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Trade Study for the Hardware Design of an AI-Driven Rocket Engine Health Monitoring System: Key Insights and Suggestions

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Abstract

In the framework of the Horizon Europe project called "European iNitiative for Low cost, Innovative & Green High Thrust Engine", new technologies are being developed to be applied on future launch vehicles. One focal technology explored is the incorporation of on-board Health Monitoring Systems (HMS) with the inclusion of artificial intelligence (AI) at a propulsion and launcher level for failure detection and identification (FDI) during its entire mission profile. This paper follows the ongoing trade study process performed for the preliminary design of such a rocket engine health monitoring system (EHMS), including the key design considerations and decisions made. Firstly, different aspects of the high-level architecture are discussed, resulting in establishing a distributed heterogenous system where each EHMS unit monitors a single rocket engine. A brief component trade-off analysis concludes that combinations of "commercial off-the-shelf" (COTS) components could be promising candidates for high performance edge AI inferencing within such an EHMS unit. Finally, the challenges associated with performing the study were raised, namely the difficulty in assessing the validity of COTS components for space applications and the lack of test datasets for evaluating space AI applications.

Keywords: *Engine health management, Health monitoring systems, Fault detection and isolation, Embedded systems, ENLIGHTEN*

1. Introduction

With the upcoming development of a new generation of launch vehicles, Europe is currently seeking disruptive technologies to make their launch vehicle market more competitive. One particularly sought-after feature is booster reusability. Rocket engines are generally the most complex and as a result cost-, material- and process-intensive components on a launch vehicle, and on expendable boosters these are not recovered in a usable state post-flight. The current front-runner in this capability is SpaceX in the United States, and the results speak for themselves: Falcon 9 rockets are globally among the cheapest and most popular work-horse launch vehicles in the market.

Ensuring the engine's integrity is monitored and actively maintained throughout a flight is critical to attaining post-flight reusability. Engine health monitoring systems (EHMS) also present additional benefits: intelligent detection of engine faults can enable corrective actions that safeguard engine integrity and mission success, as well as help guide the refurbishment of used engines for follow-up launches, reducing cost and turnaround times. Rapid detection of faults is also critical in a human spaceflight context, increasing the time a crew has to jettison a compromised spacecraft and improving their odds of survival.

There currently exists no in-flight advanced control and diagnosis onboard European launchers. Although some activities were performed in the frame of the ESA Future Launchers Preparatory Program (FLPP) [1] or by CNES [2] the current state of the art consists of post-flight analysis of data gathered via telemetry. On-board solutions are thus sought to enable real-time sensing and actuation. The broader space industry is currently experiencing a boom with the application artificial intelligence

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(AI) and machine learning (ML) for fast and accurate data processing applications with high data throughput.

One particular ongoing European project, ENLIGHTEN, focuses on harnessing edge AI and ML algorithms to develop an EHMS capable of real-time fault detection and isolation (FDI). Within the promise of these technologies belies a complex, interdisciplinary design challenge. This paper aims to guide engineers through the process for sizing and designing a general HMS, considering key parameters and decisions for future system development. While the study predominantly addresses the electronic hardware design, it embraces an embedded systems approach, emphasizing the symbiotic relationship between software and hardware in edge AI applications. Following the top-down design process employed in the ENLIGHTEN EHMS study, the paper begins with a discussion on design drivers and high-level architecture definition, proceeds to component-level trade-off analysis, and concludes with a discussion of the results and challenges faced along the process to date.

1.1. Trends for Engine Health Monitoring

The concept of monitoring an engine's condition mid-operation is far from novel. However, given the limitations in processing and sensor technologies at the time, many of the earlier implementations of HMS for rocket engines were in ground-fire testbeds, where there were the requirements for real-time processing and constraints on the HMS SwaP (Size, Weight and Power) footprint were significantly more relaxed compared to on-board implementations. These early iterations focused on data collection and early detection of engine failure modes and rapid shut-down of these, with the goal of prevention of human and material damage during tests and preservation of the test article for future experimentation [3].

Recognising the importance of the role of health monitoring for attaining the goal of the world's first reusable launch vehicle, one of the earliest implementations of an EHMS can be seen on the Space Shuttle Main Engines (SSMEs), where a combination of redlines was implemented. Key engine parameters were monitored during the main stage ascent phase and an engine cutoff command is issued if a measured value exceeds a pre-determined limit, set at levels beyond which safe engine operation is compromised [4]. This approach was far from perfect: faulty sensor readings would occasionally result in premature engine cutoff commands and engine and component damage was still recorded during several SSME ground tests [4].

The survey performed by Wu on liquid-propellant rocket engines HMS in 2005 identified "huge-capacity, massively parallel-processing computers" as a key technology in enabling new generations of FDI algorithms [3]. Rocket engines are complex thermodynamic systems with nonlinear phenomena that are hard to model accurately, limiting the effectiveness of model-driven techniques especially as conditions deviate from the design point. These problems therefore lend themselves well to neural networks and other forms of data-driven AI approaches [5]. Other appealing features are the ability for transfer learning to facilitate an EHMS model being integrated across different engines, and the tighter incorporation of this EHMS in the control avionics for the engine for local decision-making with the aim of a fully autonomous propulsion system. Present-day advances in both the AI domain as well as the continuing miniaturization of processing technology is finally enabling relatively lightweight yet powerful solutions that have a compact SWaP footprint.

1.2. Design Methodology

The procedure followed for designing an EHMS closely mirrors the "V-shaped" method commonly used for space systems design. Starting with the global top-level requirements and design drivers, these inform the high-level architecture and establishes high-level system blocks which describe the EHMS from a functional perspective. Then a top-down approach is used to further define these system blocks, where the components are decided through a trade-off study.

The scope of the design work performed in ENLIGHTEN to date is contained within first half of the V-shape (the top-down portion). The outcomes of this phase conclude with the preliminary design proposal, which is reviewed with the other project stakeholders as well as external advisors. With a general approval on the preliminary design, work may then proceed in the bottom-up phase, with a greater focus on the integration and interplay between the selected components within the preliminary design. This first occurs at a subunit level (eg: within a power supply unit in the EHMS hardware) before proceeding to wider board-level integrations and concluding with an integration of the EHMS within the wider launch vehicle.

2. Requirements and Design Drivers

Both requirements and design drivers are derived from the high level mission objectives. Requirements will be used to guide the design approach and also serve as a baseline with which to verify and qualify the product at later stages. Design drivers do not necessarily need to be explicit or verified, but when faced with choices during the design process, these can be used to influence decisions.

From the EHMS-specific perspective, a main source of requirements will be derived from the expected fault modes that the EHMS is expected to detect. These fault modes are discovered through a failure mode and effects analysis (FMEA) performed on the propulsion system of the launch vehicle [2]. This will result in a definition of the sensors required and their time and data resolution. This will in turn inform the EHMS design of the types of data it must accept, it's processing frequency and the data throughput it must support from both a data transfer and processing perspective.

2.1. Requirements Flow

The approach chosen by the ENLIGHTEN team mirrors that followed in space mission design. A two-tier hierarchy was adopted. The objectives and information derived from the project brief was condensed into a list of high level requirements, which within this activity were termed as product requirements. These mirror the concept of high level mission requirements for traditional space missions, but narrowed in scope to only focus on the product and its objectives. These high level requirements are then broken down into more discrete system requirements that are more actionable and can be translated into concrete design choices, mirroring the "technical" or "sub-system" requirements in space mission design. These system requirements are categorised into types, representing different aspects of the product such as interface, electrical, environmental, computational, among other categories.

This process of breaking down the product-level requirements into system-level requirements and linking the latter back to the former not only promotes a finer resolution in the definition requirements but also introduces requirements traceability, which will aid with subsequent steps in defining and designing the product architecture, as well as testing and verification to make sure that the final product conforms to the original requirements and objectives of the activity.

2.2. Design Drivers

Given the background for the ENLIGHTEN project, three clear design drivers were identified.

The first is to produce a powerful AI computing platform, that is capable of keeping up with and foster the development of state-of-the-art AI and ML FDI algorithms. Most of the advanced FDI algorithms have been run on very powerful ground computers, hence their implementation on edge cases are often not fully understood. To maximise the potential of these algorithms and maintain relevance of the EHMS' processing capability in the medium term (within the coming decade), the ENLIGHTEN EHMS design team has adopted a conservative approach where the processing demands of the EHMS hardware were oversized. This will impact the processors considered in the trade-off, the sizing of the application memory and the data interfaces and bandwidth expected.

The second focuses on providing the EHMS as an augmentation to existing engine controllers already on-board the target launch vehicle. It is necessary to properly define the scope of the EHMS in order to focus time and effort in developing and designing for the truly required needs of the project. By designing an EHMS that integrates with an existing rocket Engine Control Unit (ECU) the aim is to incorporate this additional level of augmentation that validates the implementation of more complex and capable AI in future EHMS which will inevitable be more integrated within the launcher propulsion systems. Careful attention will therefore be given to ensure compatibility and ease of integration with the target ECU. It also means that some features may be already be provided by the ECU which the EHMS does not need to concern itself with in its design, such as the actual control of propulsion subsystem elements or potentially certain data pre-processing steps.

The third design driver is to have a reliable EHMS platform. Given the criticality of the EHMS function and the foreseen inclusion in future, more complex integrated HMS, it is important to establish a reliable and available EHMS architecture from early on in the design phase, to increase system dependability.

3. High-Level Architecture

To avoid project risks regarding time and cost expenses, the best approach is to derive a conceptual design for the EHMS straight from the requirements. The end goal is to generate a comprehensive understanding of the system, composed of functional system blocks. These blocks are responsible for satisfying the different sets of requirements without delving too deeply in the technical challenges necessary to solve these requirements. This results in a preliminary concept that is fluid to adjust around requirement changes yet concrete enough to engage collaborative work among the different work partners and receive constructive feedback for further refinement.

3.1. System Configuration

The initial step involves determining the configuration of the EHMS based on the rocket engine configuration. For a simpler propulsion subsystem, a single EHMS that processes sensor data from all engines may suffice. However, as health monitoring is data-intensive, larger engine clusters run into data throughput and processing bottlenecks.

For example, the SSME controller was a cross-strapped, dual-redundant computer unit. Each unit had self-contained random access memory (RAM), processors and power supply, and was capable of simultaneous operation and execution of HMS and engine control programs. The redundant unit operates in a standby mode which monitors both the condition of the engine and the main unit, such that when the main unit fails, the redundant takes over, in a hot redundancy scheme [6]. Since both computers are electrically and functionally independent of each other, a failure in one unit will not propagate and cause a failure in the other.

When implemented as part of an engine cluster, an EHMS may have the ability to control subparts of cluster. Benefits will also arise in the optimisation and simplification of avionics (for example, one may share a single processor across several engines, and each EHMS unit's design will be identical allowing for economies of scale), as well as robustness to data degradation. It then raises the questions of whether to perform HMS decisions at the individual engine level versus at the cluster level [7].

For testing FDI capabilities on a single rocket engine, attaching an EHMS to an individual ECU simplifies hardware design. This setup can easily scale up for testing an entire engine cluster. Therefore, in initial research and feasibility stages, system-level redundancy is less significant.

3.2. Homogeneous and Heterogeneous Computing Systems

Much like a conventional spacecraft Data Processing Unit (DPU), all EHMS require at least one central processing unit (CPU). Most traditional space DPUs are homogeneous systems which a single CPU or CPU cluster to execute all the use case data processing. Heterogenous systems contain different types of processing units and distribute the data processing across these units. This introduces increased design complexity in hardware through for example internal data communication, electronic FDI and power management, as well as in software through device drivers, toolchain development and data pipelining. However, the use of heterogenous architectures enables for the subdivision of processing tasks, allowing for a main CPU to run an OS and communicate with the ECU, where for the FDI algorithm and AI applications, dedicated AI co-processors can be leveraged which are significantly faster at AI model training and inferencing. Furthermore, if engine diagnostic data is provided in different formats such as serial, video or sound, then these can likewise be processed more efficiently.

For the above reasons, while the CPUs analysed in this trade study were considered for homogenous architectures, the AI use case motivates for the adoption of a heterogenous architecture.

3.3. COTS Components and New Space Approaches

High-level architecture definitions, while generally independent of component technology, benefit from the early consideration of technology choices to focus the trade study. This encompasses technology type and novelty, involving trade-offs between performance against reliability and flight heritage. The use of commercial off-the-shelf (COTS) components in data processing units (DPUs) is a topic of hot debate. COTS offers substantial performance gains compared to traditional "Old Space" processors but lack space environment qualification, posing significant design risks [3]. The "New Space" approach seeks components from sectors like automotive, defence, and industrial applications, known for their robustness in harsh environments. Such components require less up-screening, mitigating risks.

ENLIGHTEN's core objectives include boosting European competitiveness and fostering technological innovation, providing an opportunity to experiment with EHMS systems that could leverage high performance COTS technologies. Furthermore, traditional space processors have limitations in supporting AI applications, while COTS products have successfully enabled edge AI applications in fields like the automotive and industrial [8]. Incorporating this technology not only promotes further exploration of COTS adoption in space but also stimulates broader research into AI applications.

3.4. Form Factor and Interfaces

Tackling the topics of interfaces and form factor concerns situating the EHMS hardware in its operational environment and how it interacts with the greater launcher vehicle ensemble.

The choice of hardware form factor is primarily influenced by ECU interface compatibility. Traditional ECUs typically adhere to proprietary form factors. In contrast, the New Space design philosophy favours standardized form factors for cost-effectiveness, and compatibility across diverse clients and use cases. They enable modular layouts and incorporate various electrical, data and mechanical interfaces.

Besides standards and physical dimensions, form factor also determines available interfaces, and influences the module's external area for interface placement. External data interfaces shape internal data connections within the EHMS, limiting compatible devices for these connections. Additional internal connections may facilitate dedicated high-speed inter-processor communication.

From an electrical perspective, it is important to consider the supply voltage at the interface. It may be necessary to include voltage conversion within the EHMS. Non-constant or otherwise unregulated supplies, such as with ECUs powered by the rocket engine’s alternator, require voltage stabilisation.

Thermal interfaces are usually important for space electronics, providing heat dissipation. The mechanical interfaces may provide sufficient thermal dissipation on their own. Finally, fluidic interfaces may also be considered especially when the EHMS may be placed near the rocket engines. As the preliminary EHMS is designed for ground tests, these were not significant considerations.

3.5. Safety Barrier Approach

The “safety barrier” is a concept commonly proposed in ESA mission classifications targeting space mission with COTS technologies onboard or with New Space design approaches. The fundamental idea is that a fault originating in a subsystem (presumably caused by a less reliable COTS component) must not be allowed to propagate to its more reliable host system and compromise it. In the context of this application where the EHMS interfaces with an ECU for example, a fault in an EHMS processor should not affect the functionality and integrity of the ECU.

From a hardware perspective, this can be seen mainly in the prevention of electric faults in the power supply and data lines feeding the EHMS. For the software level, two main considerations exist. The first is data validation, to ensure that e.g: erroneous commands sent to the ECU will not inadvertently compromise the mission. The second is to ensure the EHMS’ availability and that it is always responsive to the real-time commands sent by both the ECU as well as the engine sensor data.

4. Component-level Selection

With the high-level architecture defined through the aforementioned system-block approach, it is now possible to populate these individual blocks one by one with candidate components.

4.1. Main Processor, Co-Processors and AI Accelerators

The main CPU manages the EHMS AI application, board management programs, and ECU data flow. Due to its critical role, space-grade processors, radiation-hardened by design, are typically chosen.

Traditionally, field-programmable gate arrays (FPGAs) are common co-processors for spacecraft DPUs, offering high data throughput. However, they are challenging to reconfigure for AI model training. An emerging alternative from the COTS realm is graphics processing units (GPUs), capable of parallelizing demanding AI computations with high performance. Drawbacks include increased power consumption and greater vulnerability to radiation effects.

Dedicated AI accelerators, such as neuromorphic (NPUs), tensor (TPUs), and vision processing units (VPUs), promise superior AI inferencing performance at lower power consumption compared to GPUs. Despite very limited flight heritage, they hold promise for low-power AI applications.

Finally, combinations of the above processors can be found bundled together in systems on modules (SoM) that provide a pre-designed, more efficient integrated system which also includes software toolchains for system management, at the loss of control over the configurability of the system.

Evaluation criteria for these processors include assessing floating point operations per second (FLOPS) during inferencing on a reference dataset, peak power consumption, and FLOPS per Watt for power efficiency [9]. The data quantisation is another consideration, as it will constrain the accuracy of the neural networks and ML algorithms implemented. Another important factor that should not be underestimated is the software toolchain supported by these processors, as this will play a major role in the HMS algorithm implementation efforts later on in the project.

4.2. Internal Supervisor Processor

In line with the safety barrier approach previously discussed, it is necessary to complement the powerful, yet less mature (from a space heritage perspective) COTS processors with a robust board management solution. This processor will relay information on the EHMS board-level health to the ECU, as well as relay commands to and from the ECU to the other components within the board. At the same time, it will perform reliability and availability assurance tasks on the other EHMS processors, such as watchdog functionality, component-level health monitoring and power sequencing of the processors.

At the time of writing, two primary classes of processors present attractive, radiation-hardened options. The selection is guided by the board-level management and safety barrier tasks foreseen to run on this processor, and the corresponding requirements.

On one hand, FPGAs provide highly configurable logic blocks and interfaces which lend very well for processors which need to insert themselves within the EHMS data stream. This enables them to, for example, perform sensor data validation tasks, or act as sensor data buffers to ensure that the onboard EHMS algorithms do not skip data frames in case of instantaneous unavailability of the main processor. Selecting an FPGA for this role must be done with caution: without prior design experience it is easy to adopt a conservative mindset that oversizes the FPGA and compromises on the benefits that edge computing provides regarding reduced power consumption and board footprint.

On the other hand, microcontroller units (MCUs) provide a sleek, yet generally undersized alternative to board-level management. An important consideration is the limited pincount of MCUs (especially compared to FPGAs), which constrains the amount of board-level state sensors that it can interface with.

In either case, when considering the implementation of a specific supervisor processor, it is wise to consider the procurement of developer kits to study the integration of such processors within your EHMS architecture, without necessarily committing to a full prototype design of these. Alternatively, these components generally are sold as families of components with varying quality grades ranging from e.g: automotive to military to aerospace, and sourcing a lower quality version of the considered component can be a cost-effective way of obtaining equivalent performance and experience with integration (as they share the same pinout and form factor).

4.3. Data Storage

DPUs feature different storage types for distinct purposes. RAM stores the FDI algorithm during runtime, requiring rapid write speeds and adequate size to accommodate the algorithm. Cold data storage, while used for storing intermediate data processing steps, and is less critical for real-time systems. The file system, stores the OS boot image for the main CPU.

Sufficient memory size is essential for the boot image, and for added reliability, redundancy may be considered to mitigate radiation effects. Given the criticality of the boot image for ensuring successful start-up and hence availability of the data processors, it is generally advised to select space-grade options which feature error correcting codes (ECC) and error detection and correction (EDAC) algorithms.

4.4. Electrical Power Distribution

The electrical power subsystem, overseen by the main CPU, comprises power conversion regulators, current monitoring components, polarity protection diodes, and latch-up protection for radiation induced effects on transistors. At its core, selection aligns with the external power interfaces and internal power bus definition of the EHMS.

Most conventional electronics, both COTS and space-grade, operate on a mix of standard voltages such as 1.8V, 3.3V, 5V and 12V. Depending on the design of the host engine or the rocket's existing embedded electronics, these voltages may already be provided. When these are not available, or when designing an EHMS that targets several potential host engines, a versatile conversion solution is necessary that accepts a range of voltages and then converts to a standard voltage within the EHMS.

Very early design iterations for ENLIGHTEN explored the possibility of sourcing the electrical power directly from an alternator installed on the rocket engine. Focusing on the electronic hardware complexities resultant from the inclusion of such an alternator, this had introduced two characteristics driving the EHMS power supply design. The first is an unregulated power bus which may present a minimum nominal voltage but otherwise requires voltage regulation and the understanding of peak voltage behaviour. The second is that alternators usually generate voltages, falling in the realm of high voltage electronics design.

Regarding component level power supply, two common topologies exist in space electronics design. One is having a central voltage conversion unit which provides conversions into an ensemble of power buses, one for each of the voltages used in the board. The alternative is point-of-load conversion, where there is a single main board power bus and the necessary voltage conversion is performed near the components. The advantage of the former is that it simplifies integration of different components as the complexity of the power supply is contained at the board-level. The advantage of the latter is having a more simplified board-level design, and more distributed secondary voltage conversion which should reduce energy dissipation from Joule heating (due to the higher main bus voltage), component-level conversion can be incorporated with the component's power sequencing, health monitoring and latch-up detection circuitry as well as potentially reducing the bareboard complexity as fewer copper power planes may be necessary.

5. Results

Based on the findings and decisions outlined in this paper, the suggested preliminary design for the EHMS research is as follows: one EHMS module communicating with one ECU, with hardware adhering to a standard form factor and a designated external connector. This connector incorporates high-speed lanes for efficient ECU interfacing, low-speed lanes for hardware interfacing and debugging, an electrical power supply, and a robust mechanical interface.

The inclusion of COTS components has expanded the scope of potential processor technologies, leading to the adoption of a heterogeneous computing architecture. This architecture allows for dedicated processors, facilitating low-latency, high-throughput distributed AI inferencing for various types of rocket health data. These components will be integrated into a compact COTS SoM with a comprehensive software ecosystem supporting AI toolchains. Despite the absence of flight history, selecting a suitable SoM from an industry with demanding quality standards, enables for up-screening.

From the electrical power distribution perspective, the EHMS directly interfaces with an ECU that supplies one of the standard electronics voltages. Voltage regulation was

With the established design parameters and component selection, a prototype hardware module can then be developed to estimate mass and power budgets. Operational and environmental constraints for the overall system can be estimated by aggregating the worst-case constraints of individual components. As the design matures, these approximations can be refined through simulations.

The ongoing ENLIGHTEN study will conclude with a preliminary design review involving project stakeholders and external subject matter experts to assess the design's feasibility. Development of functional hardware prototypes will facilitate practical evaluation of AI/ML algorithms and foster close hardware-software co-development. The goal of this initial ENLIGHTEN project phase is to successfully integrate and conduct hardware-in-the-loop testing of a fully functional ECU on a laboratory test bench.

6. Current and Future Challenges

The development of EHMS and the accompanying trade study have revealed challenges hindering technology adoption in the launcher segment.

6.1. Lack of Data on Components

The absence of data on COTS components for launch or space environments limits assessment of the components for a trade-off analysis. In the preliminary design phase, focusing on aligning component nominal environmental limits with design requirements can mitigate but not fully eliminate risks of design changes later in the project.

6.2. Access to Use Case Data

A similar challenge presents itself in the availability of relevant use case data, namely engine sensor/failure data). This is primarily due to the cost, time and material constraints surrounding engine development and testing and has long been an ongoing problem in the field [3,10,11].

As the target rocket engine is likewise in ongoing development, there are few data sets specifically for it. It is not realistic to resort solely to experimentation to acquire enough test data under a comprehensive suite of faulty conditions due to the cost and danger involved in these artificial failure tests [3]. A consequence of this is the imbalance in availability of nominal versus anomalous/failure data [10], which when unaccounted for will bias the performance of data-driven algorithms such as AI as well as the resultant hardware performance.

In an edge computing environment, design factors such as power consumption and data bandwidth are heavily influenced by use case data. The time resolution and complexity of the failure mechanisms motivates the processing speed and number of sensor data channels. Therefore not only FDI algorithm development is hampered but also the sizing and evaluation of the supporting hardware.

Efforts to provide computational performance benchmarks for space applications exist [12], but primarily target satellite applications. Fault modeling and simulation therefore plays an important role in the failure modes analysis and FDI algorithms studies applied to rocket engines and by extension the EHMS. The production of simulated fault data from nominal engine data and digital twins with the purpose of enriching these datasets is an active area of research [13,14,15].

These challenges stem from the novelty of the use case and the lack of heritage. As research and development activities mature and more data is collected, a better understanding of engine health monitoring and the screening of COTS components for space are expected to emerge.

6.3. Hardware and Software Co-Development

The EHMS work package has been divided into hardware-specific and software-specific tasks, that generally are attributed to different members given each members' particular area of expertise. Given the scope and ambition of the project, design work and technological innovation is being performed in both fronts. This can lead to a knowledge rift to form between the EHMS hardware and software design teams and result in a lack of synchronization, which has the potential for several different negative downstream effects at a design and project level.

To tackle this challenge, it is necessary to enforce tight and frequent communication within the different collaborating partners to ensure unrestricted and timely flow of information. Within the EHMS work package, group-wide meetings Another equally effective measure is to allocate subject matter specialists within the other working group. For example, having an embedded software expert in working alongside or in close contact with the hardware design team usually encourages the hardware design to be more software-oriented.

6.4. European Supply Chain

Given the European nature of the project, it is in the interest of the ENLIGHTEN project to procure a Euro-centric approach to the supply chain and procurement of components and technologies for the EHMS. While there are ongoing initiatives such as the European Processor Initiative, which aims to develop designs and stimulate a European ecosystem for edge AI processors, the majority of state-of-the-art COTS edge AI processors are still developed and commercialised outside of the European Union [16,17].

This raises additional design considerations from the supply chain and product/project lifecycle perspective: for components sourced outside the European Union, it will be necessary to include additional screening procedures, as well as the accumulation of a strategic stockpile for critical components whose supply may become constricted in the future due to component obsolescence, external market phenomena or geopolitical events.

7. Conclusion

This paper introduces the ENLIGHTEN project, focusing on developing an onboard EHMS for new rocket engines and launch vehicles. A core feature is implementing AI in the FDI algorithm to enhance rocket engine control, flight performance, and maintenance.

Key design considerations for the EHMS were covered, ranging from high-level architecture to component selection. An embedded systems engineering approach was adopted that, addresses hardware and software challenges concurrently. Examining current technologies and trends, including COTS and New Space technologies, revealed that a heterogeneous architecture utilizing a SoM is a promising candidate for further investigation. Challenges in conducting trade-off analysis for rocket EHMS hardware with COTS and AI technologies are discussed. Nevertheless, as newer launch vehicles and AI/ML technologies become more prevalent, these challenges will be mitigated.

Successful integration and testing of onboard EHMS such as the one developed by ENLIGHTEN, will enhance Europe's competitiveness in space and set the stage for future developments in reusable engines, AI health monitoring for other vehicle systems, and eventually autonomous launch systems.

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