Functional Safety for Electronic Control

HYDAC ELECTRONIC

Functional Safety for Electronic Control

April 20, 2016

Speaker
Eric Ringholm
HYDAC ELECTRONIC Division Manager
Functional Safety for Electronic Control
Functional Safety for Electronic Control
Component range for modern machines
Functional Safety for Electronic Control
Product Range
Functional Safety for Electronic Control

Agenda

- Functional safety, why?
- Relevant standards
- First steps to designing a machine
- System design
- Example system design
- Software design
Functional Safety for Electronic Control
Functional Safety for Electronic Control
Technological Progress
### Functional Safety for Electronic Control

#### Resulting requirements with regards to the components

**Complexity of a combine harvester**

- 8 CAN buses and 1 LIN bus (max. 5 per vehicle)
- Up to 25 controllers per vehicle
- > 80 electrical and electronic major functions
- >1000 sub functions
- >3000m electrical wiring
- >350 plug connections

**Controllers, the innovative force**

<table>
<thead>
<tr>
<th>The software content in a Wirtgen new generation large-size stone mill</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Application SW</strong> (without firmware)</td>
</tr>
<tr>
<td>• More than 65,000 lines of software code</td>
</tr>
<tr>
<td>• More than 200 components, modules and functions</td>
</tr>
<tr>
<td>• More than 600 global variables</td>
</tr>
<tr>
<td>• More than 4000 local variables</td>
</tr>
<tr>
<td>• 4 CANbuses using different protocols</td>
</tr>
</tbody>
</table>

**Machines with an increasing number of functions and with a complex system design, require:**

- More components with increased Functional Safety
- More components with self diagnostic functions
Functional Safety for Electronic Control

- Functional Safety
- Diagnosis
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Safety standards, comparable across all industry sectors

The system requirements are highly diverse!

Mainly Fail-Safe

Fail-Operational
Functional Safety for Electronic Control
Legal provisions, situation of the standards

CE Mark: Self-declaration from the manufacturer, all the relevant EU regulations are met

Legal basis: Machinery Guideline 2006/42/EG
Work equipment use directive 89/655/EWG

Required: Risk analysis, risk evaluation
Standard-compliant product design
Technical documentation, operation manual

Relevant standards:

**Type-A-Standards**
z.B. EN ISO 12100

**Type-B-Standards**
z.B. EN ISO 13849

**Type-C-Standards**
z.B. DIN EN 16228

Basic safety standards: Methodology, superordinate

Group safety standards: Safety of machines

Product safety standards: Drilling equipment
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Legal provisions, situation of the standards

Machinery guideline

Product safety

A standards: Basic safety standards

B standards: Group safety standards

C standards: Product safety standards

DIN EN 12999
Loader cranes

EN 13000
Mobile cranes

EN 474
Earth moving machines

EN 4254
Agricultural machines

EN 15000
Material handling

EN 16228 i.V.
Drilling machines
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Extract from the relevant standards

ISO 25119:2010, Tractors and machinery for agriculture and forestry — Safety related parts of control systems

This part of ISO 25119 sets out general principles for the design and development of safety-related parts of control systems (SRP/CS) on tractors used in agriculture and forestry, and on self-propelled ride-on machines and mounted, semi-mounted and trailed machines used in agriculture. It can also be applied to municipal equipment (e.g. street-sweeping machines). It specifies the characteristics and categories required of SRP/CS for carrying out their safety functions.

This part of ISO 25119 is applicable to the safety-related parts of electrical/electronic/programmable electronic systems (E/E/PES). As these relate to mechatronic systems, it does not specify which safety functions or categories are to be used in a particular case.

It is not applicable to non-E/E/PES systems (e.g. hydraulic, mechanic or pneumatic).


This International Standard specifies performance criteria and tests for functional safety of safety-related machine-control systems (MCS) using electronic components in earth-moving machinery and its equipment, as defined in ISO 6165. The procedures of ECE R79, Annex 6, ISO 13849-1 or IEC 62061 can be used as an alternative, provided verification and testing is carried out by the manufacturer using Clause 7 of this International Standard.

ISO 13849-1:2006, Functional safety — Safety related parts of a control system

This part of ISO 13849 provides safety requirements and guidance on the principles for the design and integration of safety-related parts of control systems (SRP/CS), including the design of software. For these parts of SRP/CS, it specifies characteristics that include the performance level required for carrying out safety functions. It applies to SRP/CS, regardless of the type of technology and energy used (electrical, hydraulic, pneumatic, mechanical, etc.), for all kinds of machinery.
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First steps to designing a machine
DIN EN ISO 12100: Safety Analysis

Safety analysis of machines according to DIN EN ISO 12100

Safety measures (3 Steps)

1. Inherent safe construction
   Construction / design measures w/o controls with adequate risk reduction according to EN ISO 13849

2. Technical safety measures
   One possibility are safety functions with electric/electronic/programmable control systems.
   Proof that required safety level was achieved according to IEC 61508 or EN ISO 13849

3. User information
   Last option, proof that step 1 + 2 are not possible
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Comparison between SIL and PL

<table>
<thead>
<tr>
<th>Probability of dangerous failures per hour</th>
<th>SIL Safety Integrity Level EN 62061 (IEC 61508)</th>
<th>PL Performance Level EN 13849-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^-8</td>
<td>3</td>
<td>e</td>
</tr>
<tr>
<td>10^-7</td>
<td>2</td>
<td>d</td>
</tr>
<tr>
<td>10^-6</td>
<td>1</td>
<td>c</td>
</tr>
<tr>
<td>3x10^-6</td>
<td></td>
<td>b</td>
</tr>
<tr>
<td>10^-5</td>
<td></td>
<td>a</td>
</tr>
<tr>
<td>10^-4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SIL: Safety Integrity Level
PL: Performance Level

a < b < c < d < e
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The right choice
Functional Safety for Electronic Control
Comparison EN 13949 with IEC 62061, SIL or PL?
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DIN EN ISO 13849 design process
- Safety related parts of control systems SRP/CS
- For each relevant safety function

1. Identify safety functions
2. and properties of SF

3. Define required
   Performance level $PL_r / AgPL_r / SIL_r$

4. Realisation of safety functions,
   Identification of SRP/CS

5. Calculation of achieved PL
   Software: exclude systematic failures

6. Verification
7. Validation
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Hazard & Risk Analysis

Participants in a risk analysis:
Generally, a representative group of persons, who are familiar with the machine throughout its whole life cycle.

- Marketing / product management
- Design engineers
- Test engineers
- Production / commissioning
- Service / maintenance
- Machine operator / driver
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Hazard & Risk Analysis

List of machine functions

Example:

<table>
<thead>
<tr>
<th>List</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving functions</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Speed control (foot throttle)</td>
</tr>
<tr>
<td>2.</td>
<td>FIIR control (forward, neutral, reverse)</td>
</tr>
<tr>
<td>3.</td>
<td>Indicator control</td>
</tr>
<tr>
<td>4.</td>
<td>Transmission shift</td>
</tr>
<tr>
<td>5.</td>
<td>Cruise control</td>
</tr>
<tr>
<td>6.</td>
<td>Inching</td>
</tr>
<tr>
<td>7.</td>
<td>Parking brake</td>
</tr>
<tr>
<td>8.</td>
<td>Steering / auxiliary steering</td>
</tr>
<tr>
<td>Release functions</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Safety lever</td>
</tr>
<tr>
<td>2.</td>
<td>Road travel switch</td>
</tr>
<tr>
<td>Work functions</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Lifting / lowering</td>
</tr>
<tr>
<td>2.</td>
<td>Rotating</td>
</tr>
<tr>
<td>3.</td>
<td>Telescopic function</td>
</tr>
<tr>
<td>4.</td>
<td>Auxiliary attachments</td>
</tr>
<tr>
<td>Automatic functions</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Parallel lift control</td>
</tr>
<tr>
<td>2.</td>
<td>Continuous path control</td>
</tr>
<tr>
<td>Further functions</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Fan drive speed control</td>
</tr>
<tr>
<td>2.</td>
<td>Suspension functions</td>
</tr>
<tr>
<td>3.</td>
<td>Levelling</td>
</tr>
<tr>
<td>Safety systems</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Load moment indicator</td>
</tr>
<tr>
<td>2.</td>
<td>Limitation of workspace</td>
</tr>
</tbody>
</table>
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Hazard & Risk Analysis

Definition of malfunctions

Example: Proportional machine control function

- Unintended start
- Unintended stop
- Moving in wrong direction
- Unintended reverse movement
- Unintended fast movement
- Unintended slow movement
- Unintended acceleration
- Unintended deceleration
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Hazard & Risk Analysis

Determination of required performance level for each specific safety function

Risk analysis based on EN ISO 13849-1

H&R Analysis

Assessment
S: severity of injury:
F: frequency and/or duration of exposure to danger:
P: probability of avoiding the exposure

Machine function

Determination of required performance level for each specific safety function.
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Hazard & Risk Analysis

Determination of required performance level for each specific safety function

Risk Graph:

Required risk minimisation and Performance Level:

Severity of injury:
S1 slight (usually reversible injury)
S2 serious (usually irreversible injury which may include death)

Frequency and / or duration of exposure to danger:
F1 rarely up to infrequent and / or the time of exposure to danger is short
F2 frequently up to continuously and / or the time of exposure to danger is long

Probability of avoiding the danger:
P1 possible under certain conditions
P2 rarely possible
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Hazard & Risk Analysis

Safety function

Each function in a machine whose malfunction can lead directly to an increase of the risk is defined as a safety function.

A safety function is thus a function that can minimise a risk to an acceptable level by taking adequate (e.g. control) design measures.

Examples of safety functions:

<table>
<thead>
<tr>
<th>Safety function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>- safe standstill (no operation)</td>
<td>avoiding an unintended start</td>
</tr>
<tr>
<td>- safe moving direction</td>
<td>avoiding movement in a wrong direction</td>
</tr>
<tr>
<td>- safe lift function</td>
<td>avoiding exceeding a load limit (LMI)</td>
</tr>
<tr>
<td>- safe acceleration</td>
<td>avoiding exceeding an acceleration limit</td>
</tr>
<tr>
<td>- function for a safe stop in case of emergency</td>
<td>achieving a defined safe state in case of a failure</td>
</tr>
</tbody>
</table>
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System Design

Safety related part of a control system  SRP/CS
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System Design
PL column chart according to EN ISO 13849-1

Illustrates the relations between PL, MTTFd, category and DC
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System Design

PL column chart according to EN ISO 13849-1

Illustrates the relations between PL, MTTFd, category and DC

Example 1:

Performance Level „PL d“ for a machine function is required.
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System Design

PL column chart according to EN ISO 13849-1

Illustrates the relations between PL, MTTFd, category and DC

Example 1:
Performance Level „PL d“ for a machine function is required.
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System Design

The achieved safety level results from (balance) the combination of the characteristics:

- Architecture
- Reliability of the used components
- Recognition of the safety-relevant failures
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- Category
  
  Architecture / Design
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Overview of the Control Architectures (Categories)

Kategorie B und 1:

<table>
<thead>
<tr>
<th>I</th>
<th>L</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>!</td>
<td>Input Signal</td>
<td>Output Signal</td>
</tr>
</tbody>
</table>

Kategorie 2:

<table>
<thead>
<tr>
<th>I</th>
<th>L</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring</td>
<td>Input Signal</td>
<td>Output Signal</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Monitoring</td>
<td></td>
</tr>
</tbody>
</table>

2nd switch-off path or indication path

Kategorie 3

<table>
<thead>
<tr>
<th>I1</th>
<th>L1</th>
<th>O1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring</td>
<td>Input Signal</td>
<td>Output Signal</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I2</th>
<th>L2</th>
<th>O2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitoring</td>
<td>Input Signal</td>
<td>Output Signal</td>
</tr>
</tbody>
</table>

design for "normal safety level" vs. design with "increased safety level"
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- Reliability of the applied components
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- **MTTFd**
  Mean time to dangerous failure

  Statistically expected value of the average time to dangerous failure

  Note:
  indicator of the quality of a component
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Characteristics

**MTTF**
Meaning: Average period until failure occurs
Scope of the directive: Valid for units which are not intended for repair.

**MTBF**
Meaning: Average period between failures
Scope of the directive: Valid for units which are intended to be repaired.

**MTTFd**
Meaning: Average period until dangerous failure occurs.
Scope of the directive: Valid for units (components, systems), used in safety-critical systems.

**B10**
Meaning: Statistically expected value of the number of cycles, in which 10% of the components have exceeded the defined limits (switch delay, leakage, switch pressure, etc.) under the defined conditions.

**B10d**
Meaning: Expected number of cycles in which 10% of the components have had dangerous failures.
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Sensors with increased safety and/or diagnostic functions

Example: Pressure Transmitter – HYDAC
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Sensors for pressure, position and distance

- **Pressure transducer** HDA 8000
  - Category 2
  - MTTFd high (190 years)
  - DC: low (87%)
  - Safety level: PL d, SIL 2

- **Pressure transducer** HDA 4000
  - Category 3
  - MTTFd high (976 years)
  - DC: low (84%)
  - Safety level: PL d

- **Position switch** HLS 100
  - Category 2
  - MTTFd high (419 years)
  - DC: low (88%)
  - Safety level: PL d, SIL 2

- **Linear position sensor** HLT 1000
  - Category 2
  - MTTFd high (83 years)
  - DC: low (91%)
  - Safety level: PL d, SIL 2

- **Valve position switch** HLS 200
  - Category 2
  - MTTFD high (110 years)
  - DC: medium (91%)
  - Safety level: PL d
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Products with increased safety and/or diagnostic functions

Example: Controller (ECU)

Cat 2 – Architecture, PL d

- 2 CPUs monitor one and another
- Supply
- Diagnostic supply
- Actuator for safety-critical applications
- Redundant switch-off for the outputs to activate the „safe state“

Diagram:
- MainCPU
- Watchdog CPU
- Sensor
- Current feedback
- Release
- FET monitoring
- Diagnosis
- Monitoring
- Diagnosis of safety-relevant inputs
- Monitoring of the PWM outputs
- Periodic tests of RAM, Flash, CPU-Registers, Stack storage
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Challenges for complex electronic systems

- Multi-Controller-Systems
- Machine functions distributed over a number of controllers
**Functional Safety of Electronic Controls**

**Controller and I/O modules**

Example: Controller and I/O modules HYDAC

- Standard and with increased functional safety level
- Certified units; **IEC 61508 SIL 2 and SIL 3; ISO 13849 PL d**

### Safety Certified Controllers

<table>
<thead>
<tr>
<th>Model</th>
<th>Inputs</th>
<th>Outputs</th>
<th>Safety Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>HY-TTC 30SH</td>
<td>14</td>
<td>14</td>
<td>EN ISO 13849</td>
</tr>
<tr>
<td>HY-TTC 77</td>
<td>39</td>
<td>26</td>
<td>EN ISO 13849</td>
</tr>
<tr>
<td>HY-TTC 90, HY-TTC 94</td>
<td>28</td>
<td>20</td>
<td>IEC 61508 &amp; EN ISO 13849</td>
</tr>
<tr>
<td>HY-TTC 200</td>
<td>33</td>
<td>36</td>
<td>IEC 61508</td>
</tr>
<tr>
<td>HY-TTC 500 Family</td>
<td>39</td>
<td>36</td>
<td>IEC 61508 &amp; EN ISO 13849</td>
</tr>
<tr>
<td>HY-TTC 500</td>
<td>28</td>
<td>20</td>
<td>IEC 61508 &amp; EN ISO 13849</td>
</tr>
<tr>
<td>HY-TTC 50 Family</td>
<td>20</td>
<td>20</td>
<td>IEC 61508 &amp; EN ISO 13849</td>
</tr>
<tr>
<td>HY-TTC 540</td>
<td>52</td>
<td>44</td>
<td>IEC 61508 &amp; EN ISO 13849</td>
</tr>
</tbody>
</table>

### General Purpose Controllers

<table>
<thead>
<tr>
<th>Model</th>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>HY-TTC 30H</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>HY-TTC 50 Family</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>HY-TTC 60</td>
<td>28</td>
<td>20</td>
</tr>
</tbody>
</table>

### Safe I/O Modules

<table>
<thead>
<tr>
<th>Model</th>
<th>Inputs</th>
<th>Outputs</th>
<th>Safety Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>HY-TTC 30XSH</td>
<td>14</td>
<td>14</td>
<td>EN ISO 13849</td>
</tr>
<tr>
<td>HY-TTC 30XSI</td>
<td>26</td>
<td>4</td>
<td>EN ISO 13849</td>
</tr>
<tr>
<td>HY-TTC 48XS</td>
<td>28</td>
<td>20</td>
<td>EN ISO 13849</td>
</tr>
<tr>
<td>HY-TTC 30X Family</td>
<td>14</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>HY-TTC 30XO</td>
<td>16</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>HY-TTC 30XI</td>
<td>26</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

### I/O Slave Modules

<table>
<thead>
<tr>
<th>Model</th>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>HY-TTC 30X</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>HY-TTC 36X</td>
<td>26</td>
<td>16</td>
</tr>
<tr>
<td>HY-TTC 48X</td>
<td>28</td>
<td>20</td>
</tr>
</tbody>
</table>

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**Product Safety & Compliance Seminar**

April 19 - 20, 2016  Rosemont, IL
Functional Safety for Electronic Control

Challenges for complex electronic systems

HMI (Human – Machine – Interface)

Example:
Combination between Display and manual buttons and switches

- Joystick with function keys
- Hardware switches and buttons for safety-relevant operating functions
- 10,4” Touch Display
  - Machine configuration
  - Monitoring of the functions
  - Failure display and diagnosis
  - Convenience functions

Hydraulic main switch
Functional Safety for Electronic Control

- System design

- Example -
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System design

Example:
Required: PL<sub>r</sub> c

![Diagram showing hazardous movement and fluidic actuator with PL c components]
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System design

Example 1:

Pressure sensor
PL = c

Controller
PL = c

Valve
PL = c

PL_{low} = c
N_{low} = 3

The „simple“ way to the system

<table>
<thead>
<tr>
<th>PL_{niedrig}</th>
<th>N_{niedrig}</th>
<th>Gesamt PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>≥4</td>
<td>Kein PL, nicht erlaubt</td>
</tr>
<tr>
<td></td>
<td>≤3</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>≥3</td>
<td>a</td>
</tr>
<tr>
<td></td>
<td>≤2</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>≥3</td>
<td>b</td>
</tr>
<tr>
<td></td>
<td>≤2</td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>≥4</td>
<td>c</td>
</tr>
<tr>
<td></td>
<td>≤3</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>≥4</td>
<td>d</td>
</tr>
<tr>
<td></td>
<td>≤3</td>
<td>e</td>
</tr>
</tbody>
</table>
### Example 2:

- **Pressure sensor**: $PL = d$
- **Controller**: $PL = c$
- **Valve**: $PL = c$

#### System Design

The „simple“ way to the system

#### Table: $PL_{niedrig}$ vs $N_{niedrig}$ vs Gesamt $PL$

<table>
<thead>
<tr>
<th>$PL_{niedrig}$</th>
<th>$N_{niedrig}$</th>
<th>Gesamt $PL$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>$\geq 4$</td>
<td>Kein $PL$, nicht erlaubt</td>
</tr>
<tr>
<td></td>
<td>$\leq 3$</td>
<td>a</td>
</tr>
<tr>
<td>b</td>
<td>$\geq 3$</td>
<td>b</td>
</tr>
<tr>
<td></td>
<td>$\leq 2$</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>$\geq 3$</td>
<td>c</td>
</tr>
<tr>
<td></td>
<td>$\leq 2$</td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>$\geq 4$</td>
<td>d</td>
</tr>
<tr>
<td></td>
<td>$\leq 3$</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>$\geq 4$</td>
<td>d</td>
</tr>
<tr>
<td></td>
<td>$\leq 3$</td>
<td></td>
</tr>
</tbody>
</table>
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Example: System design for a function with an increased safety level

Category 2 design
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System design

Manual verification through the design engineer, or with the help of software tools i.e. software assistant SISTEMA

Software Assisant SISTEMA
(Sicherheit von Steuerungen an Maschinen)
(Safety of Controls in Machines)

Offers support for the evaluation of control safety, based on DIN EN ISO 13849-1.
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System design
Software assistant SISTEMA
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Software design

Some requirements for the design of „safe“ software

- Modular and structured design and coding
- Taking into account the safety-related provisions of the electronic controls manufacturer (safety manual)
- Structured specification with safety requirements
  Specification has to be checked by second person
  (Safety functions incl. PL, reaction times, hardware interfaces, recognition and the control of external failures)
- Checking of the software code by a second person
Functional Safety for Electronic Control

Software design
Designing a “safe software“ according to V-Model
Functional Safety for Electronic Control
Software design
Designing a “safe software” with design tool MATCH

[Diagram showing the process of software design and validation, including System Definition, Application Programming, Test & Simulation, Commissioning & Test, Requirements Specification, Application Software Development, System Validation, and Safety Declaration.]
## Functional Safety for Electronic Control

Products with increased functional safety

Sensors, Controllers, Software

### Table: Functional Safety Products

<table>
<thead>
<tr>
<th>Funktionale Sicherheit</th>
<th>Sensoren / Sensors</th>
<th>Steuerungen / Controller</th>
<th>IO-Module / IO-modules</th>
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Thank you for your attention!
Please discuss your applications with us.