Health Monitoring of Reuseable Rockets: Basics for Sensor Selection

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Introduction to Health Monitoring for RLV

Considerable efforts are currently being taken worldwide to increase the number of actually reusable subsystems of RLVs. This is associated with new challenges in the field of HM. From the data provided by sensors, the reusability of individual components has to be predicted for the next launch. Only by means of this process, it is possible to achieve functional reliability and cost reduction without having to carry out renewed validation tests for each launch.

Abstract

With regard to the space field, the number of the sensors has grown for a middle-sized spacecraft from more than 500 at the beginning of the twenty-first century [1] to several thousands for nowadays applications. Meanwhile, Reusable Launch Vehicles (RLVs) moved their steps from demonstrators to commercial working systems. As a result, Health Monitoring (HM) is conquered its own space in the field and sensors are the primary elements required for implementing a monitoring unit. The innovative concept of reusable rockets requires, from the point of view of HM implementation, not only the evaluation of the vehicle health status but also the prediction of the reusability of the individual subsystems w.r.t. the next launch cycle. Therefore, the goal of this work is divided in two parts. The former is to identify the most critical points for the development of reusable rockets, focusing on theoretical working conditions and analysis or failures. The latter is to discuss the sensing units useful for addressing the defined points, describing the possible innovative approaches for sensing the system conditions. Among them, piezoelectric units, fiber optics, imaging units, and conductive layers can be identified for enhancing the comprehension of the system working conditions.

Keywords Health monitoring · Sensors · Reusable vehicles · Critical points

1 Introduction to Health Monitoring for RLV

The term RLV stands for a launcher system allowing the re-use of its components, partially or as a whole. The RLV
advantages must not be adversely affected by the HM implementation. These main advantages are [2]:

- Cost reduction: the overall system cost is divided among the number of times the system is re-used;
- High operational readiness level: reusing already qualified components eliminates the need for manufacturing and testing. This is valid also for HM systems;
- Sustainability: reusability may reduce space debris and definitely reduce the resources needed (material, energy, etc.).

For achieving these goals, it is convenient to implement an HM system able to extract and evaluate the data coming from the vehicle.

The main goal of HM is to prevent system failures and, in particular, the ones concerning safety-critical and mission-critical aspects w.r.t. every possible application case, from space launchers to human life [3]. The key functionality in this sense is that every failure can be detected and properly characterized, within a different range, using the right strategy, instrumentation, and model. The ideal achievement of an HM system would be to contribute to the design of a system with low failure rates and easy maintenance in a context of high operational availability.

For doing what mentioned, it is necessary to understand the most interesting application case and the sensor technologies that can be used. The other part of this work is about these goals.

## 2 Critical Points for Reusable Launchers

In this chapter, the main criticalities related to the development of the reusable launchers w.r.t. HM are presented. First, a theoretical analysis of the launcher is promoted for outlining the references for the sensors selection. Then, the principal launcher failures that occurred in the last years have been investigated for defining a real-case scenario and adding further information.

### 2.1 Challenges for RLVs: Important Functionalities to be Monitored

Considering the reusability, there are several differences w.r.t. a standard launch. For this reason, the analysis of the reusable mission-critical aspects [4, 5] is presented. Some of the presented points can also be referred to Expandable Launch vehicles (ELVs) given that the two typologies share several aspects.

For simplifying the analysis, just the Vertical Take-off and Vertical Landing (VTVL) is evaluated among the different possible configurations of the reusable vehicles, because considered the most promising one in the near future from the point of view of market development [5]. A VTVL RLV mission can be split into four main phases: the ascent phase, a large change of attitude in ballistic mode followed by a boost to modify the velocity vector to prepare the effective re-entry, the follow-up ballistic re-entry phase, and the boosted landing. These phases involve environmental conditions which have to be considered for HM too [6]:

- High uncertainty: design assumptions and approximations in the vehicle bring to a relatively high level of uncertainties;
- Fast dynamics: during the re-entry phase, the velocity of the vehicle changes significantly, from above Mach 20 to about Mach 2 and rapid changes of attitude are also presented;
- Non-linearity: given the huge impact of the aerodynamic moments on the vehicle during the re-entry phase, the related motion study presents an outstanding number of non-linearities.

Considering what was described, the most critical aspects related to the RLVs can be described below. They can be used for distinguishing between HM for monitoring the functionalities of a system and HM for predicting reusability for the next launch. Some of the main criticalities are:

- Structures and Thermal Protection System (TPS) [7]: during missions occur mechanical vibration, shock and acoustically induced loads, thermal-induced loads due to atmospheric friction during launch and re-entry, different heat transport mechanisms in the vacuum and flow regimes;
- Stage separation [8]: the process of stage separation is critical in terms of stresses the structures and the electronic components have to withstand. In case the system has to support multiple separations, during a certain number of missions, the sum of the stresses have to be carefully monitored for avoiding sudden and hazardous ruptures of the system;
- Aerodynamic surfaces deployment and positioning [6]: during the non-propelled section of the re-entry phase, the aerodynamic surfaces have a prominent role in the management of the system control. Deployment timing and position management are two fundamental aspects related to these structures;
- Flush Air Data System (FADS) [6, 9]: it promotes the definition of the right moment in which to initiate a defined mission action. It is usually positioned on the launcher nose cap and it gives information about the pressure distribution related to the angle of attack, Mach number, the angle of sideslip, etc.;
• Navigation systems [4]: for being able to land the system in a precise location (such as on the surface of a ship), the navigation system has to be very precise, especially during the re-entry phase to define the correct re-entry corridor. Consequently, advanced methods such as Hybrid Navigation Systems (HNS) can be used. In this case, inertial units are combined with non-inertial units such as Global Navigation Satellite System (GNSS) and Differential Global Positioning System (DGPS) to improve the positioning performances;

• Multiple re-ignitions [4]: various ignitions are usually required and different engine throttling percentages are necessary for improving the management accuracy of the system. Consequently, accurate control of the propulsion system is fundamental. In this sense, considering the related stresses due also to transitory phase of re-ignition and re-use, the degradation of the valves, sensors and thrust chambers can be critical as well;

• Sloshing and other dynamic propellant effects [8]: they are related to the rapid attitude change the system faces up during the change of attitude phase. Consequently, accurate analysis of propellant dynamics is important for ensuring the proper system functioning;

• Cryogenic tanks [7, 10]: considering the negative effect of the cryogenic tanks on the total system thermal balance, these structures are considered as critical points. This has to be considered in particular also during the refurbishment phase;

• Approach and Landing System (ALS) [8]: during landing phase, various effects are considered at the same time. These are: the precision of the landing procedures to ensure the system safety and reusability; a precise time deployment; the landing approach position tracking, and the absorption of residual kinetic energy derived from the re-entry phase.

To reduce the time between two missions, the human failure rate and the unexpected loss of vehicles are considered. The health monitoring implementation can also be used for automatic validation and verification processes.

Also, the transportation from and to the launch pad has to be considered. This phase is one of the main contributors to the structure’s high-cycle and low-amplitude vibrations.

The report from Paul Birkeland et al. [11] presents a set of possible criticalities related to reusable launch vehicles and an overview of the principal failure modes related to a generic RLV.

### 2.2 Failure Analysis from the Past Years

Together with the theoretical analysis of which are the main critical points for the RLVs, it is interesting to evaluate the launch failures verified in the past years with the scope of evaluating which are the primary limitations to overcome for improving the launchers safeness and effectiveness. The majority of the described failure data refer to the ascent phase because of the higher number of expandable launchers w.r.t the reusable ones that flow in the last years. In addition, the data which are possible to extract from specialist/informative reports regarding launch failures are in most of the cases just referred to as catastrophic conditions bringing to the complete loss of mission. This is because the minor and negligible failure situations are usually not visible from the outside. Consequently, what is presented in the next lines is just a glimpse of the total amount of failures that the sensing subsystem had to analyze during the various missions. Defined the framework through which discussing the failures, it is possible to discuss the data about the launch failures occurred in the last years [11–13]. Considering the period between 2006 and 2020, 72 failures have been reported out of a total of 1282 launches, and among them, 20 failures’ causes are unknown (about 28% of the total failure number). These data could present either a lack of openly shared information or a lack of sensing capabilities. Neglected the unknown failures, the distribution of the faulty cases is the following:

- about 53% related to the propulsion system (about 28 launches);
- about 23% related to GNC and AOCS;
- about 16% referred to as stage separation system.

Referring to the report proposed by FAA [14], presenting the failures of the expandable vehicle between 1957 and 2007, it is possible to denote similar statistical values than the reported ones, showing that the main of the failures are still not referred to the reusable vehicles.

Deepening the propulsion system failures, the following distribution has been identified [13]:

- about 41% of failures is referred to the feeding system;
- about 14% is related to the structure of the pipes;
- about 9% is referred to the thrust chambers;
- about 9% is related to the structures.

In terms of reusable launchers, the following failures were described [12, 13]:

- Space X Falcon 9:
  - Oxygen tank damaged by a bolt suffering material/insulation defect;
  - engine defects (at least 3).

- RocketLab Electron:
  - Telemetry problems;
Electronic connections in the upper stage.

- Virgin Orbit LauncherOne:
  - Issues in the propellant feed line.

From the analysis of the available data, it is possible to extract the most critical aspects to improve the reliability of the launcher vehicles in general.

2.3 Summary from the Analysis of the Points to be Addressed

The discussion in this chapter only allows a vague statement about which are the most critical factors to be considered because of the limited data available. Even if these cannot be considered conclusive, the following points have been underlined:

- Propulsion system: in particular feeding lines, valves, turbo-pumps, thrust chamber;
- GNC and AOCS: electronic interfacing between components and sensors as well as the accuracy of the related sensing system;
- Structures: debris/external bodies impact, mechanical and thermal loads;
- Electronic connections: human failures and environmental factors;
- Staging system: electronic components and separation units.

An interesting point to be taken into account is that, traditionally, about 50% of the whole sensors were related to temperature and about 30% to electrical component evaluation (such as voltage measuring units, etc.) [1]. Even if it has not been possible to find a trustable source for the actual situation, it is possible to presume that temperature and self-analysis are still two of the main points to be addressed.

Selecting other sensors that could gain more attention in the establishment of HM solutions for reusable rockets, the structural analysis could be one of the principal points to be addressed. The structures require a solid way to be monitored for extracting precious parameters in terms of the impact of external bodies as well as the usage degradation and environmental conditions withstanding. The propulsion system is also a crucial element for determining a reliable system. If not working as intended, the vehicle is not able to conclude successfully the mission. Moreover, all the sensors related to the aerodynamic surfaces and the stage separation could be improved for allowing more precise management of the launcher management and positioning FADS. Concluding, the electronic interconnections subject to harsh environment require an automated evaluation system for establishing the health state.

### 3 Classical Sensing Methodologies for Launch Vehicles

Considering a more general point of view than the sole reusable vehicles, the main sensing typologies applied to the various subsystems of launcher vehicle w.r.t. the HM implementation are listed below [15, 16]. This part is useful for defining the context upon which the innovative sensing units selection is structured.

Regarding the propulsion system, it is possible to define the following blocks:

- Combustion chamber:
  - Evaluation of the working conditions of all engines as well as verification of the chamber health condition: mainly temperature and pressure sensors;
  - Evaluation of the working conditions concerning the combustion: flow and flow dynamic sensors;
  - Analysis of wall grain regression: resistive wires inserted into the wall structure.

- Feed system:
  - Evaluation of the working conditions and avoidance of cavitations in pump feeding systems: temperature and pressure sensors;
  - Evaluation of the flow of fluids toward the thrust chamber: flow sensors;
  - Analysis the state of the valves and turbopumps (in pump feeding systems): pressure, position, and flow sensors;

- Tanks:
  - Analysis of the working conditions as well as the level of fuel and the health status: load cells, pressure, and temperature sensors;

Considering then the structures, it is possible to define:

- Analysis of thermo-aerodynamic effects and reciprocal displacement of the structural elements: pressure, position and temperature, and strain sensors;
- Evaluation of the degradation of joining parts (such as bolts): pressure, position, strain sensors, as well as smart painting.

Concerning the Attitude and Orbit Control System (AOCS) and the Guidance, Navigation and Control (GNC), it is possible to identify:

- Analysis of thermo-aerodynamic effects and reciprocal displacement of the structural elements: pressure, position and temperature, and strain sensors;
- Evolution of avionics and navigation system positioning: navigation systems (GPS/GALILEO/GLONASS) and position sensors. With also regards to the payload,
additional sensing elements are added: star trackers, sun sensors, horizon sensors, and magnetometers;
• Management of the reaction control system: reaction wheels for the mission phases under microgravity, mag-
netotorquers, and position sensors;
• Management of the thrust vector control: gimbal posi-
tioning sensors in addition to the standard sensors used for the thrust subsystem;
• Handling the aerodynamic surfaces: position and pres-
sure sensors.

In terms of electronic units, it is possible to evaluate:
• Stage separation: position and (sometimes) temperature sensors as well as magnetometers;
• Power electronic management unit: temperature and cur-
rent/voltage sensing elements;
• Electronic bay: temperature sensors and magnetic field analyzers (sometimes);
• Interconnections: pressure and humidity sensors.

4 Discussion of Selected Sensor Technologies for Application in HM

In this chapter, various sensor technologies are analyzed w.r.t. the selected functions of the launcher and with a per-
spective on their use in HM. Not all functions are included. For functions not listed here, but which have already been dealt with in Chapters 2 and 3, the analysis is planned within the framework of the EU-funded ASCenSiOn project men-
tioned in the introduction. The following parts have been considered:

• cryogenic tanks;
• Structural analysis;
• Wireless modular instrumentation system;
• Sensors for drag monitoring;
• Engine condition analysis;
• Integrated modular avionic;
• Analysis of mechanical connections.

4.1 Cryogenic Tanks

The adoption of cryogenic tanks is promising for the RLVs [10] and in its first phases of application approbation. How-
ever, the potential use of cryogenic tanks and the thermal insulation that would then be required is associated with risks. An HM unit needs to capture insulation issues, potential icing, and associated structural stresses. The following technologies can be considered:

• Imaging techniques [17];
• Wave analysis such as ultrasounds, X-ray backscattering, and terahertz waves [18] approaches to locate and evalu-
ate the damage size and fatigue propagation;
• Temperature variation and gradient analysis techniques [19] to detect the possible presence of the failure;
• Resistance variation analysis [17].

The imaging techniques are expected to perform well if the cameras are applied in a strategic position of the spacecraft w.r.t. insulating foam analysis. Anyway, it is possible to detect the rupture just in relation to the camera sensitiv-
ity. Wave analysis is a widely used technique of damage analysis, but in the case of the foam, the high values of signal attenuation and scattering can represent a problem for the analysis. Moreover, the energy required by the high-
frequency waves (such as terahertz and X-rays required for having high resolution) usually does not allow their application during the operating phases of the mission. The same signal degradation problems also affect the resistance analy-
sis, and consequently, the most suitable way to analyze the foam structure is expected by means of temperature variation investigation. From the authors’ point of view, this approach is quite interesting for the foam analysis because of the high-
temperature gradient caused by damages in the cryogenic insulation. However, the main problem of this technique is that the damage is detected just when the rupture is big enough for causing a consistent variation of the temperature. Even considering the disadvantages, a network of tempera-
ture sensors can be interestingly integrated for monitoring the variation of working and structural conditions of the cryogenic tanks.

4.2 Structural Analysis

The main points to be investigated for the analysis of structural conditions are [3, 20]:

• Pressure, forces, vibration, and shocks present in the dif-
f erent phases of the mission;
• Temperature gradients;
• Impact of possible external parts, especially Micromete-
oroid and Orbital Debris (MMOD);

The combination of all these elements can bring to material properties degradation and even cracks:

• Cracks verification and propagation: this can be a result of mechanical quasi-static loads, dynamic loads, and material fatigue due to environmental conditions (space and atmosphere);
• Repeated impacts [21]: above a threshold of repetitions to be determined, material fatigue, and consequently structural failure can occur.
For analyzing the system, several sensor methodologies can be used (such as fiber optics [22], piezoelectrics [23], pyroelectric devices [17], resistive layers and components, and electromagnetic elements [24]), to measure pressure [17], force, temperature, vibration, shocks, cracks, and material fatigue properties. Piezoelectric and fiber optical sensors are considered in detail hereafter.

### 4.2.1 Piezoelectric Structural Analysis

The following advanced piezoelectric [17, 18] approaches are available for structural analysis [17, 18]:

- **Piezoelectric wafer active sensors (PWASs)** [25]: They are, for example, made out of lead zirconate titanate (PZT) and attached to the surfaces of the structure. The main characteristic is the possibility to apply multiple PWASs to the structure, obtaining an improvement of the waveform because of constructive interfaces;

- **Piezoelectric in phased arrays**: The phased approach is used for being able of tuning in a more precise way the waves. In this case, the wave phase shift among the piezo array parts is able to promote a more accurate constructive interaction among the components, defining a precise frequency selection. Another great feature is the capability to achieve high directionality of analysis by the phases difference;

- **Sol–gel-based piezoceramic element** [26]: the main characteristic of this approach is that the piezo powder is sprayed on the surface, being able to adapt the different structures easier than otherwise. In this way, it is also easier to shape the piezoelectric structure according to the design requirements;

- **Ultrasonic Active Sensor Fiber (UAFS) method**: it is based on applying the wave in a guiding structure such as fibers for having reflection-based modulation analysis. By means of this technique, the signal degradation is notably reduced w.r.t. a typical piezoelectric unit, but the architecture is more complex.

The phased array approach seems to be the most interesting one because of the possibility to modulate the produced excitement wave affecting the structures. However, if the signal degradation or the length of application represents a problem, the last approach has the advantages of relatively large area of coverage. A summary of these methods can be seen in Table 1.

Apart from the described approaches, it is possible also to use hybrid structures combining the piezoelectric elements with other technologies [17, 18]:

- **Adoption of Fiber Optic Sensors (FOS)** [22]: it consists in the combination of a piezoelectric generator and an optical fiber, in which light is transmitted. The principle is that FOS are sensitive to acoustic pressure (fiber polarimeters) or induced strain [Fiber Bragg Grating (FBG) sensing units]. Consequently, by means of the mentioned structure, it is possible to achieve an interesting goal: remote signal analysis in a very effective way, independently of the local structure characteristics. Basically, a light signal is impelled in the FOS, which is attached/ integrated into the structure so as to reach the remote location of analysis. At the application point, a piezoelectric unit operates creating light waves in the FOS and the consequent parametric variations are monitored. The main problem in this case is the limited design flexibility, given that the FOS has to be attached to the structure and just limited bending angles are allowed;

- **Using a laser vibrometer for detection** [23]: basically, this approach is used for being able to monitor wider sections than w.r.t. a standard pulse-echo or pitch-catch piezoelectric approach. The piezo is used as a pulser and a 3D laser vibrometer is used for detailed analysis of the structure response signals. This technique achieves high accuracy but the main issue is that it requires an external laser source for collecting the distributed notes. In this way, this technology can be adopted as improvement during detailed ground analysis;

- **Adopting ultrasonic wave generation by laser** [27]: in this technique, a contrary approach w.r.t. the previous one

| Method of analysis | Main benefit | Main drawback |
|--------------------|--------------|---------------|
| Piezoelectric wafer active sensors (PWASs) | Can be geometrically composed to define different modulations and interactions | Not simple to couple properly |
| Piezoelectric structural array | According to the geometrical distance, it is possible to have positive waves interaction | The geometric placement has to be very precise |
| Piezoelectric in phased arrays | Phase shift increase accuracy of the operation and produce interesting waves interaction | Require a more complex wave excitement programming |
| Sol–gel-based piezoceramic element | Can be sprayed on the structure of interest | Not very accurate |
| Ultrasonic Active Sensor Fiber (UAFS) | Can reach higher area coverage than usual | More complex to be produced and integrated |
is used. Namely, a laser mounted on a rotation stage is used for exciting all the interesting points on a structure and the piezoelectric elements present in the structure are used for catching the related structure response. This allows a wider and/or more accurate analysis in case of ground testing, but it is not really usable by means of an on-board system, because an external testing unit is necessary;

- Using wireless analytical techniques based on microwaves: it consists of a wireless methodology based on inductive and capacitive coupling and microwave structural excitement [18, 24]. It can be integrated with laser solutions or piezoelectric units. The microwave generators are used for injecting energy into a system according to inductive or capacitive interactions. If the energy is modulated according to certain rules, receivers can be used for monitoring the health of the system.

A summary of these hybrid options can be seen in Table 2.

These hybrid/alternative methodologies have been described as options useful for overcoming possible sensing limitations that can be related to the application of the sole piezoelectrics. From the authors’ point of view, all four techniques are interesting. The one based on the FOS can be particularly interesting in the case of resources optimization and multi-channel piezoelectric driver. The other three options are mainly adopted as external monitoring units and they are interesting especially in case the complexity and resources management of the rocket do not allow automatic on-board ground re-validation.

### 4.2.2 Fiber Optic Sensors

As already mentioned in the previous subsection, the Fiber Optic Sensors (FOSs) [22, 28, 29] are useful for monitoring remote areas with relatively low investment and a minimally invasive approach. In fact, they represent an interesting solution also in the circumstance in which it is not possible to directly integrate the electronics near to the point to be sensed. This could be the case if:

- The sensing point working conditions are too extreme for applying the electronic circuits in situ;
- The electronic referring to sensing circuits is limited in a confined area, and consequently, optic fibers are used for better monitoring the working conditions and optimizing the electronic components protection materials distribution and costs;
- It is preferable to use just one sensing system for monitoring various points of the vehicle, reachable with some fiber structures.

In terms of fibers, particular attention should be given to the Fiber Bragg Gratings (FBGs) [29] option, because it is possible to use them for meeting all the previously defined usage cases. This is because of the high application and measuring flexibility. FBGs are characterized by a defined modulation (usually periodic) of the refractive index along their length that can be obtained by UV photoetching. Therefore, it is possible to define at which point of the line, a certain event is originated. The main value that can be measured is related to the strain effects originating from mechanical or temperature deviations in the fiber.

### 4.3 Wireless Modular Instrumentation

In this subsection, a practical implementation of a wireless health monitoring unit investigated by NASA [28] is exemplarily presented. The main purpose was to develop, within the framework of the NASA innovation program, a temperature and structural monitoring unit to be integrated on the space shuttle and the ISS according to the necessities. A space-grade box instrumentation unit is connected to the structure of the vehicle to increase/establish the desired sensing capabilities. Several boxes could be allocated within the system and they are based on wireless communication for establishing a network of devices communicating to a central data logger. Through the various version of it, the main applied sensors were to measure: temperature, pressure, acceleration, strain, acoustic, and structural properties. This example represents a good starting point for the idea of creating a modular ecosystem for system health monitoring. The Wireless Instrumentation System (WIS) [30] was created as a sole component to be integrated into the vehicle.

| Alternative method                  | Main advantage                        | Main disadvantages                  |
|-------------------------------------|---------------------------------------|-------------------------------------|
| Fiber Optic Sensors (FOS)           | Reach remote areas for the analysis   | Interfacement between piezoelectric and FOS |
| Laser vibrometer for detection      | Wide area for response analysis       | Data management is not straightforward |
| Ultrasonic wave generation by laser | Large area of analysis                | High power demand                   |
| Wireless analytical techniques based on microwaves | Large area of analysis               | Several interferences to be considered |
and communicate with external/internal computers. In this sense, the typical architecture of WIS is based on [31]:

- Network communication board: it is used for handing the communication orchestration;
- Digital signal processing board: this is established for having on-board data processing capabilities to transform the signals into semi-meaningful information;
- Front-end data acquisition board: it is used for data manipulation and conditioning;
- Patch or WIP/dipole antenna: it is used for effective communication;
- Battery: the goal is to provide autonomy of operation w.r.t. the main power supply;

Consequently, the WIS can be seen as a complete smart unit being able to operate autonomously and the idea can also be adapted to an already present system wireless vector. For letting the additional units be integrated into the existing network, it is possible to rely on an adaptable network.

A different application case could consist in using the added element as a stand-alone unit able to collect the information and store them until they are read by the operators. This approach consists in considering the unit as a black box just useful for collecting data and the related information can be read after the scientific investigation time frame. However, this option is not preferable given that it is very limited in terms of usability and collection of data. In fact, an operator is required for handling the data collection.

Apart from sensing units, also processing and information storage components can be integrated. In this way, from the authors’ point of view, it is even possible to re-adapt the system to the possible increased resources requirement or for bypassing damaged components without interfering with the vehicle design. That solution could be particularly interesting in the case of human space flights.

### 4.4 Sensors for Drag Monitoring

Pressure and strain sensors can be inserted into the structures to measure the drag effects during atmospheric passage in the ascent phase as well as during re-entry [32]. The results of these sensors are also useful for the evaluation of fatigue effects of the structural materials as well as for subsequent damage assessment. Piezoelectric sensors can be chosen for the defined working conditions using a network approach.

An example of the application of piezoelectric sensors is represented by the FADS of the Indian reusable demonstrator [9]. The pressure sensors on the nose of the vehicle are used to monitor important mission parameters such as Mach number and angle of attack. The data are essential for the GNC subsystem and the navigation system.

### 4.5 Engine Health Monitoring

Together with GNC and structure analysis, engine monitoring represents the most important application for space launchers monitoring [16]. The proper engine working conditions are fundamental for ensuring mission success. In this sense, the term Engine Health Management (EHM) is defined as the part of HM implementation for monitoring, detecting, isolating, predicting trends, and mitigating actions related to engine degradation and possible failures [3]. The concept of EHM was initially developed for ground testing and it has been also applied also during flight operations. The main function is the Module Performance Analysis (MPA). The main sensed aspects are: temperature, pressure of the feeding lines, pressure of the chamber, and strain.

As alternative to the classical sensors, other modules could also be used to further the analysis and support the reusability of the system with a correct safety margin. These could be, for example, ultrasonic sensors [26] to characterize combustion processes and the structures present in the system. Various optical analysis systems [17] are also used to verify the correct performance of the vehicle w.r.t. predefined parameters.

As mentioned earlier, most of the detailed analyses are usually performed during ground tests. However, to effectively assess system reusability, it is important to integrate these types of analyses directly into the vehicle. For example, ultrasonic systems [33] can be used in the operational phases to also obtain more information about the application parameters.

Again, with regard to possible alternative sensor methods, an implementation of optical fibers for integration into the structure could be interesting. These are able to withstand high temperatures. In this sense, vibrations and material degradation can be effectively analyzed with a minimally invasive approach.

A simpler approach than the fibers could be the application of simple wires embedded into the structures or piezoelectrics [25] attached to the external surface of the engine; even if the related accuracy could be very limited. This sensing approach consists in just locating the wires with a U shape (also called crack wires) [16] in the structure for registering a change of electrical resistance when the curved section of the wires is damaged. A typical application of the crack wires is within the investigation of the engine wall/grain regression.

In conclusion, piezoelectric and fiber optic sensors are preferable to increase the detection capabilities even before the material fails. An interesting application case could be to use fiber optics as the U-shaped elements, so simplicity and parameter variations related to the length of the fiber itself are inherited.
4.6 Integrated Modular Avionics: Toward the Modularity of the System

The avionic module is historically the one which the highest sensing system advancement because of its importance for mission success. Consequently, the investigation focus is moved from the sensor units to the sensing methodology, because it is where more advancement is required from the authors’ point of view. In fact, even if the quality levels of the present sensors are high, several mission failed just because of this subsystem [3]. Due to lack of access to data and detailed information in literature, no exact causes can be given. Therefore, possible causes shall be categorized as follows [2]:

- Errors in assembly, integration and test: incorrect connection or placement of sensors;
- Faulty or non-existent self-check for internal sensor errors;
- Inaccuracies in data management and structuring.

The first two points can be addressed by the realization of a subsystem self-checker unit useful for detecting if a certain sensor works properly and that can also be realized at virtual level. In terms of structural organization of the avionic section, instead, it is possible to promote the development of an Integrated Modular Avionics (IMA) [3, 34]. The main goal in this sense is to increase the standardization of the avionic units and to reduce the required resources. Even if the standardization is usually referred to as an increase in resources demand, it is possible to define the following points as references for the investigation:

- Reduction of the devices number and diversity. Having a reduced number of elements can be useful for simplifying the overall system management. In this sense, it is possible to aggregate the units in multi-functional boards. To overcome the reduced number of elements, the collected data could be combined with a theoretical model of the avionics;
- Reduction of the number and length of wires by implementing common busses’ structures. In the case of busses, it is possible to optimize the number of wires and given certain physically limited interconnection pins on a board, this approach can bring to a lower final lines length. A further way to reduce the length and number of the wires could be the establishment of a wireless network.

Moreover, the avionic unit is usually divided into sub-groups and, for instance, four main elements are present in Ariane 5 (based on a federated architecture) [34]:

- Flight controls and management system (SSCV): it contains the main computer and covers the mission-critical parts;
- Telemetry system (SSTM): it collects and send data to the ground station and use them also for internal verification purposes;
- Power line distribution system (SSPE): it manages the power distribution and the related devices’ power management;
- Safety system (SSSA): this module intervenes in case of a catastrophic failure in the system. It is the origin of re-configuration and safe neutralization procedures.

The alternative modular solution proposed in the article from Annighofer Bjorn et al. [34] is based on:

- The division of functionalities in computational (plus storage) and I/O (sensors, actuators, and other elements for management) units. This approach can promote the development of redundancy in an easy and effective way;
- Usage of pre-defined interfaces cabinets to simplify the allocation of functionalities and the interfacing between elements. This can promote the standardization of the system.

From the authors’ point of view, the standardization of the system interfacing is for sure a goal to be pursued. Instead, the separation of the circuit in logical blocks can be useful just in case of a well-defined general approach. Anyway, in the specific case, the standardization is facilitated by the fact that the avionic units are mainly integrated into the same vehicle location. Therefore, a logical division of the resources can be operated limiting the interconnections overhead.

4.7 Electrical Interconnections Analysis

A point to be highlighted in terms of interconnection health analysis is the fact that during standard maintenance procedures, it is usually not possible to check all the interconnections, apart from a very limited set correlated to mission-critical processes [16]. In this way, an autonomous HM system for interconnection monitoring could be a keystone for being able to intervene before the system enters a dangerous state. Discussing methods for promoting the aforementioned analysis, several approaches can be used, both direct and indirect.

To increase the reliability, it is possible to establish the redundancy of the mission-critical lines, so that in case one interconnection gets broken, it is possible to rely on the others. The redundancy can be implemented on the entire “critical line” or just with reference to the interconnections.
Instead, w.r.t. active analytical tools, the main sensing techniques are based on:

- Reflectometry [17]: it is a technique based on the reflection of waves because of the system material characteristics. In this category fits well the already described piezoelectric elements because of their capabilities to impulse and detect the reflected wave;
- Smart electrical coatings [20]: another method, which can be even used in addition to the previous one, is the usage of coatings on the wires and on the interconnections surfaces. The idea is creating a layer of dielectric material, in contact with the interesting part, on which to have a layer of conductive material for not interfering with the interconnection and to be able to work as a simple fuse w.r.t. the interconnection. If there is a breakage in the coating circuit, the interconnection can be considered as faulty. In the case of the wire coating, it would be possible to integrate the analytical element (“fake fuse”) directly inside the original coating paying huge attention to the possible coupling effects on the signal flowing in the line. Another alternative is to simply spray conductive material connected to two terminals. However, in this case, defining a homogeneous and well-defined resistance of the fuse-like component is difficult and intermittent failures (characterized by phases of attachment and detachment) are difficult to detect;
- Smart “visual” coating [3]: it is the same principle of the previous point, but it is based on a simple spray-based material to be deposited on the interconnections and which change its color characteristics when its continuity is interrupted (a failure is present). In this way, autonomous cameras or professionals can visually detect the failure.

A summary of these techniques can be seen in Table 3.

Table 3 Summary of the main techniques for interconnection analysis [3, 16, 34]

| Method of analysis          | Main benefit                                      | Main drawback                               |
|-----------------------------|--------------------------------------------------|---------------------------------------------|
| Reflectometry               | Precise insight of material condition            | More complex than the others               |
| Smart electrical coatings   | Simple and effective also in intermittent failure conditions | It has to cover directly the part of interest |
| Smart “visual” coating      | Simple                                           | It requires further units, usually not very accurate |

5 Perspectives on the Next Steps

The ultimate scope of the work that brought to this paper is the creation of an HM tool for helping the reusable launcher operator to decide about the reusability of the system or subcomponents of it. Consequently, after having evaluated the HM functionalities and requirements, the step confronted in this work is defining the fundamentals, in terms of critical analysis and technologies discussion, useful for defining the basis for the selection of:

- The possible point of analysis w.r.t. the RLVs’ investigation. This is defined according to the critical analysis of the RLVs;
- The most interesting technologies to adopt for the analysis. After selecting the point of application, the most promoting technology of investigation can be defined.

The next planned step is creating the mini-scale application of the selected technologies, according also to the facilities availability. Consequently, HM prognostic methodologies will be investigated for establishing algorithms able to operate on the defined structure.

6 Conclusion

RLVs not only need an HM system to monitor the functions of the individual systems, but also to analyze and make decisions on the re-use of the components for the next launch cycle. Within the EU-funded ASCeNSIon project—among many other aspects of RLVs—the basis for the development of an HM and prognostic tool for reusability will be investigated. Due to the very limited number of RLVs and hardly any publication on them, the critical points were first defined and then possible sensing solutions discussed. This step was important given that when referring to HM, most of the literature does not look into the sensors’ point of view because of focusing on the software side. In the first part of the document, the most promising application points for HM implementation were identified. These points have been addressed considering the prospect of technologies and methodologies from which to start the design of a possible
HM system. In this sense, also some application cases were discussed. From this work, it is clear that the piezoelectric units, fiber optics, imaging units, and conductive layers can be useful for improving the actual understanding of the operating vehicles. After this first investigation about sensors for HM systems, that can be used for a safe prediction of the reusability of systems, the next step is the clear differentiation between sensors useful to ensure the RLV functions and the sensors that are actually necessary for the reusability prediction. From these bases, a prediction tool can then be used to follow up on the decision for use and maintenance of each subsystem for the potential next launch of the rocket.

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