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5 Part 3

Quality Management in the Automotive Industry

Capability of Optical Sensors and Image Processing

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Note on gender

For reasons of readability, the masculine form is used throughout this text. However, all information applies to both genders.

Foreword

In the automotive industry, optical measurement and inspection systems are commonly used in production for quality assurance purposes as well as in sensor systems within vehicles. Thanks to advances in sensor technology as well as software-based image processing, such systems can be found more and more frequently. Despite this, developers and users of such systems still require standards and clarification regarding efficient proofs of capability as well as series release.

Light carries a vast amount of information (direction, intensity, spectrum/color, polarisation, etc). Therefore, optical systems make it possible to carry out a variety of measurement and inspection tasks. However, using light appropriately and deriving the relevant information reliably requires effort. Optical measurement and inspection processes consequently feature special characteristics which differentiate them from the one-dimensional approach proposed in VDA Volume 5. The present VDA Volume 5.3 aims to close this gap by providing practical recommendations.

VDA Volume 5.3 focuses on the following key aspects:

- To the extent possible, the methodology for obtaining proofs of measurement and inspection process capability for production and the vehicle is based on VDA Volume 5.
- In VDA Volume 5.3, attributive inspection is discussed in greater detail.
- VDA Volume 5.3 also covers the proof of capability of measurement and inspection processes whose software includes components that have been generated by means of machine learning.
- VDA Volume 5.3 addresses optical systems that are used as unique products or in small number in laboratories, development and production (quality assurance) but also those that are produced in large series and installed in street vehicles.
  These include e.g. front cameras for detecting vehicles ahead in order to activate emergency braking assistant functions, or cameras inside the vehicle for monitoring the driver’s level of

alertness.

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1 Standards, guidelines and literature

VDA Volume 5 should be considered the basis of this VDA volume. Necessary or additional sources are listed in the following table.

Objective	International/national standards and documents	Industry standards and additional literature
Design of QM systems/inspection process management	DIN EN ISO 9000 ff DIN EN ISO 10012 DIN EN ISO/IEC 17025 DIN 32937 IATF 16949	VDA Volume 6.1 VDI/VDE 2600-1 VDA Volume Special Characteristics (SC) VDA Volume 1
Determination of measurement uncertainty	Measurement technology, general: DIN 1319 ISO/IEC Guide 98-3 (GUM) DIN ISO 22514-7 Dimension metrology: Beiblatt 1 DIN EN ISO 14253-1	Industry association standards VDMA 8720 EA-4/02 M:2013 VDA 5.2 VDI/VDE 2600-2
Determination of measuring system capability/measurement process capability	DIN ISO 22514-7	AIAG MSA Works standards
Taking the measurement uncertainty into account	DIN ISO14253-1	AIAG MSA Works standards
Acceptance and reverification tests for coordinate measuring systems (CMS) – Part 13: Optical 3D CMS	ISO 10360-13	
Standard format for scene description in case of systems with environment sensors in the vehicle	ISO 23150	Final report Pegasus project ASAM OpenSCENARIO

Assessment of performance and requirements regarding the output “image data” provided by sensors and sensor systems in the vehicle, e.g. 13228 for lidar sensors	ISO/PWI 13389 ISO/PWI **13228** ISO/WD TS 22133 ISO 34502-34504 CIR (EU) 2022/1426 EU General Safety Regulation ISO 21448	
Standardized definition of environment test scenarios for systems in autonomous driving	ISO 34502	

2 Benefits and scope

The objective of VDA Volume 5.3 is to provide further guidance regarding proofs of capability for optical sensors and image processing systems. The methods used are based on VDA Volume 5 but also include certain particularities in relation to optical systems.

2.1 Areas of application and their delimitation

Optical measurement and inspection processes within the meaning of this volume use light and the information transported by it in order to make inspection decisions in production as well as development, and – deliberately expanding VDA Volume 5 – to obtain targeted information about the environment for systems within vehicles.

There are no restrictions in this volume regarding the type of information transported by light and used:

Spectrum (e.g. color), direction (e.g. geometry, 1D to 3D), light travel time (e.g. distance), intensity (e.g. surface in case of reflexion, volumetric characteristics in case of transmitted light), change over time (e.g. film) polarization (e.g. material tension), etc.

Regardless of the specific application, it can be assumed that the functional design of the systems consists of (a source of) light, optics and sensor technology, image processing (algorithm), and an output interface (e.g. a display).

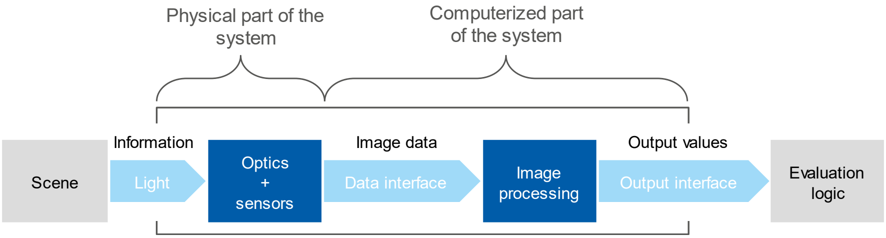

Figure 2-1: Key parts of information processing in optical measuring and inspection systems. The present volume focuses on the parts highlighted in dark blue and only covers the gray parts to the extent necessary. These parts are connected by means of interfaces (light blue).

The volume focuses on the proof of capability. The design of the individual components (e.g. optics, sensor technology, algorithms) depends on the individual application. It therefore falls within the scope of system development and will not be covered in detail here. In particular, systems that use machine learning (ML) algorithms are also included in the scope of this volume.

Examples of applications that fall within the scope of this volume are provided in the following:

- Optical measuring systems used to capture geometries (e.g. dimensional accuracy, distance) → chapter 5
- Optical size measurement (e.g. brightness, intensity, wave length, brightness distribution, temperature, material) → chapter 5
- Quality rating of codes → chapter 6
- Inspection of condition (e.g. orientation, position, completeness) → chapter 6
- Sorting inspections (e.g. color type, comparisons of samples) → chapter 6
- Surface and volume inspections (e.g. defect detection, homogeneity, transmitted light methods with x-rays) → chapter7
- Inspection of the characteristics of vehicle sensors (intrinsic and extrinsic parameters) → chapter 8

The respective application solutions can make use of different various technologies and different wave length ranges. There are different modes in terms of sensor output, e.g.:

- Image-generating (e.g. 2D camera, x-ray machine)
- Scalar (e.g. laser distance sensor, pyrometers)
- Distribution (e.g. spectrometer)

Examples of applications that do not fall within the scope of this volume include, among others:

- Development and implementation of the measuring and inspection systems
- Evaluation logic and reactions to measurement / inspection results e.g. in case of automated driving or sorting, as this involves a decision logic that falls outside the scope of quality assessments for products and/or processes
- Concrete measurement and inspection processes for which there are specific standards, as contradictions and redundancies in standards and guidelines are meant to be avoided (e.g. standardized methods in non-destructive inspection technology)
- Systems without automatic output of measurement or inspection results(e.g. display systems for visual inspection by humans, computed tomography scanners for evaluation of data by users, monitoring and surveillance cameras, high-speed cameras for testing purposes)
- Optical systems that are not used for quality assurance purposes within the production environment or that are subject to Poka-Yoke principles (e.g. code scanner successfully scans/fails to successfully scan a code, or the scanned code is clearly linked to a reference value), and whose evaluation algorithm has been validated by the manufacturer
- Measuring and inspection systems that are not used as products within the automotive industry or that do not serve to develop or verify the quality of automotive products (e.g.

occupational health and safety systems for monitoring safety areas)

- Considering the improper use of optical measuring and inspection systems
- Self-learning systems that continue learning during use and adapt their behavior accordingly. Their behavior is different from the behavior when the proof of capability was obtained. The proof of capability therefore loses its validity

2.2 Differences with regard to VDA Volume 5

Optical sensors and image processing systems, as well as their use within the vehicle, come with a few particularities that require changes with respect to VDA Volume 5.

In the following, these particularities are first described irrespective of the individual application or area of application. Chapters 4 to 8 outline how these particularities should be dealt with when it comes to uncertainty analysis.

Optical measurement and inspection processes in production and within the vehicle mainly differ with respect to two aspects:

1. *Variations in environmental conditions*
   Production processes are subject to environmental conditions that are much more easily controllable than those in vehicles.

2. *Number of systems under consideration*
   While concrete measurement and inspection processes in production are typically used for unique parts or parts available only in small number, optical measurement and inspection processes are used in the large-scale series production of vehicles.

Some of the requirements with regard to proofs of capability are therefore different, which is why chapter 8 is dedicated to systems in vehicles. Compared to VDA Volume 5, there are also a few additional potential influencing quantities for optical measuring and inspection systems (see chapter 2.3), given that the systems are often used directly in production lines where environmental conditions are less controllable than they are e.g. in laboratories or measuring rooms.

Further major features that require more in-depth consideration in comparison to VDA Volume 5 are listed in the following:

Light

Light is an obligatory component of optical measuring and inspection systems. It serves as a carrier of information but can also have an interfering influence on the measurement and inspection task (extraneous light, see chapter 3.1). These influences represent a challenge when it comes to determining the measurement uncertainty (see chapter 5.1.1.4). In certain applications, the light itself is the measured / inspected variable (e.g. color). In others, it only transfers it indirectly (e.g. difference in color/intensity for geometric measurement on a component edge). This can make it necessary to drastically filter/compress the stream of information between the object and the inspection result (e.g. 2D camera image to scalar length value). When it comes to obtaining proof of capability, a large number of influencing quantities which are not directly related to the measurement or inspection task may consequently have to be taken into account.

Temperature

In contrast to VDA Volume 5, where the temperature influence is limited to the measured object or the inspected object, the influence of the temperature on the medium (e.g. air) and the sensor system itself must also be taken into account in case of optical systems. Here, the electro-optic response behavior, the optical power input / output or the wave length of the light / its distribution can change.

Linearity

In keeping with VDA Volume 5, the linearity deviation is understood to mean the variability of the bias of a measuring system over the scope of application. Optical systems can have significant linearity deviations, e.g. distortion at the edge of camera images). This topic is therefore explicitly addressed in chapter 5.1.1.5 of the present volume.

2.3 Influencing factors in case of optical sensors and image processing systems

In VDA Volume 5, influences on the uncertainties of measurement results are summarized in an Ishikawa diagram (Figure 5-1 in said volume). This diagram is included in this volume as well, and certain information was added in order to take account of the specific requirements of optical measurement and inspection processes (see the parts highlighted in light blue in Figure 2-2). Categories highlighted in blue relate to verification (i.e. the analysis of the measuring system under laboratory conditions, see chapters 5.1.1 and 5.2.1); categories highlighted in green related to validation (i.e. the analysis of the measurement process, see chapters 5.1.2 and 5.2.2).

The main influences can be subdivided into many subcategories. The list of categories in Figure 2-2 is meant to provide orientation and is not exhaustive. It is advisable to make individual adjustments for concrete applications, to identify relevant influencing quantities and to derive potentials for optimization of the measurement process.

The recurring, major influencing quantities as well as the associated standard uncertainties are covered in chapter 5.

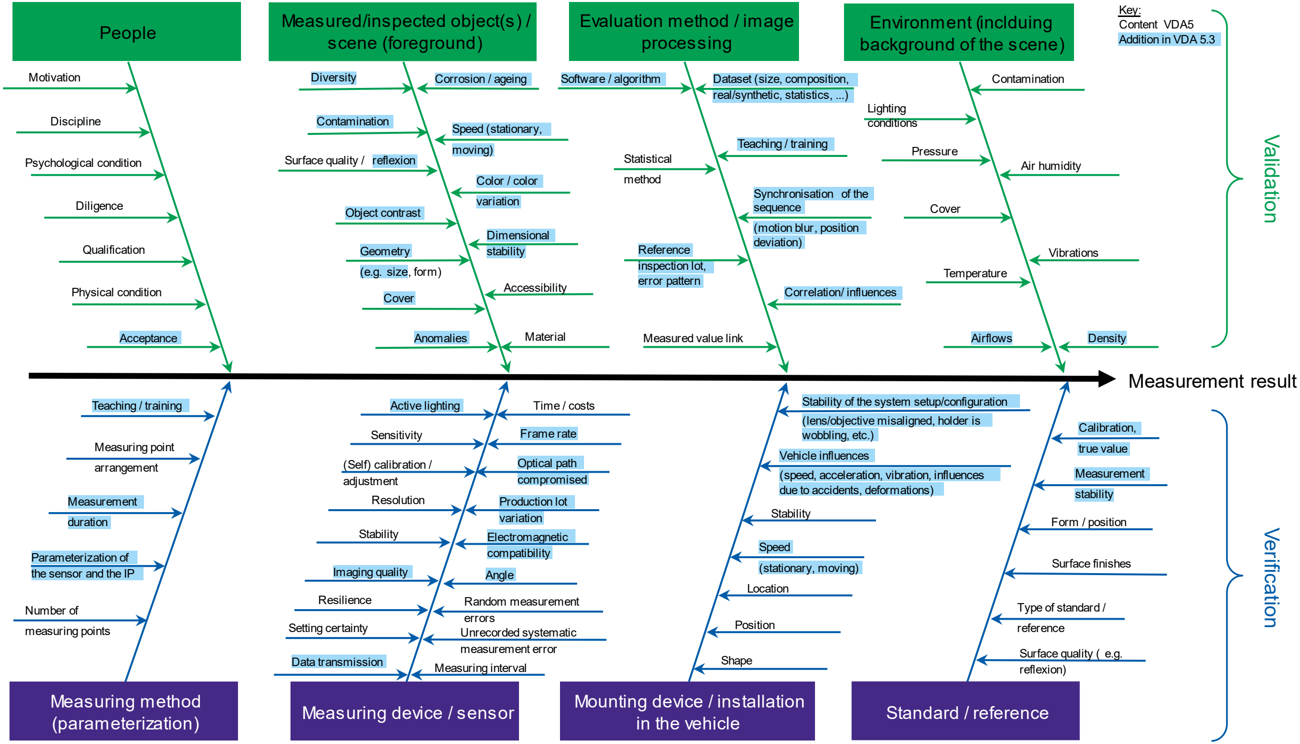

Figure 2-2: Ishikawa diagramm of influencing factors in relation to the measurement result

3 Terms and definitions

3.1 Glossary

Generally, the terms defined in VDA Volume 5 are used in the present volume as well. In the following, terms that are frequently used in this volume are added to the glossary and individual definitions are changed or made more precise in order to fit the context of this volume.

Acceptance
Written declaration by the customer stating that the customer is accepting the product (in the legal sense). Within the scope of the acceptance procedure, a range of inspections are carried out which serve to convince the customer/purchaser that the product fulfils the specified requirements.

Artificial intelligence (AI)
An “artificial intelligence system” (AI system) is a piece of software which has been developed based on the concept of machine learning, logic or knowledge-based concepts or statistical approaches and which can - on the basis of objectives specified by humans - provide results such as contents, predictions, recommendations or decisions that influence the environment with which they interact (according to [4]).
In this volume, it is understood to mean a system which uses algorithms generated by means of machine learning.

Attributive
Attributive systems assign characteristics to discrete classes. Attributive systems are used for classification.

Background
Part of the scene which does not belong to an object and is not included in the image processing task. This part can have an impact on the performance and the capability of the system. [2]
In case of optical sensors in production, it is for example the part of the surroundings of the inspected object which is in the field of view
(see also “Foreground”).

Capability
A system or process is capable if the relevant requirements are met and the purpose of use is fulfilled.

Classification
Allocation of a characteristic of an object to a previously defined class. The definition provided in VDA 5 is extended in this volume, such that the term “classify” is also applicable to attributive systems.

Combined system
Overall system which consists of multiple measuring systems and/or attributive systems.

Detection of anomalies
Detection of object characteristics that deviate significantly from the known classes (based loosely on [1]). This is meant to allow for production systems to classify even previously unknown errors as NOK, to the extent possible.

Entangled system
A system which provides a combination of attributes and measured values in the scene description, whereby it is not possible to separate between isolated classifying and measuring subsystems (see chapter 7.3).

Exposure time
Time period during which the incoming light is integrated by a sensor for the purpose of image capturing.

Foreground
The part of the scene which is to be investigated or detected. In production, this is the inspected object. In case of sensors in a vehicle, it is the entirety of the objects that were specified in the scene description (see also “Background”).

Image data
Output signals of optical sensors. These can be traditional 2D data in the form of a matrix of intensity values, but also e.g. 3D data from a laser scanner. The term can refer to a single image as well as to a longer time period.

Image processing (IP)
Evaluation of digital images by means of algorithms. It involves reducing the amount of information of the digital image up to the measurement or inspection result.

Improper use
Negligent or deliberate operation, application, or use of a system outside of the intended or prescribed scope of application.

Inspected object
Object which is being inspected (see “Object”).

Inspection decision
Result of the conformity assessment, obtained by comparing characteristics with a defined specification.

Inspection equipment user
Role in inspection process management, also referred to as ‘operator’ or ‘inspector’ (see chapter 4.1).

Inspection equipment operator
Role in inspection process management (see chapter 4.1).

Inspection equipment management
Inspection equipment management is part of inspection process management and serves to provide suitable resources for ensuring valid, reliable and comparable monitoring and measurement results.

Inspection process
Performing an inspection and reaching an inspection decision by comparing the result of a measurement process and/or classification process with a given specification with due consideration of the determined measurement uncertainty.

Inspection system
Measurement and/or classification system that is used for an inspection

Inspection system developer
Role in inspection process management (see chapter 4.1).

Intentionally defective unit (red rabbit)
An object which the system is meant to classify as an exception, i.e. as defective in production. It is deliberately introduced to the scene in order

to trigger the relevant output and to show that the system is functioning correctly.

Learning lot
Scenes / objects / datasets which are used for the development / optimization of the measuring or inspection system. It must not be used for the proof of capability.

Light
Within the meaning of this volume, light constitutes electromagnetic waves which are present in the scene and a part of which reaches the optical sensors, thus determining or influencing the image data generated there (see definition in chapter 3.2 “Definition of light”).

Lighting
Deliberately introduced light (see chapter 3.2 “Definition of light”).

Limit sample
Limit samples define the acceptable quality levels of the upper/lower tolerance limit (e.g. determined by customer or development specifications), similar to the way this is described in VDA Volume 16 [3] by means of the maximum tolerable process level (MTP).

Machine learning (ML)
An artificial system which identifies correlations based on examples (learning data) and generalizes them. For this purpose, algorithms automatically create models which represent these correlations in the learning data (see also “Artificial intelligence”).

Measuring interval
A measuring interval is the set of values of quantities of the same kind that can be measured by a given measuring instrument or measuring system with specified instrumental uncertainty, under defined conditions [5]. In case of continuous or ordinal quantities, the measuring interval is typically defined by a minimum and a maximum value.

Measured object
Object which is being measured (see “Object”).

Measuring volume
The measuring volume is thus the sum of the geometric positions at

which a measurement of the influencing quantity to be analyzed is possible.

Object
Object of interest on which particular characteristics are measured, classified or detected. Also referred to as measured object or inspected object, depending on the application.
Part of the foreground of a scene.

Optical measurement process
A process consisting of an optical measuring system, a person / persons, a measured object and the environment (see also chapter 3.3 “Definition of optical measuring system and optical measurement process”).

Optical measuring system
An optical measuring system is defined by an optical measuring device, a measurement method and an associated standard (see also chapter 3.3 “Definition of optical measuring system and optical measurement process”).

Optical sensor
A sensor which converts incoming light into image data.

Parallel system
In parallel systems, multiple characteristics are inspected or measured in the same overall system, and the associated results are output accordingly (see chapter 7 “Combined systems”).

Planer
Role in inspection process management (see chapter 4.1).

Reference
A reference is a reference value/reference body/reference material associated with (at least) one known characteristic value.

Reference examiner/team
Qualified personnel with a high level of expertise in conducting visual inspections for the purpose of identifying or classifying characteristics.

Reference inspection lot
Entirety of the objects proof of capability reference evaluation inspection system and is therefore separate from the learning lot.

Release
Confirmation that an inspected system fulfills the requirements and can be used for its intended purpose.

Resimulation
Resimulation means evaluating system behavior by playing previously recorded images of real and/or virtual scenes.

Resolution
The resolution of an optical measuring system in its entirety is influenced among other things by the resolutions of the optics, sensors and algorithm subsystems. It represents the smallest change in the scene which reliably affects the output (see [2] and chapter 3.4 “Definition of the resolution of optical measuring systems”).

Safe launch
Temporary safeguarding of an inspection characteristic by means of implementing an additional inspection level prior to final release (see chapter 6.2).

Scene
Part of reality captured by the sensors. Includes the background and optionally the foreground with one or more objects.

Scene description (SD)
Result provided by the measuring or inspection system. It includes information about the possible objects in the foreground of the scene as defined in the specification.

Sensors
All optical sensors within the system under consideration, at least one sensor.

Sequential system
In sequential systems, the inspection process consists of several steps. Downstream inspection steps are based on the results of the previous steps. In this volume, it is often just the final results that is taken into consideration (see chapters 7.2).

Statistical test design (DoE)
Statistical procedures used to reduce the effort required for testing while maximizing the amount of information obtained. Can be used to create test designs.

Teaching
Teaching refers to the data-based adjustment of a system by means of a number of references, such that the characteristics allocated to the references are reproduced (also see chapter 6).

Test design
In the test design, the experiment is described in terms of the number of repetitions per investigated influencing variable in order to determine the measurement uncertainties and their interdependencies with reasonable effort. Designing a test requires experience and an understanding of the problem as well as the system (see also [6], [7]).

Tolerance (for production systems)
Deviations of a characteristic from the target, as defined in the specification of inspected objects. Not to be confused with measurement uncertainty.

Tolerance (for vehicle systems)
Deviations of a characteristic from the target, as defined in the specification of the sensors.

Type 1 error
Erroneous rejection, also referred to as pseudo-error or “false bad”.
The inspection decision provides an error class even though the characteristic meets the requirements.
In production, these are the less critical errors, as they do not cause a defective part to be delivered.

Type 2 error
Erroneous acceptance, also referred to as slippage or “false good”.
The inspection decision provides an acceptance class even though the characteristic does not meet the requirements.
In production, these are the more critical errors, as they cause a defective part to be delivered.

Validation
Verification that the specified requirements are appropriate for the

intended purpose (see [5]).
With regard to measuring systems, validation is the second step of the process of obtaining proof of capability under operating conditions.

Verification
Provision of objective evidence that a unit of observation fulfills specified requirements (see [5]). It must be specified which requirements are being verified.
With regard to measuring systems, verification is the first step of the process of obtaining proof of capability with standards under laboratory conditions. In case of entangled system, the measuring system part is evaluated here.

α-Risk
Also referred to as the manufacturer risk: Probability of occurrence of type 1 errors which lead to erroneous rejections. This is often determined approximately based on the relative frequency of type 1 errors in a sample.

β-Risk
Also referred to as the consumer risk: Probability of occurrence of type 2 errors which lead to erroneous acceptance. This is often determined approximately based on the relative frequency of type 2 errors in a sample.

3.2 Definition of light

In this volume, light is defined as electromagnetic waves which are contained in the scene and of which a part reaches the optical sensors. This definition is in line with the everyday use of the word and differs from the physical definition according to DIN 5031. For a more detailed description, five narrower terms are used in the following.

The light present in the scene comes from three types of light sources (see Figure 3-1):

- **Deliberately introduced light:** Light actively generated within the scope of the measurement/inspection process for the purpose of illuminating the scene (e.g. lidar, fringe projection, flashlight, ring light)
- **Emitted light:** Light emitted by objects themselves (e.g. vehicle headlights, displays, traffic lights, thermal radiation)
- **Ambient light:** Light from any source, which is present independent of the measuring/inspection system and is not directly emitted by the inspected object (e.g. sunlight, street lights, hall light, system-external lighting)

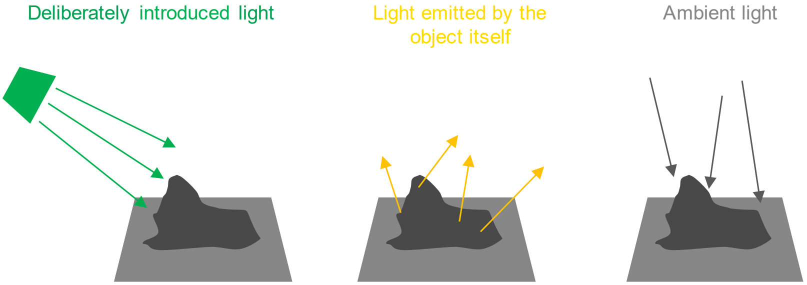

Figure 3-1: We can distinguish between three types of light sources: Light deliberately introduced within the scope of the measurement/inspection process for the purpose of illuminating the scene (left), light emitted by the inspected object/foreground itself (center) and ambient light which is present independent of the measuring/inspection system (right).

Part of the light present in this scene is captured by the sensor and can be subdivided into **interfering light** and **usable light** (see Figure 3-2):

- **Interfering light:** Light which is not required for the measurement or inspection task, and which may have a negative impact on the completion of the measurement or inspection task. Interfering light can for instance lead to an unfavorable signal-to-noise ratio or sensor saturation. The contrast between the object and the background may therefore be too small, or the inspection characteristic may no longer be visible. Interfering light can for instance be caused by system-external lighting or light scattering on contamination
- **Useful light:** Light that is required in order to carry out the measurement and inspection task correctly. The light could come from specific lighting techniques, from the environment, or could be emitted by the object itself

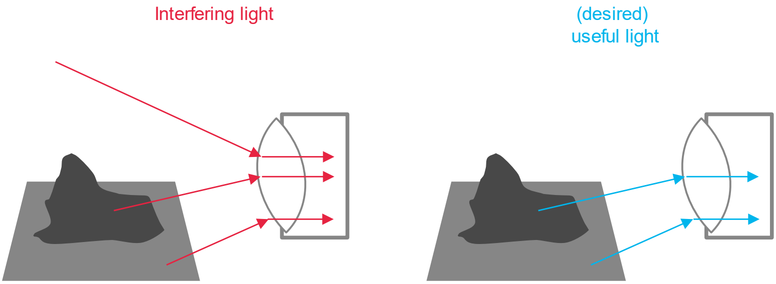

Figure 3-2: Light present in the scene reaches the sensor. It is necessary to distinguish between interfering light (left) and desired usable light which is used for the measurement/inspection task (right).

3.3 Definition of optical measuring systems and optical measurement process

Optical measuring systems generally differ from those discussed in VDA Volume 5. An optical measuring system is defined by an optical measuring device (optics+sensor and image processing), a measurement method and an associated standard. The optical measuring device is a piece of equipment used for measuring and evaluating intensity, spectral distribution, polarization or other characteristics of light (see chapter 3.1). The equipment may include the following components: Sensor, source of light, optics, holders for installation.

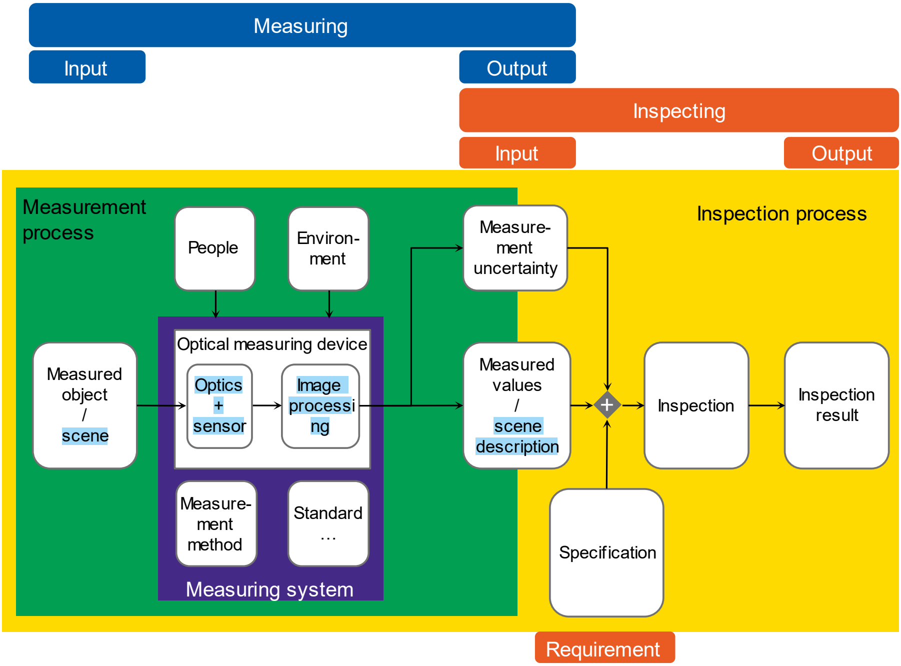

Figure 3-3: Relationship between measuring system, measurement process and inspection process based on VDA Volume 5. Additions are highlighted in light blue.

An **optical measurement process** must be considered as a whole. The optical measurement process consists of the optical measuring system, a person/persons, the measured object and the environment.

Attributive optical evaluation process: A process which assigns at lease one attribute to an inspected object using optical methods.

Attributive optical inspection process: An inspection process provides an inspection result (e.g. good/bad) by comparing attributes to specified targets.

A comparison of the relationships between the measuring systems, measurement processes and inspection processes of measuring and attributive systems can be found in Figure 3-3 and Figure 3-4.

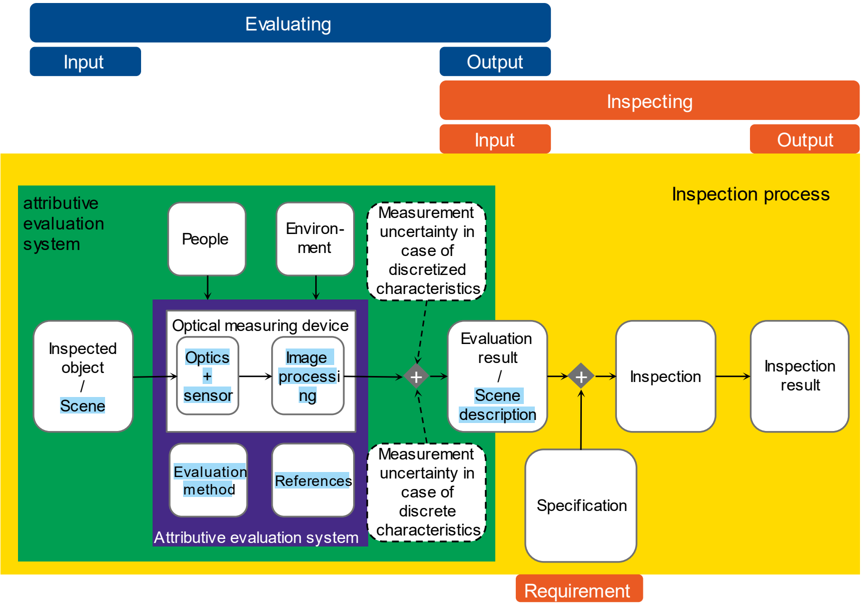

Figure 3-4: Relationships in the attributive case analogous to Figure 3-3

3.4 Definition of the resolution of optical measuring systems

The **resolution of an optical measuring system** in its entirety is influenced among other things by the resolutions of the optics, sensors and algorithm subsystems. It represents the smallest change in the scene which reliably affects the output (see also [2]).

The output can be provided via an output interface (particularly in case of vehicle systems) or by means of a direct display. Resolution as it is defined here therefore corresponds to the “display resolution” described in VDA Volume 5.

Depending on the application of the inspected optical measuring system, resolution may also refer to e.g. the spatial, temporal or spectral dimension.

Figure 3-5: The usable resolution on the output interface (resolution of the system) results from the evaluation of the overall path of the flow of information of the light up to the output interface. It is crucial for the proof of capability.

Note: *The term resolution as it is used here must not be confused with the term "resolution of the optical sensor” frequently used in practice!*

4 Inspection process management

In general, inspection process management for optical systems should follow the approach described in VDA Volume 5. In case of attributive inspections, there are a few additional aspects to take into consideration regarding the inspection planning process as well as the roles and responsibilities.In case of inspection processes involving measurements, the procedure described in VDA Volume 5 can be applied.

The inspection planning process additionally requires the role of the inspection system developer, given that attributive systems are often designed on a customer-specific basis and therefore require the involvement of inspection system development. In addition, specific expertise required in the field of industrial image processing is also taken into account.

In contrast to optical measuring systems, measurement uncertainties can usually not be determined in case of attributive optical inspection systems. Instead, the expected α and β risks, i.e. the risk of incorrect inspection decisions (see Table 4-1) are taken into account within the scope of the proof of capability: This can either be done explicitly by means of limit values for the risks or implicitly by means of the relevant capability ratio limit. This approach is described in greater detail in chapter 6.

Table 4-1: Confusion matrix (based on VDA Volume 5, chapter 4.1.1, Figure 4-2)

		Actual state	
		Inspected object OK	Inspected object NOK
Inspection decision	Inspected object accepted	Correct decision	Type 2 error erroneous acceptance
	Inspected object rejected	Type 1 error erroneous acceptance	Correct decision

The procedures described in VDA Volume 5 in relation to risk-based assurance, the complaint process, inspection equipment management, proof of efficiency inspection process management and the safeguarding of inspection results, taking the measurement uncertainty into account, can also be used in case of optical measuring systems.

4.1 Roles and responsibilities in inspection process management

4.1.1 Roles in inspection process management

In general, all roles in inspection process management are described in VDA Volume 5, chapter 4.2.1.

Optical inspection systems require additional tasks, competences and responsibilities. The relevant roles are described below, including the description provided in VDA Volume 5 as well as aspects specific to VDA Volume 5.3 which have been added or changed accordingly. Roles which remain unchanged are not listed here.

An additional role is introduced in VDA 5.3: In case of attributive inspection systems, it is advisable to take inspection system development into account as well. This can be covered by external resources if necessary.

As described in VDA Volume 5, multiple roles can be assigned to one and the same person or to a group of persons, depending on the structure of the organization.

Planner (inspection process)

- Carries out inspection process planning based on the characteristics of product development and the manufacturing process of planning
- Evaluates the inspection process in the context of the risk-based assurancerisk-based assurance of inspection decisionsinspection decisions (for information on the

determination of the risk class and the resulting degree of assurance, see VDA Volume 5, chapter 4.3 and VDA Volume 5.3, chapter 6.1)

- In case of attributive optical inspection systems: Specifies the inspection types, error types and inspection tolerances in an error catalog
- In case of attributive optical inspection systems: Specifies and provides the reference inspection lot
- In case of attributive optical inspection systems: Submits a request to the inspection system developer to conduct feasibility studies – depending on the risk classification
- Compiles specifications for the measuring or inspection system, including the definition of the acceptance criterion for the proof of capability. In case of attributive optical inspection systems: Defines the reference inspection lot for the proof of capability

  Note: Depending on the type, the number, and the combination of characteristics (see chapter 7), the efforts required for design and validation can increase significantly. It is therefore necessary to critically question the technical feasibility and the necessity of the scope of inspection.
- Initiates the purchase order by the procurement department
- Plans the initial training on the measuring or inspection system by the supplier
- Organizes the initial acceptance procedure for the measuring or inspection system, including proof of capability and, if necessary, validates the evaluation software used
- Transfers the measuring systemto the inspection equipment management system for monitoring, and defines the boundary conditions (e.g. the monitoring method and interval)
- Hands the measuring or inspection systemover to the inspection equipment operator

Inspection system developer

- Carries out a feasibility study upon the planner’s request

- Designs the inspection system (hardware and software), taking the specified environmental conditions and requirements into account
- Defines the conditions for successful implementation of the inspection system within the scope of the environmental conditions specified by the planner
- Documents the results of the feasibility study as well as the design of the hardware and software
- Carries out the initial adjustment of the inspection system in production
- Optimizes the inspection system until final release in accordance with the specifications and acceptance criteria

Inspection equipment user (also referred to as examiner, user)

- User who uses the measuring equipment
- Responsible for the exclusive use of approved inspection equipment
- Verifies compliance with the calibration date
- Carries out checks for signs of obvious damage to the inspection equipment before use
- Reports potentially faulty inspection equipment
- Blocks potentially faulty inspection equipment
- Uses the inspection equipment as intended and in compliance with control requirements

Inspection equipment operator

- Bears primary responsibility for the measuring and inspection systems and for the inspection process
- Manages the measuring equipment/inspection equipment used
- Introduced and implements the required processes
- Creates process descriptions
- Ensures that the employees have the necessary qualifications
- Determines the inspection intervals
- Blocks faulty inspection equipment

- Ensures that calibration/verification is carried out
- Conducts failure analysis with respect to the inspection equipment
- Ensures that the inspection system is regularly maintained (including cleaning, if necessary) and checked (see chapter 6.7)
- Operates only inspection equipment that has been released
- Initiates improvements of the inspection system: Optimizations by the inspection system developer, or changes to the inspection program / adjustments to parameters by the inspection equipment user and ensuring that the necessary release processes are carried out

It is essential that the roles of product development, manufacturing process planning and inspection process planning as well as inspection system development are coordinated in order to attune tolerances, inherent manufacturing process variation and measurement uncertainty (in case of optical measuring systems) or the α/β risks according to the specifications in the sense of a capable manufacturing process (see chapter 4.2).

4.1.2 Qualifications and skills in inspection process management

All employees must be suitably qualified for the roles assigned to them. Based on VDA Volume 5, the following table shows recommendations for role-specific skills. Skills specific to optical systems have been added.

Table 4-2: Recommendations for role-specific skill sets in inspection process management

Role Competence	Process owner inspection process management	Product developer	Planner (production process)	Planner (inspection process)	Procurer (measuring or inspection equipment)	Calibration laboratory worker (internal or external)	Inspection equipment officer	Inspection equipment operator	Inspection equipment user	Process auditor	Inspection system developer
Quality management	2	1	1	1	1	1	1	1	1	2	1
Measuring and inspection technology	2	1	1	1	1	2	1	1	1	1	2
Calibration	1	-	-	-	-	2	1	-	-	-	2
Inspection equipment management	2	-	1	2	-	2	2	1	1	1	1
Determination of measurement uncertainty and proof of capability	2	1	1	2	-	2	1	1	1	1	2
DIN EN ISO/IEC 17025 – Testing and calibration laboratories	2	-	-	-	-	2	1	-	-	2	-
Industrial image processing	-	-	-	1	1	-	-	1	1	1	2
Proof of capability of attributive optical inspection systems (VDA Volume 5.3)	2	-	1	2	-	-	1	1	1	-	2

Key: 1 = basic level / 2 = expert level, highlighted in light blue: Addition to VDA Volume 5

The “quality management”, “measurement and inspection technology” and “inspection equipment management” skill sets have already been described in VDA Volume 5. The newly introduced skill set in relation to industrial image processing includes the following skills/areas of knowledge:

- Areas of application of image processing
- Structure and functional principle of imaging sensors
- Types and handling of optics
- Lighting: Influence of intensity, direction and type
- Fundamentals of image processing methods, including image pre-processing, pattern detection, image evaluation and machine learning processes
- Assessment of the potential and limits of image processing
- Evaluation of digital interfaces (data rate, cable length, data security, costs, availability, etc.)
- Structuring of the image processing task as a chain of interlinking subsystems
- Understanding of the problematic relationship between type 1 and type 2 errors in case of attributive inspection systems

4.2 Inspection process planning

For attributive optical inspection systems, the approach presented in chapters 6.1 to 6.3, as illustrated in the following flow chart (see Figure 4-1) is recommended in addition to VDA Volume 5. This means that for systems whose component structure has not yet been specified, a feasibility study is carried out However, the procedure according to VDA Volume 5 can be implemented without any changes in case of optical measuring systems.

When it comes to inspection process planning for optical systems, the various influencing factors shown in the Ishikawa diagram (see chapter 2.3, Figure 2-2) must be taken into account . In particular, light is an influencing factor that requires special attention. Light is a high-dimensional influencing quantity characterized e.g. by the spectrum, direction, intensity, polarisation and intensity modulation (PWM).

The decisive factor is what counts as light for the system (and not for the human eye). In order to be able to take the relevant influencing factors into account during planning, it is necessary to be familiar with the way the system functions.

The influence of the ambient light can be minimized by means of optical filters (e.g. bandpass filters and/or polarizers) which have been adjusted according to the light used by the optical measuring system or by means of measuring the ambient light if the software takes the results into account. The remaining influences on the inspection process must be taken into account when it comes to the proof of capability.

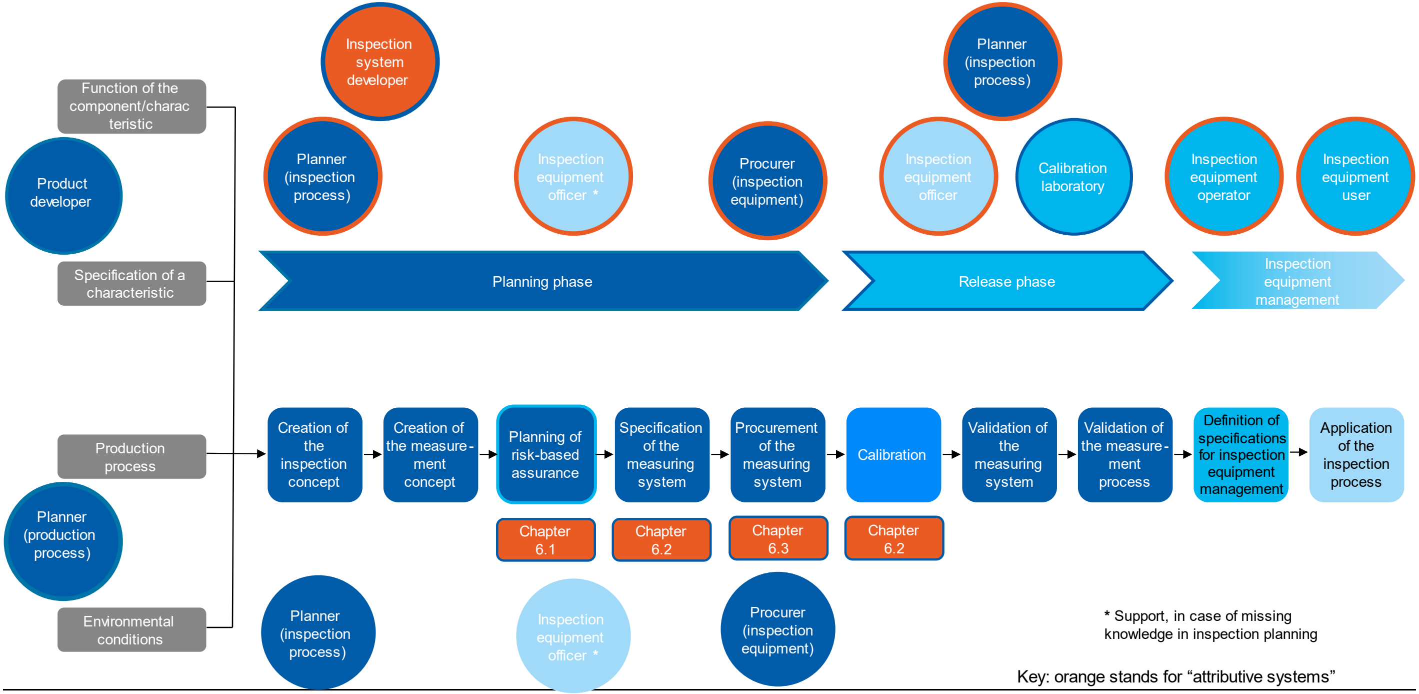

Figure 4-1: Schematic sequence of inspection process planning, taking the particularities of optical measuring and inspection systems into account

4.3 Notes on setting up optical measuring systems

When it comes to optical measuring and inspection systems,, the term calibration is used differently in literature and in practice than it is in production measurement technology. The calibration of optical sensor systems – in particular cameras – serves to determine the geometric camera model which is described by the so-called intrinsic parameters (see [8]). Among other things, this includes determining the position of the projection center on the image sensor as well as the distortion and color corrections. In addition, sensor systems can be calibrated radiometrically so that the physical properties of the light can be analyzed. Corrections are made here, such as corrections of defective sensor elements (pixels), irregular sensitivity of pixels, as well as vignetting and the reduction in brightness at the edge of the image.

In accordance with VDA Volume 5.3, the calibration of an optical system is understood to be part of the preparatory set-up process. In the case of a coordinate measuring device, this is comparable to the calibration process of a probe, whereby this measuring device is made ready for measurement for the subsequent calibration.

Within the scope of geometry determination by means of several sensors, so-called multi-sensor systems, the sensors must be calibrated in order to determine the extrinsic parameters (orientation and position relative to each other). When considering sensors in a vehicle, the former are related to a specific vehicle coordinate system.

Calibration is imperative particularly in the case of optical sensors (e.g. cameras, lidar, 3D sensors), as it provides the basis for determining the deviation of the measuring system from a standard. In some cases, geometric or radiometric calibration must also be carried out and taken into account in the planning process for attributive inspections. This is done by determining the type of calibration procedure and the calibration standards used, to the extent that the inspection task necessitates this. The planner and the inspection system developer must coordinate all of these aspects (see Figure 4-1).

in general, the following types of calibration standards must be taken into consideration during the planning process (see Figure 4-2):

- Geometric standards: Calibration plate or body, specifically manufactured standards that are similar to the actual component
- Radiometric standards: Color calibration card, Planckian radiator (e.g. Ulbricht spheres)

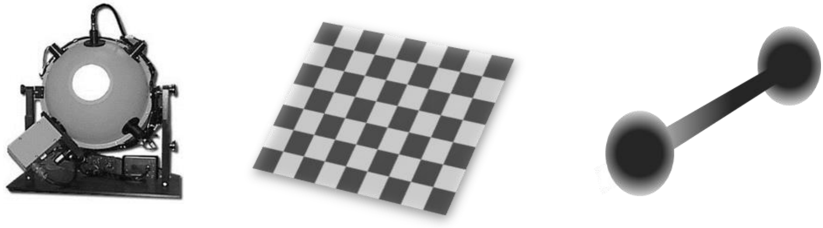

Figure 4-2: Radiometric and geometric standards. From the left: Ulbricht sphere (source: Wikipedia), calibration target for camera calibration and calibration target for 3D / multi-sensor calibrations according to VDI/VDE 2634-2

The initial set-up of an optical system provides the basis for the proof of capability. However, it is not necessary to obtain a new proof of capability after each new calibration within the scope of a set-up.

Should deviations be identified during the measurement or inspection process, e.g. due to external influences or ageing processes of the system components, all calibration parameters must be redetermined within the scope of a new set-up (see VDA Volume 5, chapter 4.3.3)[1].

If no standards can be used for calibration, it is necessary to specify a reference part that has been calibrated with traceability and that is representative of the measurement task.

If a calibration of the measuring or inspection system is not possible, e.g. due to a lack of standards or traceable reference parts , a functional inspection must be specified for verification purposes. The type of inspection as well as the inspection cycle must be taken into account and the result must be documented. In this case, no traceable

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[1] In this context, the relevant calibration intervals should be scrutinized and/or counter-measures should be reevaluated.

measurements are possible. Only comparative measurements can be made.

5 Proof of capability for inspection processes involving measurements

Measurements and inspections are inherently associated with uncertainties. Determining these measurement uncertainties is a central part of the proof of capability of inspection processes involving measurements. This applies irrespective of the measuring or inspection system used. The principle behind the key figure for evaluating capability is to correlate the uncertainty of the measurement result with tolerated deviations of the measured quantity.

The general process of obtaining the measurement and inspection process capability (including a description of the influencing quantities and the quantification of the measurement uncertainty contributions) is described in chapter 5.1. Chapter 5.2 covers the combined measurement uncertainty, and the process of determining the extended measurement uncertainty is discussed in chapter 5.3.

5.1 Overall procedure for measurement and inspection process capability

The general process for proving measurement and inspection process capability for optical measuring systems follows the same approach as in VDA Volume 5 and is based on the requirements set out in that volume. Given that optical measuring systems come with additional influencing quantities and uncertainty components, these are described explicitly in the present volume (chapters 5.1.1 and 5.1.2). All influencing quantities and uncertainty components that are not explicitly described must be determined and taken into account in accordance with VDA Volume 5. Methods that are transferable are not explicitly described (e.g. analysis of the MPE for u_{MS}: in case of a reliable MPE, this is completely identical to VDA Volume 5).

The principle behind the approach described below is as follows: The measurement, i.e. the determination of the influencing quantities, is subject to influences that are due to various factors. The most important influences are described individually, and a procedure is described which can be used in order to determine the strength of their effect. The objectives are:

a) Estimating the measurement uncertainty realistically and not underestimating it by overlooking/disregarding influencing quantities
b) Determining which influences must be (better) controlled in order to successfully obtain the proof of capability.

To determine the effects of the individual influencing factors (see Figure 2-2, Ishikawa diagram) on the measurement uncertainty, tests are carried out and analyzed by means of ANOVA. If evaluation by means of ANOVA is not possible due to missing repetitions of settings, it is advisable to use the Lenth's Method [9] in order to analyze the significance of effects when designing tests. When specifying the test design, it is necessary to weigh between sufficient separation of the influencing quantities on the one hand and the number of measurements to be carried out on the other hand. Practical experience has shown that a full factorial design which can separate between all effects and interactions of any order between the influencing quantities under evaluation is not always necessary. A fractional factorial design can be sufficient if the main effects of interactions can be determined separately.
In the following, the standard influencing quantities to be considered are described. In addition to the factors, the methods to determine them as well as suggestions for designing tests are provided.

If there are further relevant influencing quantities which are not described in chapters 5.1.1 to 5.1.2, they must be taken into account by carrying out additional tests. When conducting measuring system or measurement process capability studies, it is important to ensure that redundant repetitions of the effects of these influencing quantities are avoided. This can for example be done by integrating the additional influencing quantities into the statistical test design described above. As soon as the value of an uncertainty component of a potential additional influencing quantity is smaller than 10 % of the largest uncertainty component, it can be neglected in accordance with VDA Volume 5, chapter 6.3.7.

It is impossible to discuss all influencing quantities relevant in each individual case and to provide specific recommendations for action here.

Furthermore, an influencing quantity that is considered important may be difficult or impossible to control in concrete individual cases.

Controllable means that the value of the influencing quantity is known, can be influenced, and can be kept sufficiently stable throughout the test period.

In case of influencing quantities that are uncontrollable or difficult to control, it is thus not possible to adequately replicate the influence on the measurement in the tests, and the associated uncertainty validly quantifiable. This applies for example to ambient temperatures in production.

Influencing quantities that are difficult to control are actively varied, to the extent possible. In case of uncontrollable influencing quantities, measurements are carried out in a targeted manner if these influencing quantities take different values (e.g. tests at nighttime and during the day to analyze different ambient temperatures). The uncertainties can then be extrapolated from the expected range of fluctuation of the influencing quantities (e.g. values during summer and during winter). This extrapolation in order to determine the maximum uncertainties can be done on the basis of non-linear models. For simplified assumptions, it is also possible to assume a linearity with a safety factor. However, non-linear effects can mean that these estimates turn out to be inaccurate, which represents a residual risk.

5.1.1 Measuring system

In the following, uncertainties typically associated with the measuring system are discussed. In particular, this includes influencing quantities that are attributable to the measuring system under ideal laboratory conditions (see Figure 2-2 and Figure 3-3).

One of the objectives when conducting measuring system tests is to determine the residual bias as accurately as possible. If the ambient light, or at least a part of it, is useful light, it has a systematic influence on the measurement result and therefore has to be taken into account in the test. Blocking the ambient light during the measuring system test is not permissible in this case.

If the ambient light is blocked in order to optimize the measurement/inspection process, this must be consistently taken into account in the measuring system and measurement process tests.

5.1.1.1 Display resolution – u_{RE}

As described in chapter 3.4, the resolution of the system is the smallest detectable change in the scene. Based on VDA Volume 5, the term display resolution u_{RE} is used here to refer to the resolution of the system defined in chapter 3.4. The uncertainty should be quantified as described in VDA Volume 5.

5.1.1.2 Calibration uncertainty of the standard/the reference – u_{CAL}

The calibration makes the entire measuring system traceable to a national/international standard. The calibration uncertainty is the measurement uncertainty associated with the reference value of the standard. Ideally, this is determined during calibration of the standard and indicated in the calibration record. The calibration uncertainty is determined based on the procedure described in VDA Volume 5 (chapter 6.3.3).

If small quantities are measured and the tolerances are small, it is often not possible to obtain proof of capability. This can be due to systematic deviations between the reference value and the measured value of the system under inspection. Among other things, this difference can occur because the measuring system under inspection and the measuring system used for calibration use different measuring principles. If this is the case, it is advisable to use a different standard which has been calibrated using the same measuring principle. An example for this are roughness measurements using tactile or optical measurement methods.

5.1.1.3 Repeatability of the measuring system – u_{EVR}

The repeatability of the measurement on the reference (u_{EVR}) is used to analyze the dispersion behavior of the measuring system. It is advisable to take all influencing quantities of the measuring system (except for u_{RE}, u_{CAL} and u_{BI}) into account in a combined test design. Besides the influence of the light (see chapter 5.1.1.4), this also includes linearity influences (see chapter 5.1.1.5) as well as further influences on the measuring system. “Further influences” include influences that are relevant in concrete individual cases but are not explicitly discussed below (see Ishikawa diagram, Figure 2-2, influences highlighted in blue).

For all tests, all steps required for preparing and carrying out the measurement process (e.g. in production) must also be followed for the analysis and the proof of capability of the measuring system (e.g. spraying the surface in case of glass surfaces in order to allow for a measurement to be carried out). The standard/the reference must represent all significant characteristics of the real component (e.g. surface characteristics, dimension, geometry).

The following options are available for designing and conducting tests:

Option 1: 30 repeat tests
This option must be chosen if all other influencing quantities (e.g. size, position, orientation and light) can be considered insignificant.

Option 2: 3x10 repeat tests
This option must be chosen if only one influencing quantity can be considered significant. The procedure is comparable to the linearity analysis according to VDA Volume 5. This approach requires an influencing quantity with three factor levels. In case of deviations from three factor levels, tests must be designed in such a way that at least 5 tests per setting and at least 30 tests overall are carried out.

Option 3: Dedicated test design
A dedicated statistical test design must be created if it cannot be excluded that two or more influences are significant. Please refer to the introduction to chapter 5.1.1 for test design. At least 5 repeat tests per setting and at least 30 tests overall must be carried out.

Note: *The number of tests can be reduced by optimizing the measuring system (and the measurement process) e.g. by ensuring a fixed position.*

In order to evaluate the test results from option 1, u_{EVR} is estimated based on the total variation of the tests. For option 2, the simplified linearity analysis according to VDA Volume 5 (see chapter 6.3.6.2.1) can be used. For option 3, the test results are analyzed by means of ANOVA.. The influences are listed separately, and their significance is evaluated by means of the p-value. Step by step, all insignificant influences (evaluation criterion $p > \alpha$, with α as significance level, typically $\alpha = 5\ \%$) are removed, starting with the largest p-value. The standard uncertainties of the individual influencing quantities are derived from the ANOVA results.

5.1.1.4 Light – $u_{LIGHT.MS}$

Light is an obligatory part of optical measuring systems. In terms of the lighting conditions, a distinction is made in VDA Volume 5.3 between deliberately introduced light and ambient light. The relevant terms, including influencing light and usable light, are defined in chapter 3.1. Both the interfering light and the variation of the usable light within the specified, permissible range can lead to a measurement uncertainty, referred to here as $u_{LIGHT.MS}$.

When it comes to determining the measurement uncertainty resulting from the influence of the light, it is possible to distinguish between various scenarios according to Table 5-1, depending on the design of the measuring system and the associated distribution of usable light and interfering light. The consequences for the necessary test design and the determination of the uncertainty component $u_{LIGHT.MS}$ are specified in the table.

Scenario 1 represents the general case. Scenarios 2 to 4 are special cases which typically occur and which can lead to a simplification of the approach. They are therefore considered separately. In these cases, it must be ensured that the application limits are observed and that their observance is transparent, e.g. by means of describing the system setup/configuration.

Table 5-1: Scenarios of different influences of the light on the determination of the measurement uncertainty in the measurement process

Scenario	**1**	**2**	**3**	**4**
Main light source	(random) combination of deliberately introduced light and ambient light	Deliberately introduced light produces useful light	Ambient light	(random) combination of deliberately introduced light and ambient light
Useful light	(random) combination of deliberately introduced light and ambient light	Deliberately introduced light produces useful light	Ambient light	(random) combination of deliberately introduced light and ambient light
Interfering light	(random) combination of deliberately introduced light and ambient light	Ambient light	Ambient light	(random) combination of deliberately introduced light and ambient light
Influence of interfering light	not negligible or unknown	negligible	not negligible	negligible
Determination of the measurement uncertainty				
Measuring system	Fix the ambient light to a representative value for subsequent use (operating point). In addition, variation of the deliberately introduced light.	Variation of the deliberately introduced light	Minimize variation	Not explicitly taken into account
Calculation $u_{LIGHT.MS}$	$u_{LIGHT.MS}$ from ANOVA	$u_{LIGHT.MS}$ from ANOVA	$u_{LIGHT.MS} = 0$	$u_{LIGHT.MS} = 0$ But taken into account in the measurement process test (see chapter 5.1.2.2)

If it must be assumed that measuring system capability cannot be proven due to the influence of the ambient light, there are two possible options:

Option 1: Optimizing the measuring system to reduce the influence of the ambient light (e.g. by means of a suitable housing or a bandpass filter)

Option 2: Carrying out the analysis of the measurement process (chapter 5.1.2). If the capability of the measurement process can be proven, the entire proof of capability has been obtained.

5.1.1.5 Linearity – u_{LIN}

According to VDA Volume 5, linearity is the variability of the bias (systematic, uncorrected measurement error) of a measuring system across the scope of application. In case of optical measuring systems, there can be a variety of reasons for the variability of the bias in the measuring volume . In case of camera systems, for instance, distortions at the edges of images can increase the measurement uncertainty at the edge in comparison to the center, and line scan cameras can have different uncertainties for length measurements in x and in y direction.

However, there can be strong correlations between influences such as the size of the object, the position of the object, the orientation of the object and the color of the object, so that the requirements (independence, among others) set out in VDA Volume 5 are not fulfilled. It is therefore recommended to estimate the uncertainty in a combined test together with the repeatability on the standard/ on a reference (see chapter 5.1.1.3). In general, all influences related to the degrees of freedom of the measuring volume must be taken into account in the linearity analysis (see Figure 5-1). As is it not necessary to separate the individual contributions retroactively, it is possible to use sampling procedures which vary all influencing quantities simultaneously and keep the effort required for testing low (e.g. [10]).

Depending on the existing knowledge and risk assessment in relation to the measuring system, (see VDA Volume 5, chapter 4.3.2), linearity influences can be taken into account in the measuring system test in different ways. Only if the significance of individual linearity influences can be reliably controlled (e.g. by ensuring that the measured object is always in the same position) can the influences be neglected.

The combined uncertainty $\mathrm{u_{LIN}}$ is estimated according to VDA Volume 5, chapter 6.3.6. If the estimated value of $\mathrm{u_{LIN}}$ thus determined equals a significant percentage of $\mathrm{Q_{MP.max}}$ (e.g. larger than 10 %), the estimated value determined here is not sufficient in order to specify the overall uncertainty reliably. In this case, mathematical modelling according to ISO/IEC Guide 98-3 (GUM) must be used, or the measuring system must be changed in such a way that the measured objects only cover a smaller part of the measuring volume in which $\mathrm{u_{LIN}}$ is small enough.

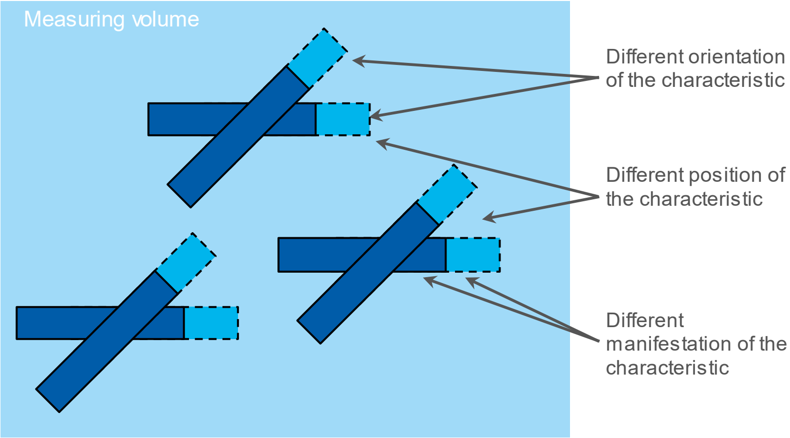

Figure 5-1:Schematic diagram of the variation of manifestation, position and orientation for length measurement

5.1.2 Measurement process

5.1.2.1 Repeatability on the measured object – u_{EVO}

The repeatability on the measured object$\mathrm{u_{EVO}}$ describes the dispersion behavior of the entire measurement process under repeat conditions.

Repeat conditions analogous to VIM [5] chapter 2.20 means that repeat measurements are to be carried out at the site of operation at short intervals on real parts by the same operator in an identical manner. Details regarding the test are provided in chapter 5.1.2.11.

When it comes to selecting the measured objects, the typical variation of the object characteristics must be covered in the best possible way. This comprises:

- The tolerance range of the measured quantity, plus the expected range of exceedance
- The maximum expected values of the influencing quantities of the measurement process which cannot directly influence the measured quantity but can influence the measurement process (e.g. surface characteristics such as gloss level, roughness, color, absorption, sharpness of the contours).

Note: *Variation relates to the variation from component to component here. Variations within a component are taken into account by means of the inhomogeneity* $\mathrm{u_{OBJ}}$ *uncertainty component (chapter 5.1.2.4).*

5.1.2.2 Influence of the light on the measurement process – $u_{LIGHT.MP}$

Besides the influences of the light on the measuring system, there are additional influences on the measurement process, some of which were already captured in the measuring system test. For this reason, Table 5-1 is extended with respect to the determination of the measurement uncertainty regarding the measurement process.

In order to avoid overestimating the measurement uncertainty due to the influences captured both in the measuring system test and the measurement process test, only the larger of the two values is used to determine the combined measurement uncertainty u_{MP} (see formula (2), chapter 5.2.2).
The ambient light must be qualitatively comparable during the measuring system test and the measurement process test, for example with respect to color and temperature.

Table 5-2: Scenarios of different influences of the light on the determination of the measurement uncertainty in the measurement process

Scenario	**1**	**2**	**3**	**4**
Main light source	(random) combination of deliberately introduced light and ambient light	Deliberately introduced light produces useful light	Ambient light	(random) combination of deliberately introduced light and ambient light
Useful light	(random) combination of deliberately introduced light and ambient light	Deliberately introduced light produces useful light	Ambient light	(random) combination of deliberately introduced light and ambient light
Interfering light	(random) combination of deliberately introduced light and ambient light	Ambient light	Ambient light	(random) combination of deliberately introduced light and ambient light
Influence of interfering light	not negligible	negligible	not negligible	negligible
Determination of the measurement uncertainty				
Measuring system	Fix the ambient light to a representative value for subsequent use (operating point). In addition, variation of the deliberately introduced light.	Variation of the deliberately introduced light	Minimize variation	Not explicitly taken into account
Calculation $u_{LIGHT.MS}$	$u_{Light.MS}$ from ANOVA	$u_{Light.MS}$ from ANOVA	$u_{Light.MS}$ = 0	$u_{Light.MS}$ = 0
Measurement process	The deliberately introduced light and the ambient light are explicitly taken into account in a test design, if necessary by means of test times with different ambient light	Variation of the deliberately introduced light	The variation of the ambient light is taken into account in the test design, if necessary by means of test times with different ambient light	Not explicitly taken into account
Calculation $u_{LIGHT.MP}$	$u_{LIGHT.MP}$ from ANOVA	$u_{LIGHT.MP}$ from ANOVA	$u_{LIGHT.MP}$ from ANOVA	$u_{LIGHT.MP} = 0$
Taken into account in u_{MP}	$max(u_{LIGHT.MS}; u_{LIGHT.MP})$	$max(u_{LIGHT.MS}; u_{LIGHT.MP})$	$max(u_{LIGHT.MS}; u_{LIGHT.MP})$	Standard VDA5

Scenario 1 represents the general case where all influences are captured completely. It therefore has the biggest informative value. In particular, potentials for optimization can be derived. However, this scenario correspondingly requires significant effort. In the special cases involving scenarios 2 to 4, the effort decreases gradually. In order to apply them, the relevant requirements (see description of the scenarios) must be met.

5.1.2.3 Further environmental influences

A major difference between the measuring system capability and the measurement process capability are the environmental influences. The latter are typically only controllable to a limited extent and are therefore difficult to take into account in tests. Minimizing them is already of great importance during the planning phase.

Important environmental influences include:

Ambient *temperature*

The influence of the temperature on dimensional measurement technology is discussed in detail in VDA Volume 5. This also applies to optical measurement technology. Parts in the environment which emit light due to thermal radiation constitute a special case insofar as the relevant range of wavelengths is captured by the optical system and influences the measurement result. In this case, a separate uncertainty component must be captured.

As the ambient temperatures during the measurement process can in many cases not be completely replicated during the measurement process test, temperature must be taken into account in the proof of ongoing capability.

Contamination

In general, it is possible to distinguish between random and systematic contamination. Systematic contamination, i.e. contamination occurring as a result of the oiling of parts during the production process, must be treated as an object influence.
Randomly occurring contamination, i.e. contamination that cannot be

quantified using reasonable effort, should already be avoided by means of suitable measures when planning the measurement process. Unavoidable residual contamination is included in the measurement tests as a cumulative result (also see VDA Volume 5, chapter 5.3).

Vibrations

Vibrations can also influence measurement results in case of optical measuring systems. Therefore, avoidance strategies should already be followed when planning the measurement process. Movement-related blurring when capturing the measured objects can be reduced e.g. by reducing the exposure time in a suitable way. If the relative position of the measured object and the sensor has an influence on the measurement result, suitable measures should be taken to limit the oscillation amplitude - depending on the frequency - in such a way that the influence becomes negligible.

Note: As part of the proof of ongoing capability, influencing quantities of the measurement/inspection process which change over longer periods of time should additionally be taken into account.

The impact of environmental influences on the measurement process are determined within the scope of the measurement process test. In order to quantify this impact adequately, the measurement process test should be carried out under real conditions which cover the entire spectrum of the expected environmental influences. Influences should not be reduced during the tests carried out to reduce the measurement uncertainty.

Medium of light propagation

In specific types of measurement processes, the sensitivity of the measuring method in relation to the optical characteristics of the light is so high that it becomes necessary to take the medium of light propagation into account separately. This can for example include interference measurements or measurements of light travel time across long distances. While e.g. the refractive index of a medium such as air is constant in the first order, it can change due to temperature, atmospheric pressure or airflows.

5.1.2.4 Inhomogeneity of the measured object – u_{OBJ}

The inhomogeneity of the measured object describes the variance of the characteristics of the measured object on the measured object. This includes the measured quantity (actual inhomogeneity) as well as characteristics which influence the measurement process (apparent inhomogeneity). Thus, a perceived inhomogeneity of the measured object (overlap between the actual and the apparent inhomogeneity) is generated. Actual inhomogeneities might include e.g. typical surface defects or local density fluctuations.

There are two different methods which can be used in order to quantify the measurement uncertainty contribution.

Inhomogeneity from preliminary information (Method B)

According to VDA Volume 5, chapter 6.4.6 method B describes the quantification of preliminary information and primarily relates to the actual inhomogeneity of the measured object. The uncertainty results from the maximum deviation (see a_{OBJ} in VDA Volume 5). For dimensional metrology, this is usually the uncertainty resulting from the maximum form deviation of the measured object.

In practice, the applicability of method B to apparent inhomogeneities is limited. Using this method requires prior knowledge regarding the cause of the effect which leads to the apparent inhomogeneity, as well as an evaluation as to whether it is transferable to the relevant measurement process.

If the actual inhomogeneity is known, and transferability in terms of the apparent inhomogeneity has been established, the procedure for determining the uncertainty component u_{obj} according to VDA Volume 5 can be applied. If this is not the case, method A must be selected.

Inhomogeneity from experiment (Method A)

In order to quantify the uncertainty contribution of the inhomogeneity, the measurement process test (see chapter 5.1.2.11) can be extended. For example, it is possible to take measurements in multiple places on the object or to vary the optical characteristics in a targeted manner (e.g. by means of reference parts). The object influence can be determined by means the ANOVA method in accordance with VDA Volume 5 (see s_{OBJ}). It may be necessary to distinguish between different characteristics (e.g. form deviations and surface gloss).

If there are multiple characteristics that cause inhomogeneities, the number of necessary tests increases. Creating a test design to determine the approach is strongly recommended. The characteristics investigated must be varied in a targeted manner in order to be able to quantify the uncertainty.

Given that the measurement process to be evaluated is generally unable to differentiate between the actual and the apparent inhomogeneity, and instead provides the perceived inhomogeneity, a combined uncertainty component can be determined if test are planned appropriately (measuring points and components which cover both types of inhomogeneity). This also excludes determining the actual inhomogeneity e.g. by means of method B and determining the apparent inhomogeneity e.g. by means of method A.

Note: *The influence of the inhomogeneity of the measured object can be reduced during the planning phase of the measurement process by changing the measurement strategy or by pretreating the measured object (e.g. by following cleaning steps such as removing an (inhomogeneous) oil film which influences the optical characteristics).*

5.1.2.5 Temperature (measured object) – u_{TEMP}

Temperature effects can have a significant influence on the measurement. For measured objects consisting of homogeneous materials with known thermal expansion, the influence can be estimated as described in VDA Volume 5. In case of complex component geometries, this mathematical method only provides rough estimates, as form changes can occur in addition to expansion effects.

When planning the measurement process test, it must be ensured that the temperature influences to be expected during the measurement process are taken into account.

Temperature differences between the component and the environment can lead to convection. If this occurs in the beam path of the optical measurement, it can have influences on the measurement process. Given that these effects can not be simulated or calculated with justifiable efforts, they must already be minimized when planning the measurement process.

5.1.2.6 Reproducibility of the operators – u_{AV}

The approaches used to determine the influence of the operator correspond to those described in VDA Volume 5. The operator is taken into account in the measurement process test (chapter 5.1.2.11).

5.1.2.7 Reproducibility of measuring systems

The approaches used to determine the influence of the reproducibility correspond to those described in VDA Volume 5.

Note: *For the analysis of the measuring system, the latter is seen as a black box. If, for example, a multi-camera system is used in order to measure an individual measured quantity, the multi-camera system counts as a measuring system.*

5.1.2.8 Short-term stability – u_{STAB}

The influence of the short-term stability must be minimized during the planning phase of the measurement process, to the extent possible. If it is not possible to avoid changes to the measurement results over the measurement time - e.g. due to measured value drift while the measuring system is heating up - or between regular, short-term adjustments, the influence must be determined by means of tests. The approaches used to determine the influence of the short-term stability correspond to those described in VDA Volume 5 (see VDA Volume 5, chapter 6.4.5).

5.1.2.9 Interactions

If interactions are to be determined, this must be taken into account when planning the tests. If individual significance tests are to be carried out for all interactions, a full factorial test design must be used [7].

VDA Volume 5 chapter 6.4.3 outlines the approach to be followed in order to take interactions into account when evaluating the measurement process test by means of ANOVA. The same approach can also be applied to optical measurement and inspection processes.

5.1.2.10 Further influences

Just as described in VDA Volume 5, all further influences on the measurement process must be taken into account separately. The residual uncertainties $u_{MP.REST}$ must be clearly defined and individually named so that they can be clearly assigned. The components of the residual uncertainties must not be contained in other influencing variables.

5.1.2.11 Measurement process test

In principle, at least 30 measured values must be recorded in the measurement process test on components.

To determine the repeatability on the measured object, measurements are taken in the same position in the measuring volume under repeatability conditions, given that influences of the position in the measuring volume are already taken into account in the linearity uncertainty component u_{LIN}.

If interactions between the measured objects and the position in the measuring volume are to be expected, they must be evaluated in a separate test or by means of a suitable test design.

In general, a fractional factorial or a full factorial test design must be created as soon as more than two influencing quantities must be taken into account [7]. Otherwise, the approach outlined in VDA Volume 5, chapter 6.4.9 can be followed.

5.2 Determining the combined uncertainty

The combined measurement uncertainty is determined according to VDA Volume 5. However, due to the particularities of optical measuring and inspection systems described in chapter 5.1, a few adjustments must be made. For the evaluation of the measuring system, these are described in chapter 5.2.1 and for the evaluation of the measurement process, these are described in chapter 5.2.2.

The use of the formulas to determine the measurement uncertainty is subject to the requirements according to VDA Volume 5. The formulas cannot be used in case of:

- non-linear relationships
- significant correlations
- non-standard distributed values for repeat measurements
- linear relationships with sensitivity coefficients not equal to 1
- multi-dimensional measured quantities.

If VDA Volume 5.3 cannot be applied for one of the reasons named above, modelling and determination of measurement uncertainty e.g. according to ISO/IEC Guide 98-3 (GUM), technology-specific approaches, VDI/VDE 2600-2, or similar guidelines is required.

5.2.1 Measuring system

The combined measurement uncertainty of the measuring system is determined based on VDA Volume 5:

$$u_{MS} = \sqrt{u_{CAL}^2 + max(u_{EVR}^2\,, u_{RE}^2) + u_{BI}^2 + u_{LIN}^2 + u_{LIGHT.MS}^2 + u_{UMS.REST}^2} \tag{1}$$

5.2.2 Measurement process

The combined measurement uncertainty of the measurement process is determined based on VDA Volume 5:

$$u_{MP} = \sqrt{\begin{gathered} u_{CAL}^2 + max(u_{EVR}^2, u_{RE}^2, u_{EVO}^2) + u_{BI}^2 + u_{LIN}^2 + max(u_{LIGHT.MS}^2, u_{LIGHT.MP}^2) + u_{UMS.REST}^2 \\ + u_{AV}^2 + u_{GV}^2 + u_{STAB}^2 + u_{OBJ}^2 + u_{TEMP}^2 + u_{MP.REST}^2 + \sum_{i=1}^{n} u_{IA.i}^2 \end{gathered}} \tag{2}$$

5.3 From the combined measurement uncertainty to the proof of capability

The combined measurement uncertainty is extended to the extended measurement uncertainty by using the coverage factor k in accordance with the definitions provided in VDA Volume 5.

The extended measurement uncertainty of the measuring system can be calculated as follows:

$$U_{MS} = k \cdot u_{MS}$$

The extended measurement uncertainty of the measurement process can be calculated as follows:

$$U_{MP} = k \cdot u_{MP}$$

As described in VDA Volume 5 (chapter 7), capability ratios can be defined for both the measuring system and the measurement process.

The capability ratios Q_{MS} (measuring system) and Q_{MP} (measurement process) are available for this. To calculate these respective capability ratios, the extended measurement uncertainty is divided by the characteristic tolerance.

Capability ratio of the measuring system: $Q_{MS} = \frac{2U_{MS}}{T}$

Capability ratio of the measurement process: $Q_{MP} = \frac{2U_{MP}}{T}$

For optical measuring systems, capability ratio limits of $Q_{MS.max} = 15\ \%$ and $Q_{MP.max} = 30\ \%$ can initially be assumed. This particularly applies to measurement processes in which measuring systems replace tactile measuring systems.

For documentation and reporting in relation to proofs of capability, please refer to VDA Volume 5 (chapter 7.3). For the handling of incapable measuring systems/measurement processes, please refer to chapter 5.5 of this volume.

5.4 Ongoing capability for inspections involving measurements

The ongoing capability is described in detail in VDA Volume 5, chapter 10. The approaches described there can be followed without limitations to optical measuring systems and should be applied in accordance with the risk classification (see VDA Volume 5, chapter 4.3).

The methods are as follows:

- Regular calibration
- Regular execution of parts of the proof of capability process
- Regular execution of the complete procedure to determine measurement and inspection process capability
- Continuous monitoring tests with the stability charts

5.5 Handling of incapable measuring systems/measurement processes

When it comes to handling incapable optical measuring systems/measurement processes, the approaches outlined in VDA Volume 5 can be applied without limitations. Due to the particularities of optical measuring systems / measurement processes, additional options are presented in the following, which can be applied.

If there is a difference between the measuring principle of the calibrated standard and the measuring principle of the measuring system under evaluation, the associated effects should be explicitly analyzed. A potential solution is to align the measuring principles.

Influences of the light on the measurement are typically assigned to the measurement process test. However, light is an obligatory part of the measurement in case of optical measuring systems. It is therefore also part of the measuring system test. In case of significant influences of the light, the effects of the ambient light on the capability ratio Q_{MS} can mean that proof measuring system capability cannot be obtained. In such cases, it can be checked whether proof of measurement process capability (Q_{MP}) can be obtained. If this is the case, capability can be considered proven. If proof of measurement process capability process cannot be obtained either, the influences of the light can be analyzed and, if necessary, reduced. A potential solution is enclosing the measuring system in order to reduce the amount of interfering light in the measuring system/measurement process.

If capability cannot be proven due to the variation of the measurement results, it is possible to look into the option of multiple measurement. As noted in VDA Volume 5 (chapter 7.4.5.2), random uncertainty components can be reduced by the factor $\sqrt{n}$ by means of multiple measurements. Especially due to the frequently short measurement durations in optical measuring systems, multiple measurements offer significant potential for reducing the measurement uncertainty.

For a pure conformity evaluation, it is possible to split the measurement process into two parts if the capability ratio limit is exceeded. For the first part, i.e. the optical measurement, the conformity range is limited in accordance with the measurement uncertainty and DIN EN ISO 14253. If measured values are within the now defined acceptance range, conformity is confirmed. In case there are measured values within the uncertainty range, a second measurement process with a lower measurement uncertainty must be used for the conformity decision in relation to the relevant measured component (e.g. a tactile measurement in a measuring room).

6 Proof of capability for attributive inspection processes

In case of attributive optical inspection systems, it must be ensured that the latter are suitable for the relevant task. Just as with measuring systems, it is recommended to follow a risk-based approach here which scales the effort required for the proof of capability depending on the task and the level of experience with the functional principle of the attributive inspection.

The proof of capability marks the end of a release process, which is described in chapter 6.2. There are various procedures to obtain proof of capability, which are presented in this volume. The approaches have specific advantages and disadvantages. It is therefore not possible to propose a universal procedure, as was already outlined in VDA Volume 5 in chapter 9.2. The user must select the respective procedure based on the specific characteristics, the inspection system,, organization-specific requirements and experience. The comparison of procedures in chapter 6.6.7 provides orientation in this regard.

6.1 Risk-based approach

The reasons why obtaining proof of capability can be very time-consuming in case of attributive inspections, and the restrictions that apply in these cases, are explained in detail in VDA Volume 5, chapter 9. Therefore, a risk-based approach based on VDA Volume 5, chapter 4.3 is followed here for the proof of capability of attributive optical inspection systems in order to strike a balance between practical applicability and technical/statistical necessity.

It is possible to distinguish between four risk classes (RC1 to RC4). Risk class 1 (no risk) can be applied if the characteristic to be monitored will be monitored at a later point in time using a suitable inspection process, or if the inspection process is only used for data collection, internal process control or process analysis. In contrast to this, the inspection of special safety-relevant and approval-relevant characteristics (SC S: safety requirement, SC A: approval-relevant characteristics) [see VDA Volume “Special Characteristics”] is always associated with the highest risk class (RC4).

For all other inspection decisions, including those for special characteristics related to function (SC F), risk-based assurance is based on the determination of a risk class for the respective inspection process according to two dimensions:

- Consequences (see Table 6-1) and
- Probability of occurrence (see Table 6-2)

of an incorrect inspection decision.

The criteria for classifying the consequences of an incorrect inspection decision must be defined on a company-specific and, if necessary, application-specific basis. These criteria are then obligatory.

It is assumed that a decision has already been made whereby an inspection is considered necessary. This means that the probabilities of occurrence and evaluations of consequences of errors used applied here are subject to different criteria than those set out in the VDA/AIAG FMEA handbook.

The consequences can for example be classified according to Table 6-1:

Table 6-1: Example categories of the consequences of incorrect inspection decisions

Consequence	Justification (examples)
High	An erroneous decision leads to: • a danger to life and limb, e.g. SC S • a risk to the environment • non-conformity (product characteristics) as delivered, e.g. SC A • a risk of liability on the part of the customer, and associated significant compensation claims • very high internal and external follow-up costs
Medium	An erroneous decision leads to: • a customer-relevant malfunction of the product • significant process disturbances • significant, but manageable follow-up costs
Slight	An erroneous decision leads to: • no customer-relevant deviation from the specifications on the end product (e.g. characteristics which do not serve to prove conformity, or which are subsequently safeguarded by other means) • no effect on the release of products (e.g. within the scope of tests) • low follow-up costs

The consequence of an incorrect inspection decision must be assessed by the technical bodies, which can evaluate the relevance of the characteristic for the quality of the final product or process.

The probability of occurrence of an incorrect inspection decision depends on the quality of the production process and the ß-error of the measurement process used. These values can only be determined accurately once the inspection process is already in use. They must therefore be estimated beforehand. The criteria for estimating the probability of occurrence must be specified on a company-specific basis. For example, this can be done in accordance with Table 6-2:

Table 6-2: Categories of probability of occurrence of incorrect inspection decisions

Probability of occurrence	Justification (examples)
High	• Little experience with the product characteristic and the assurance of characteristics • Missing correlation between boundary samples and functional impairment • Poorly controlled production process without sufficient safety margin (e.g. based on experience from comparable processes) • Strong influence of the examiner • Strong influence of uncontrolled environmental conditions in the inspection process • Little experience in dealing with the inspection process
Medium	• Experience with the product characteristic and the assurance of characteristics • Weak correlation between boundary samples and functional impairment • Controlled production process (based on experience from comparable processes) • Moderate influence of the environmental conditions on the inspection decision • Influencing quantities with respect to the inspection decision are not fully controlled
Slight	• Extensive experience with the product characteristic and the assurance of characteristics • Clear correlation between boundary samples and functional impairment • Well-controlled production process (based on experience from comparable processes) • Inspection process under controlled conditions (e.g. in the laboratory) • Inspection process is robust against external influences

The probability of occurrence of an incorrect inspection decision must assessed by the body having the competence to assess the capability of manufacturing processes and the uncertainty of the inspection process. If the classification of the probability of occurrence is uncertain or if the probability of occurrence is considered “high”, it is advisable to carry out a feasibility study in accordance with chapter 6.3.

The risk class is determined depending on the consequences and the probability of occurrence of an incorrect inspection decision. Alternatively, the risk assessment for the respective inspection process can also be based on a preceding FMEA.

Table 6-3: Example for determining the risk class

Example for deriving the risk assessment in production				
Consequences of incorrect inspection decisions (from table 6-1)	High	Risk class: high (RC4)	Risk class: high (RC4)	Risk class: high (RC4)
	Medium	Risk class: medium (RC3)	Risk class: medium (RC3)	Risk class: high (RC4)
	Slight	Risk class: low (RC2)	Risk class: medium (RC3)	Risk class: medium (RC3)
		Slight	Medium	High
		Consequences of incorrect inspection decisions (from table 6-2)		

The result of the risk assessment must be subjected to document control as documented information. Depending on the risk class, the effort and the scope required for inspection decision assurance can be scaled according to the following table.

Table 6-4: Example matrix for determining the level of assurance

Example determination of the assurance				
Risk class	None (RC1)	Low (RC2)	Medium (RC3)	High (RC4)
Prior feasibility study	No	No	Feasibility study Case I/II, see chapter 6.3.2	Feasibility study Case III, see chapter 6.3.2
Reference value for inspection samples for feasibility studies	0	0	Case I: 0–3 / characteristic type Case II: 3–5 / characteristic type	Case III: 5–10 / characteristic (including boundary samples according to the definition in chapter 6.4)
Methods for safeguarding capability	(informal) confirmation of the principle by the competent body (equivalence class testing)	Confirmation of the principle by the competent body	Statistical evidence	Statistical evidence
Reference value for inspected objects per inspection characteristic in the reference inspection lot	3–5	5–10	At least 30–50	Results from the previously specified limit values (e.g. for α and β risk) see procedure in chapter 6.6
Characteristics of the release lot	Reliable reference	Main influencing quantities taken into account (see chapter 2.3) by means of boundary samples	Main influencing quantities taken into account (see chapter 2.3) by means of representative release lot (see chapter 6.4)	Main influencing quantitiestaken into account comprehensively (see chapter 2.3) by means of representative release lot (see chapter 6.4)
Safe launch	No	No	Recommended	Recommended
Continuous monitoring	No	No	Recommended	Yes

6.2 Release process and continuous monitoring

The validation and release of image processing systems should take place according to a controlled, six-phase process. Depending on the concrete requirements of the respective application, which are derived in particular from a risk-based analysis (see chapter 6.1), individual phases can be shortened or adapted.

The release process typically follows the development process of the image processing system or starts at the beginning of the development, particularly in case of machine learning systems, as validation has a strong influence on the selection of a suitable ML procedure and the generation of a training dataset. The training dataset is used to teach the behavior of the inspection system. The words teach and train are often used synonymously.

The validation and release model comprises the following six phases:

0. Feasibility analysis
I. Preparation
II. Preliminary release
III. Optimization
IV. Final release
V. Continuous monitoring

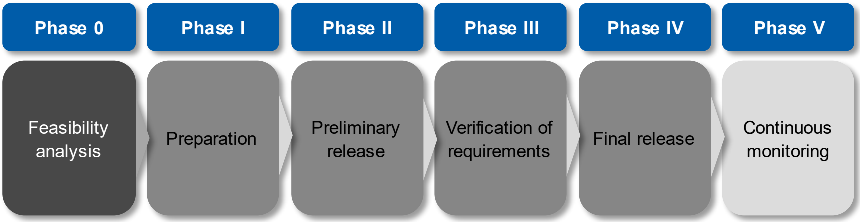

Figure 6-1: Phase model of the release process of optical inspection systems

The six phases can be shortened (e.g. no safe launch in phase III if the risk class is low).

Phase 0: Feasibility analysis (optional)

Input phase 0: inspection requirements, catalog of errors / error definitions, type specification, sample parts

Output phase 0: General specification (inspection concept and image processing components)

Description phase 0: In this phase, it is determined which components of the inspection system are likely to be suitable, and their interaction is tested in advance.

Phase I: Preparation

Input phase I: Requirement specification for the inspection system, functional specification for the inspection system (specification of the inspection system, inspection system hardware, inspection system software (classic IP)), (estimation of) the characteristic value distribution in the reference inspection lot(chapter 6.4)

Output phase I: Result of the risk analysis (chapter 6.1), release criteria, including procedures, preliminary test dataset, specification of the reference inspection lot

Description phase I: In this phase, the foundations for the subsequent validation and release of the optical inspection system are laid. This includes carrying out a risk analysis, specifying the validation and release criteria and procedures (see chapter 6.6), and making the required reference inspection lot available for release. Typical values for the number of reference inspection lots are provided in Table 6-4, which has been derived from practical experience as well as expert opinions.

Particular attention must be paid to ensure that the expected limit values for later series production are replicated in the reference inspection lot. If this is only possible to a limited extent, this must be documented accordingly and rectified in phases III and IV. This limitation presents a risk in terms of successful acceptance in phase IV and the following series production phase.

If ML is used in the optical inspection system, this phase often takes place concurrent with the development of the IP system [reference phase in VDA Volume 5, chapter 4.4.: “Procurement of the measuring system”]. Thus, phases II and III must usually be completed. Particularly in case of machine learning processes, the reference inspection lot and the learning lot are selected at the same time.

Due to the black box property of ML-based IP systems, the reference inspection lot should be significantly larger than with rule-based systems as the system decisions are initially less reliable.

Phase II: Preliminary release

Input phase II: preliminary reference inspection lot, validation and release criteria, inspection system software (training completed in case of ML)

Output phase II: IP system meets the requirements based on the preliminary reference inspection lot.

Description phase II: Fulfillment of the requirements is verified based on the preliminary reference inspection lot. Thus, it can be ensured that the IP system is generally capable and that in-depth validation during series production has a good chance of success (phases III+IV). Besides the technical release, the employees’ acceptance of the system (in particular in case of ML systems) is also important here.

Phase III: Validation of requirements

Input phase III: Insights from preliminary use (inspection system, production process), specified characteristic value distribution in the reference inspection lot (chapter 6.4)

Output phase III: Employees involved have confidence in the capability of the system. Characteristic specification is refined (stricter limit values or addition of further characteristics, if required), corrected reference inspection lot, as agreed upon between the supplier of the inspection system and the customer.

Description phase III: The provisionally released IP system is exposed to series production. Depending on the risk analysis, it is advisable to implement a “safe launch”, meaning that the IP system is run concurrently with a reliable, 100% quality control (e.g. manual control), such that any erroneous decisions can be registered and corrected.

Erroneous decisions are used in order to adjust the reference inspection lot for the final release (phase IV) in such a way that all aspects relevant to release are covered.

Any cases which were overlooked or not identified as relevant in phase I require particular attention here. In these cases (e.g. additional characteristic requirements), an adjusted reference inspection lot as well as adjusted limit values must be agreed upon between the customer and the supplier of the inspection system. If necessary, all phases must be repeated.

Phase IV: Final release

Input phase IV: Requirement specification of the inspection system, functional specification of the inspection system, reference inspection lot from phase III, current status of the IP system

Output phase IV: technically released IP system for fully automatic use in series production.

Description phase IV: Implementation of the proof of capability procedure specified in phase I, taking the reference inspection lot and the limit values from phase III into consideration.

If the inspection system cannot be released, the causes must be analyzed, phases 0 to III must be repeated accordingly, and the system must be improved and then released in a repeated phase IV.

Phase V: Ongoing capability

Input phase V: Series process, released, fully automatic IP system

Output phase V: Depending on the interim results: IP system released for further operation; IP system not released for further operation

Description phase V: The scope of stability monitoring with respect to the IP system strongly depends on the associated risk assessment.

In case of a “high” risk class, continuous monitoring must be implemented. Intentionally defective units (red rabbits) can be used for this purpose. If continuous monitoring cannot be implemented, this must be justified, and an alternative procedure must be used. (see chapter 6.7)

in case of a “medium” risk class, individual monitoring tests can be used.

Phase V only ends with the end of service of the IP system.

Note on changes to SW parameters or to the ML model:

> *Given that neither the inspected parts, nor the production process, nor the image processing are changed in these cases, it is sufficient to carry out the release process on the basis of images of the reference inspection lot (see phase IV).*
>
> *In case of changes to inspected parts or to the structure of the inspection system, a new release requires a complete release inspection in accordance with chapter 6.2.*

6.3 Feasibility study

Optical inspection systems are subject to various influencing factors. In case of attributive inspections, uncertainty contributions can only be determined with great effort, making it impractical to use them in capability assessments. Feasibility studies therefore play a central role when it comes to risk mitigation.

The feasibility study results in a general specification (inspection concept and image processing components), taking the framework conditions and the requirements regarding the inspection task as well as the influencing factors into account.

6.3.1 Prerequisites for a feasibility study

Prior to the feasibility study, it is necessary to clearly specify:

- the type specification for the parts to be inspected
- the inspection type (what must be inspected: form, color, ...)
- the error catalog
    - types of errors and error characteristics
    - Error characteristics, including tolerances and limit values, alternatively boundary samples
    - categories in case of ordinal characteristics
    - particular error constellations with defective parts which belong to other production processes, but which can erroneously end up in the inspection process
- Recommended: Example images to illustrate the inspection situation - and inspected parts
- Environmental conditions for evaluating the risk under consideration of the influencing factors (in accordance with Figure 2-2 in chapter 2.3)
- Necessary aids for calibration/adjustment (e.g. color calibration card, calibration parts or samples, etc.)

The better the functional principle of the component, the specification of the characteristics, the production process and the environmental conditions (see chapter 4.2, Figure 4-1) are defined, the more precisely the feasibility study can be carried out. The risks can thus be minimized in the best possible way prior to the implementation of an optical inspection system.

When it comes to describing characteristics, it must be ensured that they are described qualitatively as well as quantitatively, insofar as the type of characteristic permits. Tolerances and limit values as well as attributes must absolutely be specified in this case.

6.3.2 Scope and implementation of the feasibility analysis

The scope of the feasibility study depends on the risk classes in accordance with chapter 6.1:

MEDIUM risk

Case I: If the probability of occurrence of incorrect inspection decisions is low, a feasibility assessment can be carried out instead of a feasibility study, provided that the former is carried out by qualified personnel and that the assessment is based on experience with an inspection setup whose proof of capability is sufficiently transferable to the task to be solved.

If these conditions are not met, the procedure described under Case II must be selected.

Case II: Feasibility analysis with limited scope, recommended in case of medium or high probability of occurrence. Preliminary testing based on individual reference parts with representative characteristic values (see chapter 6.4)

HIGH risk

Case III: Large-scale feasibility study, recommended in case of high level of complexity regarding the inspection task, the number of inspection characteristics, etc. Preliminary testing is conducted based on large numbers of reference parts with representative and borderline characteristic values (see chapter 6.4).

In case of integration into an existing series production, it is recommendable to carry out a feasibility study within the series environment in order to fully take the expected influencing factors into account.

In case of new production processes and no experience with the inspection or production parts, the following procedure is recommended:

- Use of prototypes or artificial references (see chapter 6.4, creation and use of reference parts)
- If no feasibility study can be conducted, implementing a safe launch (see chapter 3.1 glossary and chapter 6.2, Phase III) is strongly recommended.

6.4 Reference inspection lot

The capability of an attributive inspection process in which optical sensors and image processing systems are used is evaluated based on a reference inspection lot. The latter is also referred to as the sample parts catalog (see VDI/VDE/VDMA 2632-1). It always contains inspected objects and also includes reference evaluations if the accuracy and not just the repeatability of the inspection process is to be evaluated. Reference evaluations are based either on a variable countermeasure or, if not possible, on the reference decision of a reference examiner or even reference inspection teams.

With regard to the reliability of the reference statement and the values of the characteristics relevant to inspection, it is possible to distinguish between the following categories:

Reliable reference: Such inspected objects can be unambiguously assigned to a class. The inspection characteristics are unambiguous and are present in the typical form. They are sufficiently pronounced / significant enough in order for the inspected object to be assigned correctly. The inspection statements of the reference examiners also match during repetitions.

Limit sample: Such inspected objects can be unambiguously assigned to a class. However, they mark the limits of the relevant class with their inspection characteristics. The inspection statements of the reference examiners also match during repetitions.

Inspected objects in the uncertainty range: Such inspected objects cannot be unambiguously assigned to a class. This can for example be due to a lack of inspection characteristics, or due to the fact that they are only weakly present. With such objects, the inspection statements of the reference examiners often do not match / are not repeatable.

Composition of the reference inspection lot

To the extent possible, the reference inspection lot should include both safe references and limit samples.

Only if the reference inspection lot represents all characteristics to be assessed in all their manifestations, and only if it contains a sufficient number of these characteristics, can the capability of the inspection process be evaluated with them. The required number depends on multiple factors (see chapters 6.1, 6.5 and the relevant requirements for the procedures in chapter 6.6). The composition and the size of the reference inspection lot must specified thoroughly by appropriately trained and responsible personnel.

The reference inspection lot and its inspected objects must not be used for the development of the inspection system, as otherwise no objective proof of capability can be obtained.

In the reference inspection lot, no inspected objects from the uncertainty range. Inspected objects in the uncertainty range can be used for further investigation in order to determine how the inspection system reacts to them. Thus, the inspection system can be adjusted in such a way that the inspected objects are classed as defective as a precaution.

Storage of the reference inspection lot

The reference inspection lot must be stored in such a way that the optical characteristics do not change during the period of time to be defined on a company-specific basis.

Production of the reference inspection lot (production context)

The inspected objects for the reference inspection lot can be taken from the production process for which the inspection system is to be used. Alternatively, they can be produced artificially. The more artificially produced inspected objects deviates from reality, the weaker the capability statement becomes. Image data can also be generated synthetically, e.g. by means of rendering (fully synthetic) or by means of superimposing/augmenting image characteristics of physical objects (partly synthetic).

Advantages of artificial inspected objects include the defined characteristic values, the reproducibility as well as the possibility to extend to limits which are very rarely encountered in the real process. With artificial inspected objects, it is possible to make inspection and evaluation results much more easily comparable in terms of location (across multiple operation sites) and time (in relation to stability).

Real (not synthetically generated) inspected objects have the advantage that they represent the real conditions more precisely.

The creation of a reference inspection lot can be simplified by using inspected objects that do not come from the production process. Consequently, the reference inspection lot thus created does not stem from a population, as is strictly speaking required for the statistical procedures presented in chapter 6.6. It is up to the user to design the reference inspection lot in such a way that it approximates the required characteristic sufficiently closely.

Table 6-5: Advantages and disadvantages of different types of inspected objects

	Advantage	**Disadvantage**	**Recommendation of use**
Inspected object (from production process)	Highest degree of conformance; Low additional costs; Potentially available in large quantities	Potentially only available later (requires production process); Potentially only a small number of inspected objects is available with only certain characteristic values (e.g. errors); Potentially location-dependent; Potentially susceptible to ageing	Generally, most suitable for proofs of capability
Inspected object (from production process, manipulated)	High degree of conformance outside of the manipulated characteristics; (Rare) characteristic values / manifestations are reproducible in a targeted manner; High degree of reproducibility of the manipulated characteristics	Potentially only available later (requires production process); Characteristic values are possibly not realistic for the production process; Potentially high additional costs	As an addition to non-manipulated inspected objects when obtaining proofs of capability, if required; Especially if there are stringent requirements regarding the reproducibility of the characteristic values
Inspected object (artificially produced), prototypes	Does not require the production process; high degree of reproducibility during manufacturing is potentially possible; (Rare) characteristic values / manifestations are reproducible in a targeted manner	Characteristic values and/or the entire inspected object are possibly not realistic for the production process; Potentially high additional costs	As an addition to non-manipulated inspected objects when obtaining proofs of capability, if required; Especially if reproducibility/comparability must be ensured
Manipulated image	Requires production process; potentially not insignificant costs for various augmentations; Are not subject to ageing and are not location-dependent	Skips the physical part of the inspection process; Characteristic values and/or the entire inspected object are possibly not realistic for the production process	As an addition to non-manipulated inspected objects when obtaining proofs of capability, if required
Synthetic image	Does not require production process; maximum freedom; Potentially low costs for large quantities of images; Targeted generation of limits up into the uncertainty range; Are not subject to ageing and are not location-dependent	Skips the physical part of the inspection process; Characteristic values are possibly not realistic for the production process; Potentially requires special software and skills	As an addition to non-manipulated inspected objects when obtaining proofs of capability, in case of special requirements

6.5 Taking the production process into account when determining the capability ratio limit

In order to obtain proof of capability, it is necessary to specify capability ratio limits. In this regard, customer requirements (e.g. maximum error rate) and economic efficiency (e.g. costs caused by pseudo errors) must be taken into account. Both of these factors determine what the error statistics of the production process and the inspection process should look like. On the one hand, errors during use by the customer only occur if defective parts are not detected by the inspection system during production. On the other hand, however, pseudo-rejections generate costs if the inspection system falsely detects errors.

As the distribution across the categories in the production process can be assumed to be given, it is possible to derive requirements regarding the inspection process: maximum permissible α and β risks. These should be part of the requirement specification (see also [VDI/VDE/VDMA 2632-2, -3 and -3.1]). This approach is shown schematically in Figure 6-2.

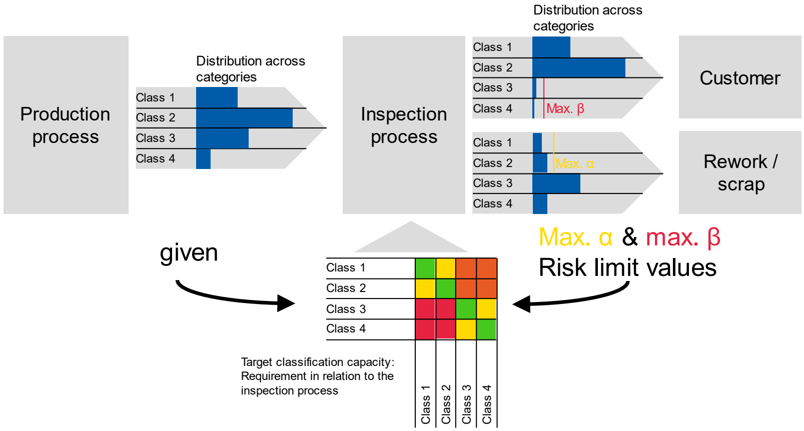

Figure 6-2: Schematic diagram of the of the interrelation between the production and the inspection process, based on the example of an attributive characteristic with four categories (classes 1&2 are OK, classes 3&4 are NOK).

In practice, the quality performance of the production process can only be estimated. This estimation is subject to uncertainty, particularly when it comes to new production processes. The risk-based approach presented in chapter 6.1 and Table 6-4 – on the topic of safe launches – provides a way to take this into account. In addition, customer feedback on errors that have occurred during the use phase can provide valuable information regarding the correction of the estimation and the reassessment of the inspection system (if required).

Approach using Fleiss' kappa

In cases in which there are quality requirements in the form of a kappa value, the approach described above cannot be followed directly.

Error rates in the inspection process cannot be easily deduced based on the experimentally determined kappa value. The procedure is described in greater detail in chapter 6.6.1, based on the following criteria.

- The characteristic to be inspected should be dichotomous (i.e. in order to be able to apply the calculations provided, there can only be two, mutually exclusive values the characteristic can take)
- The scope of the study in the reference inspection lot must be approximately the same for both characteristic values, such that the best possible estimation of kappa can be achieved.
- For polychotomous characteristics (i.e. there are more than two mutually exclusive values the characteristic can take), the Fleiss' kappa calculation is equally applicable, will however not be further discussed in the following.

Case-specific quality requirements (maximum permissible α and β risks) must be specified as described above, on the basis of the consequences of incorrect inspection decisions. Based on the limit values specified for the α and β risks, it is thus possible to derive the required kappa limit value κ.

Using these limit values and estimating the quality performance of the production process, it is possible to draw conclusions regarding the effective quality performance for the customer by means of the error propagation.

6.6 Selection of procedures

The procedures differ in terms of e.g. the relationship between required effort and reliability or additional benefit. Their applicability is in some cases subject to conditions that the inspection systems have to meet. An overview in the form of a table is provided after the description of the individual procedures in chapter 6.6.7.

6.6.1 Fleiss' kappa

The kappa method [see VDA 5] is suitable for nominal characteristics, i.e. the characteristic categories do not have a natural ranking. The results are therefore only checked for consistency.

Kappa compares the proportion of agreement between the examiners with the randomly expected agreement. If a sufficiently large “over-random” proportion of matches is found, the inspection process is considered capable.

Cohen’s kappa constitutes a special case of the more generally applicable Fleiss’ kappa procedure. Therefore, only Fleiss’ kappa will be discussed in the following.

Execution

A pseudo-random sequence for feeding the inspected objects to the examiners should be aimed for with a view to avoiding recognition and the resulting repetition of results. This means that the examiners will evaluate the inspected objects alternately per run in random order under the typical inspection conditions of the inspection process.

Key figures

$$\kappa = \frac{P_{observed} - P_{random}}{1 - P_{random}}$$

The appropriate value range is from -1 to 1.

$P_{observed}$ is the actual proportion of agreement.

P_{random} is the expected agreement with purely random categorization.

In the simplest case, a table with 4 fields can be formed to count the number of matches (A and B are the examiners, a-d are the counts of identical decisions):

Table 6-6: Results matrix for two examiners (see Table 4-1)

		B (reference)	
		OK	**NOK**
A (inspection system)	**OK**	**a**	**b**
	NOK	**c**	**d**

$$\mathrm{P}_{\mathrm{observed}} = \frac{\mathrm{a} + \mathrm{d}}{\mathrm{a} + \mathrm{b} + \mathrm{c} + \mathrm{d}}$$

$$P_{random} = \frac{c + d}{a + b + c + d} \cdot \frac{b + d}{a + b + c + d} + \frac{a + b}{a + b + c + d} \cdot \frac{a + c}{a + b + c + d}$$

$$\text{Proportion of type 1 errors } \frac{c}{a + c}$$

$$\text{Proportion of type 2 errors } \frac{b}{b + d}$$

Assessment and limit values

The aim is to get kappa κ as close to 1 as possible. Kappa limits $\kappa \geq$ 0.75...0.9 are applied after consultation with customers, but cannot completely exclude misclassification, see Table 6-7 regarding slippage. The relationship between kappa κ, the proportion of type 1 errors and the proportion of type 2 errors in case of a specific ratio of OK versus NOK is derived in [11] (in the simplest case, i.e. in case of a 1:1 ratio, κ = 1 – “proportion of type 1 errors” – „proportion o type 2 errors“).
In order to be able to specify a sample size, a maximum permissible deviation of the slippage is required in addition to the targeted slippage .
There is consensus in the relevant sources that κ > 0.9 is considered

acceptable [VDA 5, MSA 4]. Other limit values can be defined upon consultation between customer and supplier.

Sample size

The lines in Table 6-7 show the required number of NOK parts to validate the hypothetical slippage, with the respective relative deviation of the slippage shown in the columns (alternative hypothesis) at a specified confidence level (0.9 and 0.95). The required number of NOK parts can be determined based on the permissible slippage and its relative deviation. The table is based on a hypothesis test (see section 6.6) and is also valid in case of a hypothetical α risk. The necessary size of the reference inspection lot is derived from the required number of NOK and OK parts.

Table 6-7: Required number of NOK parts, depending on the slippage and slippage deviation for the confidence intervals 0.9 and 0.95.

		Slippage deviation		
Confidence interval = 0.9		1x	2x	5x
Slippage β risk	0.1%	12,461	3,988	1,016
	1%	1,230	392	99
	5%	232	73	18
	10%	107	33	7

		Slippage deviation		
Confidence interval = 0.95		1x	2x	5x
Slippage β risk	0.1%	15,746	5,039	1,284
	1%	1,554	496	125
	5%	293	92	22
	10%	135	41	9

Sample size often not feasible in practice

Statement not (practically) relevant

Example for the use and determination of the sample size and the limit value for kappa:

A maximum β risk (slippage) of 5 % is selected at a confidence interval of 0.9 and a maximum relative slippage deviation of factor two. This results in a minimum number of 73 NOK parts in the reference inspection lot. In order to weigh the α risk and the β risk equally, the same number of OK parts is used. The simplified formula can thus be sued, according to which $\kappa = 1 - \alpha - \beta$ (here 0.9). Should the number of OK parts and the number of NOK parts differ significantly, κ must be determined according to the approach in [11].

Advantages of the procedure

For the basic formula provided above, there are further developments for special cases such as with or without external standard, i.e. available or unavailable OK and NOK reference evaluation. The kappa method according to Fleiss is the most suitable method for all combinations of examiners and repetitions relevant in practice. When it comes to image processing systems in the automotive environment, it is practically always assumed that a reference and a system to be evaluated are available (see Table 6-6).

Disadvantages of the procedure

Table 6-7 shows the required sample size in order to ensure specific slippage limits. If a small hypothetical β error is to be validated, a large sample size is required in order to obtain meaningful results. In case of a small β error and a sample size that is too small, no erroneous classifications may occur in the sample. The observed slippage would be outside of the quantifiable range, and the kappa value would be correspondingly high, but not meaningful.

6.6.2 Kendall’s W rank correlation

Kendall's W [12] [13] is a non-parametric statistic for rank correlation. and therefore does not come with any requirements regarding underlying characteristic distributions. It is thus universally applicable in case of ordinal data with three or more levels (see VDA Volume 5). Kendall’s W is a statistic for rank correlation, which however does not necessarily allow for conclusions to be drawn as to whether the characteristic distributions match.

If Kendall’s rank-correlation analysis is to be carried out, the user must specify the sample size, as the latter should be selected depending on the input variables (acceptable slippage, number of ranks). Defining a reference examiner can require varying degrees of effort depending on the individual case. However, it is usually a requirement in typical applications.

When it comes to proving complete agreement, it is recommendable to conduct a Friedman test [14], whereby the user should select a sensible significance level.

6.6.3 Hypothesis testing based on binomial distribution

The inspection process is viewed as a Bernoulli process in a simplified manner here. Thus, the probability of occurrence of inspection errors is assumed to be a constant characteristic of the process. Consequently, it is possible to determine how high the probability of an inspection error can be, based on the binomial distribution and by means of a sample.

To evaluate the inspection process, the confusion matrix - also referred to as a contingency table - must be drawn up. In the simplest case, it is a 2x2 matrix (shown with examples of inspection results):

Table 6-8: Confusion matrix (from VDI/VDE/VDMA 2632 Bl.3)

		Reference evaluation	
		OK	NOK
Inspection result	OK	99.20%	0.20%
	NOK	0.80%	99.80%
	∑=	100.00%	100.00%

Besides the desired correct inspection results, there can be two types of inspection errors, type 1 and type 2 errors, in the inspection process. Both of this must be evaluated separately by means of hypothesis testing, as the underlying probabilities are usually not the same.

As hypothesis testing can lead to incorrect results as well, reliability must be specified. In this regard, it is again necessary to distinguish between type 1 (inspection system developer risk) and type 2 (inspection system user risk). The so-called confidence level must be specified for both. Typically, the same confidence level (e.g. 0.95) is selected for both, so that both parties bear the same risk.

The confidence levels for type 1 and type 2 errors during hypothesis testing have an influence on the sample size required for proving capability. The sample size is about the same as for the proof of capability by means of Fleiss' kappa. The concrete calculation is described in greater detail in VDI/VDE/VDMA 2632 3.1 [VDI 2632-3.1].

To determine the sample size and the acceptance limits for the relevant hypothesis test, the following hypotheses are made:

Null hypothesis: The system has an average error rate of c_0.

Alternative hypothesis: The system has an error rate larger than c_1.

The error rate c_0 is the value achievable by the inspection system as indicated by the inspection system developer in the functional specification (see chapter 4.1.1). The error rate c_1 constitutes the maximum acceptable upper limit of the error rate from the perspective of the inspection process planner (see chapter 4.1.1).

Figure 6-3 shows the sample sizes and the acceptance limits for error rates c_0 and c_1, which can stand for both the α and the β risk. In the example provided, an inspection system designed for a β risk of 1 % was tested against an upper limit of the actual slippage of 3 % by using 521 NOK inspected objects in the reference inspection lot, of which a maximum of 9 inspected objects were allowed to be erroneously classified as OK in order to still be able to consider the inspection system capable.

Note: The c1/c0 ratio corresponds to the slippage deviation factor in chapter 6.6.1, Table 6-7.

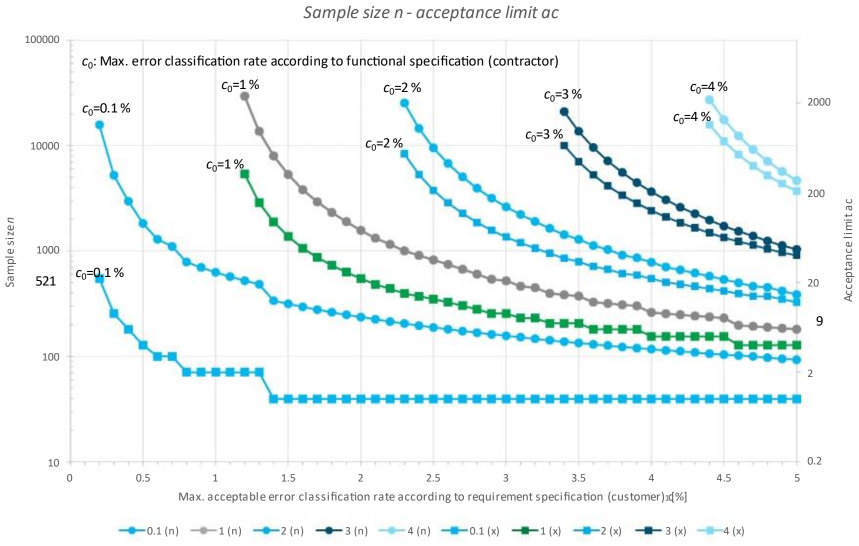

Figure 6-3: Required sample size for different c0 and c1 error classification rates (confidence level = 0.95) [VDI/VDE/VDMA 2632 Bl. 3.1]

6.6.4 Discriminatory power

This procedure can be used if an attributive characteristic is evaluated and assigned to a class by an optical inspection system with the help of a quantitative auxiliary characteristic (e.g. characteristic x in Figure 6-4).

To use this procedure, the inspection system must output the value of the auxiliary characteristic in addition to the assigned class.

The basic principle behind the “discriminatory power” acceptance procedure is as follows: The value ranges of such an auxiliary characteristic – for two classes in the simplest case (e.g. class 1 / good / OK and 2 / bad / NOK) – should be far enough apart that they can be clearly distinguished (”discriminated”), taking the measurement uncertainty into account when determining the characteristic values, and taking general acceptance methods into account (see e.g. DIN EN ISO 14253-1, reference handbooks) (see Figure 6-4). The MSA methods according to AIAG (4th edition) [15] are used for quantitative evaluation.

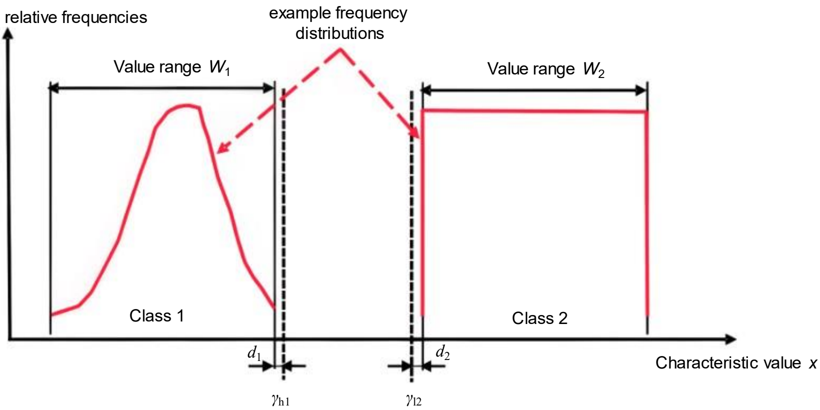

Figure 6-4: Basic principle behind the “discriminatory power” procedure according to [14]

The concrete procedure is described in greater detail in VDI/VDE/VDMA 2632 3.1.

With this procedure, reliable capability statements can be made even in case of comparatively small sample sizes. In VDI/VDE/VDMA 2632, a sample size of at least 25 parts with 2 repeat tests per characteristic class is recommended. In case there is a smaller number of available parts, the number of repetitions must be increased.

When using this procedure, it must be ensured that the boundary conditions are observed, e.g. that the value ranges W1 and W2 do not overlap and that the characteristic values themselves are accessible, which should ideally already be taken into account designing the inspection system and thus specified in the requirement specification.

6.6.5 Analysis of the characteristic distributions

This procedure can be used if an attributive characteristic is evaluated and assigned to a class by an optical inspection system with the help of a quantitative auxiliary characteristic (e.g. number of pixels in Figure 6-5). To use this procedure, the inspection system must output the value of the auxiliary characteristic in addition to the assigned class.

When following this approach, the auxiliary characteristic values x used for classification are determined based on the acceptance sample for all classes to be distinguished. Based on this sample, the parametric distribution is adjusted for each class. This requires suitable statistical distributions across the value range.

A suitable parametric distribution can for example be a normal distribution, whose expected value is estimated based on the arithmetic mean, and whose standard deviation is estimated based on the standard deviation of the sample.

If the characteristic value limits used for classification are now specified, the classification rates can be calculated based on the quantiles of the class-specific distributions. If the classification rates thus determined are equal to or better than those agreed upon in the requirement specification / functional specification, the optical inspection system is deemed accepted based on the acceptance procedure “analysis of characteristic distributions”.

Good and bad parts are for example distinguished by means of a characteristic whose characteristic value is determined with an optical inspection system, and the resulting frequencies in the reference inspection lot are shown schematically in Figure 6-5.

By determining the relevant characteristic distribution functions, estimated values can be derived for the slippage rate / the pseudo-error rate as a proportion of the population of products.

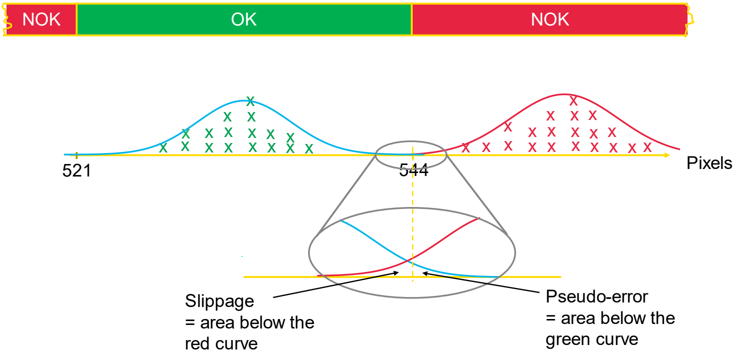

Figure 6-5: Schematic diagram of the slippage (type 2 errors) and pseudo-errors (type 1 errors)

The procedure can equally be used to make statements regarding capability in case of comparatively small sample sizes, as the auxiliary characteristic values provide more precise information regarding the image processing system compared to a purely attributive evaluation. In VDI/VDE/VDMA 2632 3.1, a sample size of at least 50 inspection results per characteristic class is recommended.

It must be noted that the outliers of the estimated distribution functions (and thus the estimated slippage and pseudo-error rates) strongly depend on the composition of the reference inspection lot, especially if only a small amount of data or no data was captured in this range.

Using this procedure requires suitable statistics software in order to be able to determine the probability distributions.

Once the distribution models are known, the threshold value of the auxiliary characteristic for distinguishing between OK and NOK must be appropriately specified in order to achieve optimal inspection system performance. If no threshold value can be found at which the requirements for both the α and the β risk are met, the optical inspection system is not capable and must be improved accordingly.

6.6.6 Handling multiple characteristics on one component

If an inspection system is to evaluate a characteristic in multiple places on the component, this results in interactions between the individual evaluations with respect to the overall assessment of the component. In this regard, the inspection is considered as a combined system as described in chapter 7.1 .

6.6.7 Comparison of the procedures (advantages / disadvantages)

Table 6-9: Advantages and disadvantages of statistical procedures for attributive inspection processes

Procedures	Advantages	Disadvantages and limitations
Fleiss' kappa	The procedure does not require access to the basics of the classification decision within the optical inspection system; the optical inspection system can be used as a “black box” system. This is beneficial if the manufacturer of the optical inspection system cannot or does not wish to disclose the structure of the system.	Type 1 and type 2 errors are considered collectively.
Hypothesis testing	The procedure can be traced back to known statistical methods and can therefore be interpreted mathematically. The procedure does not require access to the basics of the classification decision within the optical inspection system; the optical inspection system can be used as a “black box” system. This is beneficial if the manufacturer of the optical inspection system cannot or does not wish to disclose the structure of the system.	If very small error classification rates (≪1 %) or very large classification rates (≫99 %) have to be checked, very large sample sizes are required.
Analysis of discriminatory power	Relatively few references (reference parts) are required. Higher statistical reliability compared to hypothesis testing, even with small sample sizes. Potentials for optimization can be derived from the statements regarding repeatability.	Characteristics must be made accessible by the manufacturer of the optical inspection system. This must be agreed upon, e.g. in the requirement specification. It is necessary to find characteristics whose value ranges do not overlap for the classes to be distinguished. Expanding this procedure to classifiers which use more than one characteristics requires additional considerations, see chapter 7.1.
Analysis of the characteristic distributions	Relatively few references (reference parts) are required. Higher statistical reliability compared to hypothesis testing, even with small classification rates and small sample sizes. Expected error classification rates can be determined quantitatively. Potentials for optimization can be derived.	Characteristics must be made accessible by the manufacturer of the optical inspection system. This must be agreed upon, e.g. in the requirement specification or in functional specification. The modelling of the distribution (e.g. normal distirbution) must be accurate.

Particularly in the area of machine learning, there are further procedures and key figures for evaluating systems with regard to agreement between their results and the actual conditions. For example, “recall” and “precision” can be named here, or the frequently used combination of these values to obtain an “F_1 score” by calculating the harmonic mean.

While there is a simple correlation between recall and slippage (type 2 errors) - they always add up to 1 -, the number of pseudo-errors (type 1 errors) that will occur cannot be derived directly from precision. Given that the number of pseudo-errors is important for evaluating the costs and for acceptance when using the optical inspection system in production, and given that it can subsequently be easily compared with the actual number that occurs, this parameter is preferable.

Just like Fleiss’ kappa, the F_1 score requires that the consequences of slippage and pseudo-errors be evaluated the same. If using these parameters in connection with special characteristics (SC S or SC A), it should be thoroughly checked whether this assumption is true or whether weighted parameters or other methods should be used.

6.7 Assessment of continuing capability

The basic principle described in VDA Volume 5 for assessing the ongoing capability of an inspection process can also be applied to those inspection processes which are based on optical sensors with image processing. The initial proof of capability covers only a limited period of time. Relevant influencing quantities can change over time, or new influencing factors may emerge which are not known at the time of the initial . Therefore, the capability of the measurement and inspection process can be negatively impacted.

Based on the determined risk class of the inspection process, a suitable procedure must be specified to monitor ongoing capability. It must be ensured that all necessary aspects of capability are covered by the relevant selected method, or a combination of several methods. One of these methods could be a regular inspection by means of error simulation.

Besides the assessment of ongoing capability, additional measures can be taken to increase the stability/robustness of the inspection process, such as monitoring system elements or avoiding and/or detecting faults, e.g. lighting failure, fading, or further influences (see Ishikawa diagram in chapter 2.3).
In case of doubts regarding capability, follow-up measures must be taken (see VDA Volume 5, chapter 4.5):

- Complaint process VDA Volume 5, chapter 4.3.3
- Maintenance and, if necessary, new validation/release.

Depending on the risk classification, the following methods can be used to ensure ongoing capability:

- Functional testing: Insert reference parts (e.g. per shift), and check for correct detection (evaluatoin e.g. by means of the short method). If reference testing is not successful, the complaint process according to VDA Volume 5, chapter 4.3.3 must be initiated.
- Monitoring the decision statistics, e.g. in terms of error frequencies: in case of significant changes, the process is analyzed and the complaint process is triggered, if required. The decision statistics can for example be evaluated by means of an attributive quality control chart (C-chart) for the production process.

  Note: *An intervention limit should particularly be specified to reduce the occurrence of errors, as the cause might lie in the inspection system.*

  Note: *This is not applicable in case of ordinal characteristics (Kendall’s W).*
- Monitoring of characteristic values (see chapter 6.6.5) which are used for attributive inspection: In case of significant changes to the distribution or to their parameters, the process is analyzed and the complaint process is triggered, if required. A stability control chart according to VDA Volume 5, chapter 10.3 can be used for this purpose.
- Monitoring of system components such as lighting, sharpness of images (defocusing), signal strength, plausibility of the results

(e.g. distances in case of lidar), orientation of the camera or lighting.

- Manual inspection (visual inspection) and comparison with the results of the optical inspection system.

The relevant selected methods must be applied regularly in order to ensure ongoing capability.

7 Combined systems

In many cases, multiple measuring or attributive subsystems can be connected to create a combined overall system. For such combined system, a general recommendation will be provided in the following, which is based on chapters 5 and 6.
There are three basic types of combined systems, all of which are associated with different strategies for obtaining proof of capability:

- **Parallel systems**: In parallel systems, multiple characteristics are inspected or measured in the same overall system, and the associated results are output accordingly. The characteristics can be independent of each other, but they do not have to be.
- **Sequential systems**: In sequential inspection systems, the inspection process consists of several steps. Downstream inspection steps are based on the results of the previous steps. A requirement is to be able to access the (interim) results of the relevant steps for the proof of capability.
- **Entangled systems**: In case of entangled systems, multiple (measurement/inspection) subtasks are completed in such a way that no (interim) results are available for the proof of capability. This is for example the case when detecting and simultaneously measuring objects by means of neural networks.

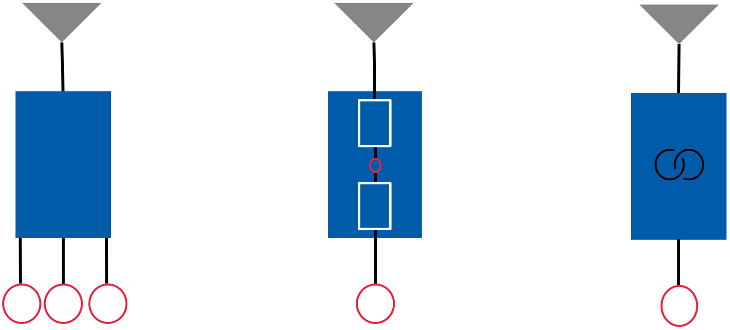

Figure 7-1: Schematic diagram of a parallel system with three output characteristics (left), a sequential system with three steps (center) and an entangled system (right).

In addition, systems consisting of any combination of these basic types are also possible. In particular, it can be assumed in the following that sequential and entangled systems only have one final (i.e. conformity-relevant) output characteristic. Otherwise, the systems are initially seen as parallel systems which can then be divided into fictitious subsystems with only one respective output characteristic.

7.1 Proof of capability for parallel systems

In accordance with the definition provided above, parallel systems can also be designed in such a way that a separate inspection or measuring system (with only one output characteristic each in this case) is used for each output characteristic.

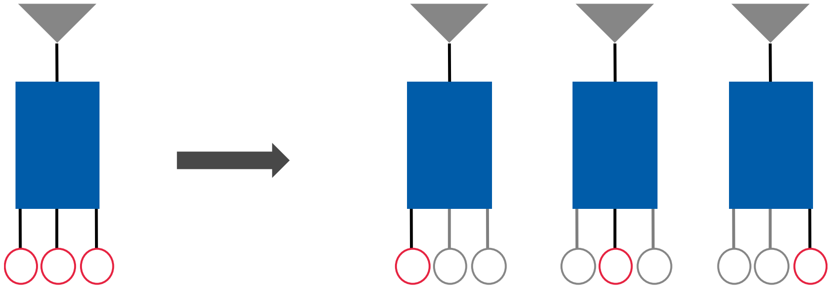

Figure 7-2: A parallel system with three outputs is taken as three systems with one output each for the purpose of obtaining proof of capability.

Thus, a separate proof of capability is obtained for each output characteristic in accordance with chapters 5 and 6, and the output of the other characteristics is ignored. The reason for this is that decisions regarding the individual characteristics can be associated with drastically different risks (see chapter 6.1), requiring different levels of effort to obtain proof of capability. VDA Volume 5, chapter 4.7.4 can be used for simplification in case of multiple characteristics.

Furthermore, it is advisable to specify in advance how the proof of capability for the overall system is composed of the proofs of capability of the individual systems assessed. Consequently, it must be specified how the permissible overall erroneous decision budget is distributed among the individual output characteristics if tolerances of the same parameters are used:

- If there are separate requirements for (part of) the output characteristics, the proof of capability must be obtained according to chapters 5 and 6 with respect to these requirements.
- Otherwise, or for the rest of the output characteristics, it can in individual cases make sense to distribute the overall erroneous decision budget, or an individual erroneous decision budget of must be specified. After that, the procedure according to chapters 5 and 6 can be followed.

Ultimately, the prior distribution of the overall error is only relevant in terms of estimation, and the actual distribution must be determined by means of inspection.

If there is an overall erroneous decision budget for the type 1 error, it can be distributed among the individual systems assessed. According to Bonferroni's inequality [16], the sum of type 1 errors, erroneous rejection by the relevant individual systems, can be seen as the upper limit for the overall erroneous decision budget. The overall budget regarding the type 1 error can be distributed arbitrarily among the individual systems. The same applies to erroneous acceptance by the individual systems, i.e. the type 2 error.

The relationship between the erroneous decisions of the overall system and the individual systems is explained in the following based on the example of a system with two output characteristics (both of which are attributive OK/NOK):

As can be seen in Figure 7-3, the erroneous decisions (type 1 and type 2 errors) from the perspective of the overall system only cover part of the cases in which (at least) one subsystem makes an erroneous decision.

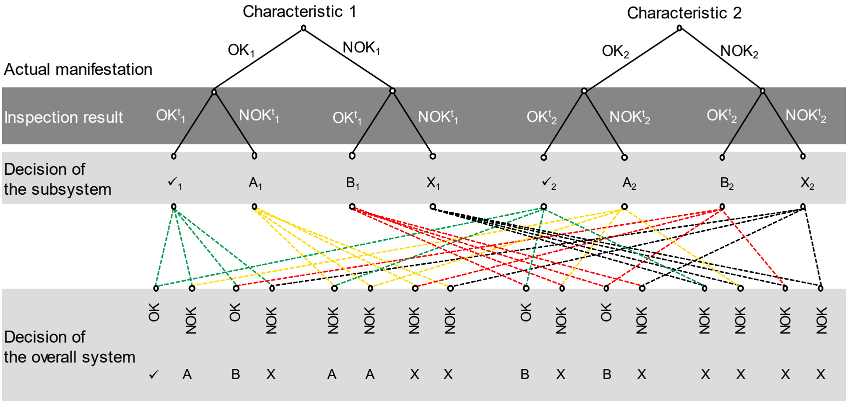

Figure 7-3: Tree diagram for a parallel system with two attributive output characteristics (OK/NOK) and the respective type 1 and type 2 errors (yellow-orange and red).

$A_i :=$ Subsystem i makes a type 1 error (erroneous rejection)

$B_i :=$ Subsystem i makes a type 2 error (erroneous acceptance)

$A :=$ Overall system makes a type 1 error

$B :=$ Overall system makes a type 2 error

$X_i :=$ Subsystem i correctly rejects (detects error correctly)

$ü_i :=$ Subsystem i accepts correctly (detects absence of errors correctly)

In the following, it is shown that the probability of occurrence of erroneous decisions by the overall system directly results from those by the subsystems. The probability of an erroneous decision by the overall system is calculated as follows:

$$\alpha = P(A) = P(A_2 \cap ü_1) + P(ü_2 \cap A_1) + P(A_1 \cap A_2),$$

$$\beta = P(B) = P(B_2 \cap ü_1) + P(ü_2 \cap B_1) + P(B_1 \cap B_2).$$

If the decision paths of the subsystems do not influence each other, it can be assumed that the decisions are made independently. Based on the assumption that the decisions for the output characteristics are made independently, is follows that

$$\alpha = P(A_2)\,P(ü_1) + P(ü_2)\,P(A_1) + P(A_1)\,P(a_2),$$

$$\beta = P(B_2)\,P(\ddot{u}_1) + P(\ddot{u}_2)\,P(B_1) + P(B_1)\,P(B_2),$$

i.e. the probability of occurrence of erroneous decisions by the overall system can be calculated based on the probabilities of erroneous decisions by the subsystems. If no independent decision-making can be assumed, conditional probabilities must be used, and there is no longer a direct correlation between the probabilities of erroneous decisions by the subsystems and the probabilities of erroneous decisions by the overall system.

On the basis of assumed independence, it is also useful to design the associated reference inspection lot in such a way that the different characteristics to be inspected are varied “simultaneously, so that it is not necessary to have a separate reference inspection lot for each inspection characteristic. However, this may not always be possible.

7.2 Proof of capability for sequential systems

In chapter 7, sequential systems were characterized as systems involving multiple steps, in which downstream steps use the results of previous steps, and in which the results of the individual steps (and not just the end result of the overall system) are available for the proof of capability. Furthermore, as explained in chapter 7, it can be assumed without limitation that sequential systems only output one characteristic.

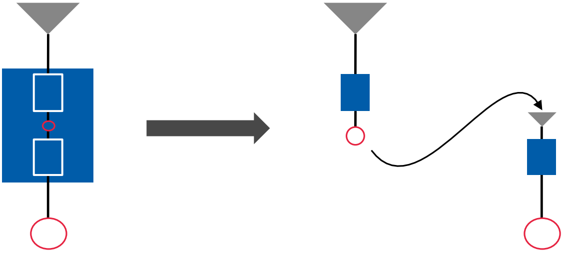

Figure 7-4: For the purpose of the proof of capability, a sequential system with two steps is seen as two systems, and proofs of capability are obtained for both of them.

If the interim results of the individual steps are available for the proof of capability, the proof of capability can be obtained separately for the steps in accordance with chapters 5 and 6. It is advisable to follow the order of the steps, i.e. to start with the proof of capability for the first step. It is then ensured that erroneous inputs to the subsequent steps are highly improbable (meaning that the required α and β risks for the overall system are observed). In accordance with a risk-based approach (see chapter 6.1) it is then possible to simplify the proof of capability for the subsequent step(s), as it can be assumed that the subsequent step(s) only receive correct inputs from the previous step(s). The proof of capability for the subsequent steps is simplified as the proof of capability regarding incorrect inputs can be omitted/limited to a larger extent. This is naturally associated with more extensive efforts, as the range of potential incorrect inputs is significantly larger than the range of correct inputs. For those cases not taken into consideration, it is assumed that the overall system provides an incorrect output (even though this does not always have to be the case, as the chain of erroneous decisions in the individual steps could still lead the overall system to make a correct decision).

The simplified version of the proof of capability is illustrated in the following based on the example of a system with a 2D camera, whose evaluation follows three steps:

Step 1: Object detection
Step 2: Measurement of a geometric quantity (of the object detected in step 1)
Step 3: Assessment (OK/NOK) of the quantity output in step 2, based on a specification.

The object detection in step 1 must provide an object that is measurable in step 2. This can for example be done by providing (the pixel coordinates of) reference points, a pixel-precise object mask or an object frame.

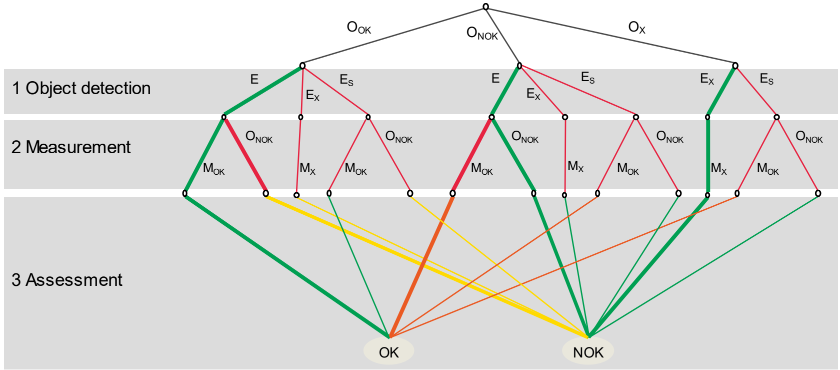

Figure 7-5: Tree diagram for a parallel system with two attributive output characteristics (OK/NOK) and the associated type 1 and 2 errors (yellow-orange resp. red)

O_{OK} := Object is present and meets the requirements
O_{NOK} := Object is present and does not meet the requirements
O_X := Object not present
E := Object is detected
E := No object is detected
E_S := Pseudo-object is detected
$M_{i.O.}$:= Measurement provides measured value that meets the requirement
M_{OK} := Measurement provides measured value that does not meet the requirement
M_X := Measurement does not provide a measured value

The decision tree diagram (see Figure 7-5) shows the various possible paths through the three steps of the sequential system. The lines above the steps show which reference which reference situation the system is confronted with. In step 1, object detection, there are three options: Detecting an object (E) correctly, not detecting an object (E_X) or detecting a “pseudo-object” (E_S, meaning objects that are not looked for, or more or fewer than the objects looked for). In steps 1 and 2, the paths shown in light green provide a correct decision with respect to their own steps. In step 2, the object provided by step 1 is measured and the relevant measured value is provided, or no measured value is provided as there is no object. In step 3, the measured value is evaluated in accordance with the specification, and the inspection process outputs an OK/NOK result. For the third step, the colors in Figure 7-3 are used for OK/NOK and type 1 and type 2 errors. Overall, there are 13 possible paths the system can take until the output. To make the diagram clearer, no further cases were distinguished in step 2, such as whether the measurement guideline is applied correctly or whether the measured value is in the acceptance, rejection or uncertainty range (43 possible paths).

If following the recommendation provided above for the proof of capability for sequential systems, a proof of capability is first obtained for step 1.

It is necessary to ensure that the objects searched for are detected with sufficient certainty (both those that meet the requirements and those that do not meet them), and that objects not searched for are with sufficient certainty not output as searched objects. Sufficient certainty means that the overall system itself would meet the required α and β risks even if the errors in step 1 would always lead to an error by the overall system (meaning that errors in different steps cannot combine in such a way that the overall systems makes a correct decision). It then follows that it is no longer necessary to obtain a proof of capability for steps 2 and 3 for paths on which step 1 fails. The tree diagram in Figure 7-5 can then be simplified to the tree diagram in Figure 7-6. Proofs of capability are only required for the paths highlighted in bold in steps 2 and 3.

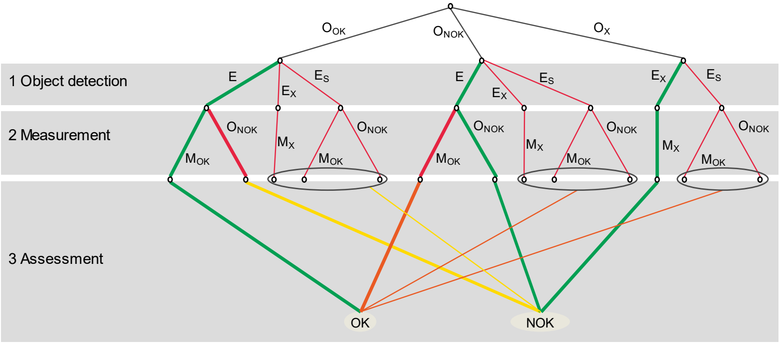

Figure 7-6: Simplified tree diagram of the decision paths in the example, under the assumption that errors in step 1 always lead to errors by the overall system.

The probability of type 1 and 2 errors by the overall system are then calculated as follows

$$\alpha = P(O_{OK} \cap E \cap M_{NOK}) + P\big(O_{OK} \cap (E_X \cup E_S)\big),$$

$$\beta = P(O_{NOK} \cap E \cap M_{OK}) + P\big(O_{NOK} \cap (E_X \cup E_S)\big) + P(O_X \cap E_S).$$

The elements not printed in bold constitute contributions to the error of the overall system which result from erroneous decisions in step 1. Consequently, only the error contributions printed in bold are relevant to the proof of capability of steps 2 and 3. This proof of capability is obtained in accordance with chapter 6.

7.3 Proof of capability for entangled systems

In contrast to sequential systems, entangled systems are defined as black-box systems in chapter 7, i.e. no interim results are available for the proof of capability. The error conditions of such systems can therefore not be resolved, and the proof of capability of individual steps cannot be obtained separately. Consequently, the proof of capability must be obtained using a brute-force approach, with the aim of following all (unknown) internal paths of the entangled system sufficiently frequently in order to achieve statistically valid assurance. In case of an attributive inspection system, the attributes, i.e. the parts above and below the specification limit in the case of a measuring system, should occur with roughly equal frequency, as the confidence intervals of the estimated values otherwise become unnecessarily large.

Hypothetically, it is also possible to have a case where the proof of capability of a sequential system can be treated as in an entangled system, if the situation permits.

The reference inspection lot must be large in order to cover all critical situations. As this is often not possible in practice, it is necessary to think very carefully about possible situations that could realistically occur and that could challenge the system. These should then be represented accordingly in the reference inspection lot reference inspection lot.

The sample size can be derived from chapters 5 and 6, in particular chapter 6.1 in case of risk-based methods in machine learning.

When it comes to creating the reference inspection lot, the user can follow two paths – also simultaneously – in relation to boundary samples in entangled systems:

- Orientation towards the specification of the inspected object according to the characteristics
- Orientation towards the problems of the inspection system

The first path means that the reference inspection lot includes many examples in which the object is close to the specification limit, as erroneous decisions can be expected to be more frequent here and corresponding probabilities of occurrence (type 1 and type 2 errors). (reference to VDA Volume 5, chapter 9.5.1.1)

In the second path, however, it is first determined empirically which inputs lead to increases in erroneous decisions, or this information is derived from prior knowledge. The reference inspection lot is then designed in such a way that these problems are represented.

The proof of capability is then obtain according to chapter 5 and chapter 6.

The overall error rate (type 1 and type 2 errors) cannot be obtained exclusively by linking the error rates of the individual steps, as the individual paths are used more or less often depending on the input. The frequency with which the paths are taken should therefore also be evaluated.

8 Optical sensors in vehicles

The previous chapters in this volume explained methods relating to inspections within production. Optical sensors can however also be used in vehicles. This changes the perspective: While previously, the capability of optical inspection equipment was determined, the optical senors (which often serve as the basis for driver assistance systems) now take the place of the inspection equipment and are meant to reliably provide information regarding the environment or the interior of the vehicle.

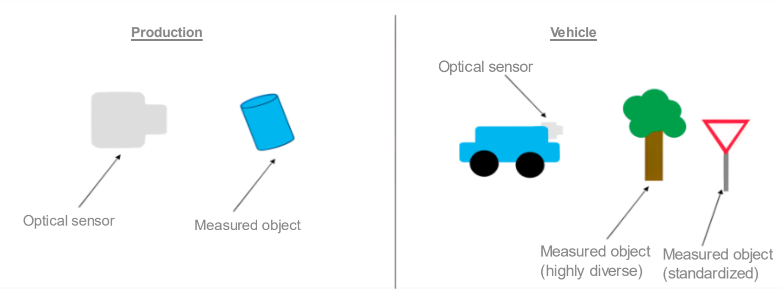

Figure 8-1: Comparison of optical sensors in production and in the vehicle

A proof of capability requires that the sensors used stay within their specification range, even in installed condition. This may sound trivial at first, given that the sensors were already in the specifications which were checked by the supplier’s production department and are thus capable as such from the moment of delivery. However, there can now be additional influences in the vehicle, which may restrict the function of the sensor.

The typical influences on optical sensors are other optical materials which are used for the purpose of protection but which can change the path that the light takes. Examples include the windshield when it comes to the front camera, or the instrument panel trims when it comes to the interior camera. A further influence on the function is the mechanical orientation. The latter can be unfavorable due to an external holder or can change due to thermal distortion.

When it comes to inspecting series parts, the starting point are optical sensors whose series release has been completed and which are then installed into the vehicle as individual elements. Generally speaking, design errors are therefore excluded, and only production errors after integration should be identifiable.

The present chapter is meant to provide a way to verify capability, i.e. proving the capability of the associated individual optical sensors that are installed. Throughout this process, synergy is meant to be created between the previous evaluations of inspection equipment and the use of optical sensors in the vehicle.

In this chapter, the continuous proof of capability during series production of an optical sensor is discussed (see Figure 2-1). The initial discussion focusses on a front camera - this can also be expanded to include other optical systems.

8.1 Influencing factors and risk assessment

To establish whether the sensor is capable at any time during operation, the functionality of the sensor within a certain operating range must be proven.

The further considerations are based on the premise that all sensors have already been individually inspected by a manufacturer and classed as OK. Whether it is necessary to evaluate the functions of an installed optical sensor in the production line and also across the lifespan is something that must be decided individually for each type of sensor. A risk estimation, e.g. by means of FMEA, can help to identify specifications that are relevant for the inspection. The Ishikawa diagram (Figure 2-2) in chapter 2.3 can provide orientation and a basis for estimating the risks of the potential influences in such a system.

If characteristics should require an inspection, the scope of inspection should be determined as part of the PFMEA. Furthermore, the monitoring of safety-relevant functions can already be taken into account via the initial sensor design.

It can be sufficient to evaluate the communication between the sensor and the central control unit, if the sensor itself can adequately check that it is functioning correctly.

However, such measures and algorithms which evaluate the functionality during operation in the field still often require a correct first initialization. This can for example be the initial calibration of a camera. For such a case, the requirements regarding the initial calibration also constitute the acceptance range for evaluating the sensors in installed condition. Observing the acceptance range that resulted from product validation can thus be interpreted as the actual proof of capability. Essentially, this interpretation is a written form of the integration testing of systems according to the V-model.

8.2 Inspections

In the following, potential inspection scenarios relating to an optical sensor are discussed based on an example system. The functional inspections, the justification as to why they are necessary, their scope at the inspection stations, the final inspection at the supplier's premises, the integration inspection at the customer's premises and the inspections regarding operation in the field are addressed.

As an example, characteristics of the front camera are selected which are relevant to the upper inspection stations. Especially when it comes to the integration inspection at the customer's premises, as well as the inspection regarding operation in the field, the installation position, behind the windshield in this example, must be taken into account. The following list Table 8-1 of possible inspections does not claim to be complete and is only meant to show the thought process and the practical relevance behind the proof of capability.

Inspections of the front camera

The following table is meant to provide an example of the influences may have to be re-inspected or monitored once a sensor which has previously been inspected by a supplier is installed or once it is used in the field. This necessity or these requirements depend on the use of the camera and can therefore lead to different risk levels. This also changes the inspection and the monitoring requirements:

Table 8-1: Inspections of the characteristics of a front camera

Characteristic	Prior to installation / to be inspected at supplier's premises	After installation/ to be inspected at the manufacturer's premises	To be inspected in the field / during operation	Influenced in installed condition by e.g.	Risk	Degree of risk	Measures, e.g.
Intrinsic parameters	Yes	Yes, if required	No (plausibility check)	Windshield (optical path)	Misalignment, functional impairment (resolution)	Emergency brake assistant – medium Autonomous driving – high	Recalibration
Extrinsic parameters	No	Yes	Permanent monitoring and adjustment	Windshield (optical path), mounting/suspension tolerance	Misalignment	Emergency brake assistant – medium Autonomous driving – high	Recalibration
Image sharpness	Yes	No (plausibility check)	No (plausibility check)	Windshield (optical path)	Functional impairment (resolution)	Emergency brake assistant – low Autonomous driving – medium	impossible
Dynamics (brightness)	Yes, if required	No (plausibility check)	No (plausibility check)	Windshield (optical path, transmission material)	Functional impairment	Overall function – medium	Readjustment
Color fidelity	Yes, if required	No (plausibility check)	No (plausibility check)	Windshield (transmission material)	Functional impairment	Overall function – low, certain robustness of the function is required	impossible
Contamination	Yes	Permanent monitoring, if required	Permanent monitoring, if required	Windshield, cleanliness in production	Functional failure	Overall function – medium	Cleaning
Defective pixels	Yes	No	No	Wear	Functional impairment	General function – low to medium	Replacement

In line with the table above, the inspection requirements in relation to the capability of a functioning sensor prior to installation, after installation, and during operation in the field are discussed based on three characteristics.

Intrinsic parameters

Uninstalled state

The intrinsic parameters describe the inner geometry of the camera sensor across a set of parameters. In contrast to this, the extrinsic parameters describe the orientation and position in relation to the vehicle. Intrinsic parameters for instance include the field of view, its orientation/direction, angular resolution and optical distortion. Each of these parameters has a specified, permissible tolerance range within which it must stay. This means that for each pixel in a digital camera image, it must be clear with sufficient certainty which visual ray or which section of the real scene it corresponds to.

For this purpose, the so-called intrinsic parameters of the camera module are measured and are compared with the specification in order to discard NOK parts. If necessary, the parameters are stored in order to be able to use them later on in the overall vehicle system. The parameters are stored e.g. in the EPROM of the camera module itself and can then be read and used from there in the vehicle.

Installed state

In the installed state, the optical path of the camera through the windshield is influenced. Curvatures of the windshield can lead to changes in the angular orientation of the pixels. This influences the parameters of the intrinsic calibration and the size of the field of view. Depending on the orientation of the camera, the angular deviation can also change.

The intrinsic parameters can be recalibrated after installation. If it can be largely excluded that these parameters change during operation in the field, it is generally only necessary to monitor the tolerable deviation.

Should the camera or the windshield be replaced due to a defect, e.g. after an accident or damage due to stones, the same requirements must generally be met as for the initial calibration after initial installation by the manufacturer. A recalibration of the intrinsic parameters in a workshop can then be necessary in order to reestablish the capability of the functions.

Extrinsic parameters

Uninstalled state

The extrinsic parameters relate to the orientation and the position of the camera with respect to the vehicle and depend on the intrinsic parameters. The extrinsic parameters can not be determined prior to installation. An inspection is therefore only possible in the installed state.

Installed state

As soon as the sensor has been installed, the tolerance chain of all relevant mechanisms (from the wheels and the axles up to the camera holder itself) takes effect. The camera then has a specific orientation and position which must be within a certain tolerance range in order for the functions to be functions to work correctly. Consequently, it may be necessary to conduct checks after installation if the risk of an incorrect orientation is high or if the extrinsic parameters cannot be safeguarded by means of other methods.

During operation in the field, the significant temperature fluctuations in the area of the windshield as well as the dynamic driving situation are relevant. As the reference point is always determined in relation to the vehicle, continuous monitoring and recalibration of the extrinsic camera parameters are generally necessary. If the orientation and position of the camera is within the specification range, the camera can be considered capable with regard to its functional purpose.

Should the camera or the windshield be replaced due to a defect, e.g. after an accident or damage due to stones, the same requirements must generally be met as for the initial calibration after initial installation by the manufacturer. A recalibration of the extrinsic parameters in a workshop can then be necessary in order to reestablish the capability of the functions.

Contamination

Uninstalled state

Contamination can manifest itself in different ways. Contamination can occur within or outside of the sensor during the production process of the sensor. Examples include organic particles such as hairs, metal chips from threads or fingerprints on an optical component.

A rudimentary check for contamination can be done by means of a visual inspection. Particularly with stray light testing, it is possible to generate measured values and specify an acceptance window which is required for the functional capability of the camera.

Installed state

Further contamination can also occur during installation. Particles can even fall onto the lens of a front camera which is held mechanically by a holder. Equally, there can be contamination on the windshield after installation, which can compromise the optical path of the front camera and its function.

As in uninstalled condition, visual inspection and stray light testing can be used here.

During operation in the field, there is typically contamination on the windshield (dirt, snow, leaves, condensation), which can significantly limit the function of the camera. To ensure that the camera functions properly, it is therefore necessary to continuously monitor for a clear/unobstructed view as well as any disruptive factors. Stray light methods can be an option here, too.

For installation in a workshop, there is a similar requirement to check for contamination, just like after initial installation by the manufacturer.

8.3 Conclusions and outlook

In the final chapter of the present VDA Volume 5.3, optical sensors in vehicles were addressed, and an attempt was made to establish a link to the previous chapters, thus allowing for an assessment of capability of sensors in installed condition. A front camera was taken as an example of an optical sensor, and various characteristics were discussed. An individual assessment is required in order to determine whether an inspection of these characteristics in installed condition is reasonable after production and during operation in the field. These principles are generally valid in that the risk assessment with respect to the influences in installed condition is also applicable to all other (optical) sensors. 360° cameras, interior cameras, lidars or thermography camera can be named as examples here. Depending on the intended use of the optical sensor, the influencing factors, which are determined by means of the Ishikawa diagram (Figure 2-2), can provide different contributions in terms of the risk regarding fault-free operation. The user must take these contributions into account on a case-specific basis when it comes to risk-based assurance.

The overall risk will increase with the growing interest in autonomous driving, and further methods for handling risks will therefore certainly be developed in the near future.

Bibliography

[1] VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik, VDI-Statusreport Maschinelles Lernen, 2020.

[2] VDI/VDE/VDMA, Richtlinie 2632 Blatt 1:2023-01 - Industrielle Bildverarbeitung - Grundlagen und Begriffe, Berlin: Beuth Verlag, 2023.

[3] VDA – Verband der Automobilindustrie e.V., VDA-Band 16 – Dekorative Oberflächen von Anbau- und Funktionsteilen im Außen- und Innenbereich von Automobilen, Berlin: VDA e.V., 2016.

[4] Proposal for EU Regulation 2021/0106(COD) - The Artificial Intelligence Act, 2021.

[5] Joint Committee for Guides in Metrology, JCGM, International Vocabulary of Metrology, Basic and general concepts and associated terms (VIM), 3rd ed., 2012.

[6] D. C. Montgomery, Design and Analysis of Experiments, 10 ed., Wiley, 2019, p. 688.

[7] W. Kleppmann, Versuchsplanung – Produkte und Prozesse optimieren, München: HANSER-Verlag, 2020.

[8] T. Luhmann, Nahbereichsphotogrammetrie: Grundlagen - Methoden - Beispiele, VDE Verlag, 2023.

[9] R. V. Lenth, "Quick and Easy Analysis of Unreplicated Factorials," *Technometrics,* vol. 31, no. 4, pp. 469-473, Nov. 1989.

[10] K. Ye, "Orthogonal column Latin hypercubes and their application in computer experiments," *Journal of the American Statistical Association,* vol. 93, no. 444, pp. 1430-1439, 1998.

[11] R. Sanchez-Marquez, F. Gerhorst and D. Schindler, "Effectiveness of quality inspections of attributive characteristics – A novel and practical method for estimating the “intrinsic” value of kappa based on alpha and beta statistics," *Computers & Industrial Engineering,* vol. 176, p. 109006, February 2023.

[12] M. G. Kendall, "A New Measure of Rank Correlation," *Biometrika,* no. 30(1–2),, p. 81–93, 1938.

[13] M. G. &. S. B. B. Kendall, "The Problem of m Rankings," *The Annals of,* no. 10(3), p. 275–287, 1939.

[14] M. H. a. D. A. Wolfe, Nonparametric Statistical Methods, New York: John Wiley & Sons, 1973, p. 139–146.

[15] A.I.A.G. – Chrysler Corp., Ford Motor Co., General Motors Corp., Measurement Systems Analysis. Reference Manual, Michigan, USA, 2010.

[16] J. Galambos and I. Simonelli, Bonferroni type inequalities with applications, New York: Springer, 1996.

[17] "Pegasus-Projekt," 01 April 2020. [Online]. Available: https://www.pegasusprojekt.de/files/tmpl/pdf/PEGASUS_Abschlussbericht_Gesamtprojekt.PDF. [Accessed 04 Juli 2023].

[18] M. Scholtes, "6-Layer Model for a Structured Description and Categorization of Urban Traffic and Environment," *arXiv:2012.06319v2,* 2021.

[19] ISO - International Standard Organization, ISO 26262-1: Straßenfahrzeuge - Funktionale Sicherheit - Teil 1: Vokabular, Berlin: Beuth Verlag, 2018.

[20] ISO - International Standard Organization, ISO 21448: Straßenfahrezuge - Sicherheit der beabsichtigten Funktionalität, Berlin: Beuth Verlag, 2022.

[21] COMMISSION IMPLEMENTING REGULATION (EU) 2022/1426 - General safety regulation 2 (GSR2), 05.08.2022.

[22] Deutsches Institut für Normung, DIN 1319-1:1995-01 - Grundlagen der Meßtechnik - Teil 1: Grundbegriffe, Berlin: Beuth Verlag, 1995.

[23] J. W. T. Stößel, "Trennschärfe: Innovatives Abnahmeverfahren für diskret prüfende Systeme," *VDI-Berichte, Messunsicherheit praxisgerecht bestimmen und Prüfprozesse in der industriellen Praxis,* no. 2319, p. 321–332, Düsseldorf, 2017.

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Qualitäts Management Center (QMC)

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Phone +49 (0) 30 89 78 42-235,
Fax +49 (0) 30 89 78 42-605,
Email: info@vda-qmc.de, Internet: www.vda-qmc.de

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