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# Diagnostic concepts for automated assembly and workpiece inspection systems (AAWIS)

*Prof. Dr. Stephan Sommer*

University of Applied Science (UAS) Würzburg-Schweinfurt,
Faculty of mechanical engineering, Department for Quality management and production metrology

**Abstract** – Automated assembly and Workpiece Inspection Systems (AAWIS) must fulfill ever higher requirements. At the same time, the high expenditures have to be compensated by high availability as well as high quality and quantity performance. In addition to these requirements, recently a new quality characteristic has been gaining importance, namely the fail-safety of AAWIS. While the manual calibration of inspection processes is state of the art, for automated processes the question arises: Who monitors the inspection devices? The difference between automated production measurement and laboratory measurement lies in monitorability. In laboratory measurement, the operator can check the measured values for plausibility and carries out an evaluation afterwards, whereas automatic production is not capable of this “common sense” process. These influences cause the measurement uncertainty of AAWIS to show larger variations. Nowadays, we face these challenges by using robust measurement systems with systematic and periodic manual monitoring and calibration. However, this method brings about a conflict between quality performance and availability of an AAWIS. One possible solution for this conflict is the use of fail-safe Automated Workpiece Inspection Systems. These systems are characterized by automatic monitoring of their operability, which reduces the frequency of manual monitoring. This helps to meet the growing quality requirements and the tightened liability regulations.

**Keywords** Measurement in production, diagnostic, error detection

## 1. INTRODUCTION

In order to implement the successful combination of highly automated systems with highly qualified staff in Germany as economically as possible, Automated Assembly and Workpiece Inspection Systems (AAWIS) must fulfill ever higher requirements. For instance, the product (assembly) differentiation requires a high flexibility of AAWIS [1]. At the same time, the high expenditures have to be compensated by high availability as well as high quality and quantity performance (high quality, efficiency) with low service efforts (maintenance properties) as quickly as possible (short amortization period).

In addition to these requirements, recently a new quality characteristic has been gaining importance, namely the fail-safety of AAWIS. While the manual monitoring of automatic processes is state of the art [2], for automated processes the question arises: Who monitors the inspection devices? To meet these new requirements, additional diagnostic concepts are necessary. The systematic structuring, planning and implementation of these diagnostic concepts contributes significantly to the increase in quality performance and availability of AAWIS. Fig. 1 shows an example of AAWIS.

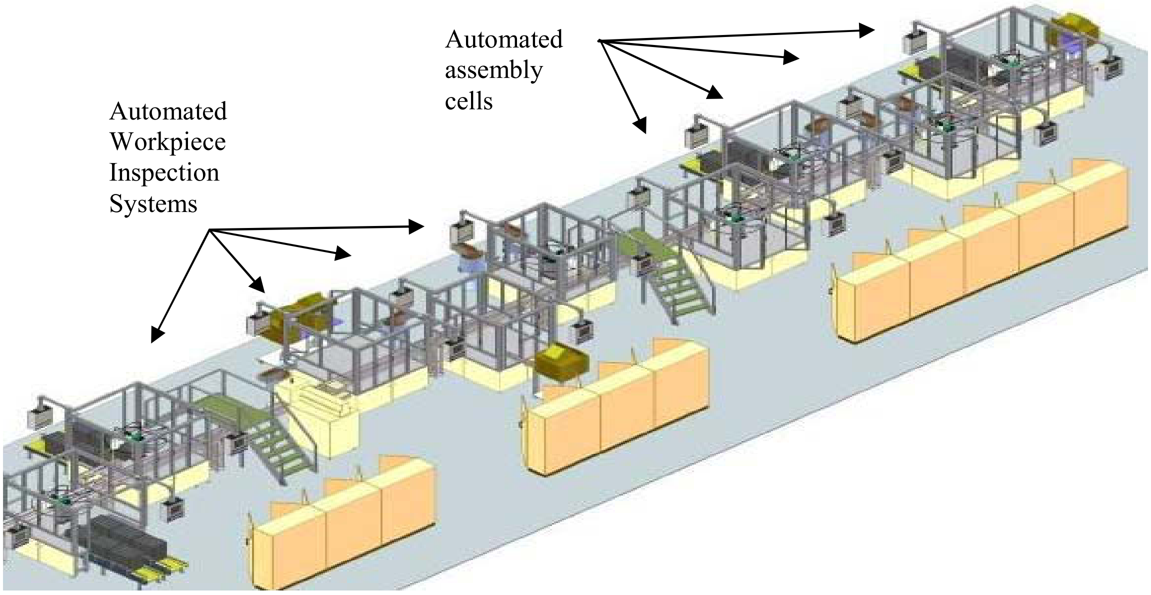

Fig. 1: Automated Assembly and Workpiece Inspection System (AAWIS)

The difference between automated production measurement technology (PMT) and laboratory measurement technology (LMT) lies in monitorability. In laboratory measurement, the operator can check the measured values for plausibility and carries out an evaluation afterwards, whereas automatic systems are not capable of this "common sense" process. In LMT, the operator and the measurement strategy dominate the measurement [3], whereas these factors play a less important role for PMT. In PMT, the measurement result is influenced by the uncertainties of the workpiece, the reliability of the measurement system and the ambient conditions [4]. In automated inspection processes, workpiece hygiene (e.g. cleanliness) can vary from measurement to measurement. In addition, the ambient conditions are normally far less stable than in the measurement laboratory.

## 2. DIAGONSTIC CONCEPTS FOR FAIL-SAFE AAWIS

This paper is about the planning and implementation of diagnostic concepts to create fail-safe AAWIS by using automated methods of error detection .

**Error detection – definition:**

Analyzing an AAWIS with automatic methods to find out deviations between actual state and desired state.

The aim is to improve quality performance and availability of these systems. Fail-safety means the ability of AAWIS to detect errors immediately or shortly after their appearance.

**Fail-safety – definition:**

The ability of an AAWIS to detect errors immediately after their occurrence.

While manual methods of error detection (e.g. calibration, counter measures with reference parts) bring about a delay between the occurrence of an error and its detection, which leads to a larger number of Not-OK Parts due to the error, diagnostic concepts are automatic methods that are characterized by the fact that the occurrence of an error is detected either immediately or after a short period of time. Systems with integrated diagnostic concepts are called *"fail-safe"*.

Using diagnostic concepts in AAWIS reduces the number of Not-OK Parts. Errors are detected at an early point in time and can be eliminated. The share of scrap and rework parts during assembly is minimized and that of the good parts is maximized. This increases the quality performance of production metrology.

The methods of error detection are divided into the following groups: Redundancy concepts, self-tests and plausibility criteria (Fig. 2).

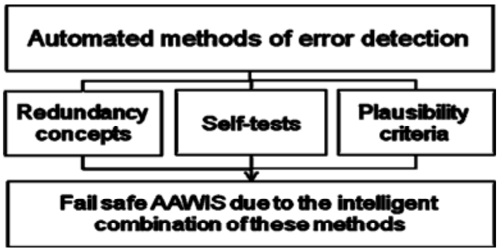

Fig. 2: Methods of error detection

### *2.1. Redundancy concepts*

Redundant systems are used in many industrial sectors. They help to increase the output quantity, to create a system that is safe in the event of a failure, and to increase availability and fail-safety. For fault-prone or unsafe inspection components, several inspection systems (normally two)[2] are provided [5].

**Redundancy – definition**

"The presence of more functional means in a unit than would be necessary to fulfill the function requirements" [6]

Redundancy can be divided into hardware redundancy and analytic redundancy Fig. 3.

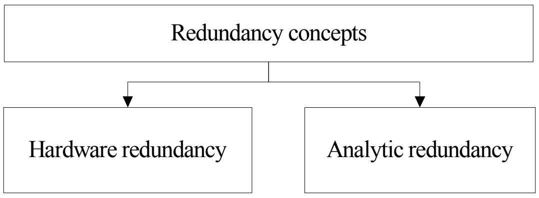

Fig. 3: Redundancy concepts

### *2.1.1. Hardware redundancy*

Hardware redundancy can be divided into homogeneous redundancy, "…where all means are of the same type…", and diverse redundancy, "…where the means are of different types…".[6] This means that homogeneous redundancy has the same functions and the same active principles, and that diverse redundancy has the same functions but different active principles. Homogeneous redundancy holds the risk that, due to the homogeneous structures and the homogeneous active principles, certain influences equally affect all redundant systems. This kind of error is called "common-mode error". When diverse redundant systems are used, it is important that the measuring results of the systems can be compared due to the different active principles.

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[2] Unlike safety-relevant systems, e.g. in aircraft construction or in nuclear power engineering, where triple redundancy is standard, production metrology needs to be guarded by one additional system only.

While in safety technology, diverse redundancy is the best choice to detect common-mode errors, it is less desirable in measurement technology. A main reason for this is that the different measuring and active principles lead to different measurement uncertainties. Consequently, the permissible maximum difference increases, which leads to an avoidable deterioration of error detection.

Fig. 4 shows a measuring station as an example of homogeneous hardware redundancy. The application is based on the calculation and evaluation of the difference between the measurement results. The permissible maximum difference is the basis for setting tolerance limits for the difference control chart; it depends from the (measurement) uncertainty of the measuring systems.

As mentioned above, one disadvantage is that common-mode errors (e.g. wrong reference part used for both stations) are not detected. This is the reason why additional methods (e.g. calibration control chart) should be employed for detecting common-mode errors. This could be a subject for further research and will not be discussed in detail here.

**Structure and principle** of the example shown in Fig. 4: The characteristic is measured in the first measuring station and then in the second. The active principle is the same in both measuring stations.

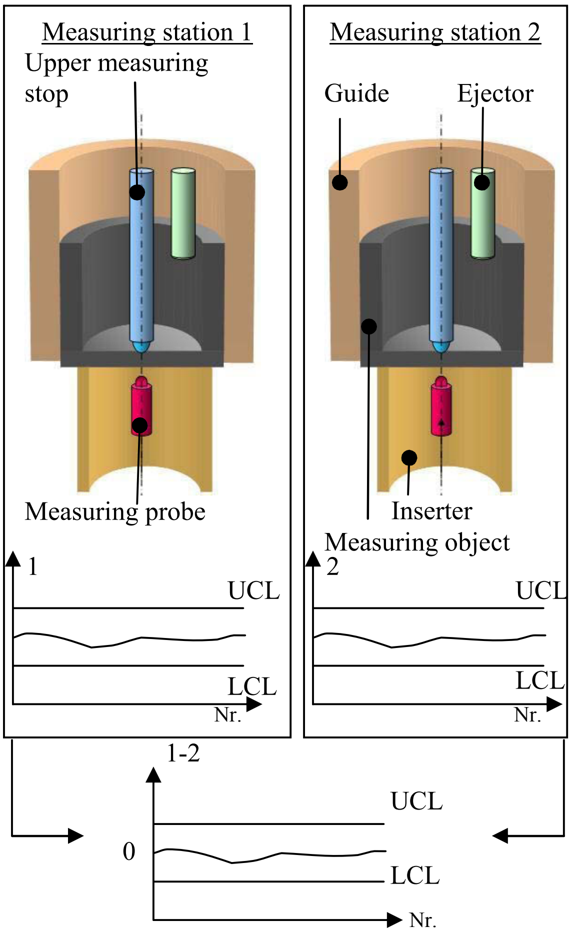


Fig. 4: Example for homogeneous redundancy in measuring stations

**Evaluation:** Calculation of the two measurement results (e.g. 1-2) and evaluation of the difference as a scale for the stability of the measurement value. The difference must lie within a set tolerance. For evaluating the characteristic, the measurement result of the measuring station with the lower measurement uncertainty can be used. If the uncertainties are the same, which is probable in this structure, an average value from the two results should be created. This can additionally reduce the measurement uncertainty (root n – law [7]).

**Advantages:**

- Highly reliable measurement result,
- Errors are detected immediately,
- Optimization of calibrating cycles is possible and
- Condition based maintenance of the AAWIS.

**Disadvantages:**

- Additional measuring station,
- Additional meas. value input in meas. computer and
- Additional space necessary in assembly unit.

**Additional requirements:** This structure is very sensitive to disturbance variables (e.g. dirt). Therefore, the process must be additionally guarded. The number of subsequent Not-OK evaluations should be monitored. Permitting no more than three subsequent violations of the control limits in the difference control chart has proven to be a good method.

The permissible difference between station 1 and station 2 depends on the measuring uncertainty. Fig. 5 shows the approach to calculation of the permissible maximum difference between station 1 and station 2.

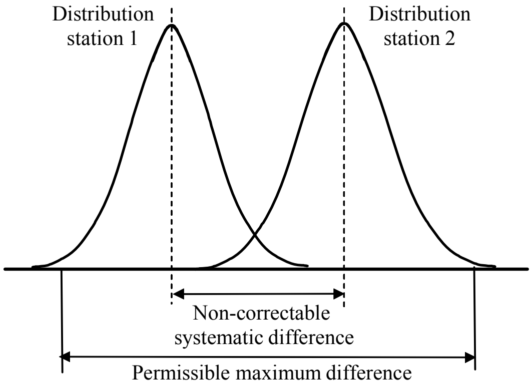


Fig. 5: Difference between the two measuring stations

The difference comprises the random and the non-correctable systematic portion of the measurement uncertainty (Fig. 6).

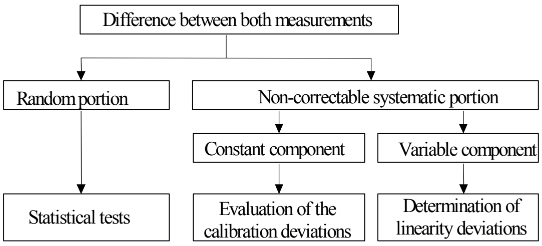


Fig. 6: Influences and their determination on the difference between the two measurements

The portions are defined as non-correctable systematic deviations and are therefore linear added (1) to create the permissible maximum difference between the two measurement results [8]. When applying the model in day to day practice it is helpful to have an additional portion that represents deviations, which are not determined by the performed uncertainty studies. This portion is determined by the user depending on measurement needs.

$$\Delta_{Max.} = \Delta_{Random} + \Delta_{Calibration} + \Delta_{Linearity} + \Delta_{Practice} \quad (1)$$

$\Delta_{Max.}$ : Permissible maximum difference between the measuring results
$\Delta_{Random}$ : Random portion of the difference
$\Delta_{Calibration}$ : Portion from calibration deviation between the measuring stations
$\Delta_{Linearity}$ : Portion of the linearity deviation
$\Delta_{Practice}$ : Practice deviation

Fig. 7 shows an example of the difference between two measuring stations with identical construction (homogeneous hardware redundancy).

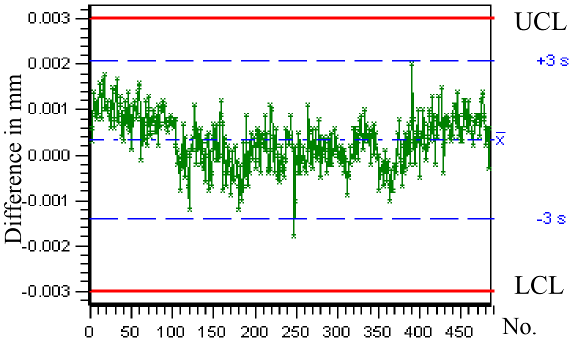


Fig. 7: Example for the difference calculated as station 1 minus station 2

### *2.1.2 Analytic Redundancy*

Methods for error detection that are based on analytic redundancy make use of information that is already available in the process. In this method, data that was originally generated for other purposes is logically combined, which makes it possible to deduce monitoring information from it.

**Definition**: Analytic redundancy gains the redundant information from knowledge that is already available in the process observed.

An example for analytic redundancy are parallel measuring stations in AAWIS. Parallel measuring stations with identical construction are used in AAWIS for quantity performance reasons. The redundancy created in this way can be used for cross-monitoring the measuring stations. Errors, such as an offset due to faulty calibration or influences on the measuring device during production, can thus be detected. The fail-safety is based on the comparison of the two measuring stations' measurement results by way of calculating the difference. Fig. 8 shows a schematic illustration of parallel measuring stations with identical construction. The parts are produced in an assembly station and distributed to the two measuring stations in random sequence.

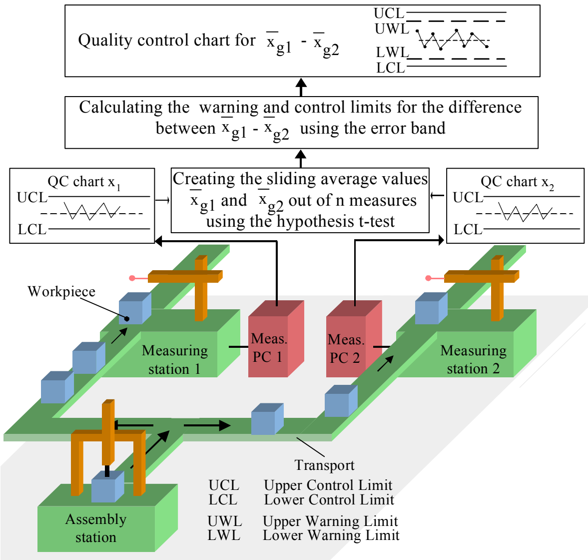


Fig. 8: Assembly station and parallel measuring stations with identical construction

At first, the measurement results are monitored with an original value control chart (QC chart) as usual. In addition, sliding average values are created from original n-values. Based on a test run, a hypothesis test (t-test) is carried out to evaluate the appropriate number n for creating a sliding average value [9].

This is an iterative process that is continued by a computer program until a number n has been found that constitutes a representative volume of random tests for the course of the process. The optimization aim is to smooth the test statistic $t_{Prüf}$ with a preferably large n, and at the same time a preferably short delay in the response behavior with a preferably small n. Fig. 9 shows a test run with a measurement deviation from original value 51.

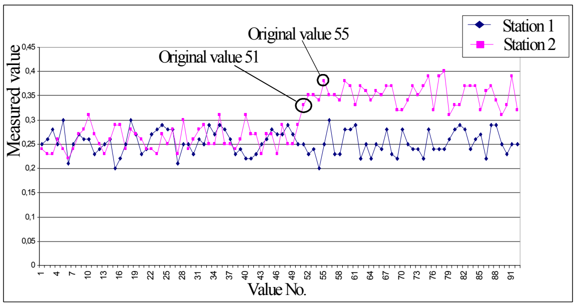


Fig. 9: Test run with measuring deviation due to an error starting with original value no. 51

The hypothesis test shown in table 1 is an original value comparison with a t-distributed test statistic ($t_{Prüf}$) and is therefore also called t-test.

Table 1: Mathematic bases of the t-test [10]

<table>
<tr><th colspan="2">Zero hypothesis</th><th>Alternative hypothesis</th></tr>
<tr><td colspan="2">$\mu_1 = \mu_2$</td><td>$\mu_1 \neq \mu_2$</td></tr>
<tr><td colspan="3">with the test statistic $t_{\mathrm{Pr}\ddot{u}f} = \dfrac{\overline{x}_1 - \overline{x}_2}{s_d}$</td></tr>
<tr><td colspan="3">The null hypothesis is abandoned when:<br>$\left| t_{\mathrm{Pr}\ddot{u}f} \right| > t_{f;1-\alpha/2}$</td></tr>
<tr><td>with:<br>$s_d^{\,2} = \dfrac{s_1^{\,2}}{n_1} + \dfrac{s_2^{\,2}}{n_2}$</td><td>$\dfrac{1}{f} = \dfrac{c^2}{n_1 - 1} + \dfrac{(1-c)^2}{n_2 - 1}$</td><td>$c = \dfrac{\dfrac{s_1^{\,2}}{n_1}}{\dfrac{s_1^{\,2}}{n_1} + \dfrac{s_2^{\,2}}{n_2}}$</td></tr>
<tr><td colspan="3">$\overline{x}_1 = \overline{x}_{g1}; \overline{x}_2 = \overline{x}_{g2}$…sliding averages of station 1 and 2<br>$n_1$, $n_2$…number of values to calculate the sliding averages<br>$s_1$, $s_2$…standard deviation of the values used to calculate the sliding averages; $s_d$, f, c …parameters for calculation</td></tr>
</table>

The test is among the "…robust statistical methods…", in which "…the test result is only slightly affected by a deviation of the probability distribution from the normal distribution".[11] Therefore, a test on normal distribution is dispensable. The t-test is carried out with a level of significance of 99.9% ($\alpha$ =0,1%) and 99.0% ($\alpha$ =1%).

Fig. 10 shows the t-test with n=6. The level of significance of 99.9% is exceeded at data point 50. This equals original value 55 in Fig. 9. This defines the response behavior with 5 production parts after the occurrence of the significant measurement deviation.

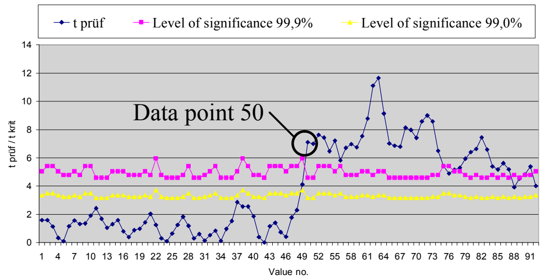


Fig. 10: t-test with n=6

After further knowledge about the behavior of the assembly and measuring process has been collected, the selected n is checked iteratively until a stable monitoring process has been defined.

The warning and control limits for the quality control chart are determined with the error band on different levels of significance. Experts recommend a error band of 99% for the control limits and a error band of 95% for the warning limits [12]. The calculation (2) is carried out according to [10]:

$$\boxed{\overline{x}_1 - \overline{x}_2 - t_{f;1-\alpha/2} \cdot s_d \le \mu_1 - \mu_2 \le \overline{x}_1 - \overline{x}_2 + t_{f;1-\alpha/2} \cdot s_d \quad (2)}$$

If the error band is left, it can be assumed with a certainty of P = 1 - $\alpha$ that the measurement uncertainty of one of the two measuring processes has increased significantly.

Since sliding average values are used for calculating the limits, the warning and control limits are also "sliding". Therefore, the user must set an "average" limit. Fig. 11 shows the average warning and control limits based on the stable part of the test run (Fig. 9 up to original value 50).

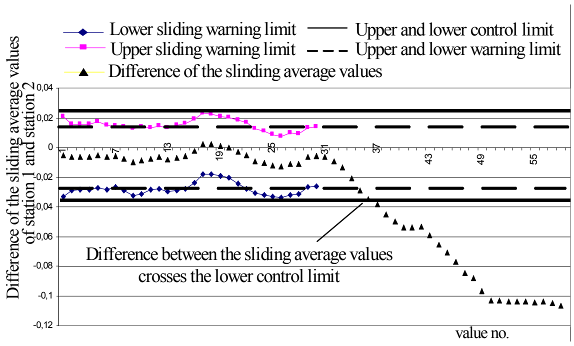


Fig. 11: Warning and control limits in the quality control chart for the difference of the sliding average values

In assembly technology, outliers can frequently occur. These would affect the variation of the sliding average value such that it would not deliver a representative picture of the overall variation. Therefore, outliers should not be used for creating the sliding average value. In automated monitoring, this can be effected with the definition of threshold limits. Measured values that violate these threshold limits are not used for the calculation. Control limits, tolerance limits or additionally defined limits can be used as threshold limits.

### *2.2 Self-tests for error detection*

Definition:

> With self-tests, individual components of AAWIS test their functionality on their own. This can be effected with software, e.g. with cyclic tests, or with hardware, with mechanical or electric components.

Self-tests can be activated in defined periodical intervals, after manual interferences (e.g. maintenance, repair) or during each restart of the system.

An example of self-tests is given for measuring chains (transducer, cable and evaluating unit) with strain gage measuring bridge (Wheatstone bridge circuit). These measuring chains can be tested by monitoring the zero-point and calibration value (Fig. 12). Both tests are operated under idling (no load) condition.

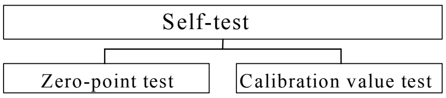
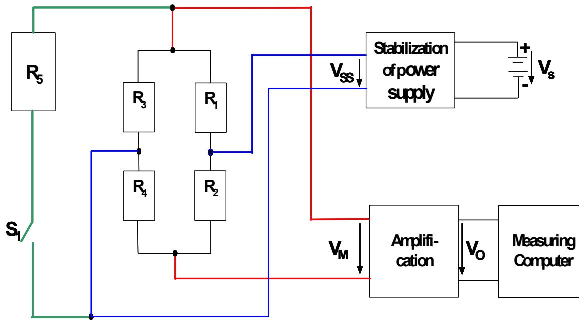


Fig. 12: Example for self-tests in a measuring chain with strain gages in a Wheatstone bridge circuit

**Zero-point test:** With the zero-point test, the correct balance of the measuring bridge under no load is checked. It can vary for example due to changes of the strain gage adhesion point and damage to the strain gages due to over load. In the zero-point test, a defined direct current supply voltage ($V_S$) is applied (e.g. 5V). The calibration resistance $R_5$ is disabled. The result from current flow and internal resistance of the measuring bridge is a (response) measuring signal of $V_M$ = 0V, but only if the measuring bridge is balanced. If the measuring bridge is detuned, the measuring signal deviates from a permissible tolerance, in this case e.g. 0V +/- 20mV (Fig. 13).



$R_1 – R_4$ ... Strain gages; $R_5$...calibration resistance
$V_{ss}$... Stabilized supply voltage in V
$V_M$...Measuring signal in mV
$V_O$...Amplified measuring signal in V
$S_1$...Switch to activate the calibration value test

**Fig. 13: Wheatstone bridg**e circuit with calibration *resistance for detuning [4]*

**Calibration value test:** In the calibration value test, the measuring bridge is selectively detuned via the calibration resistance $R_5$ by closing a switch (Fig. 13). Supply voltage $V_S$ is applied like in measuring mode (e.g. 5V). The system is under no load in idling condition. The result of the detuning can be measured as the signal $V_M$. If the measuring bridge has a defect, the measuring signal deviates from a permissible tolerance.

The advantage of the calibration value test is that the measuring chain can be additionally checked by monitoring a characteristic (response) signal of functional strain gage measuring system. Critical errors that affect the measurement, e.g. a change in the adhesion point of the strain gage measurement strips, can thus be detected more reliably.

In each application, the response signal and its expected variation must be defined depending on the transducer and the supply voltages applied.

In both tests described, the entire measuring chain, e.g. transducer, cable, measurement amplifier and evaluating unit, can be tested. Differences occur only when different voltages are applied.

Its applicability depends on the technical design of the transducer.

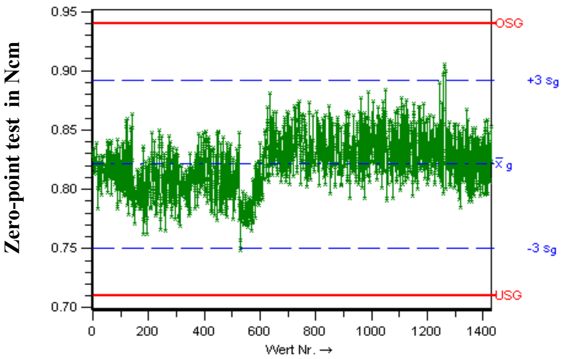


Fig. 14: Zero-point test at a torque sensor with Wheatstone bridge circuit.

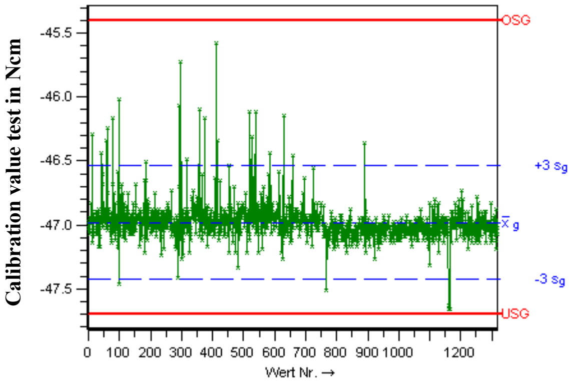


Fig. 15: Calibration value test at a torque sensor with Wheatstone bridge circuit.

## *2.3 Plausibilty criteria*

Plausibility criteria are methods of failure detection, which enable to evaluate the right dimension of an assembly or measurement result.

**Definition:** Methods for the evaluation of the regularity and coherence of incidents in AAWIS.

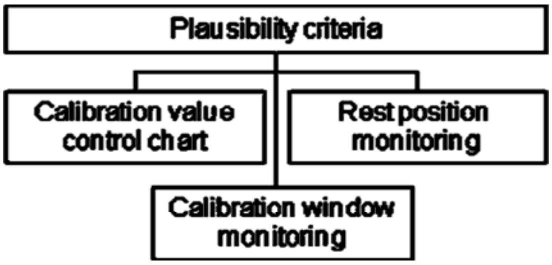


Fig. 16: Examples for Plausibility criteria [4]

### *2.3.1 Calibration value control chart*

The calibration value control chart will be used for checking if the calibration of a measurement system lies in the range of the expected calibration result. For that purpose, a calibration standard with a known and to international standards traceable actual value will be measured by the measurement system. The displayed value will be registered in a quality control chart and compared with the control limits, which were defined before. The control limits represent the extended measurement uncertainty (+/- U) [4].

### *2.3.2 Rest position monitoring*

The rest position monitoring in the measuring chain will be realized by the definition of a rest position range and a measuring position outside this range. After the start of the measuring procedure, the measurement signal (point 1) must leave the rest position window and return to it after completion (point 2 in figure 17). Damages in the measuring chain, as e.g. defect measuring sensor, cable breakage or a faulty adjustment of the sensor can be detected by using this plausibility criterion.

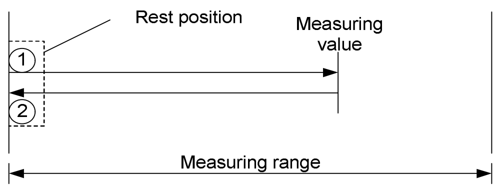


Fig. 17: Rest position monitoring [4]

### *2.3.3 Calibration window monitoring*

For this plausibility criterion, the calibration must be executed in a calibration area which was defined before. This should be in the middle of the measuring range. The guidance value for the width of the calibration window is twenty percent of the measuring range. The monitoring of the measuring range has two functions. Firstly, linearity faults will be minimized. Secondly, adjustment faults, damages at the measuring chain and measuring station as well as excessive wear will be detected.

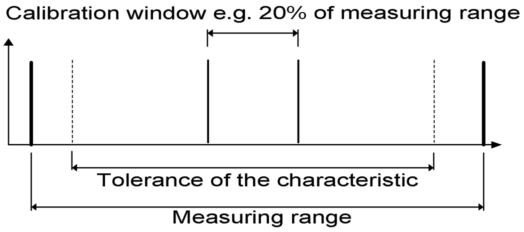


Fig. 18: Calibration window monitoring [4]

## 3. CREATING DIAGNOSTIC CONCEPTS BY INTELLIGENT COMBINATION OF METHODS

As innovation at the planning of AAWIS, the methods of the failure detection will be combined to diagnostic concepts, so that they improve in their whole the quality performance and availability of AAWIS. It will be distinguished between a standard safety package (SSP) and additional diagnostic methods [4].

### *3.1 Standard safety package (SSP)*

The SSP should be applied in all AAWIS. All failure detection methods which are necessary as a prerequisite for an acceptable quality performance of an AAWIS are combined in this standard (Tab. 1).

| | |
|---|---|
| Measuring chain | Rest position monitoring<br>(monitoring of idling position of the sensor) |
| | Calibration window monitoring |
| | Multi-position calibration at measurement systems, whose linearity behavior must be defined in the measuring range (e.g., pneumatic measurement systems). |
| | Automatic calibration interval |
| Station level | Check availability of workpiece |
| | Position and location monitoring of workpieces |
| | Monitoring of start and end position of movements |
| Process level | Mandatory parts evaluation “unknown“, till all assembly and inspection procedures are positively finished. |
| | Ban with permit<br>Good track is blocked in the setup and automatic operation |
| | Bad part acknowledgment |
| | Stop after several subsequent (normally three times) bad part evaluations |
| | Change of the (normal) basic conditions (e.g., fouling) must lead to a bad part evaluation |
| | Bad part classification; for each bad part feature an own storage space.<br>Exception: reasonable combination of features |
| Manual intervention | Idle cycling after manual intervention. Discharge remaining quantity of the machine |
| | Clear sorting at emergency stop or stop at idling position and at restart (e.g. after disturbances) |
| | Colored marking of reference parts |
| | Non-manipulable bad part containers and transport belts |
| | Reference parts (e.g., calibration and plausibility parts) will be discharged automatically |

Table 1: Standard safety package [4]

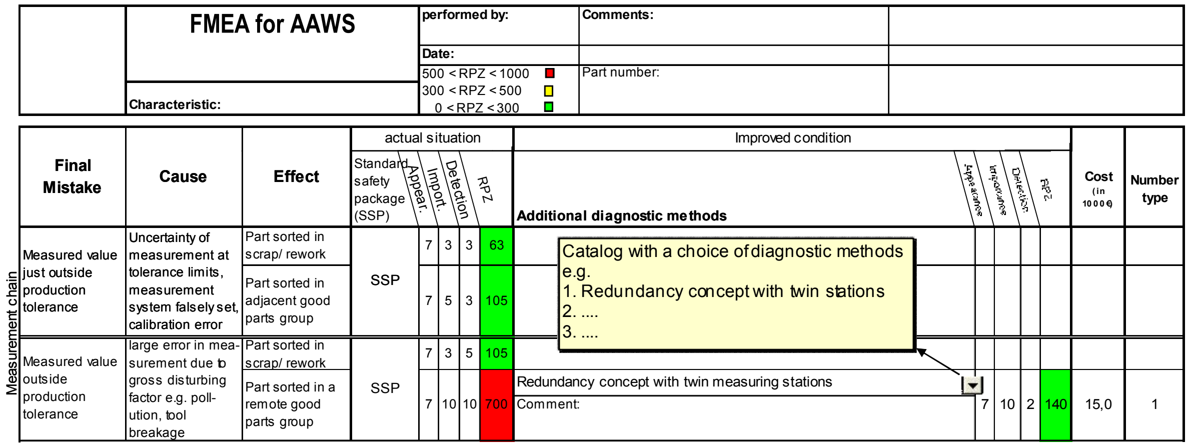
### *3.2 Additional safety package (ESP)*

The ESP includes all methods of failure detection, which do not belong to the standard. Whereas the SSP consists of standardized failure detection methods, the ESP however can be planned variably. Depending on the failure possibilities which will be planned for the AAWIS, the planning team will work out a demand-oriented combination of the methods.

For that purpose a planning tool has been created, which will be used by the planning team for the evaluation of final faults through the standard safeguarding algorithm and for the execution of a risk analysis with a risk priority number (RPN).

The detection probability (E) is one measure for the failure detection of a method. One measure for the significance of the final failure are the incidence and the weight. The incidence, weight and detection as well as the estimated costs for the failure detection methods were defined by a team of experts (fig 19).

The costs arise per type, this means per execution. The costs for the reference normal (working normal) for example arise normally per characteristic which has to be measured, the costs for the automatic program change however arise only one-time at type change. The indication of the cost height is a non-binding estimate and must be adjusted to the respective branch (e.g., automotive supply industry).



| | | | |
|---|---|---|---|
| | **FMEA for AAWS** | **performed by:** | **Comments:** |
| | | **Date:** | |
| | **Characteristic:** | 500 < RPZ < 1000 🟥<br>300 < RPZ < 500 🟨<br>0 < RPZ < 300 🟩 | Part number: |

| | **Final Mistake** | **Cause** | **Effect** | actual situation | | | | | Improved condition | | | | | **Cost** (in 1000 €) | **Number type** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Standard safety package (SSP) | Appear. | Import. | Detection | RPZ | **Additional diagnostic methods** | Appearance | Importance | Detection | RPZ | | |
| Measurement chain | Measured value just outside production tolerance | Uncertainty of measurement at tolerance limits, measurement system falsely set, calibration error | Part sorted in scrap/ rework | SSP | 7 | 3 | 3 | 63 | | | | | | | |
| | | | Part sorted in adjacent good parts group | | 7 | 5 | 3 | 105 | | | | | | | |
| | Measured value outside production tolerance | large error in measurement due to gross disturbing factor e.g. pollution, tool breakage | Part sorted in scrap/ rework | SSP | 7 | 3 | 5 | 105 | | | | | | | |
| | | | Part sorted in a remote good parts group | | 7 | 10 | 10 | 700 | Redundancy concept with twin measuring stations ▾<br>Comment: | 7 | 10 | 2 | 140 | 15,0 | 1 |

Catalog with a choice of diagnostic methods
e.g.
1. Redundancy concept with twin stations
2. ....
3. ....

Fig. 19: Combination of methods of error detection by using a FMEA to create diagnostic concepts

## 4. SUMMARY

The commonly know tool FMEA is used to combine methods of error detection to intelligent diagnostic concepts to guarantee fail safe AAWIS. Fail-safety of AAWIS is the ability to detect errors immediately or shortly after their appearance. This is the precondition for minimizing manual preventive maintenance in the form of inspection and calibration without risking a reduction of an AAWIS' quality performance. This helps to meet the growing quality requirements and the tightened liability regulations.

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**Author:** Prof. Dr.-Ing. Stephan Sommer, University of Applied Science (UAS) Würzburg-Schweinfurt, Faculty of mechanical engineering, Department for Quality management and production metrology
Ignaz-Schön-Straße 11, 97421 Schweinfurt, Germany, phone +49 9721 940 895, stephan.sommer@fhws.de