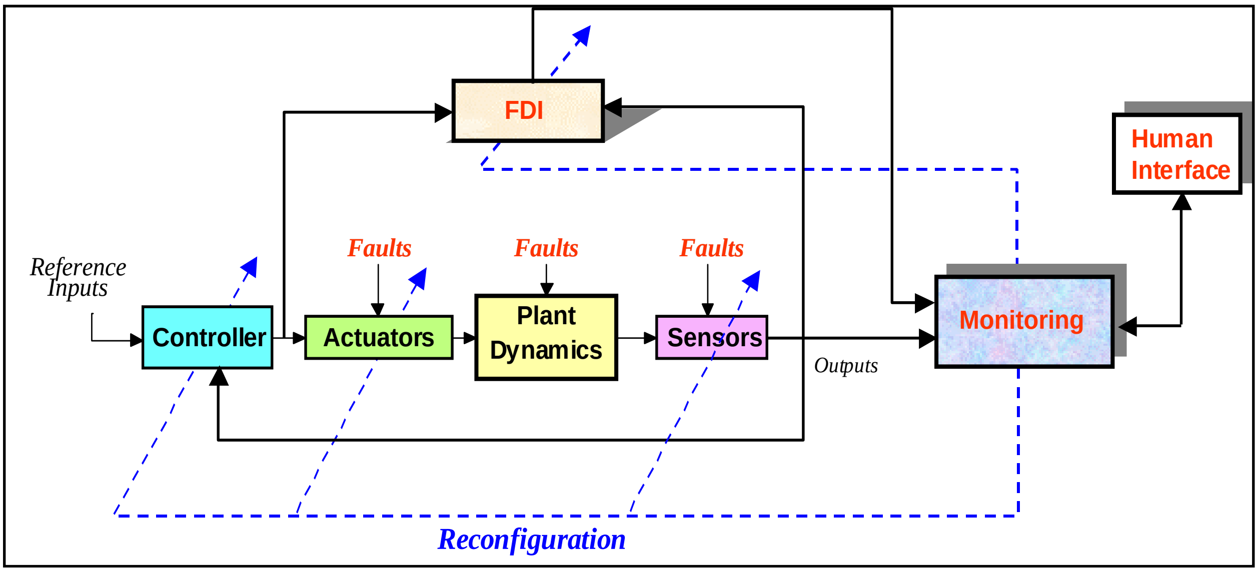

Figure 7 : General Fault Tolerant Control structure

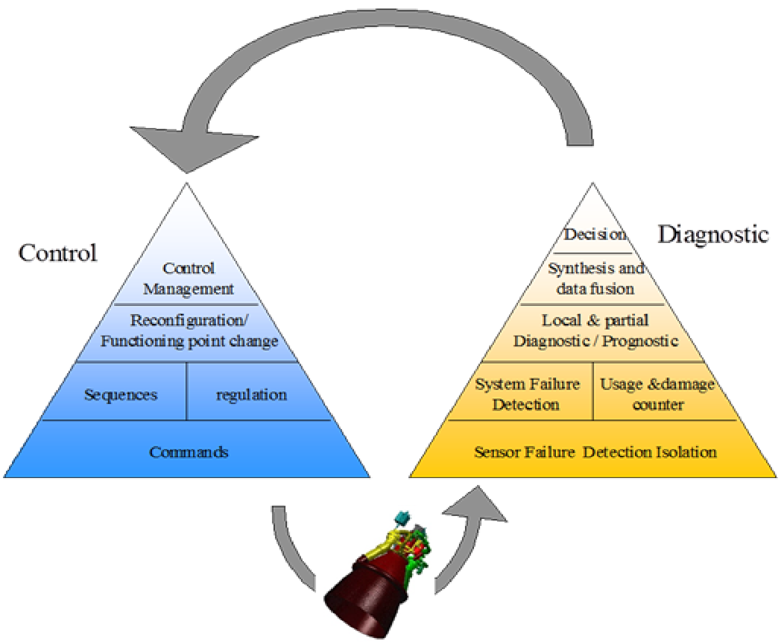

Figure 8 : HCI Pyramidal representation

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HCI general functioning description

The propulsion system is composed of N identical engines. Each engine uses a computer called Rocket Engine Electronic Controller (REEC), equivalent to the Full Authority Digital Electronic Control (FADEC), well known in aeronautics) in which the "Hybrid Control Law" (sequence and all control loops) and the "Health and Usage Monitoring System" (HUMS) are found.
The REEC takes the decision for its engine and immediately adapts the configuration and/or set point to reach the best ratio reliability/availability. At the same time, a message is transmitted to the launcher HMS (in launcher on-board computer) that, as a super-user adapts the mission profile.

The detailed architecture can be illustrated in the following drawing. General aspects regarding an overview on the automatics domain of application are provided in reference [10] and more details can be available in the document [7].

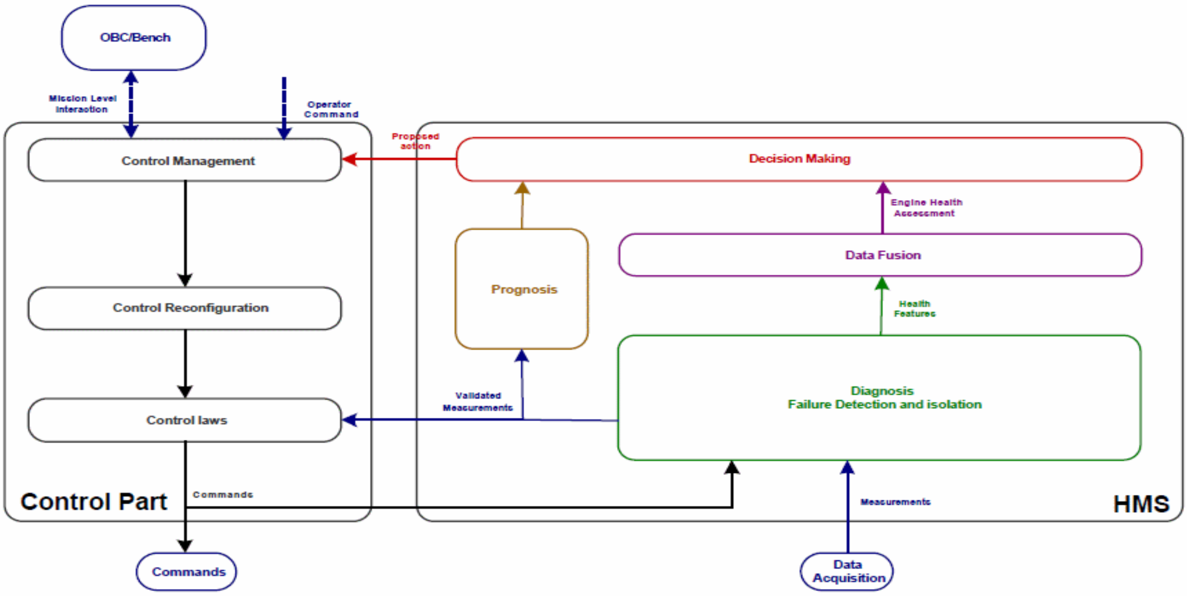

Figure 9 : Example of HCI architecture

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6. Propellant Active Management description

Propellant active management (PAM) is a way to increase launcher performance due to reduction of propellant performance reserves and knowledge of the real loaded propellant mass all along the mission.

In the frame of reusable application, a PAM allows avoiding the overloading in order to warranty the appropriate quantity of filling. Nevertheless the major efficiency is based on two encapsulated layers.

The first is the engine closed-loop (cf. § 4), and the second is the mixture ratio adaptation using the tank level measurement (discrete or continuous) combined with tank pressure and temperature, acceleration and attitude.

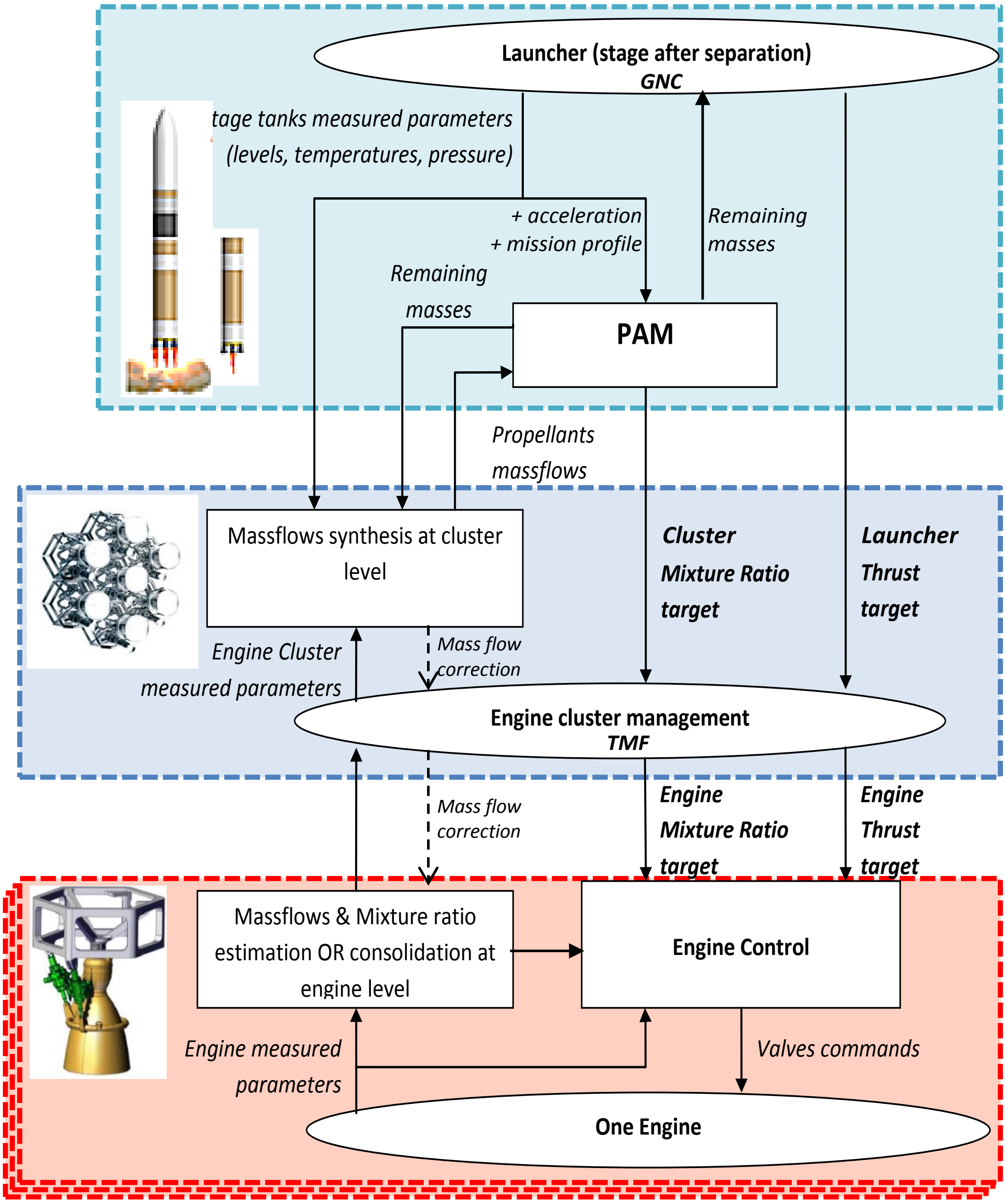

Figure 10 : Overall PAM architecture

Each engine of the cluster is responsible for providing the cluster management function with its consumed propellant mass flow, measured and consolidated at engine level. Through appropriate fusion filter algorithms, the PAM function at cluster level is then in charge of combining the elementary engines flows with discrete or continuous tank level measurements in order to continuously maintaining the best real-time estimate of the propellants mass remaining in tanks. Based on this knowledge, PAM shall adapt the cluster global mixture ratio target for optimizing the inter-tank depletion.

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7. Overall thrust vector control of engine cluster

During propelled phases, the vehicle attitude control is mainly achieved through the deflection of the total thrust of the engines.

7.1 Overall thrust vector control architecture

Basically, total thrust deflection can be achieved by two kinds of actuation: engine gimballing and differential thrust level adjustment between engines. At a first glance, allowing a bidirectional gimballing of every engine looks an expensive over actuated control solution but looking at it more carefully (the number of ignited engines changes over flight phases, RAMS considerations…) it appears not that easy to simplify this architecture. First, in terms of functional performances, the control means are not equivalent. Notably, the bandwidth of the control means are different: thrust level adjustment bandwidth is limited by the inertia of the feed pumps whereas engine deflection bandwidth can be scaled in a wider range. Moreover, from economical viewpoint, reusable launch vehicles increase the return on investment of actuators and there is an interest to minimize the number of engine configurations.
Finally, a full bidirectional gimballing of every engine is proposed as baseline architecture even if it is indeed strongly over actuated during some flight phases.

7.2 Main objectives under nominal conditions

Overall thrust vector control is required to fulfil two needs at launcher attitude control level: static torques balance and dynamic attitude control.
Most commonly, the last need can be derived into a dynamic deflection / deflection rate trade and the TVC required deflection need is the sum of the static torques balance deflection need and the dynamic deflection need. Here the static balance need could possibly be addressed by differential thrust and dynamic deflection by engine gimballing in order to optimize the power resources sizing.
In addition to attitude control, launcher guidance defines a total thrust set-point.
Globally, launcher trajectory and attitude control loops define a global thrust torque to be applied by the cluster. The overall thrust vector control aims at distributing the thrust torque among the numerous actuation degrees of freedom. There are many possibilities and one shall add some extra criteria in order to define univocally the actuators set-points (engine thrust and gimballing actuators elongation set-points).

7.3 RAMS considerations

Multiplying the number of engines ineluctably increases the complexity and hence decreases the overall reliability. This issue must be addressed at least in a quantitative way. Moreover, the safety issue of a reusable launcher is not limited to the take-off phase as landing is a risky phase to be tackled as well.
The main questioning here is to assess if the intrinsic robustness of the cluster architecture is sufficient to deal with or if local redundancies have to be added in the design. Typical questions are: Shall the design be compliant with the loss of one engine during launch phase, during landing phase...? Shall the design be compliant with the loss of the gimballing of one engine? Is it possible to reroute the launcher during landing in case of anomaly?

To cope with anomalies, mitigation strategies can be implemented at different levels: locally at hardware level or more globally at cluster level or even at launcher level. If guidance loop is indeed aware of some limitation concerning total thrust, the trajectory could be adapted to some extent in order to fulfil mission objectives or to minimize mission objectives degradation while satisfying the limitation. Likewise, if the attitude control loop is aware of some total thrust deflection limitation, it could be to some extent counterbalanced by the use of additional control means depending on the flight phase (aerodynamic torque or Roll Control System thrusters). So, in addition to the main function of distributing the torque set-point among actuators, overall thrust vector control may also conversely define dynamically the accessible torque domain towards GNC.

Notwithstanding, whatever the mitigation strategy, propagation of an anomaly must be avoided, and this may require specific hardware design.

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7.4 Functional organization

The propulsive cluster management function shall be responsible for computing the appropriate repartition, for each engine, between thrust magnitude command and thrust orientation command, taking also into account the eventual degraded situations (one or more engines in reduced thrust mode or shut-down for instance).

8. Electrical system architecture

8.1 Context

The extraordinary progress of electronics integration and software design of the past decade pushes strongly the electrification of the rocket engines design. Aeronautics world has already crossed the frontier with the well-known "FADEC".
Moreover, the market of space launcher is living a revolution with the apparition of newcomers all over the world. The competition imposes huge R&T efforts. The improvement of the electrical/avionics devices is one of the key topics allowing enhancement of the existing rocket engine design. Ariane Group, in the frame of the Ariane6 new launcher development, works on it and some on-board engine control technologies are already used.

For example, the by-pass valves of the Vinci engine are electrically actuated. Another example remains in the ETID demonstration engine which integrates only electrically actuated valves managed by an electronic controller deported on ground.

8.2 Engine Electrical System Overview

For liquid propulsive engines, the operating point (thrust and mixture ratio) is tuned by managing the propellants flows, at several places in the engine lines and components. Embedded equipment is spread all over the engine and allows managing these propellants flows, which depend on targeted thrust and mixture ratio on one hand and current thrust and mixture ratio on the other hand.

Consequently, the electrical system of the engine shall fulfill the two mains functions:

F1. To control the flows of the propellants at several key places of the engine
F2. To observe the current operating point of the engine

F1 is performed by moving valves (the valves are placed on strategic engine propellant lines).
F2 is performed by measuring some physical behavior at strategic places on the engine, using dedicated sensors.

Of course, additional peripheral functions are required to control the engine.
In the scope of a full electrical engine, the valves are composed of electrical actuators and the engine integrates an embedded controller which performs: the measures interpretation (coming from the sensors), the control law and HMS software, the valves commands and the communication with the launcher.

Reference [9] provides a view on recent activities dedicated to the full electric rocket engine.

In any case, a specific entity is in charge of the engine behavior. For example, it could be the launcher on-board controller in a flight configuration or the bench control system in an on-ground configuration. This managing entity is called ULA, standing for Upper Level Authority. Thus, an electrical communication link between the engine and the ULA is required.

8.3 Electrical System Composition

Here are the main engine electrical system components:

- The valves electrical actuators
- The electro-valves actuators
- The sensors
- The REEC
- The harnesses

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8.3.1 Focus on the electrical actuators

Placed on the propellant lines, the valves allow tuning the flow of liquid. The flow is controlled with a range of angles from opening position to closed position. The valves are actuated by the electrical actuator integrated in it and which converts the electrical power into a mechanical power (move).

Several technologies exist for the electrical actuators. The most common is the Permanent Magnet Synchronous Motor (PMSM) because it is cheap, robust and easy to integrate. The PMSM control logic requires a high level of calculation performance.

To control the valves, the embedded intelligence needs the information of the valve position. Thus, the valve integrates a system to measure its position. Two technologies are commonly used: the resolvers or the inductive sensors.

8.3.2 Focus on the REEC

The REEC gathers the hardware components
A functional analysis of the REEC is given below:

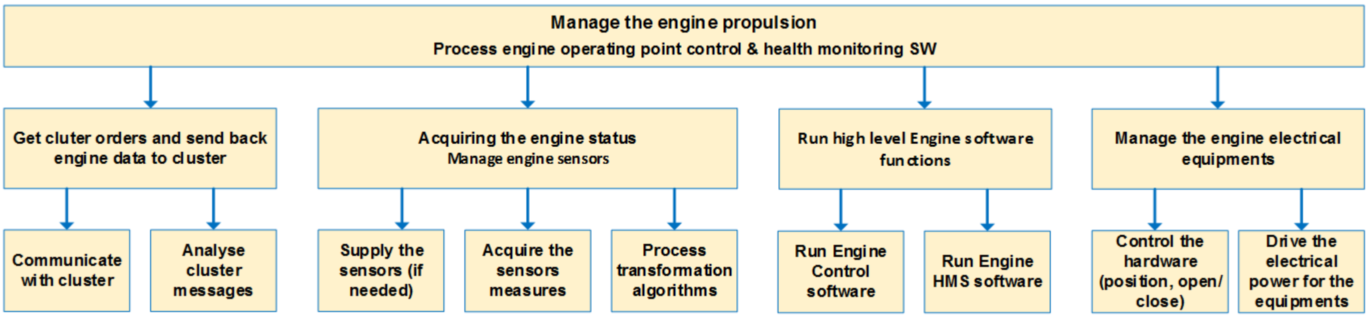

Figure 11 : Functional analysis of the REEC

8.4 Fault Tolerance applied to the Electrical System

Different architecture solutions exist in order to make the electrical system meeting the reliability requirement. Nowadays, most of the launchers' electrical systems keep relying on the redundancy of each subsystem (communication busses, computers, power electronics, electrical motors, etc.) in order to ensure a Fail Operational behavior, even if it wouldn't mandatorily be applied considering the effective reliability contribution of each part.

Trade-off of such systems with a heavy low-cost driver shall be performed considering a better estimation of each fault probability, in order to choose the cheapest strategies at each level:

- No redundancy due to sufficiently robust intrinsic design
- Hot redundancy (without switching time): several identical software entities running simultaneously on different processors or hearts or computers, 2 electrical motors mechanically linked to a same valve, several sensors providing the same physical parameter, etc.
- Cold redundancy (with a switching logic asking more or less time depending on the function)
- Presence or not of a voting independent function, for choosing the best channel in case of failure

The main criteria of such a trade-off are: impact on the global reliability, availability and maintainability, performance, recurring cost and the engine autonomy. This last criterion is of most importance as it indicates how the engine is autonomous during all its life: integration, progressive tests, flight and maintenance. For instance, studies have already shown that the REEC shall be linked to its own engine, so as the data regarding its life and damage status will follow it all along its manufacturing, testing, flight and maintenance before another cycle.

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8.5 Cluster Opportunity for Engine Electrical System

The fact that several engines are simultaneously present in the cluster allows the eventual sharing of some functions. In particular, a patent was issued by ArianeGroup, Vernon premises, proposing that each engine control software code shall be run by two or three other computers owning to neighbor engines. This would allow avoiding the redundancy of each computer, using the others as back-up devices running the same software. This is possible thanks to the cluster data busses linking all the computers together.

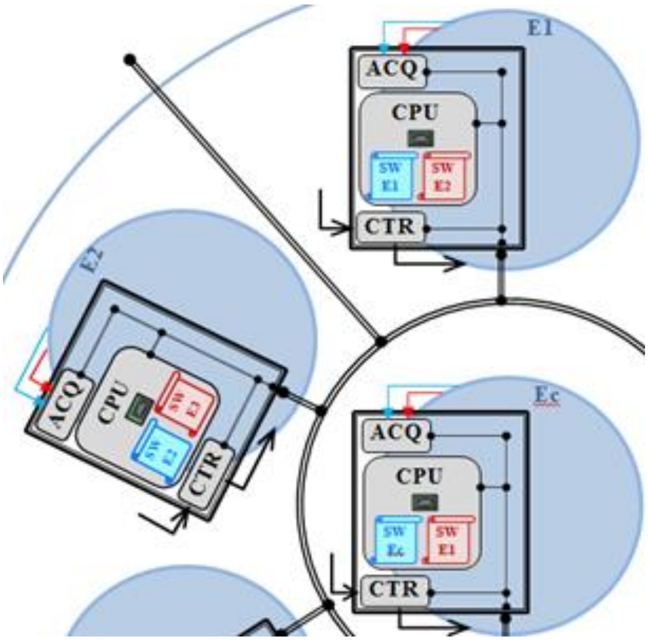

Figure 12 : Illustration of CPU sharing between different engines for a cheaper redundancy

This sharing positive effect on tolerant architecture simplification shall be studied with respect to other sub-systems of the electrical system, like for the power supply devices for instance.

9. Concept evaluation and tests means

The complexity of the overall system imposes specific means, particularly in the automatic and electrical frames.
That is the reason why the hybrid test bench, also named HIL test bench, will be used.
Configuration of such a system will allow simulating the hydraulic torque effects applied on valves and actuators, the gimballing dynamics, the flight trajectory and fluid dynamics in front of the algorithms, while progressively introducing some real devices in the loop.

This test bench means will allow validating:

- Each software components and their reactions in front of engine cluster behaviour
  - Control (every control loop)
  - Health monitoring reaction
  - Reconfiguration
  - Propellant active management

- Overall closed loop behaviour using all electrical parts:
  - Actuators
  - Rocket Electronic Engine Controllers
  - Cluster Management
  - Cabling and power supply
  - Instrumentation

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In order to be efficient, this test bench will have the ability to simulate at least:
- Torque reaction
- Sensor values
- Failure cases

This type of test facility already exists, even if necessitating some adaptations, at launcher level (FTF platform at Les Mureaux premises) as well as at engine and stage level (ISFM at Vernon premises, [14]).

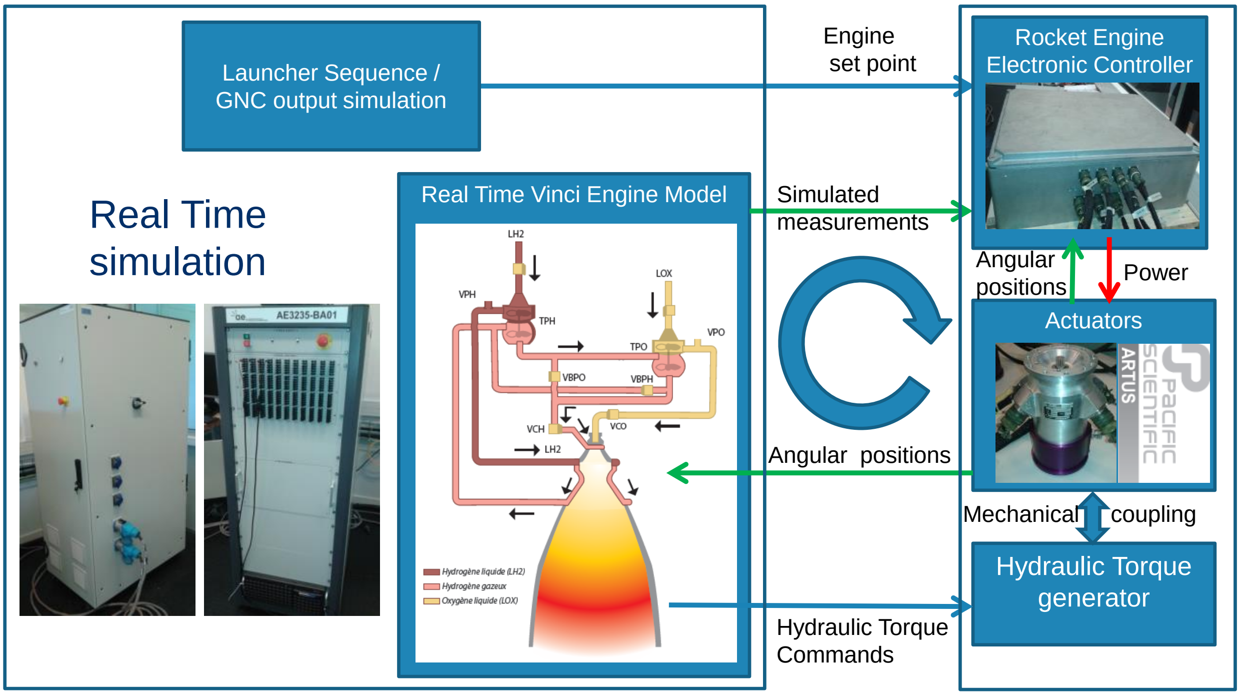

Figure 13 **: ISFM test bench simplified view (Vernon premises)**

In the frame of health monitoring system, particular platforms shall be used with enhanced real-time capabilities and a faculty to help maturation of complex HMS algorithms and architectures before integration in target flight hardware. Such a mean, called DIADEM, has already been designed in the frame of FLPP program and used in hot firing Vinci test environment (see reference [5]).

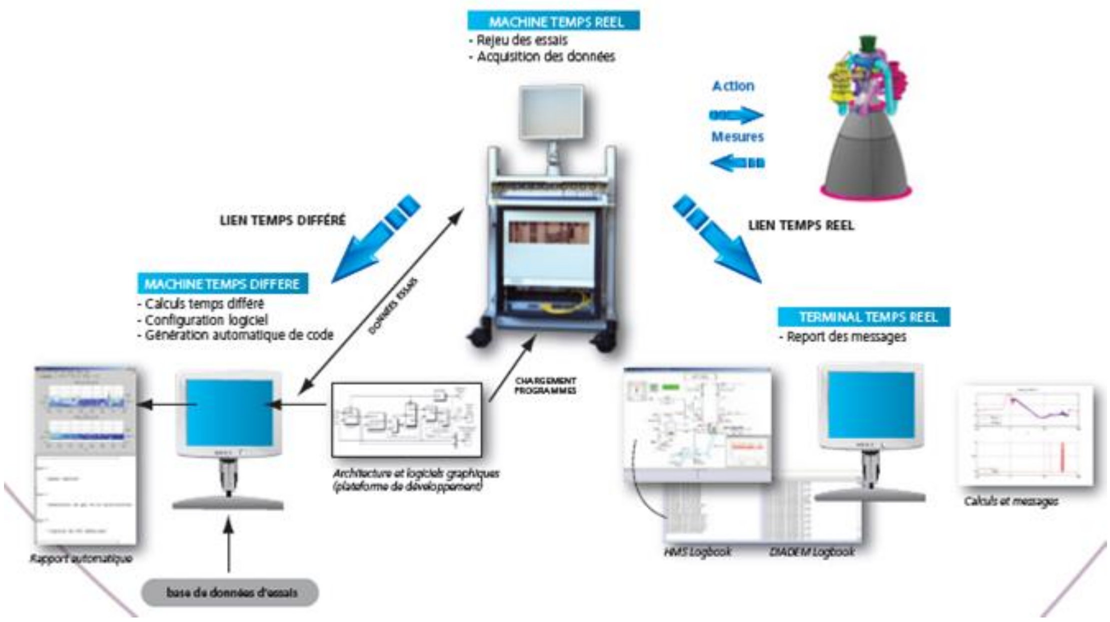

Figure 14 **: DIADEM, test facility for training of complex HMS algorithms in real time**

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10. Conclusion

Engine cluster analysis is currently in progress at ArianeGroup. Some reflections dedicated to command and control topics at software and hardware levels are illustrated in the present paper, providing a point of view and highlighting the potential problematics.

These elements will allow performing the R&D road-map for the upcoming years and demonstrate a high imbrication between activities usually considered as more disconnected up to now. For instance, the strong coupling between GNC and Engine Control functions is of primary interest to reach global launcher performances like propellant performance reserves reduction.

An important task will consist in designing an optimal cluster management function particularly in charge of optimally distributing the launcher thrust and torque request between all the engines of the bay and for each of them the adequate repartition between thrust orientation variation (TVC) and thrust magnitude adaptation (ECS), with the goal of minimizing the off-axis propulsion losses and taking into account eventual degraded operation of some rocket engines.

In order to meet the severe low cost, high reliability and availability requirements for reusable systems, major topic should be in the frame of the Health Monitoring and the Health-Control Interaction (also named AFTC), which should be part of a surrounding integrated vehicle health management at launcher level. Its goal is to warranty the success of the mission despite the presence of some faults in the system, through the appropriate recoveries offered by a multi-engine architecture. At least, the system should autonomously be able to choose the reconfiguration minimizing the mission degradation.

Avionics hardware design and optimal fault tolerant architecture at the lowest cost as possible is another challenge to be considered. Opportunities to benefit from a multi-engine cluster and in particular the ability to duplicate same functions on several cheaper standard hardware devices instead of designing more complex intrinsically redounded devices shall be investigated in the frame of upcoming studies.

All these strategies shall be evaluated, validated and finally qualified on specific simulations and test platform means giving the opportunity to mix simulated and real functions. Such facilities already exist in each technical field, at GNC, mission and propulsion level and the upcoming challenge shall consist in merging all these means for full integrated GNC-Propulsion tests.

Finally and in a prospective manner, the high complexity of some algorithms and particularly the treatment of great amount of data, for damage counter evaluation and maintenance optimization, could highlight in the future the possibility to progressively use the data science tools for optimizing processes through the learning of some key parameters along successive flights. These advanced tools are not treated in the present paper but shall not be forgotten in further studies for preparing the future.

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