A Proposal for Improvement of Smoke Detectors

Prof. Dr.-Ing. David Schepers[1] and M. Sc. Sarah Schwarzer[1]

[1] Hochschule Ruhr West, Duisburger Str. 100, 45479 Mülheim a.d.R., Germany

Abstract. Smoke detectors are used to warn people of hazards due to fire and smoke. When smoke is detected, an acoustic alarm signal is emitted in combination with a red flashlight signal. False alarms, which can be caused by component failures, are extremely undesirable, depending on the field of application.
Therefore, this paper presents a concept developed according to the requirements of the generic safety standard IEC 61508:2010. The aim of this development is to avoid false alarms due to component failures and additionally to increase the availability of the safety function (smoke detection). This concept includes a fault detection system that can detect all random hardware failures and assign them to the channel in which they occur. The channel, which is affected by the hardware failure can then be deactivated and the remaining channel is able to keep the safety function alive until the system is repaired or replaced.
Besides an introduction to the normative basics, the advantages of the newly developed safety architecture are described. Based on a comparison of the safety characteristics PFH_D and PFD_{avg} (Average Probability of Dangerous Failure per Hour and Average Probability of Dangerous Failure on Demand), it is argued why the newly developed circuit has an advantage compared to other (classic) structures. The long-term goal is to develop a smoke detector that meets all the requirements of IEC 61508:2010 (including the necessary measures for fault avoidance for hardware and software development). Thus, it can be shown that such a development offers considerable advantages compared to a development which consider the classic specific product standards for smoke detectors only.

Keywords: smoke detectors, reliability, functional safety, safety engineering, IEC 61508:2010

1 Introduction

The smoke detector is a "device in which all the components necessary to detect smoke and generate an acoustic alarm signal (with the possible exception of the power supply) are contained in a single housing". [1] It is essential for warning people of fire and smoke in case of such incident. A false alarm is “a warning or signal of danger that is given but is unnecessary”. [2] For this reason, false alarms are undesirable and very costly, depending on the application or environment. These false alarms are often caused by component failures. [3,4,5] There exist three different types of smoke detectors. However, this paper deals exclusively with scattered light smoke detectors. Because of this, only the principle of this type of smoke detectors, which belongs to the class of optical smoke detectors, will be explained. Basically, it contains a light-emitting diode and a photo element in its measuring chamber. The light emitting diode emits infrared radiation and the photoelement is able to detect it.

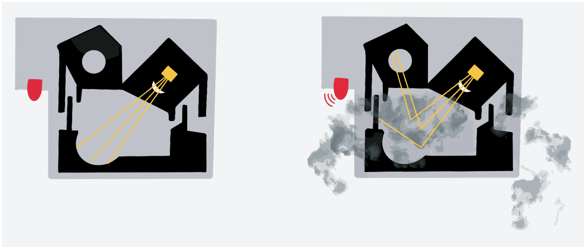

Fig. 1 General structure and fundamental functionality of a smoke detector

As shown in Fig. 1, only when there is smoke in the measuring chamber, the infrared radiation from the emitting diode will be scattered by the smoke particles and reach the photoelement, activating an alarm in order to warn people. Without smoke in the chamber, the infrared light falls onto the wall of the smoke detection chamber without reaching the photoelement. In this case, no alarm is activated.
A smoke detector developed in accordance with the functional safety requirements can avoid false alarms due to component failures and at the same time increase the availability of the smoke detection function if an appropriate architecture is applied. For this reason, such a development and the resulting advantages will be examined in more detail in this paper.

First, the current requirements and product standards for smoke detectors are presented. Both the general requirements (regarding the technical aspects) and the test requirements are discussed. Additionally, the requirements of functional safety are presented, which are defined in the generic safety standard IEC 61508:2010. After that, the advantages of the applied 1oo2D structure and the calculation of the PFH_D and PFD_{avg} values for this and other possible structures are discussed in order to draw a comparison between the different possible system structures. It shall be shown that the 1oo2D structure is the best structure for balancing the requirements for the availability of the smoke detection function and the avoidance of false alarms. Finally, the lessons learned from this publication are summarized and an outlook for future works is given.

2 Current Standards and Requirements for Smoke Detectors

The product standard for smoke detectors is EN 14604:2005, which specifies all technical and test requirements for smoke detectors. In addition, further specific requirements for scattered-light smoke detectors are defined in Part 7 of EN 54 standard series, which contains high-level requirements for fire alarm systems. The mentioned standards are European standards and currently there is no internationally applicable standard. Nevertheless, there are other directives that apply in addition to the above-mentioned European standards: UL 217:2020 9th Edition [6] and NFPA 72:2019 [7].

2.1 General Requirements

Chapter 4.2 of EN 54-7:2018 sets out requirements for operational reliability. These include, among other things, that each smoke detector must have its own red signal light so that it can be recognized which detector has triggered when the smoke detectors are reset (in case that several detectors are installed in the same room or facility). [8] Furthermore, both standards require protection against intrusion of foreign particles. This requirement is intended to prevent insects or other objects from entering the smoke detection chamber and thus triggering a false alarm. [1] If a smoke detector is software-controlled, the development of this must be documented accordingly. In addition, minor requirements are defined for the software development, such as modularization or the avoidance of endless loops in the program flow. [1]

2.2 Test Requirements

As required by EN 54-7, the smoke detectors must be tested regarding various influences. [8] These are carried out by using a test aerosol in a smoke channel setup. In the context of smoke detection, the response threshold is the measured aerosol density at the time the smoke detector emits an alarm signal. [8] The ratio between the largest measured response threshold and the lowest response threshold must not exceed defined limits. Some tests also require that the lowest response threshold does not fall below a certain value. In addition, individual tests require that the smoke detector emit or does not emit an alarm signal during or after that test. Furthermore, resilience against environmental influences (like supply voltage variation, artificial light sources, air humidity, high and low ambient temperatures, atmospheric contamination, corrosion, mechanical stress, vibration, EMC etc.) must be proven by appropriate tests (based on the relevant test standards).

However, the requirements of EN 54-7 and EN 14831 do not include the relevant aspects of functional safety. Only disturbing (environmental) influences are assumed to be the cause of false alarms, whereby false alarms can also be triggered due to component failures. And of course, the smoke detection function might fail due to component failures.

3 Functional Safety Requirements for Advanced Reliability

Functional safety is a part of the overall safety that depends on the correct functionality of a safety-related E/E/PE system (electrical/electronic/programmable-electronic). For the purpose of risk reduction on technical equipment and systems, a risk assessment is carried out in a first step in order to reveal which risks emanate from the technical equipment. The identified risks must then be mitigated by means of suitable measures.

A hierarchical approach is applied: First, constructive measures are carried out. If risks continue to exist afterwards, safety functions are implemented. This is where functional safety comes into play: Safety functions (normally consisting of sensors, logic units and actuators) are installed to detected possible dangerous situations and to react in an appropriate manner to avoid any harm. Finally, possible residual risks are displayed via warnings and information in the user manual etc.

IEC 61508:2010 is a basic and generic standard for functional safety. It contains requirements for the development of hardware and software for E/E/PE systems independent of the intended application, whereas other functional safety standards are tailored for certain application sectors (e. g. EN ISO 13849 for machinery). [9] It considers the entire life cycle of a system from specification to decommissioning. [10] For each phase, requirements are defined that are intended to ensure functional safety. These include, in particular, the avoidance of systematic faults (e.g. errors in the specification of the safety function) and the control of random failures (e.g. component failure due to aging). In addition, the documentation of all activities during each lifecycle phase is an essential part for ensuring functional safety. For each safety function, which shall be applied for risk mitigation, a so-called Safety Integrity Level (SIL) must be assigned according to the level of risk. The higher the risk to be mitigated, the higher the required SIL. Possible levels are 1, 2, 3 or 4, where level 1 is the lowest and level 4 the highest level. The higher the SIL, the more rigid are the measures for fault avoidance and fault control which must be applied for developing the safety function. In probabilistic terms, the safety integrity of a safety function corresponds to a defined maximum allowable level for the probability of a dangerous failure (i.e. maximum allowable PFH_D and PFD_{avg} values). [11] These certain levels for the different Safety Integrity Levels are specified in IEC 61508:2010. For the determination of the SIL, not only the probability for a dangerous failure but also several other parameters must be determined which will be discussed later. Part six of the standard describes different system architectures that can be used to design the respective safety-related system. The formulas for calculating the PFH_D and PFD_{avg} values for the respective structure are also given in this part. Basically, a system consists of sensor, logic and actuator subsystems.

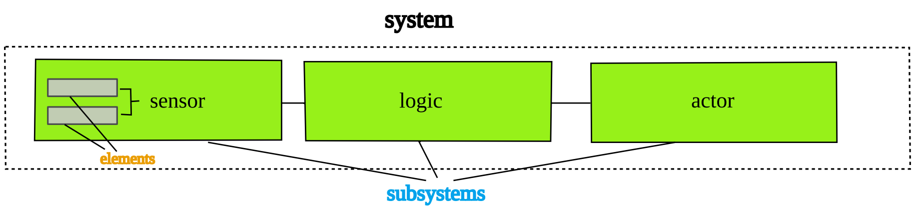

Fig. 2 general system architecture

Fig. 2 shows such a system. The subsystem may consist of several (redundant) elements. In the example, the sensor system consists of two redundant elements whereas logic and actuator are single-channel elements. This means, that if one subsystem of the single-channel system fails, the entire system fails. For example, if the logic unit failed, the smoke detection sensors could not be evaluated anymore so that in case of a fire, no alarm would be triggered. The Association of Property Insurers in Germany has explained in one of its leaflets that a development according to IEC 61508 means a considerable additional expenditure of time and money. It is argued that all the necessary requirements are specified in the product and system standards for smoke detectors (e.g. EN 54 and EN 14604). [12] From our point of view, for certain applications, which require high reliability of the smoke detection function and a low level of false alarms, development in accordance with the basic safety standard IEC 61508 might nevertheless be advantageous, since the frequency of false alarms can be reduced or even completely avoided, which helps to reduce costs for (unnecessary) fire brigade operations. And of course, the higher reliability of smoke detectors may also help to save lives.

4 Application of 1oo2D Structure: Advantages

An optimized circuit was developed for the sensor system of a scattered light smoke detector, which enables all component failures in the sensor system to be detected and assigned to the channel in which the failure occurred. This was made possible by applying the 1oo2D structure (Fig. 3).

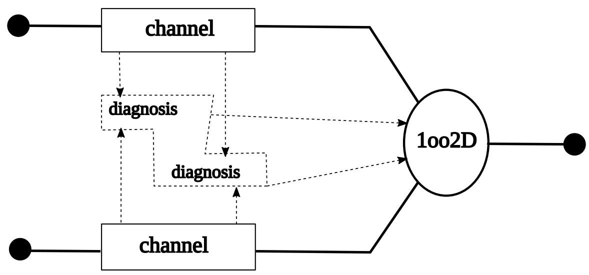

Fig. 3 1oo2D structure

In addition to improved fault detection characteristics, this design also offers increased availability of the detection function. If one channel fails due to a component failure, it can be deactivated and the other channel can continue to operate normally until the device will be replaced. Fault detection is done by means of an intelligent self-testing algorithm which is capable to distinguish between a fault in the channel and the detection of smoke. For this purpose, each channel is able to test itself and use the second channel as a reference. Thus, this concept is superior in terms of safety and availability compared to a classic single channel approach without any functional safety characteristics. In the newly developed concept, both a warning light for the alarm and a warning light for a failure were installed. This allows the user to recognize that a new smoke detector must be installed in case of a faulty channel before the second channel also fails and the smoke detector loses its intended functionality. Each channel in the sensor system consists of seven resistors, two transistors and two diodes (IR LED and photo diode) only. The logic unit consists of two simple microcontrollers that exchange information for reasons of diagnosis (cross-checking). The actuator consists of a piezo speaker and a simple amplifier circuit.

5 Results: Calculation of PFH_D/PFD_{avg} Values and Comparison to other Safety Structures

The safety parameters PFH_D and PFD_{avg} have to be calculated for SIL classification. These values represent average probabilities for dangerous failures, but with different scopes. Dangerous failure means, that the detector loses its capability to detect smoke due to a component failure. PFH_D is the average probability for a dangerous failure per hour and can be applied to classify high-demand applications (i.e. for applications, where the safety function operates in continues mode or at least one time a year). In the case of the smoke detector, this means, that the detector is triggered or subjected to a functional test (maintenance) at least once a year. PFD_{avg} is the average probability of a dangerous failure on demand and can be applied to classify low-demand applications (i.e. for applications, where the safety function is operated less than once a year). In the case of the smoke detector, this means, that the PFD_{avg} value reflects the probability, that the smoke detection fails in case of a fire incident during a long period (like 10 years) in home use without any functional test within this period. As the final application of the smoke detector is not known (high-demand mode with regular tests or low-demand mode without any test), both safety parameters will be calculated in this paper. Besides the failure rates of all applied electronic components, the quality of the fault detection mechanisms (diagnostic coverage), the probability for common cause failures (both channels fail due to a single cause), the mean repair time and mean time to restoration in case of a failure, the proof test interval (interval for complete repeat testing) and the capability of a self-test to switch over to the second channel in case of a failure must be determined for the calculation of the safety parameters PFH_D and PFD_{avg}:

The diagnostic coverage (DC) can be determined by means of two methods. It is possible to estimate the DC by using tables in IEC 61508 or EN 13849. These tables define standard fault detection mechanisms and their equivalent DC. [13, 9] The second method is to perform a Failure Mode and Effect Analysis (FMEA), which was used for the optimized smoke detector because there do not exist any estimations of the DC for this newly developed fault detection concept. The respective failure modes were determined for each applied component and their effects on the smoke detector system were evaluated. Based on this analysis, a classification into

- Safe failures (λ_{SD})
- Dangerous, but detected, failures (λ_{DD})
- Dangerous undetected failures (λ_{DU})

could be made. By means of this FMEA classification, the DC could be determined to be at least 90%, i.e. at least 90% of dangerous component failures can be detected in each channel.

Common cause failures are classified by means of β-factors according to IEC 61508 (proportion of dangerous failures which affect both channels). [14] The values β and β_D are set very conservatively to 5% each. Furthermore, the mean repair time (MRT) is set to a duration of two weeks, since it cannot be assumed that every user of the smoke detector will immediately repair or replace it. The mean time to restoration (MTTR) is assumed to be six weeks, since it is possible that the user is on vacation, for example, and thus will not notice the warning light which indicates a faulty channel. The parameter T_1 was set to 20 years, which corresponds to 175 000 h. According to IEC 61508, T_1 is defined as the interval at which a complete repeat test takes place (i.e. not just a simple functional test). Since such a test does not take place in this smoke detector, T_1 was assumed to be the maximum permissible operating time.

For the 1oo2D structure, a factor K must be determined in order to consider the fact, that the channel comparison / switch over mechanism may not be 100 % efficient, i.e. K represents the efficiency of this inter-channel comparison and switching mechanism. The FMEA which was performed for the newly developed design showed, that K can be set to 90%. This assumes, that the (redundant) logic unit works reliably and a high DC is achieved.

The failure rates for the components were taken from the Siemens standard SN 29500 [15, 16, 17]:

Table 1. Failure rates

Component	Failure rate (λ in FIT)
Diode	1
Resistor	5
transistor	3
Capacitor	10
Piezoelectric element	30
Microcontroller	150

The total failure rate of the sensor system is calculated to 43 FIT. For the logic unit, the total failure rate is 150 FIT and for the actuators 28 FIT.

The division of safe failures and dangerous failures is based on the conservative “50/50-approach”. According to IEC 61508 it can be assumed, that 50% of failures in a technical system or device are safe and 50% are dangerous. The weighting of the dangerous failures into dangerous detected failures and dangerous undetected failures results from the DC. Thus, the following values can be derived for the different subsystems of the smoke detector:

Table 2. Proportion of the failure rate

	Sensory	Logic	Actuator
λ	43 FIT	150 FIT	28 FIT
$\lambda_S = \lambda_D$	21.5 FIT	75 FIT	14 FIT
λ_{DD}	19.35 FIT	67.5 FIT	12,6 FIT
λ_{DU}	2.15 FIT	7.5 FIT	1,4 FIT

For both logic unit and actuator, a DC of 90% is also assumed, to be achieved through appropriate testing.

5.1 1oo2D Structure

The following formula is used to calculate PFH_D and PFD_{avg} for the 1oo2D structure [14]:

$$PFD_{avg} = 2(1-\beta)\lambda_{DU}\big((1-\beta)\lambda_{DU} + (1-\beta_D)\lambda_{DD} + \lambda_{SD}\big)t_{CE}'t_{GE}' + 2(1-K)\lambda_{DD}t'_{CE} + \beta\lambda_{DU}\left(\frac{T_1}{2} + MRT\right) \quad (1)$$

$$PFH_D = 2(1-\beta)\lambda_{DU}\big((1-\beta)\lambda_{DU} + (1-\beta_D)\lambda_{DD} + \lambda_{SD}\big)t'_{CE} + 2(1-K)\lambda_{DD} + \beta\lambda_{DU} \quad (2)$$

$$\text{with } t'_{CE} = \frac{\lambda_{DU}\left(\frac{T_1}{2}+MRT\right)+(\lambda_{DD}+\lambda_{SD})MTTR}{\lambda_{DU}+(\lambda_{DD}+\lambda_{SD})} \quad (3)$$

$$\text{and } t'_{GE} = \frac{T_1}{3} + MRT \quad (4)$$

Calculation for Sensor System:

$$t'_{CE\_Sensor} = \frac{(2.15\cdot10^{-9}h^{-1})\left(\frac{175200\,h}{2}+336\,h\right)+(19.35\cdot10^{-9}h^{-1}+21.5\cdot10^{-9}h^{-1})\cdot1008\,h}{(2.15\cdot10^{-9}h^{-1})+((19.35\cdot10^{-9}h^{-1})+(21.5\cdot10^{-9}h^{-1}))} = 5354.4\,h$$

$$t'_{GE} = \frac{T_1}{3} + MRT = \frac{175200\,h}{3} + 336\,h = 58736\,h$$

$$PFD_{avg\_Sensor} = 2(1-0.05)(2.15\cdot10^{-9}h^{-1})\big((1-0.05)(2.15\cdot10^{-9}h^{-1}) + (1-0.05)(19.35\cdot10^{-9}h^{-1}) + (21.5\cdot10^{-9}h^{-1})\big)\cdot5354.4h\cdot58736\,h + 2(1-0.9)(19.35\cdot10^{-9}h^{-1})\cdot5354.4h + 0.05\cdot(2.15\cdot10^{-9}h^{-1})\left(\frac{175200\,h}{2}+336\,h\right) = \mathbf{3.0228\cdot10^{-5}}$$

$$PFH_{D\_Sensor} = 2(1-0.05)(2.15\cdot10^{-9}h^{-1})\big((1-0.05)(2.15\cdot10^{-9}h^{-1}) + (1-0.05)(19.35\cdot10^{-9}h^{-1}) + (21.5\cdot10^{-9}h^{-1})\big)\cdot5354.4 + 2(1-0.9)(19.35\cdot10^{-9}h^{-1}) + 0.05(2.15\cdot10^{-9}h^{-1}) = \mathbf{3.9784\cdot10^{-9}h^{-1}}$$

Calculation for Logic Unit:

$$t'_{CE\_Logic} = \frac{(7.5\cdot10^{-9}h^{-1})\left(\frac{175200\,h}{2}+336\,h\right)+(67.5\cdot10^{-9}h^{-1}+75\cdot10^{-9}h^{-1})\cdot1008\,h}{(7.5\cdot10^{-9}h^{-1})+((67.5\cdot10^{-9}h^{-1})+(75\cdot10^{-9}h^{-1}))} = 5354.4h$$

$$PFD_{avg\_Logic} = 2(1-0.05)(7.5\cdot10^{-9}h^{-1})\big((1-0.05)(67.5\cdot10^{-9}h^{-1}) + (1-0.05)(7.5\cdot10^{-9}h^{-1}) + (75\cdot10^{-9}h^{-1})\big)\cdot5354.4h\cdot58736\,h + 2(1-0.9)(67.5\cdot10^{-9}h^{-1})\cdot5354.4 + 0.05\cdot(7.5\cdot10^{-9}h^{-1})\left(\frac{175200\,h}{2}+336\,h\right) = \mathbf{10.5916\cdot10^{-5}}$$

$$PFH_{D\_Logic} = 2(1-0.05)(7.5\cdot10^{-9}h^{-1})\big((1-0.05)(7.5\cdot10^{-9}h^{-1}) + (1-0.05)(67.5\cdot10^{-9}h^{-1}) + (75\cdot10^{-9}h^{-1})\big)\cdot5354.4h + 2(1-0.9)(67.5\cdot10^{-9}h^{-1}) + 0.05(7.5\cdot10^{-9}h^{-1}) = \mathbf{13.8862\cdot10^{-9}h^{-1}}$$

Calculation for Actuator:

$$t'_{CE\_Actor} = \frac{(1.4\cdot10^{-9}h^{-1})\left(\frac{175200\,h}{2}+336\,h\right)+(12.6\cdot10^{-9}h^{-1}+14\cdot10^{-9}h^{-1})\cdot1008\,h}{(1.4\cdot10^{-9}h^{-1})+((12.6\cdot10^{-9}h^{-1})+(14\cdot10^{-9}h^{-1}))} = 5354.4h$$

$$PFD_{avg\_Actor} = 2(1-0.05)(1.4\cdot 10^{-9}h^{-1})\big((1-0.05)(1.4\cdot 10^{-9}h^{-1}) + (1-0.05)(12.6\cdot 10^{-9}h^{-1}) + (14\cdot 10^{-9}h^{-1})\big)\cdot 5354.4h\cdot 58736\,h + 2(1-0.9)(12.6\cdot 10^{-9}h^{-1})\cdot 5354.4h + 0.05\cdot (1.4\cdot 10^{-9}h^{-1})\left(\frac{175200\,h}{2} + 336\,h\right) = \mathbf{1.9671\ \cdot 10^{-5}}$$

$$PFH_{D_{Actor}} = 2(1-0.05)(1.4\cdot 10^{-9}h^{-1})\big((1-0.05)(1.4\cdot 10^{-9}h^{-1}) + (1-0.05)(12.6\cdot 10^{-9}h^{-1}) + (14\cdot 10^{-9}h^{-1})\big)\cdot 5354.4h + 2(1-0.9)(12.6\cdot 10^{-9}h^{-1}) + 0.05(1.4\cdot 10^{-9}h^{-1}) = \mathbf{2.5903\cdot 10^{-9}}\boldsymbol{h^{-1}}$$

Total Values:

$$PFD_{avg\_\text{total}} = PFD_{avg\_Sensor} + PFD_{avg\_Logic} + PFD_{avg\_Actor} = \mathbf{1.5582\cdot 10^{-4}}$$
$$PFH_{D\_total} = PFH_{D\_Sensor} + PFH_{D\_Logic} + PFH_{D\_Actor} = \mathbf{2.0455\cdot 10^{-8}}\boldsymbol{h^{-1}}$$

The following calculations are based on the formulas of IEC 61508 [14] as well. Only the final results will be presented for reasons of simplification.

5.2 1oo1 Structure

As shown in Fig. 2, the 1oo1 structure consists of one channel only. In the event of a component failure in the sensor system, either a false alarm would be triggered immediately or the failure would immediately lead to unavailability of the safety function.

Fig. 4 Block diagram of 1oo1 structure

$$PFD_{avg\_total} = PFD_{avg\_Sensor} + PFD_{avg\_Logic} + PFD_{avg\_Actor} = 1.8834\cdot 10^{-3} + 6.57\cdot 10^{-3} + 1.2264\cdot 10^{-3} = \mathbf{9.6798\cdot 10^{-3}}$$
$$PFH_{D\_total} = PFH_{D\_Sensor} + PFH_{D\_Logic} + PFH_{D\_Actor} = 21.5\cdot 10^{-9}h^{-1} + 75\cdot 10^{-9}h^{-1} + 14\cdot 10^{-9}h^{-1} = \mathbf{110.5\cdot 10^{-9}}\boldsymbol{h^{-1}}$$

5.3 1oo2 Structure

In this structure, each channel performs the smoke detection function. If one of the channels fails, the other can still perform the function. This redundant structure allows that the loss of one channel does not immediately lead unavailability of the detection function. If one or both channels detect smoke, an alarm is triggered immediately. The same happens, if a dangerous failure is detected in one of the channels, i.e. the probability of a false alarm is significantly higher in 1oo2 structure than in 1oo2D structure.

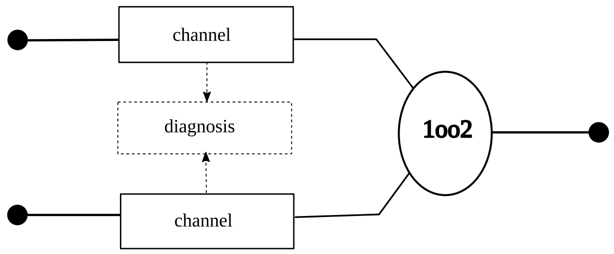

Fig. 5 Block diagram of 1oo2 structure

$$PFD_{avg\_total} = PFD_{avg\_Sensor} + PFD_{avg\_Logic} + PFD_{avg\_Actor} = 1.0483 \cdot 10^{-5} + 3.7046 \cdot 10^{-5} + 0.6814 \cdot 10^{-5} = \mathbf{5.4343 \cdot 10^{-5}}$$

$$PFH_{D\_total} = PFH_{D\_Sensor} + PFH_{D\_Logic} + PFH_{D\_Actor} = 1.0831 \cdot 10^{-10} h^{-1} + 3.8485 \cdot 10^{-10} h^{-1} + 0.703432 \cdot 10^{-10} h^{-1} = \mathbf{5.6350 \cdot 10^{-10} h^{-1}}$$

5.4 2oo3 Structure

This structure applies a total of three channels to perform the safety function. This architecture consists of three channels connected in parallel with a majority voting arrangement for the output signals, such that the output state is not changed if only one channel gives a different result which disagrees with the other two channels. It is assumed that any diagnostic testing would only report the faults found and would not change any output states or change the output voting. [14] However, if a second channel fails before the previously failed channel could be repaired, the entire system will fail. This system structure is often used in the process industry because the 2oo3 structure ensures high availability of the facility in combination with a high safety level, which is particularly important in the process industry. [18] The disadvantage of this structure are higher costs due to the application of three channels in total.

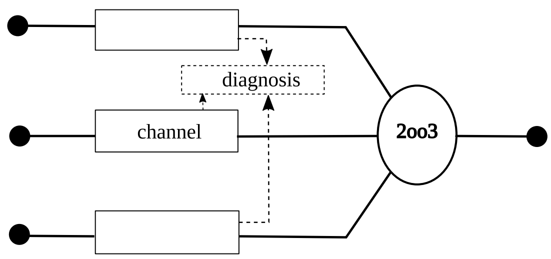

Fig. 6 block diagram of 2oo3 structure

$$PFD_{avg\_total} = PFD_{avg\_Sensor} + PFD_{avg\_Logic} + PFD_{avg\_Actor} = 1.0593 \cdot 10^{-5} + 3.8382 \cdot 10^{-5} + 0.68604 \cdot 10^{-5} = \mathbf{5.58354 \cdot 10^{-5}}$$

$$PFH_{D\_total} = PFH_{D\_Sensor} + PFH_{D\_Logic} + PFH_{D\_Actor} = 1.0993 \cdot 10^{-10} h^{-1} + 4.0455 \cdot 10^{-10} h^{-1} + 0.7103 \cdot 10^{-10} h^{-1} = \mathbf{5.8551 \cdot 10^{-10} h^{-1}}$$

If the PFH_D or PFD_{avg} values of the different structures are compared with each other, it can be seen that 1oo2 and 2oo3 usually have slightly better values regarding the probabilities of a dangerous failure than the implemented 1oo2D structure. Within the 1oo1 structure, a component failure will immediately trigger a false alarm or the smoke detector will fail without detection of the failure and this structure shows the highest probabilities for dangerous failures. The 1oo2 structure has a significant lower average probability of failure than the 1oo1 structure and does not fail undetected in most cases. Nevertheless, an increased probability for false alarms is also present for this structure as detected component failures lead to a false alarm in most cases. In contrast to that, the 1oo2D structure is able to switch to the second channel and deactivate the faulty channel in case of most detected component failures. The 2oo3 structure has higher availability of the facility and the average probability of dangerous failures is also lower than the 1oo2D structure, but its main disadvantage is, that this system structure is more expensive than the 1oo2D structure. The 1oo2D structure is also a little bit more expensive than the 1oo2 structure (because some additional components are required for the intelligent fault detection mechanism). But to put it in a nutshell, the 1oo2D structure is a good compromise between availability, failure probability and cost intensity. It can be shown that the introduced concept of the newly developed smoke detector sensor system fulfils the requirements for high reliability and high safety levels up to SIL 3 according to IEC 61508.

6 Conclusion and Outlook

In the first part of this publication, the current normative requirements for smoke detectors were presented. Based on this, it was shown, that only fundamental requirements for functional safety are considered in actual smoke detector architectures. Subsequently, the relevant requirements of functional safety were shown based on the basic safety standard IEC 61508:2010. The advantages of the 1oo2D structure were described for a smoke detector built in this structure. In addition, the PFH_D and PFD_{avg} values were calculated for 1oo1, 1oo2, 1oo2D and 2oo3 structures, respectively. A comparison of these values showed that the structures either have a high a probability for dangerous failures, show limitations regarding possible false alarms or are associated with high costs. Thus, based on these parameters, it could be shown that the 1oo2D structure is an excellent compromise between availability, failure probabilities and cost intensity.
Currently, the newly developed smoke detector sensor technology is still in a prototype status and the development of the logic and actuator technology is still pending. To achieve a high DC value for the logic, two simple microcontrollers should be applied (as already assumed in the calculations), which check their functionality via cross monitoring. The microcontrollers are also necessary for the implementation of the intelligent fault detection algorithm which is applied for fault detection in the sensory system. In addition to that, the microcontrollers should be equipped, among others, with self-tests such as a RAM test. The RAM test is applied to detect permanent errors in the RAM of the microcontroller so that the memory function can no longer be executed correctly. [19] Further functional units of the microcontroller must be tested as well,

like registers, ALU, invariant memory, communication units, clock, interrupt handling, IOs, power supply etc. If these self-tests are implemented, a DC of 90% can be achieved for the logic unit. Suitable fault diagnostics must also be developed for the actuator system. For example, the piezoelectric element can be analyzed by measuring the impedance. Based on the impedance, it is possible to make a statement about the mechanical condition of the actuator. [20]

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