Assurance Benefits of ISO 26262 compliant Microcontrollers for safety-critical Avionics

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Abstract. The usage of complex Microcontroller Units (MCUs) in avionic systems constitutes a challenge in assuring their safety. They are not developed according to the development requirements accepted by the aerospace industry. These Commercial off-the-shelf (COTS) hardware components usually target other domains like the telecommunication branch. In the last years MCUs developed in compliance to the ISO 26262 have been released on the market for safety-related automotive applications. The avionic assurance process could profit from these safety MCUs. In this paper we present evaluation results based on the current assurance practice that demonstrates expected assurance activities benefit from ISO 26262 compliant MCUs.

Keywords: Microcontroller, DO-254, Assurance, Reuse, Avionics, ISO 26262

1 Introduction

COTS hardware components are ubiquitous in Airborne Electronic Hardware (AEH) and were considered in the very beginning of the RTCA/DO-254 [1]. However, the complexity of the desired COTS components is continuously increasing, even for highly safety-critical functions. Certification authorities address this rapid evolution by delegation of research activities and provision of further guidance in COTS hardware component assurance for different types of components (e.g. MCUs or graphics processing units). The aim is to deliver advisory material as specific as possible for industrial practice. COTS hardware component assurance and Design Assurance (DA) of AEH have the same objective, which is to assure that a hardware component safely performs as intended in its operational context. But the method is inevitably distinct because of the nature that COTS hardware components were not developed according to the

RTCA/DO-254 or that COTS manufacturers do not disclose required development artefacts to be able to demonstrate compliance afterwards. So processbased evidence of the design life cycle cannot be claimed as aircraft systems concerns were not regarded during the development of the COTS product.

Avionic manufacturers employ components actually intended for other domains³. Hardware with a long market availability and operable under harsh environmental conditions is requested. These component properties are characteristic for the automotive domain. Functional safety is at least since 2011, where the ISO 26262 standard [2] has been released, a major concern for Original Equipment Manufacturers (OEMs) and also many suppliers for automotive parts like integrated circuits. MCUs developed in compliance with ISO 26262 are designed for safety-critical applications. For their development the ISO 26262 describes an approach called Safety Element out of Context (SEooC). Semiconductor manufacturers are able to create a product that can be integrated into different systems or operational contexts. AEH manufacturers observe the situation in the automotive and other safety-critical domains that request hardware components according to standards that are aimed to reduce or control the risk of hazardous failures [3]. Their aim is to exploit the fact that safety plays an essential role in more and more sectors and to influence the product lines of hardware component manufacturers that produce in high quantities.

As a consequence of the current situation, the following research question arises: How can the avionics industry benefit from this situation in the course of COTS hardware components assurance? To answer this question, the paper is structured as following: Section 2 describes how assurance is achieved for avionic systems in general and how it differs if complex MCUs shall be embedded. Evaluation of ISO 26262 compliant MCU benefit in COTS hardware component assurance is performed in section 3. Conclusions are given in the last section.

2 Assurance Methods for Avionics

The meaning of the concept of assurance varies in its understanding depending on the context and which aspects should be assured. The following sections give a brief overview of this topic in the avionics domain and distinguish between two aspects. First, these are avionic systems that mainly comprise components manufactured alongside the avionic development life cycle and second avionic systems that make use of complex MCUs. In both cases sufficient and practical assurance methods have to be performed.

2.1 Development Assurance

The term assurance methods is currently often used in the avionics domain [4,5,6]. In general, assurance can be defined as the actions that provide appropriate

³ For Development Assurance Level (DAL) A applications the general principle is to restrict the use of complex components.

confidence and evidence that a product or process meets its requirements [7]. Assurance intends to reduce the uncertainty about the correct realisation of the product. It delivers reasons why the confidence on achieving the claim is so justifiable [8] and why most assurance activities target the establishment of this confidence [9]. In a requirements-based product development this means, that the requirements specification meets the real-world needs (validation of requirements) and that the product is a correct implementation of the requirements specification (verification of requirements).

For avionic systems the airworthiness requirements [10] are on the top of their requirements specification. Summarized, it has to be assured that the avionic system design is appropriate for the intended function and that its function is provided as defined in its operational context (environmental and operating conditions of the aeroplane). These are prerequisites to ensure that it is extremely improbable that safety-critical AEH contributes to a catastrophic failure condition at aircraft level that harms human life. For safety-critical systems, assurance methods are necessary to deliver enough credit to justifiably state that the system is safe in its context⁴.

This is very challenging if the system is too complex in order to provide the requested level of confidence by exhaustive tests which fully characterise the system. Hence, the method of *Design Assurance* was defined to cope with this issue in different areas, system $[11,7]^5$, software [12] and hardware [1] development. These DA areas aim to accomplish the development in a sufficiently rigorous and disciplined way so that development errors do not impact safety [13]. DA is characterised by techniques that are applied during the whole development process in order to identify and correct errors that could occur at various steps within the development life cycle. This comprises assurance techniques like process assurance, verification coverage criteria and reviews. In addition, for the two highest development assurance levels, RTCA/DO-254 requires additional development assurance techniques that a certain design process has been followed alone. RTCA/DO-254 suggests using architectural mitigation techniques, service experience and advanced verification methods as additional development assurance activities.

For AEH embedded MCUs, DA on device level cannot be claimed or used as assurance method [14]. The reason is that most DA techniques are based on an ongoing development and the accessibility of development-time artefacts down to a level detailed enough to realize the hardware component and assure its safety aspects. For MCUs this is not possible as the development has already been accomplished and detailed development-time artefacts are not available. Thus, other assurance methods have to be determined which can reduce uncertainty in a similar magnitude creditable by the certification authorities.

⁴ For non-safety-critical systems other properties e.g. security are in the focus of assurance methods.

⁵ The safety assessment is part of development assurance to deliver the safety requirements and support the confidence of its verification.

2.2 COTS Hardware Component Assurance

As stated in [15], it is very challenging to define an assurance method for COTS hardware components in an objective way. Two aspects have to be considered for the objectivity: The method is applicable for a variety of components and following it delivers results that can be fairly assessed by the authorities. Such guidance shall support the industry in realization of certifiable AEH, embedded with COTS components, in a practical way so that certification costs do not explode and safety can be sufficiently assured.

The latest initiatives by authorities in this direction resulted in the following documents 6 and reflect the status quo:

- EASA:
 - Certification memorandum CM SWCEH-001: Development Assurance of Airborne Electronic Hardware [16].

This document represents the current attitude of the EASA about several certification aspects of AEH and in section 9 especially to COTS MCUs. The content is based on experience in COTS hardware component assurance in many certification projects gathered in the years before and funded research activities as [17].

- FAA:
 - Commercial Off-The-Shelf Airborne Electronic Hardware Assurance Methods Phase 3 Embedded Controllers [4].
 - Assurance of Multicore Processors in Airborne Systems [18].

These technical reports are the results of funded research by the FAA to develop proposals for assurance approaches for different COTS hardware.

Notable is that for different hardware component categories (e.g. multicore processors or microcontrollers) the assurance methods were separately considered. This faces the fact, that each technology has its own issues which shall be incorporated to provide methods that are useful in practice. Especially small companies and market newcomers are interested in guidelines as concrete as possible since they do not have the same amount of development experience as the larger ones [19].

All reports listed above share one similarity: COTS assurance should be managed from system level in parallel or within the AEH design process⁷. However, they lack in formulating a framework that brings them all together in a coherent approach that could be related as an deployable COTS hardware component assurance process. From these reports, the EASA certification memorandum can be considered as most relevant to identify necessary COTS assurance tasks. It represents the current position of a certification authority and defines assurance activities as an Electronic Component Management Plan (ECMP)⁸ extension.

⁶ None of these listed documents are binding guidance material.

⁷ Recommended also by RTCA/DO-254.

⁸ The term ECMP in the memorandum is misleading because typically such a process does not perform profound functional assurance activities.

FAAs research report [4] does not explicitly cover activities but has identified issues to keep track of during assurance. Also, findings and recommendations can be found in this research report. Some similar to the activities in EASAs CM, e.g. usage domain analysis, integration aspects, errata handling, and configuration management, and some similar to typical ISO 26262 implementations, e.g. robustness verification. These issues, findings and recommendations have been analysed but were not identified as obvious COTS assurance tasks and therefore not included in this paper. In addition, the other FAA research report [18] concerns multicore processors running in parallel and not in synchronized lock-step mode (LSM). For the case study in this paper, all ISO 26262 developed MCUs must be run in LSM for safety-critical applications. Report [18] is therefore not included in the analysis of this paper.

The memorandum contains sixteen recommended activities, numbered with brackets from 1 to 16 (e.g. Activity [1]). These activities are referenced in this article with the same numbering but are emphasized in round brackets instead to avoid confusion with other references in the article. These activities should be considered depending on the DAL associated by a higher level safety assessment, the magnitude of Product Service Experience (PSE) traceable from different domains and the complexity of the MCU. In the subsequent text, activities are discussed for DAL A which apply for components with the highest possible safety impact. This will extend the value of scope of this article, because targeting DAL A means that all activities have to be conducted if the PSE is inadequate. The argumentation behind these additional assurance activities is not further stated in the document but is essential for the understanding on how they contribute to COTS hardware component assurance. Thus the assumed argumentation was reconstructed.

Two top arguments were extracted that have to be assured:

Argument 1 The component performs as described by the manufacturer without anomalous behaviour.

Argument 2 The component as used satisfies the AEH requirements.

It has to be differentiated between those arguments as the MCU was not developed according to the requirements of the AEH. How these arguments can be supported depends on the complexity of the COTS component. For MCUs with a functional architecture classified as simple, the arguments can be fulfilled as following:

- Argument 1:

• Verification of component behaviour on device level as specified by the manufacturer.

The simplicity of the COTS component allows to verify all requirements on the physical device.

• Substantiate the confidence of a design free from anomalous behaviour by demonstrating device maturity or quality.

Most of the confidence on device quality is already supported by the comprehensive verification effort. However, additional errata management in activity (6) and (7) shall be considered to state that the device design is stable enough. This can be demonstrated by errata decreasing over the service time on the market. Also the errata publishing policy of the manufacturer shall be adequate to be always informed about revealed problems and to achieve that errata with potential safety impacts can be handled.

- Argument 2:
 - Verification of AEH requirements on Line Replaceable Unit (LRU) or Circuit Board Assembly (CBA) level during equipment design.
 - As requested by certification requirements, no single point of failure should lead to a catastrophic failure condition. This is also valid for COTS components in general. Activity (15) requests the implementation of an adequate architectural mitigation technique like dissimilar redundancy or monitoring.
 - An ECMP e.g. as described in IEC TS62239.

Most of the available MCUs on the market are complex or even highly complex components. For these devices, exhaustive tests on device level can not be achieved to adequately substantiate argument 1 as for simple components. Therefore additional activities for complex or highly complex hardware are necessary, which are depicted as following for argument 1 and 2:

- Argument 1:
 - Verification of component behaviour on device level as specified by the manufacturer.

The concept of usage domain as described in activity (4) resp. (5) is suggested to bound the scope of device level verification only on component behaviour that is relied on or is really used. The determined usage domain shall be compliant to the manufacturer recommendations and verified on device level. If the MCU is part of a partitioning concept, an analysis has to be performed as described in activity (16) to claim the robustness of this mechanism at device level⁹.

• Substantiate the confidence of a design free from anomalous behaviour by demonstrating device maturity or quality.

The verification on device level limited to usage domain aspects is not enough to mainly support argument 1. In comparison to simple COTS components, the correct behaviour assumption of complex hardware is more based on other activities like:

- * COTS manufacturer quality management and production process has to be assessed in activity (3).
- * Errata management as for simple components in activity (6) and (7). Additionally, activity (8) requests that the AEH manufacturer has to document own made experience with the hardware during the development (e.g. errata workarounds).

⁹ Actually, we consider partitioning aspects as a specific part of the usage domain analysis, because MCU properties shall be verified on device level.

- * Manufacturers configuration management including a change process has to be assessed in activity (9) to make sure that changes are appropriately controlled and communicated. Activity (10) additionally requests a change impact analysis to identify potential extra verification effort.
- * The PSE has to be documented by activity (13) in order to determine if it is sufficient¹⁰ to omit certain assurance activities. Specifically for DAL A and B, a minimum amount of PSE has to be reported in order to exclude really novel designs to be embedded in AEH systems. Activity (14) further increases the confidence on the maturity and stability of the MCU by requesting evidence on the rate and fact of past modifications.
- Argument 2:
 - Usage domain validation in activity (5) ensures that the usage domain is consistent to system, software and hardware requirements.
 - For complex COTS it is not sufficient to verify requirements allocated to the MCU at equipment level as for simple components. Activity (11) requests verification and validation of these requirements coming from other hardware or software components on device level in order to get confidence about its correct integration.
 - For highly complex MCUs activity (12) has to be conducted to have a clear understanding of possible device failure modes and rates depending on its configuration.
 - Architectural mitigation technique as requested by activity (15) shall also be applied.
 - An ECMP e.g. as described in IEC TS 62239 [20].

Activity (1) and (2) were not mapped to a top argument, since determining or classifying the MCU characteristic (1) and archiving public available device data (2) are required for both top arguments. It does not matter if the MCU is classified as simple, complex or highly complex.

All these explained assurance activities of the certification memorandum are only applicable for the peripheral subsystem and other functions which are not part of the processing core. The DA of the processing core is based on the software development process compliant to RTCA/DO-178 that includes software testing on the target hardware platform. This separation is based on the assumption that other MCU functions do not interfere with the software execution on the processing core [4].

The explanations about complex COTS hardware component assurance established the basis on which in the next section the potential benefits from ISO 26262 compliant complex MCUs can be examined.

 $^{^{10}}$ The metric to determine a PSE as sufficient is also defined in the certification memorandum.

3 Benefits from ISO 26262 compliant MCUs in AEH COTS Assurance

The research question asked in the introduction was: How can the avionics industry benefit from ISO 26262 compliant MCUs in the course of COTS hardware components assurance? Before starting to evaluate an ISO 26262 compliant MCU against the assurance approach from section 2.2, the differences to other MCUs on the market have to be identified first. What makes these MCUs so special? These are the aspects on which COTS assurance can probably profit in comparison to other MCUs e.g. from the telecommunication domain.

3.1 Determination of ISO 26262 specifics for reuse

The special characteristics of interest come from the development approach defined by the process requirements from ISO 26262. During previous research we made a comparison between the DA method of RTCA/DO-254 and ISO 26262- 5^{11} , which concludes that the ISO 26262 does not reach the same level of design integrity [21]¹². The reason is that only safety requirements are considered in the development life cycle of the MCU, whereas the traceability down to detailed design level is not required. For manufacturers the main focus is on the safety architecture to handle random hardware failures by adequate safety mechanisms to achieve the targeted diagnostic coverage and to be able to enter a safe state if necessary or indicate failures to external components. Thus, the main focus is not on systematic errors¹³, which is the main focus for designs following RTCA/DO-254. On the device level the characteristic of a very high diagnostic coverage makes these products something special on the market and manufacturers are very encouraged in the realization and verification of the MCU's safety architecture.

The MCU development approach has to adhere to ISO 26262-5 and referenced parts. ISO 26262-10:2012 does not define conformance requirements but gives guidance especially on MCU development. It explains the SEooC method and describes in appendix A how it could be applied for MCUs. This concept allows the realization of a component like an MCU which is deployable to different application contexts: it is *built for reuse*. Therefore the manufacturer first assumes the safety requirements that could be allocated from the system level and architecture around the component. These assumptions are necessary to develop the MCU internal safety architecture. The system integrator has to follow the manufacturers assumptions and recommendations to preserve the integrity of the MCU safety architecture in the final system context. For ISO 26262 compliant MCUs typically an additional document type is released in order to inform the

¹¹ Part five of the standard is about product development at the hardware level.

 $^{^{12}\,}$ This demonstrates reasonableness of a dedicated COTS assurance process see section 2.2.

¹³ ISO 26262 implicitly addresses systematic errors for hardware through the development process.

integrator about the ISO 26262 related information essential for system integration activities: the *safety manual* or *safety application note*. In ISO 26262-10:2012 section A.3.10 an example on the content of the safety manual is given.

As only suggestions for the safety manual content is provided, it still worth to examine which aspects have been realized in published documents. In order to assess the potential benefits of the safety manual in an avionic COTS component assurance process, the content of a representative probe of three manuals from three different vendors was analysed. The selected MCUs target ISO 26262 Automotive Safety Integrity Level (ASIL) D. They have been selected to increase the value of the scope of this article and not if they are really suitable for the avionics industry. Thus, no analysis has been performed to check the suitability of these devices for avionics due to e.g. cosmic radiation or other environmental or functional issues such as *correct* set of interfaces. The selected MCUs with respective safety manuals are: NXP MPC5744P [22], ST SPC56ELx [23] and TI TMS570LC4x [24]. The content analysis of these manuals resulted in the following two major topics of interest that can be found in each of the examined safety manual in different level of detail:

- MCU safety architecture: It describes how random hardware fault management is separated between internal hardware diagnostics and additional software diagnostics. The examined MCUs employ a three layered approach:
 - 1. All hardware blocks required for software execution are equipped with the highest degree of diagnostic coverage by hardware safety mechanisms. Two cores operate in delayed lock step and data transfers between memory and the processing cores are protected by end-to-end error-correcting code. This shall assure, that the software execution is not impacted by random hardware faults.
 - 2. Based on the integrity of software execution, peripheral functions are mainly assured by software safety mechanism e.g. informational redundancy on application layer protocols.
 - 3. Debug functions should not be used in an operational safety-related system, thus no diagnostics are provided and recommended respectively.

Worst case fault recognition times of hardware diagnostics are stated together with the failure indication and handling by entering safe states of the MCU.

- Hardware and software requirements on system level: Here the assumptions are explained which have to be followed by the system integrator. Hardware requirements define the functionality of external hardware safety mechanism like supervision of the power supply. Software requirements describe the correct way to utilize the internal hardware safety mechanisms and how software could improve the diagnostic coverage depending on the used MCU hardware functions in the safety-related system.

The avionic manufacturer could benefit from the same aspects as the automotive system integrator: At first from the ISO 26262 certified development process of the manufacturer and the process-requirements documented in the ISO 26262 respectively. At second, the additional information from the safety manual may be used. It can be assumed that the AEH supplier may get further support from the MCU manufacturer only in a limited scope, if necessary. However, these are the only public available information that can be additionally reused in particular for ISO 26262 compliant MCUs in the COTS assurance evaluation process described in the next section.

3.2 COTS Component Assurance of ISO 26262 compliant MCUs

In section 2.2, COTS assurance activities were outlined on the basis of recommendations from [16] for simple and complex/highly complex MCUs. The presented selection of ISO 26262 compliant MCUs in section 3.1 cannot be classified as simple¹⁴ and MCUs aiming at an even lower ASIL level like ASIL A or B are often based on more complex architectures. For that reason and to examine all benefits from the ISO compliance statement for every assurance activity, a classification of highly complex is assumed. The COTS component assurance activities have to be conducted by the AEH supplier and some of them are achievable with minimal or no additional support by the MCU manufacturer. These activities have to be excluded from the evaluation because they can be accomplished with MCUs in general and to claim these as ISO 26262 specific benefits would falsify the assessment results. Thus the following activities were omitted from the evaluation:

- (1) Describing the COTS component characteristics in order to classify the MCU as simple/complex/highly complex is feasible on basis of the usual public available hardware documentation.
- (2) Archiving of collected device data like errata notes or user manuals can be performed without help of the MCU manufacturer
- (5) For usage the domain validation (part of activity (5)), the avionic system developer is responsible. Validation means, that a determined usage domain has to be checked if they do not contradict any higher level requirements from system/hardware/software. It is like requirements validation, to check if a low level requirement is a valid refinement of a higher level requirement. The COTS component manufacturer is not required for that task.
- (8) Documentation of past experience made with the MCU during the AEH development shall substantiate the robustness and maturity in the field. The MCU manufacturers are not involved in this action.
- (15) Architectural mitigation techniques addressing common modes on device level. They are implemented during system development and are on a higher level than the MCU itself¹⁵. No additional support for this work can be requested from COTS component manufacturers.

¹⁴ It is assumed that the full functional scope of the MCU is used and in that case it will be not practical to verify it on that extent on device level.

¹⁵ Note that on-chip MCU architectural mitigation techniques cannot be credited for common mode issues.

Table 1 gives an overview of the evaluation results. The considered assurance activities can make use of additional MCU artefacts in particular. They are assigned according to the identified top level arguments of section 2.2 and arranged in two groups resp.: Yes if a COTS component assurance activity benefits from the ISO 26262 compliance statement and no if that is not the case.

Top Level Argument	Assurance Activity	Benefits by ISO 26262
1. The component performs as described by the manufacturer without anomalous behaviour.	(3): Quality management and production (13),(14): PSE	No
	(4), (5), $(16)^{16}$: Usage domain (6), (7): Errata management (9), (10): Configuration management	Yes
2. The component as used satisfies the AEH requirements.	l (11), (12): Integration	Yes

Table 1: Evaluation Results Overview

For argument 1 no benefits can be directly asserted for activity (3), (13) and (14). Quality management and production process requirements in (3) can not be claimed to be defined by the ISO 26262. However, in a comprehensive ISO 26262 assessment process by a third party these aspects should also be checked. Activity (13) and (14) require the documentation of the PSE. The ISO 26262 also introduces a *proven in use argument* to claim a sufficient safety integrity, but no activities are defined that the MCU manufacturer has to document the usage of their products in the automotive field. It is notable, that MCU usage in the automotive safety critical sector is creditable if it can be adequately demonstrated.

The determination (4) and verification (5) of the usage domain profits from detailed data descriptions in the safety manuals including disabling on chip functions, test of activated functions, implementation hints, mandatory requirements, assumptions, and initial configurations. Safety mechanisms described in the safety manual can also be utilized in usage domain verification tasks. Taking into account errata documents during system integration is demanded in the examined safety manual [22,23,24]. They are published and sufficiently prepared in order to allow the system integrator to determine possible safety implications. Therefore, the errata management activities (6) and (7) should have an advantage by using a ISO 26262 compliant MCU. Assurance activities (9) and (10) request an adequate configuration management or change description approach by the MCU manufacturer and additional change impact analysis by the AEH developer. According to ISO 26262 part 8 a configuration management and change management plan shall be provided by the MCU manufacturer. In the safety manuals or errata documents the applicable device revision or product

¹⁶ Partitioning considerations were allocated to the usage domain analysis.

configurations are clearly stated. It is therefore assumed that COTS manufacturers configuration management is available and in good shape.

For argument 2 table 1 shows less assurance which activities benefit from an ISO 26262 compliant MCU. Actually, most AEH requirements are already determined and verified on device level in activity (4) and (5). Usage domain determination is a mapping of AEH requirements on basis of the adequate configuration and usage of the MCU. So the actual function and properties on device level designed by the manufacturer are reused as AEH requirements. In activity (11) AEH requirements from a higher level like LRU or CBA level allocated to the component have to be verified and validated. The device level description in the safety manual for I/O functions and software requirements may help in the validation and verification process for correct integration of the device. The assurance activity (12) demands a clear understanding of possible device failure modes and rates depending on its configuration. The safety manuals will help in this activity. Several failure scenarios are covered in these documents and failure rate calculations are one of the main topic of ISO 26262 hardware development.

4 Conclusion

In this article an insight was given in the differences of assurance approaches for AEH especially when equipped with complex COTS MCUs. Based on [16] a new structured overview was presented for the COTS hardware component assurance activities. Currently, no industry consensus standard or recommendation from certification authorities is available that brings all necessary COTS assurance aspects together in an integrated approach [15]. Therefore the presented assurance activities are supposedly not complete. However, the selected assurance activities provide an adequate foundation for the evaluation of possible benefits of ISO 26262 compliant MCUs during the assurance process. Specifics of ISO 26262 compliant MCUs were described to identify the aspects that could be reused. The evaluation concentrates on assurance activities where additional support by the MCU manufacturer is most helpful. It could be demonstrated that an ISO 26262 compliant MCU is beneficial for the AEH manufacturer by conducting certain assurance activities. However, the magnitude of these advantages depend on the dedicated context in which the MCU should be integrated.

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