Concept of the 3rd Generation of Reliability for Electronic Smart Systems

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ABSTRACT

We present a novel approach for reliability assessment of the future electronic control units and smart systems. This concept of 3rd generation reliability is based on application of hybrid prognostics and health management concept for the future safety relevant electronic control modules. This approach requires development of additional sensors and detectors to be integrated into the functional electronic units so that the reaction based on a current state of health status of the electronics can be triggered on demand.

KEY WORDS: prognostics and health management, predictive maintenance, canary devices, canary features.

INTRODUCTION

Development of automotive electronic systems is driven by three major trend: Electrification, Automation, and Connectivity. Each of these trends will bring specific reliability challenges:

- *Electrification* will revolutionize the entire powertrain and the required road infrastructure. Gradually but steadily, combustion engines will decrease their market share. Power electronics will be one of the key drivers of this development by remarkable innovations. For instance, utilizing SiC and silver sintering will increase the efficiency of power electronics and will allow higher operational temperatures, i.e., significantly less cooling effort. New encapsulating materials will be introduced to meet these new requirements. In addition, sensors and control electronics will be added directly to the power stages for enhanced performance and safety. This increases the heterogeneity and complexity of these systems. Still, they need to be developed in a shorter time and at lower cost.
- *Autonomous driving* will revolutionize transportation system. By 2025, conditionally and highly automated driving will reach SAE levels 3 and 4, respectively. By 2030, it will also be available in complex traffic situations, e.g., urban areas, and will reach SAE level 5. The autonomous vehicles will increase safety, provide greater comfort, and improve the traffic flows. New service modes seem to give a clear preference to car-sharing options over individual ownership. Consequently, the total operational time will significantly increase.
- *Connectivity* will force components, originally designed for consumer electronics market, to appear in harsh environments. Advanced integration and packaging schemes, such as system on chip (SoC) and system in package (SiP) based on smallest technologies nodes (e.g., 7 nm), will soon be introduced to automobiles with more than 10 years of reliable and fail-safe operation required. Permanent connectivity will massively increase the operational time of IC packaging and ECUs used in automotive. Self-learning activities and software updates will widely fill the parking times of the car.

All these challenges and requirements necessitate the development of a new reliability concept called prognostics and health management (PHM), which is strongly supported through numerical simulation and product optimization at a very early stage of product development.

PROGNOSTICS AND HEALTH MANAGEMENT

The reliability of electronic components and systems as a professional discipline has been established in 1960's. In the first generation of reliability assessment, the electronic components were qualified based on standards such as MIL-HDBK-217 [1]. In these assessment, a single point failure rate was assumed for all devices. In 1980's, several organizations found the rules of MIL-HDBK-217 to be inaccurate and resulting in misleading reliability prognosis for many of the new applications. In 1990's CALCE was awarded a three years governmental funded project to assess MIL-HDBK-217. It was concluded that the MIL-HDBK-217 and progeny had fundamental weaknesses. The 1st generation of reliability did not consider application requirements, but tried to define a worst case scenario already in the standard.

Next, CALCE got awarded another contract to develop physics of failure (PoF) models to replace MIL-HDBK-217. As result, new standards for reliability prediction were created: IEEE 1413 and 1413.1 [2-5]. We consider this as a 2nd generation of reliability. It is based on customer defined mission profiles, the strength of the materials, and the individual design element PoF. It is expressed by the number of cycles to failure, by the time to breakdown, or by the time of other damaging effects to result in out-of-spec behavior. The current best practice in developing new electronic systems follows this approach proactively by the 'design for reliability' (DfR) policy. The lifetime is already estimated virtually based on validated simulation schemes so that pre-optimized designs are used for fabrication the first physical samples of the new ECU's. The DfR approach aims for maintenance free systems by assuring sufficient lifetime while simultaneously optimizing cost and performance. DfR is ideal for the products that have an intended finite lifetime. Concisely, 2nd generation of reliability focuses on designing the robustness into the systems so that they are able to resist the specified service loads with a specified high rate for as long as planned without replacement or any adaption of their initial configurations to the new situation. However, it is not known, which parts belong to the small fraction that fails before the targeted lifetime. Hence, functional safety can only be assured by redundancies.

We postulate that for the electronic smart systems [6] used in future automotive applications, a 3rd generation of reliability is required. This 3rd generation of reliability assessment will introduce in-situ monitoring of the state of health on local (e.g., component) and global (ECU) levels. Prognostics and health managements is the key methodology (PHM). It marks the main difference between 2nd and 3rd generation. DfR concerns the total lifetime of a full population of systems under anticipated service conditions and its statistical characterization. PHM concerns the degradation of the individual system in its actual service conditions and the estimation of its specific remaining useful life (RUL). Ultimately, the reliability approach of 3rd generation shall allow assuring full functional safety with substantially less redundancy.

For monitoring the state of health (SoH) of smart electronic systems, we propose the following model (Fig. 1). It starts with sensing a signal and its recording over time. In the simplest case, we may assume a temperature sensor like it is used in every ASIC, microcontroller, microprocessor, and in most of the ECUs. The next level is responsible for acquiring the signal and its appropriate processing for evaluation of the actual status. For example, the structure function deduced from the thermal impedance [7] can be used as a key failure indicator (KFI) - particularly for lifetime estimations in power electronic components and modules. Subsequently, the data is compared to the reference taken from the unaged system. With no damage, the measured curve stays unchanged. If there is some degradation, the measured KFI status deviates from the reference, e.g., that thermal time constant will increase, which is characteristic for the failing interface [8] such as due to a starting delamination. The change in KFI status allows the detection the faults and the assessment of the SoH at local level. Based on the local KFI and the specifics of their failure modes, the RUL can be estimated for the complete module or system, which results in the global health score. Finally, the appropriate decision can be taken e.g., by activating an alternative operation modes or by triggering a preventive maintenance.

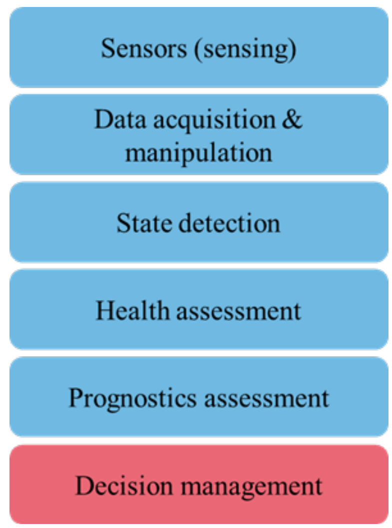

Fig. 1 PHM framework [9]

Traditionally, there are two PHM approaches in use: data driven (DD) and physics of failure (PoF). The DD estimates the current SoH of the system based on actual trend of measured parameters such as temperature, stress, etc. As an example, DD method is used to estimate the wear-out of die bonds under active power cycling, in which thermal impedance is used as an assessment parameter. In case of PoF, the physical failure mechanism is closely replicated by modeling and simulation. Solder joint fatigue can serve as example, in which the creep strain accumulated per thermal cycle is calculated by finite element analysis and the lifetime is then estimated by a Coffin-Manson model. Both methods, DD and PoF, have advantages as well as specific limitations. That is why our proposal is to use a fusion approach, which takes advantage of both, DD and PoF, so that the uncertainty in the damage prediction is reduced.

The PHM can be implemented in two steps:

- Step 1 - Condition monitoring (CM): Continuous SoH determination of the system and monitoring of the load the system and/or components are exposed to during operation.

- Step 2 - Prognostics and health management: – Determination of the RUL of a system based on the local and global indicators, KFI and health score.

These two steps allow the decision-making concerning the required system reactions.

PHM ARCHITECTURE

In order to develop a PHM methodology that can be used in future automotive systems there is a number of specific features to be developed.

Detector

An integrated signal-processing unit designed to detect anomaly or sudden change of state in the signals of the read-out circuitry. Typically, the detector will not make a decision but communicate to the local or central acquisition unit. Example of simple detector can be an ESD event detector.

Sensor

A sensor s a device that reacts to its physical environment (mechanical, temperature, humidity, etc.) or accumulated stress. Basic example can be temperature sensor.

Smart IC devices

Currently most of the microprocessor, microcontrollers and ASICs are equipped with temperature sensor. In the future, such devices will have additional detectors or sensors to measure local state of health. We call these devices smart IC devices, because they will allow for in-situ self-testing, –diagnostics and –deciding. These kind of ICs are not yet available on the market, although there is many research in this field [10-13]. The sensors newly used (or even introduced) will provide a trigger point based on which the estimation of RUL can be tried for the individual part and its service life.

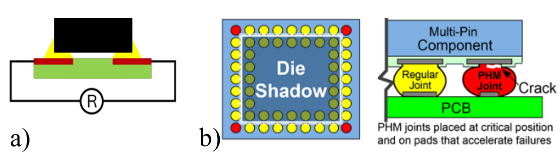

Fig. 2 a) canary device, b) canary feature [14]

Canary devices and canary features

Canary device [15] (Fig. 2a) is a simple device (small passive resistor or capacitor) without system function. It is designed overcritical or overstressed, acts as detector, and shall fail before the functional devices. Similarly, canary feature (Fig. 2b) is a single feature of a functional device (e.g. solder ball) that is designed overcritical or overstressed and is intended to fail before the features needed for the functionality.

Mechanical canary devices or features will be placed typically in the area of high stress. This will allow for early failure of this device, before functional device fails. Fig. 3 schematically shows a canary device located in the area of the screw and other functional devices placed in low stress area of the PCB.

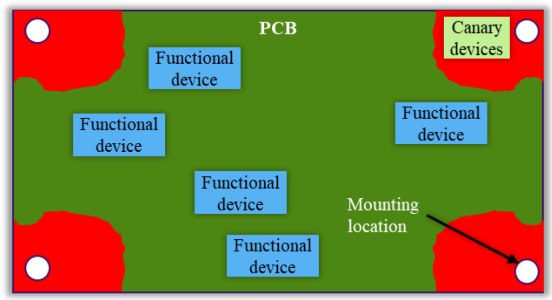

Fig. 3 Location of canary devices

Fig. 4. depicts schematically the concept of canary devices based on the example of SMD chip capacitor. This method allows to monitor the canary device that has no system function. In case, the capacitor fails, the early warning can be signaled to the user of a car required maintenance. The time of exchange of smart system is determined using state of the art lifetime models developed during development phase of the ECU.

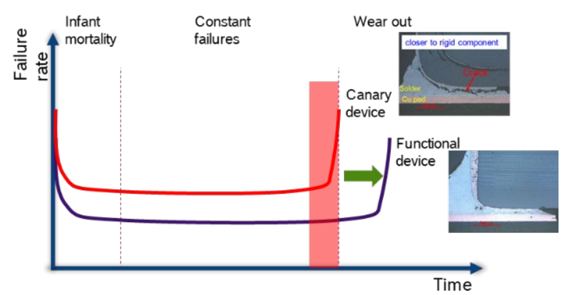

Fig. 4 Concept of end of life of canary device and functional device

Load counter

Operating conditions that automotive electronics experience vary significantly from location to location. Various sensors have been used in automobiles to document operating environments such as temperature, vibration, humility, etc. It is challenging to infer the stresses of advanced automotive electronics from these conventional sensors due to the complexity of these systems.

In order to monitor real loading conditions, advanced sensors that can measure stresses directly (e.g., piezo-resistive stress sensor) or calibrated numerical models should be employed. In our previous study [16], we demonstrated successfully a piezoresistive stress sensor as a load counter to monitor the lifetime of wire bond. The load counter function was obtained using a calibrated FEM model (Fig. 5). The load counter can be implemented in the field through a rainflow analysis.

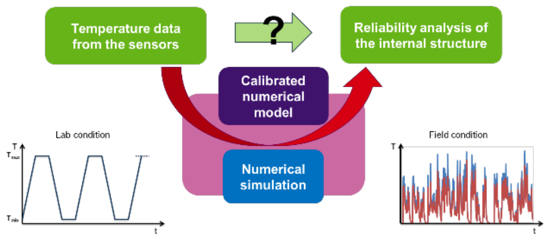

Fig. 5 Concept of load counter

Key failure indicators

Key failure indicator is a type of performance measure. KFI determines the current state of health of investigated design element. There will be different KFIs for different failure modes, and quite often for different failure mechanisms. The simplest example is the increase of the thermal impedance above 5% threshold that indicates wear-out of wire bond. We propose to have multiple local KFIs for different design elements, and one global KFI for entire smart system.

Artificial intelligence and machine learning

Artificial intelligence and in particularly machine learning will be a key enabler to make PHM for electronic smart systems available. The big challenge of reliability is very large number (>200) of failure modes [17]. Each mode can have more than one mechanism leading to failure – and vice versa. Multi-domain loading conditions (ambient temperature, internal heat generation, moisture, aggressive medium) makes it even more challenging. There is an enormous field for machine learning, with high expectation to progress on of fault classification. Still lot of research, especially on training of algorithms, is required before AI/ML will be used in the field.

Digital twin

Final estimation of the RUL in field application bases on the information from the sensors and canary features. The devices will be realized utilizing a concept of digital twin. Digital twin is a mathematical model of the physical system that in-situ evaluates data from the system (e.g. from temperature or moisture sensor) under investigation and compare with expected response (e.g. temperature or humidity) using metamodels. In the digital twin model, different patterns can be saved, and based on the answer of the metamodel estimation of the wear out can be done.

Digital twin will be a very important feature of future automotive smart systems [18] and will allow for continues analysis of the system state of health. As a result, the RUL of the individual system can be estimated accurately utilizing a "clone" of that system, so that predictive maintenance can be realized in practice.

RESILIENCE

Resilience is the ability of the system or component to resist a certain load change by adapting its initial stable configuration to the new situation. A resilient system includes detectors and sensors for in-situ event, error and aging detection. The system communicates to upper hierarchy level, e.g. to transmit health status or to coordinate alternative mode activation. Main goal of resiliency is compensation of the typical degradation and/or error of the system or components prior failure.

We consider that future resilient system will require four types of integrated sensors and detectors:

- *Indirect detectors* – that will estimate degradation of the electrical key functionalities. For example, by mission profile tracking.
- *Direct failure detectors* – monitor the function of a circuit block or the entire system, for example by comparing output signals to expectation or current consumption. Monitor output signals and through utilization of metamodels or digital twin are capable to estimate the state of health of the system.
- *Event logging detector* – provide a feedback to the system that the device was used in a limited operation conditions. Basic example is an ESD-event logger in case of electrical components.
- *Technology failure detectors* – observe wear-out that is not yet causing device or circuit block failures but indicate the onset of degradation. This can be seal ring integrity detectors, pad/IMD-crack detectors, corrosion detectors, or delamination detectors. Most of above-mentioned wear-out effects do not cause an electrical failure immediately but after a certain period, e.g., the propagation of mold compound delamination from a die corner may eventually lift the wire bond.

Once the analysis of detector information identifies a critical circuit condition, the resilience core initiates suitable compensation features, eventually involving upper system hierarchies in the decision. Obviously, the reaction is specific to the expected failure mode and must be available in time.

As a simple example, wear-out of non-volatile memory applications can be avoided by delaying the write access to the memory to a timeframe when the integrated circuit is at its moderate temperatures, storing the information in a volatile memory in between. Or for high performance SOI-CMOS, slightly increased supply voltage or forward-body-biasing techniques can compensate for degraded transistor performance.

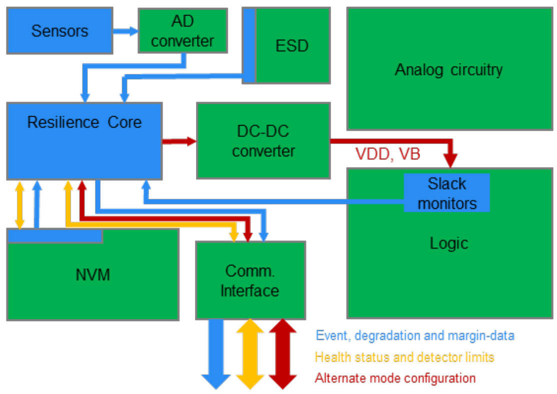

Fig. 6 A resilient IC system includes sensors, interfaces and a resilience core. Goal is to re-use existing circuit blocks to minimize additional area expenditure

Resilient systems allow detection of operation conditions that are qualified only for a limited time frame, and warn upper hierarchy levels if the qualified stress-level becomes violated.

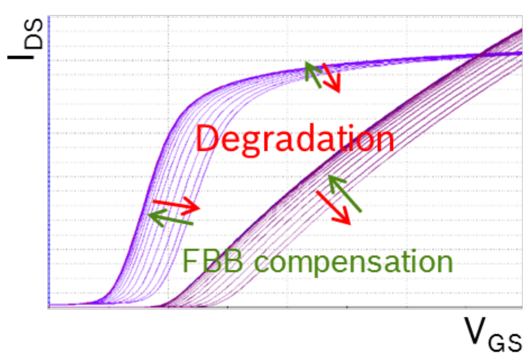

Fig. 7 Device degradation caused by combination of biased temperature stress and hot carrier injection can be compensated with forward body biasing techniques.

The priority for a resilient system is compensation, at least for limited time and eventually limited performance. But in case this is not possible, a preventive maintenance request is triggered.

PREDICTIVE MAINTENANCE

2nd generation of reliability aim for a maintenance free system. Miniaturization, increase of complexity, bringing the components from consumer electronics to the harsh environment such as automotive, will require new maintenance strategy. The anticipated heavy-duty use of automated cars can reduce the life span of electronics components. Therefore, a change in the design and reliability assessment towards maintainable or replaceable system is mandatory.

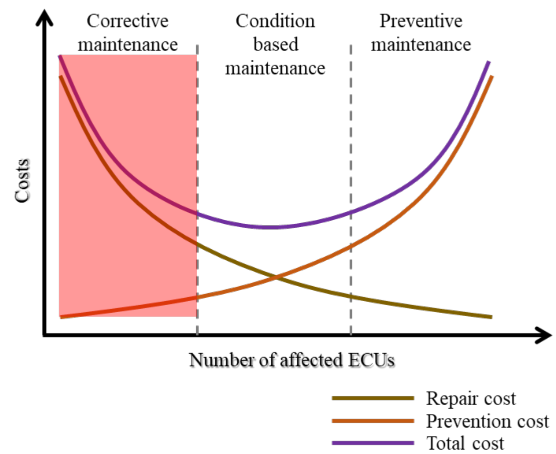

Fig. 8 Maintenance strategy vs. costs [19]

In order to realize the preventive maintenance in practice [19], the cost added needs to be considered. It is directly related to the number of components that may require maintenance. If the number is small (Fig. 8), the costs of the maintenance is high. When the number of affected ECUs increases, the cost of the proposed concept decreases so that the implementation becomes efficient for the customers.

Nowadays, there are three strategies available in automotive industry (Fig. 9):

- *Preventive maintenance* – parts are exchange after pre-defined time. Typical example in case of automotive is the oil. In case of electronics, it would mean that we still follow the 2nd generation of reliability following design for failure. Here the ECU

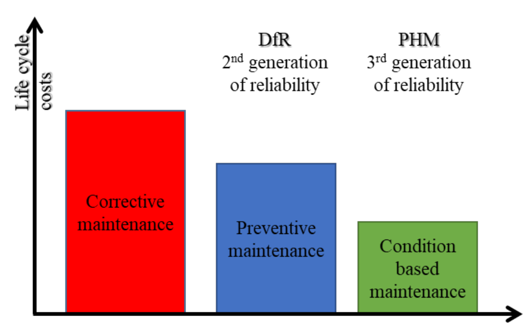

Fig. 9 Maintenance strategy [19] and its link to 2nd and 3rd generation of reliability

can be exchanged after pre-define operational interval.

- *Corrective maintenance* – exchange of the part happens after the part fail. As an example is the light bulb. For safety relevant electronics this approach is not favorable.
- *Condition based/preventive maintenance* – this is the maintenance strategy that can be applied based on the 3rd generation of reliability for electronic smart systems. PHM is a strategic approach as it will allow to estimate the state of health based on local and global failure indicators. The main factor is the cost-efficiency, as the parts will be exchange when they really need to be exchanged. Tires or batteries [20] are examples of automotive parts for which nowadays a preventive maintenance is currently in use.

CONCLUSION

Automotive electronics, especially autonomous driving, will be based on the 3rd generation smart systems and cyber physical systems. There is an urgent need to define new standards for reliability assessment and qualification criteria, which will account for the complexity of these systems including advanced packaging (SiP, PoP). Especially important is defining the responsibility for the specific design elements. Accordingly, the suppliers will request significantly more detailed information about the loading conditions in real applications. The package/board/system interaction will play a major role in this new effort.

Prognostics and health management, and resilience will revolutionize the concept of reliability assessment and pave the way for the 3rd generation of reliability, which will enable the auto industry to use electronic systems in autonomous cars, through realization of mission-profile-based estimation as a baseline for the RUL prediction.

Finally, condition based maintenance could be a solution to provide required reliability and safety for smart systems required for automated cars. Simultaneously, the total cost of electronics and maintenance could be reduced through more efficient strategy based on in-situ estimation of state of health of electronic systems using local and global health indicators.

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