DOI: 10.13009/EUCASS2022-7306
9TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

HEALTH MONITORING FOR RLVS: INTRODUCTION TO ARCHITECTURE SELECTION

Andrea Vennitti[⋆†]*, Tino Schmiel* [⋆]*, Christian Bach* [⋆]*, Martin Tajmar* [⋆]
[⋆]*Technische Universität Dresden,*
01069 Dresden, Germany
andrea.vennitti@tu-dresden.de
[†]Corresponding author

Abstract

Providing an autonomous evaluation of the system health is fundamental for promoting the reusability of Reusable Launch Vehicles (RLVs). The scope of this publication is discussing the architectural choices promoting the creation of a standardized Health Monitoring (HM) architecture. This is done both for defining a basis for a commonly adopted HM architecture and for incentivizing the exchange among researchers regarding the topic. The proposed architecture is hierarchical, distributed and hybrid.

This study is part of the ASCenSIon (Advancing Space Access Capabilities - Reusability and Multiple Satellite Injection) project, an Innovative Training Network (ITN) funded by Horizon 2020.

1. Introduction

Providing an autonomous and reliable assessment of the system's health status is fundamental for promoting RLVs development. One of fundamental aspect of HM is its associated architecture. A standardized architecture can promote an effective failure detection and response[10] and define a substrate facilitating researchers cooperation. Unfortunately, there is not a common concrete structure to be referenced in literature for this scope.

In this paper, the proposed solution is hierarchical, distributed and hybrid. A hierarchical approach[13] is selected for covering both the cases of specific unit and overall system HM, as well as for simplifying the overall system management. Instead, the term "distributed"[4] identifies a system mode in which the processing and sensing capabilities are distributed over the entire system, not being localized on single places. This approach favors the local HM implementation as well as the reduction of workload peaks. Concluding, a hybrid methodology[8] is proposed for optimizing the modularity of the system, without compromising the quality of the data.

The publication is structured according to the following main points. First, the goals of the HM implementation are presented for providing a logical basis on which to structure the work. Secondly, the architectural design alternatives are discussed, highlighting the benefits and drawbacks of each option. The intention of this publication is to propose a common architecture as the basis for a possible HM implementation.

2. Basics of HM in space applications

The key idea of HM is that all systems are subject to defects, occurring at a specific point in time and interesting the whole system or a sub-part of it.[13] The main goal is preventing undesired conditions, with focus on the ones concerning safety-critical and mission-critical aspects.[19] Through HM, the establishment of a system with low failure rates and easy maintenance is possible.

The logical pivots of the HM system are:[10,22]

- Condition monitoring: collects, filters and stores data and information about the system;
- Failure diagnosis: uses the collected data for extracting information highlighting the system's characterizing conditions (distinguished in nominal and non-nominal states);
- Fault prediction: forecasts the more probable future states of the system and the Remaining Useful Life (RUL);
- Failure mitigation/response: mitigates the effects of the failures for operating within the defined safe margins for a minimum defined amount of time or operation steps.

DOI: 10.13009/EUCASS2022-7306

The selected architecture must be composed of units able to cover one or more of the defined points.

Considering the high complexity of RLVs, which requires many development tasks distributed among several contributors, system criteria associated to the HM implementation consist of:[7,13,22]

- Adaptable and modular architecture: the HM module should be compliant to different similar conditions and vehicle structures;
- Retro-adaptive approach to existing architecture: HM functionalities should be integrable also in already existing RLV structures;
- Platform independence: the hardware and software interfacing structure should allow the application of the software solutions independently to the particular underlining hardware. For this approach, a normalized and standardized signal conditioning and conversion methodology is recommended;
- Open knowledge philosophy: for establishing a sustainable progress in terms of HM development, the international space community should structure common guidelines to be followed and open data collections to be shared worldwide to the researchers;
- Scalability: the HM implementation should reconfigure and scale with the system requirements. The system requirements can change during the mission lifecycle;
- Multi-hypothesis handling approach: to effectively identify the working conditions, the system should cover the case of multiple failures originated at the same time.

The HM functionalities can defined according to the ISO13374[10,13,16] protocol, which is composed of:

- Data Acquisition (DA): senses the system behaviour and converts the associated signals into digital format. Data conditioning, cleaning and sensors maintenance processes (such as calibration, reconfiguration) are promoted;
- Data Manipulation (DM): data management is promoted in this section. Data normalization, scaling, reduction, features identification and sensing virtualization are done;
- State Detection (SD): the reasoner useful for detecting "off-nominal" conditions and evaluating the system profiles is present here. Failure detection is usually the first step of the failure diagnosis procedure. At this level, the system can be interfaced with the external world in case the it has to notify as soon as possible the user about possible detected failures;
- Health Assessment (HA): the second step of failure diagnosis is represented by the identification of the mechanisms causing the failures. At this level, the system health status and associated variations are also studied;
- Prognostic Assessment (PA): the other cardinal concept of HM is the failure prognosis. In this step, possible futures states of the system are statistically defined. In addition, the Remaining Useful Life (RUL) value can be evaluated in the system;
- Advisory Generator (AG): the last step of the HM is the failure response. At this level, both the actual system profiles and the prognosted ones are considered for defining the optimal response.

The first two functionalities are usually technology-specific because directly related to the underlying hardware. The other blocks instead can be hardware independent thanks to a standardization procedure operated through the first two steps.[4] W.r.t the defined structure, the HM functionalities aim to create the shortest possible logical closed-loop able to mitigate the possible failure effects.

3. Architectural HM design choices

After having defined the context identifying the HM subsystem, how to structure the HM capabilities in the system has to be defined. Two principal points to be discussed w.r.t. the architecture selection and the HM functionalities distribution are: HM allocation, online versus offline processing.

DOI: 10.13009/EUCASS2022-7306

3.1 HM allocation

Allocation of the HM within the system represents an important step in the system development because the associated methodology selection has direct influence on the transducers, memory and computing units arrangement. The main options are:[25,26]

- System-level implementation. The ideal scope is analyzing the whole system functionalities at the same time and the main outcome is the definition of a high-level health footprint;
- Local implementation based. It is based on a certain part of the system. The scope of this approach is characterizing with the highest possible accuracy a certain behaviour of the system, usually referable to a single main point of interest. In space vehicles, a typical adoption of this approach regards the engines and structures;
- Hierarchical approach. The aim is to define a multi-level insight in the system, moving from an overview to some critical specific aspects. Given the limited resources availability, the related distribution is critical in this case. This approach typically brings to higher engineering workload.

3.2 Online versus Offline processing

The method of information processing can be distinguished in: online or offline.[5,18]

Online means that the processing routines are done in parallel with the overall logical flow of the system processes. Consequently, specific resources must be allocated to the HM design. Because of the contingency of execution w.r.t. the operation, this approach is defined real-time w.r.t. the system timing. As a consequence of real-time operations in multi process environment, threads orchestration is a tricky task. The main advantage of this approach is the real-time availability of the information, making the system as reactive as possible to the eventual failure.

In the offline option, instead, data collection and processing are operated in two different points in time. Also the possibility of off-boarding the processing to other systems (such as the ground stations or satellites) is considered. Data orchestration and power complexity can be scheduled more easily, preventing the formation of resources demand peaks. In case of offline processing, re-using already present devices for reducing the total number of devices and reducing the design complexity is possible. The reduction of processing units is paid off by the increment of memory storage requirement given that the data can not be reduced on the fly. The main disadvantage is that the system is no more able to operate fast failure analyses.

4. Architectural structure design choices

After the two presented methodological concepts, the main aspects to be discussed in terms of architecture implementation are: devices distribution, communication and data management methodology.

4.1 Devices distribution

Components distribution[8,21] can be:

- Centralized: a very limited set of devices represent the core of data management and processing. The main advantage of this approach is the reduced information orchestration while the main drawback is the complexity of data arrangement. With data is meant the sampled signals coming from the sensors while with information is referred the processed data;
- Distributed:[14] a network of components, able to create an inter-related operating mode, are used for data management and processing. The key idea is to decompose the system capabilities in a set of devices distributed on the region of interest. In a distributed approach, data can be processed on-site improving the Signal-to-Noise Ration (SNR) and the readiness of the system. However, information orchestration complexity grows up because the extracted features have to be aggregated and coordinated. The main disadvantage is the increased information orchestration related to synchronization and exchange of data.

DOI: 10.13009/EUCASS2022-7306

4.2 Communication methodologies

How data or information are transmitted in the system. The main alternatives are: wired and wireless communication.

The main advantages of the wired option are:[5,17]

- Power consumption reduction. The power required for data transmission is low w.r.t. the wireless alternative;
- Data reliability and safety increment. A wire represents a confined environment, so data degradation during transmission is minimized;
- Data orchestration simplification. Wireless data transmission requires a more elaborate data pre-processing than the wired counterpart.

The main advantages of the wireless option[1520] are:

- Possible reduction of the system weight. W.r.t. the wired option when the number of communicating devices is high;
- Adaptability to different possible working conditions. Having a wireless communication for a sub-part of the system can allows creating a modular application, activating just the units of interest;
- Facilitated re-configuration. Changing the communication endpoints is much simpler with a wireless configuration rather than with the wired option;
- Simplification of interconnection: it is mainly related to cables interconnection complexity.[17]

5. Architecture selection

Defined the conceptual basis for the decision, the next step is presenting a discussion motivating the effective architectural choices. As an initial warning, clarifying that creating the optimal architecture is generally case specific is important. If engineering workload resources are unbounded and if the goal is to identify the best possible architecture without considering adaptability and the possibility to welcome a common adopted methodology, the way to go may be to optimize as much as possible the HM system w.r.t. the defined vehicle necessities and architecture.

Instead, the idea of this work is to propose common directives for defining the HM architecture and not to present the way to optimize it w.r.t. the vehicle. In this way, a common guideline can guide the architectural decision leading to a simplification of the design and exchange of information with other researches. The goal is thus an 'open-hardware' guideline on which the specific application designers can apply the desired degree of optimization. Thus, the description in this section will focus on the general architecture design point of view, making just some references about where it is possible to optimize. As defined in the introduction, the architecture selection of this work is in favor of a hierarchical, distributed and hybrid HM system.

Along this section, an answer to each of these questions is presented:

- Which is the reference vehicle for the architecture definition?
- Why hierarchical?
- Why distributed?
- Why hybrid?

5.1 Reference system definition

The system considered as a reference for the architectural discussion[6,12,16] is a reusable space vehicle, based on a hierarchical structure. Given that the information derived from tests about RLVs is still poor, both extracting insights from certain locations and a general footprint from system behaviour is the target of the actual HM designs.

DOI: 10.13009/EUCASS2022-7306

5.2 Hierarchical approach

The selected HM capability allocation mode should be hierarchical[1,11] because of the capability of providing coverage of both local and system level conditions happening in the system. The hierarchical configuration matches the intrinsic hierarchical structure of complex systems such as a space vehicles. It can be designed as a net of analytical points able to cooperate for achieving a common goal.

A possible hierarchical structure, from high to low level of hierarchy, can be structured according to:[4,8,9]

- Central unit: this can be the vehicle central computer or an alternative computer representing the highest hierarchical level of the HM implementation. Its role is collecting the high-level information for promoting the highest level of HM diagnosis, prognosis and response selection. Among the three different parts, the prognosis and response are prominent at system level given that they have to take into account, first of all, the system well-being rather than the health of a single part;
- HM Area 1 to Area N: with the term of Area, a logical layer corresponding to a certain set of devices able to gather and process information coming from the lower architectural level as well as transmitting the results to the upper layer is meant. The HM area units can contain some or all the HM functionalities. The number N of the total segments is a flexible value depending on the system decomposition analysis promoted during the early phase of system design;
- Signal Area: the main goal is to aggregate, manipulate and transform the signals collected from the sensing units for extrapolating usable information. This level represents a gate from the raw data, specific to a certain application, to a standardized format;
- Transducer Area: it contains all the sensors and actuators necessary for obtaining the desired failure coverage and system states modification (response). Transducers are application specific and so an optimization step is recommendable.

5.3 Distributed approach

The next decision to be made is about the devices distribution.[13,16] Considering the complexity of a launch vehicle, the distributed alternative is preferable. Being able to process the data in real-time is important for handling in an efficient way most of the defects happening in the system. Also information off-boarding[24] can be used for reaching out more advanced processing systems, being able to extract advanced patterns about the system behaviour or for validating the decisions taken by the integrated HM subsystem. The choice is in favor of a distributed approach because of:[14,18]

- Facilitated inter-relation with the intrinsic hierarchical structure;
- Spreading of the workload. Having a centralized approach usually brings a more complex workload scheduling;
- Prevention of a unique point of failure. Having a single complex device for operating the HM functionalities can be problematic, especially in harsh environments, because defining an HM redundancy approach can be much more difficult;
- Cost of improvement. The cost of a single more performing device is usually lower than a set of devices with total comparable capabilities. Anyway, the cost of adding new capabilities or replacing certain set of skills with a new one is lower when considering a distributed approach;
- Possibility to spread the HM functionalities. Distribution of devices can help separating the HM functionalities along the system. This allows for a more stable and effective design of the HM system.

Talking about how to promote the devices distribution, the key idea is to spread the processing and storage[3,5] along the vehicle according to the requirements of the application case. In this paragraph, a theoretical point of view about distribution is considered. The trend related to this approach is creating networks of devices processing and communicating information for creating an aggregated sets.

Intrinsically related to the devices distribution is the HM functionalities allocation. At transducer level the target is defining how to arrange the processing capabilities useful for standardization.

Then, fault diagnosis has to be allocated.[22,23] Ideally, the diagnosis could be done in a single point close to the transducer level for being able to detect the failure as soon as possible. However, given the need for connecting various information patterns for being able to provide a clear outlook about the system behaviour, different hierarchical levels of diagnosis are preferable. At low level, the key factor for diagnosis is the detection and so, the processing capabilities

DOI: 10.13009/EUCASS2022-7306

can be reduced in favor of the speed of processing. Conversely, going up in the hierarchy, the isolation becomes more and more important because of the necessity to define the failure root analysis and evaluating the correlation of the collected data w.r.t. to other sources of information in the vehicle.

The other fundamental element to allocate is the prognostic element.[2,7] This functionality is usually the one requiring the most advanced processing capabilities for being able to define the overall system trend and the possible future states of the system. Given that the prognostic tool mainly relies on machine learning algorithms, centralizing the execution of the related processes is preferable for limiting the resources consumption. Thus, the primary arrangement of the prognostic tool is close to high system level.

The concluding element in the list of HM functionalities is the failure response.[8] The failure response is usually divided in two main modes: one referring to critical conditions requiring an immediate response and one referred to a condition for which a more relaxed time response can be accepted without causing irreversible effects on the system. W.r.t the first case, to distribute the response capabilities, mainly in the lower part of the hierarchy, is preferable for being able to respond as fast as possible to the failures. In the second case instead, the response formulation is preferable as directly related to the higher level of the HM system hierarchy for taking into account more easily the effects of the prognostic tool.

5.4 Hybrid approach

As discussed in subsection 4.2, wired and wireless are the two main options in terms of system data communication. In terms of communication, both wired and wireless alternatives present their specific advantages and disadvantages,[5,17,24] as it can be seen in subsection 4.2. Considering the complexity and size of a launcher vehicle, the selected option is in favor of an hybrid configuration for leveraging the advantages of both methodologies. Wireless infrastructures may be used locally for letting the sensing units to interact and re-adapt to the operation necessities in an easier way. Instead, the wired connections can be used by means of busses for transporting the data to remote locations w.r.t. the wireless network. The trade-off between wireless and wired application depends on the design constraints and the number of devices to interconnect at a certain level of the system.

W.r.t. the promoted selection, the sensing blocks at transducer level can adopt wireless communication. In the other areas, physically close devices could be arranged as a wireless network while distant units may be connected by wires or busses. In case of a region of the vehicle where different wireless networks are present because of application reasons, the wired option can be beneficial for preventing the addition of further possible disturbing units due to wireless communications mutual interferences.

6. Conclusions

The goal of this work is providing the information useful for discussing about the most promising architecture to be used as a reference by HM space researchers. Having a common architectural infrastructure is crucial for letting the HM researchers to cooperate. For this reason, a baseline is presented and different options have been discussed, motivating why a certain approach could be beneficial for the HM subsystem.

The proposed structure is hierarchical, distributed and hybrid for respecting the intrinsic hierarchy of a space launcher, increasing the system flexibility and optimizing the overall HM performances. The system is hierarchical for allocating the HM functionalities according to the system requirements and respecting the overall space vehicle infrastructure. It is distributed for increasing the modularity and the quality of information w.r.t. a hierarchical system. It is hybrid for leveraging both the advantages of the wireless and wired approaches.

7. Acknowledgments

This study lies within the ASCenSIon (Advancing Space Access Capabilities-Reusability and Multiple Satellite Injection) project, an Innovative Training Network (ITN) funded by the EU Framework Programme for Research and Innovation (Horizon 2020). The related grant agreement is the No 860956.

References

[1] Joseph A. Castrigno, Stephen J. Engel, and Barbara J. Gilmartin. Vehicle health management: Architectures and technologies. *Technology Review Journal*, 03 2006.

[2] Shuo Chang, Limin Gao, and Yi Wang. *A Review of Integrated Vehicle Health Management and Prognostics and Health Management Standards*. IEEE, 2018.

DOI: 10.13009/EUCASS2022-7306

[3] Lee Eccles. The need for smart transducers: an aerospace test and evaluation perspective. *IEEE Instrumentation & Measurement Magazine*, 11(2):23–28, 04 2008.

[4] Tim Felke, George Hadden, David Miller, and Dinkar Mylaraswamy. Architectures for integrated vehicle health management. In *AIAA Infotech@Aerospace 2010*, 04 2010.

[5] Jacob Fraden. Handbook of modern sensors. 2016.

[6] Sylvain Guedron. *RLV Concepts and Experimental Vehicle System Studies: Current Status*. American Institute of Aeronautics and Astronautics, 09 2003.

[7] Ian K Jennions, Octavian Niculita, and Manuel Esperon-Miguez. Integrating ivhm and asset design. *International Journal of Prognostics and Health Management*, 7(28):1–16, 2016.

[8] Stephen B. Johnson, Thomas J. Gormley, Seth S. Kessler, Charles D. Mott, Ann Patterson-Hine, Karl M. Reichard, and Philip A. Scandura. *System health management with aerospace applications*. Wiley, Hoboken, New Jersey, 2011.

[9] T. Laloix K. Etienne, S. Bosse. Prognosis and health monitoring applications in satellite systems. http://cabinnovation.com/sites/default/files/fichiers/HM_ESREL_2013.pdf, 2013. access: 2021-05-13.

[10] K. Keller, D. Wiegand, K. Swearingen, C. Reisig, S. Black, A. Gillis, and M. Vandernoot. An architecture to implement integrated vehicle health management systems. In *IEEE Systems Readiness Technology Conference. (Cat. No.01CH37237)*. IEEE, 2001.

[11] E. Kyle. Space launch report. https://www.spacelaunchreport.com/, 2021. access: 2021-06-12.

[12] Liansheng Liu, Datong Liu, Yujie Zhang, and Yu Peng. Effective sensor selection and data anomaly detection for condition monitoring of aircraft engines. *Sensors*, 16(5):623, 04 2016.

[13] N. Lybeck, J. Coble, M. Tawfik, and L. J. Bond. An assessment of integrated health management (ihm) frameworks. In *3rd International Conference on NPP Life Management (PLiM) for Long Term Operations (LTO)*, 05 2012.

[14] Sarah Malik, Rakeen Rouf, Krzysztof Mazur, and Antonios Kontsos. The industry internet of things (IIoT) as a methodology for autonomous diagnostics in aerospace structural health monitoring. *Aerospace*, 7(5):64, 05 2020.

[15] C. Patnaik and Dr. Prakash. Sensor applications to IVHM in aerospace systems, 2013.

[16] Xinlin Qing, Wenzhuo Li, Yishou Wang, and Hu Sun. Piezoelectric transducer-based structural health monitoring for aircraft applications. *Sensors*, 19(3):545, 01 2019.

[17] Sabooj Ray, Jeba Doss, Sheena Abraham, Pradeep N., and S. Kumar. Wireless data acquisition system for launch vehicles. *Defence Science Journal*, 63(2):186–191, 03 2013.

[18] Sabooj Ray, Sheeja Mathews, Sheena Abraham, N. Pradeep, and P. Vinod. Smart sensors for launch vehicles. *Journal of The Institution of Engineers (India): Series C*, 98(6):771–776, 10 2017.

[19] Karl Reichard, Ed Crow, and Tim Bair. Integrated management of system health in space applications. In *2007 Annual Reliability and Maintainability Symposium*, pages 107–112, 2007.

[20] John Saiz. Nasa mems technology development tim wireless instrumentation projectshigh trl case study, 2005.

[21] Abhinav Saxena, Indranil Roychoudhury, Wei Lin, and Kai Goebel. Towards requirements in systems engineering for aerospace ivhm design. *Proceedings of the AIAA Infotech@ Aerospace*, 08 2013.

[22] Chang Shuo and Wang Yi. *Integrated Vehicle Health Management Technology and Its Applications in Commerical Aviation*. IEEE, 08 2017.

[23] Ashok N. Srivastava, Robert W. Mah, and Claudia Meyer. *Integrated Vehicle Health Management*. National Aeronautics and Space Administration Aeronautics Research Mission Directorate Aviation Safety Program, 2009.

[24] George Studor. Lessons learned jsc micro-wireless instrumentation systems on space shuttle and international space statio. https://pdfs.semanticscholar.org/4347/5ffccc3f8a062f525d747959dad46889f7fa.pdf, 2006. access: 2021-06-12.

DOI: 10.13009/EUCASS2022-7306

[25] Massimo Tipaldi and Bernhard Bruenjes. Spacecraft health monitoring and management systems. *2014 IEEE International Workshop on Metrology for Aerospace, MetroAeroSpace 2014 - Proceedings*, pages 68–72, 05 2014.

[26] Qianwen Xu, Yan Xu, Pengfei Tu, Tianyang Zhao, and Peng Wang. Systematic reliability modeling and evaluation for on-board power systems of more electric aircrafts. *IEEE Transactions on Power Systems*, 34(4):3264–3273, 07 2019.