Road and Transportation Research Association (FGSV)
Infrastructure Management working group

FGSV

Working paper

Sensors for the Structural Assessment of Roads

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Note:

The working paper “Sensors for the Structural Assessment of Roads”, edition 2022, was prepared by the “Sensors for Structural Assessment” working party as part of the “Structural Assessment” working group (head: Univ.-Prof. Dr.-Ing. habil. Frohmut Wellner, Dresden).

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1 Introduction

1.1 General

This working paper summarises the current state of knowledge and research on the application of sensors in road pavements, designed to record input quantities and characteristics for structural assessment. In this working paper, sensors generally refer to technical equipment that can used to record the values of physical quantities and display them for interpretation.

The working paper deals with every type of sensor that is permanently connected to the road, i.e. sensors that are installed

- in the bound and unbound courses of the superstructure as well as in the sub-base/ sub-structure,
- next to or above the road (for example on masts)

and can contribute to structural recording and its subsequent assessment. This can also include sensors that are primarily used for a different purpose (e.g. traffic control). However, this working paper only describes the application of sensors that are installed primarily for other purposes for the sake of completeness; special publications (e.g. "Notes on detection technologies in road traffic") are available for the respective installation situations.

Structural assessment methods based solely on the measurands recorded by sensors do not currently exist. The measured variables and characteristics can make a significant contribution both to independent engineering structural assessment and to the existing draft

"Guidelines for the assessment of the structural assessment of roads" (RSO) and their further development; however, without further interpretation steps, they currently fail to provide any information on the residual structural.

1.2 Objectives of the working paper

By summarising relevant information, this working paper aims to provide help in selecting suitable sensors for specific projects and deciding whether the use of sensors makes sense from a technical perspective. That said, the working paper does not purport to provide exhaustive explanations and assessments of individual electro-technical principles and products.

Given that using embedded sensors necessitates collaboration among various specialist disciplines to a certain degree, another objective of the working paper is to define terminology that can be utilised throughout the project planning phase.

1.3 Advantages and disadvantages of using embedded sensors

The advantages and disadvantages of using embedded sensors need to be discussed from a general and a project-specific standpoint. The focus should invariably be on the expected benefits, which must always outweigh the additional costs, e.g. for installing and analysing the sensors. Future developments in sensor technology as well as increasing automation and standardisation are likely to reduce these costs.

The distinct advantages of using permanently installed sensors include directly measuring stress variables at critical points within the road structure and facilitating event-driven or quasi-continuous measurements for data collection. Statistical analyses and observations, within the meaning of big data approaches, are therefore possible.

A disadvantage is both the increased installation costs and operating expenditure that may arise. Moreover, a defective sensor cannot usually be replaced when installed and is, therefore, considered lost.

Further, it might also be necessary to consider that an unfavourable choice of sensor or installation method in the road structure could lead to unintended flaws. The shape, size and rigidity of the sensors should therefore be adapted to the surrounding material whenever possible.

Whether the permanent placement of a sensor is to be regarded favourably or unfavourably depends on the specific application and warrants further discussion. On the one hand, the measurement position is absolutely unequivocal, which can be crucial for computational modelling, for example, and, on the other hand, the selected location may later prove to be unrepresentative due to the construction process.

2 Terminology

The use of embedded sensors necessitates collaboration among various specialist disciplines. From deploying measurement technology to conveying measurement results, this process chain involves physicists, electrical engineers and civil engineers, with the road construction and maintenance authorities playing a key role as the information recipients. These target groups are defined in the following as modules (Fig. 1). The individual modules already contain various definitions of sensor terminology, which may differ in their depth and meaning and sometimes overlap.

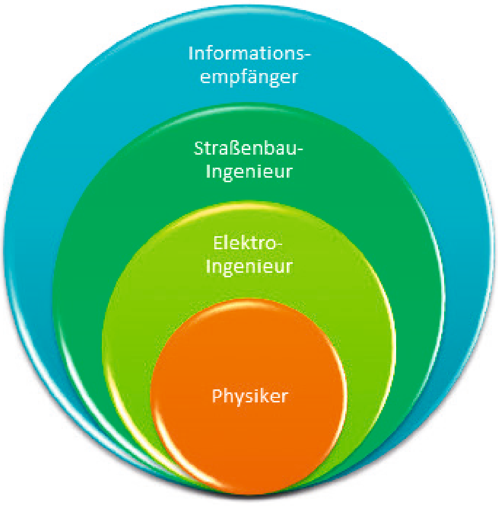

Figure 1: Module model for explaining the process chain and communication interfaces

The following definitions focus, in particular, on the module “Road construction engineer” and “Information recipient”. Any relevant deviations will be highlighted accordingly in each specific case.

The terminology is defined pursuant to standard DIN 1319-1 “Fundamentals of metrology – Part 1: Basic terminology”. If examples are required for explanation, they are described accordingly in the Annex of this working paper.

Pursuant to standard DIN 1319, the entire process of recording, processing and visualising physical quantities is referred to as the “measurement”. Moreover, the said standard refers to the equipment required as the “measuring equipment” and the parts that perform the aforesaid recording and visualisation as the “measuring instruments”. In its simplest form, the “aim of the measurement” is to convert the value of the “measurand” into a “measurement signal” using a “sensor” and then to display it as a “measured value” for assessment. The entire path, from the aim of the measurement to the display of the measured value, is referred to as the “measurement chain”.

Measurement chains can be kept very simple or become very complex through the integration of conversion, storage and other processing stages. This will be illustrated below using relevant examples.

The terms “sensor” and “sensor technology” are not used in standard DIN 1319, as these two terms are used very inconsistently. Depending on the environment of application, the term “sensor”

- only refers to the actual sensor, which, depending on the quantity value being measured, converts the quantity into another physical quantity that is more useful for the measurement (nowadays usually an electrical quantity, e.g. a resistance, voltage or current).

Table 1: Relevant terminology and meaning

Term	Category	Meaning
Categories: I = instrument, P = process, S = signal processing		
Measured object	I	Object used to determine the measurand (the object whose properties are of interest)
Aim of the measurement, target measurand (inspection task)	P	Physical quantity being measured
Measurement principle	P	Physical principle according to which there is a correlation between the (usually unmeasurable or difficult to measure) target measurand and a (more easily measurable) measurand. This principle can be used to determine the (desired) value of the target measurand from the (measured) value of the measurand.
Measurand	S	Physical quantity that is measured by the measuring equipment
Sensor	I	The commercially available technical unit, see Introduction
Measurement chain	I	Sequence of signal processing from detection in the sensor to display/storage, possibly via one or more processing steps (conversion, aggregation, storage)
Measuring equipment, measuring system	I	All measuring instruments and additional equipment for achieving a measurement result (can also include the power supply and protective systems, for example)
Measuring instrument	I	Instrument which, alone or in conjunction with other equipment, is intended for the measurement of a measurand; it represents the abstract measurement chain and accordingly consists at least of one sensor and one indicator, but may also contain further elements for reconditioning the measurement signal
Sensor (sensor, probe)	I	A measuring equipment component that detects the state of the measurand and converts it into a measurement signal
Measurement signal	S	Further processable value of the measurand from the sensor to the first processing/display instrument of the measurement chain; usually an electrical variable (voltage, current, resistance) or a flow of information (digital – electrical or optical)
Measured value	S	Value that belongs to the measurand and consists of a numerical value and a unit. It is usually assigned an accuracy that results from the measurement principle and the measuring equipment.
Measurement result	S	Estimated value obtained from measurements for the true value of a measurand
Reconditioning	P	Any processing of the measurement signal to obtain a representation of the measured information for fulfilling the task (e.g. aggregation or storage)
Aggregation	S	Spatial or temporal summarisation of measured values (e.g. to reduce the data volume in order to compensate for scattering)
Storage	S	Temporary or permanent retention of displayed measured values (e.g. to enhance transmission, to document measured values or to evaluate them as a time series)

An externally uniform component comprising a sensor with correction and reconditioning circuits that provides a transmittable signal (voltage, current, digital signal), or

measuring equipment encompassing a complete or substantial part of the measurement chain.

Standard DIN 1319 therefore expressly points out that if the terms are to be used, it must first be defined in the respective environment what is to be understood by the term "sensor" or "sensor technology".

The term "sensor" is intentionally used in this working paper, given its established usage within the discussed environment. It is used here to describe a technical unit that is commercially available, even if it contains other components (e.g. power supply, converter, transmission equipment) in addition to the actual sensor.

The terms that are usually applied in sensor projects are explained in Table 1.

Figure 2 shows a schematic diagram of what is meant by the term measurement chain. The left section indicates the spatial arrangement from the measurement location to the evaluation station. The individual parts can be very close to each other (e.g. like with a standard thermometer) or hundreds of kilometres apart (e.g. like with remote monitoring equipment). The right section shows the logical connections. Many of these elements are facultative. They can be implemented but are not necessary for every piece of measuring equipment. Depending on the actual measurement, a measurement chain can either be very simple or very complex (Annex 1). Depending on the design of the measurement chain, individual logical units can also be arranged at varying points. For example, digitalisation and initial storage can already occur in the sensor ("intelligent sensor") or only on the way from the sensor to the display (e.g. in the case of a traffic telematics system in the route station). Aggregation can take place in-situ or at the control centre, which places varying demands on the equipment of the intermediate stations and data transmission paths.

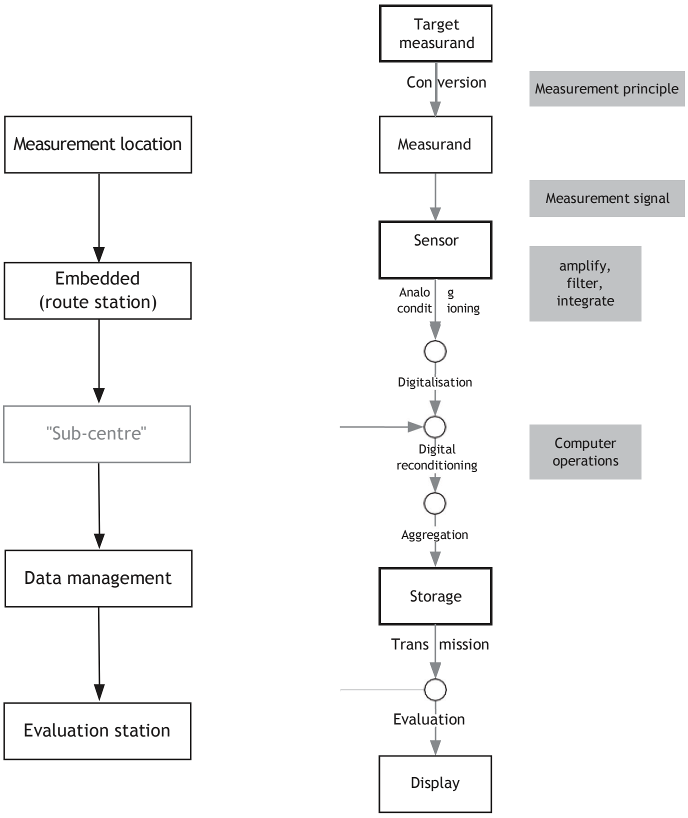

Figure 2: Abstract representation of a measurement chain

3 Objectives

3.1 Application locations, purposes and limits

The planning and implementation requirements for the instrumentation of roads with sensors and for the evaluation of the acquired data for structural assessment depend on a large number of boundary conditions. These boundary conditions impact the choice of sensors, the necessary infrastructure and the costs associated with the instrumentation.

The following aspects need to be considered:

- Application purpose
  - Which properties are to be measured?
  - Necessary measuring accuracy
  - Monitoring
- Recording requirements or triggering of the measurement
  - Event controlled
  - Regular (continuous or clocked)
- Time limited recording
  - Use of sensors within the context of time-limited tasks
  - Use of sensors for the permanent recording of characteristics
- Time of instrumentation
  - Installation of sensors during construction
  - Installation of sensors in existing structures
- Installation medium
  - Asphalt or concrete course
  - Hydraulically bonded course
  - Course without binder
  - Earthworks or in-situ soil
- Strategic time limited recording
  - Use of sensors in test areas outside the public road network
  - Use of sensors in individual defined cross-sections of the road network
  - Use of sensors over longer distances or at network level
- Spatial limitation of recording
  - Defined position of the sensors or sensors as “scattered material”
  - Consideration of the availability of any necessary infrastructure (power supply, data network connection)
  - Position in the cross section.

The combination of the aforesaid decision-making aspects, above all the application purpose to be defined in each individual case, results in the object or project-related operating conditions. Due to the large number of possible combinations, this working paper can only provide information on the possible applications that must be discussed on a project-specific basis:

- Does the effort required for the instrumentation justify the expected added value? Can the measurands be determined just as reliably from characteristics that are easier to record and suitable modelling?

- Is power supply, data transmission and data storage actually possible under the given boundary conditions? Is accessibility limited (e.g. for data readout)?
- Does the instrumentation have a negative impact on the usability and service life of the road pavement? Are (detrimental) effects on the life cycle of the road pavement to be expected (e.g. influences on operation, maintenance, the environment, dismantling and reuse)?
- Is installation possible under the given boundary conditions?

  This applies not only to the technical feasibility but also, for example, to the time required for installation in relation to the available construction periods.

Given the boundary conditions in road construction that can lead to challenges for electronic components, the following should be considered alongside the requirements and application limits for the entire measurement chain (sensor, cables, reconditioning – i.e. not only the sensor but also, for example, the recording station in the verge and the systems connected to it):

- Thermal stress
  - Installation temperature of asphalt:

    Up to 250 °C with a duration of approx. 20 minutes (for installation at the construction site)

    Attention: Electronic components are sensitive to temperatures. A temperature range is usually specified within which damage is not expected during transport and installation. Moreover, a sensor has an operating temperature range within which measured values can be recorded with sufficient accuracy (application: recording of the installation temperature).
  - Hydration heat when concreting:

    Max. 10 K at installation temperatures of 30 °C for max. 2 days
  - Temperature ranges during use (in Germany):

Surface	– 30 °C to + 60 °C
At an approx. depth of 10 cm	– 25 °C to + 55 °C
At an approx. depth of 20 cm	– 15 °C to + 45 °C
  - In areas with stationary traffic (e.g. in front of traffic lights), higher temperatures may be expected near the surface due to the waste heat from engines and catalytic converters.
- Moisture/Dampness
  - Condensation moisture (below the dew point)
  - Risk of flooding
- Chemical/Physical stress
  - pH values of concrete, chloride
  - Corrosion
  - UV
  - Other
- Mechanical stress
  - During installation (due to dynamic compaction)
  - Concrete shrinkage (leads to stress)
  - Usage phase
    - Varying thermal expansion
    - Small slab movements with concrete
    - Due to traffic load

- Other effects and risks
  - Risk of lightning
  - All kinds of accident
  - Theft and vandalism
  - Structural and operational aspects (trenching work, maintenance planning, etc.).

3.2 Relevant properties, measurement objectives and measurands for structural assessment

The measurements, within the meaning of structural assessment, serve to determine the following properties:

- System behaviour
  - System rigidity
  - Fatigue (in combination with laboratory tests)
  - Flaws/imperfections/layered composite
  - Changes to the geometry
  - Joint behaviour/condition of concrete
  - Material behaviour
    - Material rigidity
    - pH values
    - Salinity
    - Chemical resistance
    - Corrosion resistance
    - Thermal conductivity, coefficient of thermal expansion, heat transfer coefficient
    - Influencing variables (weather and traffic)

This results in the following measurement objectives (inspection tasks):

- Determination of the temperature profile through depth
- Determination of the vertical displacement at the surface
- Determination of the horizontal joint movements in concrete carriageways
- Determination of the horizontal expansion on the underside of asphalt course(s)
- Determination of the vertical pressure in the courses without binder and on the planum
- Determination of the moisture in the unbound courses and in the subgrade/sub-base
- Determination of the environmentally relevant characteristics (e.g. salinity due to de-icing salt).

To do so, the following measurands must be determined:

- Length-dependent variables
  - Joint clearance
  - Joint offset
  - Crack width
  - Expansion
  - Routes in general/displacements
  - Others, if necessary
- Compressive and tensile stress
- Acceleration (indirect length)
- Speed (indirect length)

- Temperature
- Moisture
- Porosity
- Volume/composition of traffic.

The measurands can be recorded at varying depths, locations or positions during specified measurement intervals tailored to specific concerns.

The significance and scope of recording these measurands for structural assessment are determined beyond the scope of this working paper, e.g. in regulations governing asphalt structural assessment. Moreover, variables whose potential and relevance are still under investigation in current research and development may also be relevant. For instance, this includes the impedance (resistance) of the course when periodic mechanical vibrations are applied.

Other measurement objectives and measurands, such as the aforementioned, can also be helpful in assessing the structure.

The measurement of absolute values may be associated with extensive and challenging calibration activities or may not be appropriate due to the technical complexity involved. In such cases, it must be checked whether relative measurements, e.g. moisture fluctuations, provide sufficient information for further assessment.

Sensors – measurement chain – data utilisation

The following sections highlight the individual components required for a measurement. Figure 3 illustrates the overarching context.

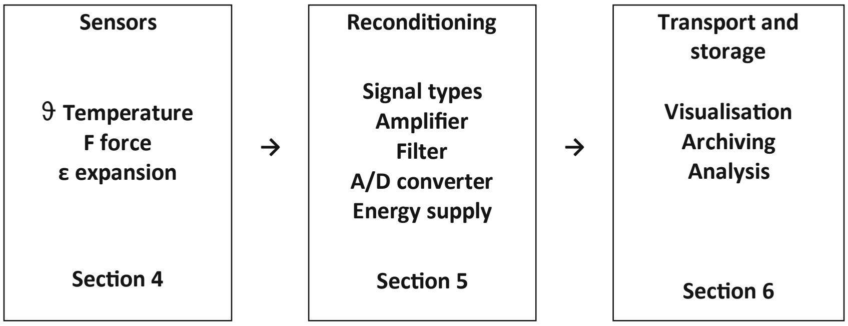

Figure 3: Block diagram of measurement

4 Sensors

The following outlines sensors and measurement principles that are currently used in road construction projects for structural assessment. This primarily concerns the measurands of temperature, expansion, pressure and moisture.

Furthermore, the measurement principles are subject to constant further development. Key objectives in this regard are enhancing precision, ensuring miniaturisation and minimising power consumption. The solutions which are still at the research and development stage are described in subsection 4.2.

4.1 Principles of commercially available sensors

The principles of commercially available and frequently applied sensors are described below. The sensors must be integrated into a measurement chain to ensure the correct recording of measurement data. Further elements of the measurement chain are explained in section 5.

4.1.1 Measurement chain of expansion sensor and pressure cell

Sensors for detecting expansion, e.g. on the underside of an asphalt base course, as well as pressure cells (embedded in the unbound area) are based on individual strain gauges or strain gauges that have been interconnected to form measuring bridges. In the simplest form, the gauges are connected to a (shielded) connection cable and routed to a switch box over several metres.

This sensor type must be connected to special, sometimes sensor-specific (complex) amplifiers. Interference can be minimised through the design of these amplifiers (e.g. carrier frequency amplifiers) and filters. The output signal of the amplifier is usually a standard signal (+/– 10 V, 0–5 V, 4–20 mA, 0–20 mA or similar). An A/D converter enables connection to a computer.

The advantage of this measurement chain is that the amplifiers with all their setting options are accessible even after installation. If the measurement is limited in time, these amplifiers can then be used elsewhere.

There are also sensors for expansion and pressure measurements that have the amplifiers integrated directly in the sensor.

4.1.2 Measurement chain temperature sensors

Temperature plays a key role in the instrumentation of roads due to its significant impact on material and system behaviour. There are several measurement principles for measuring the temperature. All of them can be used to measure the relevant standard temperature range in road construction technology.

The main measurement principles are
- resistive, a resistance changes along with the temperature (e.g. PT100, PT1000, and others, partly
- non-linear NTC/PTC thermistors),
- thermoelectric effect, also known as the Seebeck effect, a (low – just a few µV) voltage forms
- depending on a temperature difference between different materials (thermocouples),
- pyroelectric effect, measurement of thermal radiation (IR thermometer) and
- Raman effect, temperature-dependent wavelength change (fibre optic sensors).

Thermocouples do not require any auxiliary power but do supply a proportional voltage. However, a reference temperature is required (cold-junction compensation). Typically, thermocouples are connected to amplifiers that supply and take into account the reference temperature, thereby providing the temperature as a standard signal.

Resistance sensors, e.g. platinum sensors, are frequently used (PT100, PT1000). Similar to thermocouples, there are also specialised amplifiers for this purpose.

Variations in temperature within the road structure typically progress slowly, necessitating no special demands on the sampling rate.

Temperatures can also be measured digitally. Pre-calibrated semiconductor sensors are available, offering digital temperature outputs. Depending on the interface, the connection is established either through a microcontroller or directly via a network.

4.1.3 Measurement chain moisture sensor

Moisture is a relevant parameter in the unbound area, as it has an impact on the load carrying capacity. The volume-dependent proportion of water in the soil is sought. The aim of a common measurement method is to change the conductance value. The corresponding resistance measurement must be conducted with alternating voltage to prevent electrolysis, which could destroy the measuring equipment. An alternative is a capacitive measurement, where the unbound material acts as a dielectric. Regardless of the method chosen, the problem is that "in-situ" calibration is essential for an accurate measurement, as the individual surrounding material is part of the measurement chain.

As with the other measurement chains, the electrical signal obtained must then be amplified and digitalised. There are moisture sensors that include the complete measurement chain and provide a digital interface (RS485, SDI-12 or Modbus). Similar to the temperature, there are no special requirements for the sampling rate.

4.2 Sensors in research and development

The trends in the development of sensors for the structural assessment of roads are very similar, regardless of the object being analysed. In line with the global trend towards digitalisation, sensors in the construction industry should be interconnected, thus enabling the online retrieval of measurement data. National, European and international initiatives to standardise the protocols and measurement data for integration into BIM (building information modelling) have been established, but standards do not yet exist.

With the ability to manage large amounts of data automatically also comes the increased desire for the use of distributed sensors. Rather than relying on individual measurements with point information, the industry is moving towards developing distributed sensor arrays or spatially continuous measuring systems to achieve comprehensive measurements. To minimise installation requirements and sources of error, the aim is to achieve wireless data transmission wherever possible. Similarly, efforts are underway to localise the power supply (battery, energy harvesting via Peltier elements or piezoceramics, etc.). Alternatively, completely passive sensors are being explored through RFID systems (radio frequency identification). These developments also make it possible to embed sensors into the object or into construction material. This ensures that the surface remains sealed, thereby preserving the integrity of the component and optimally protecting the sensors against damage. Both established and innovative sensors are also following the general trends towards miniaturisation and cost reduction.

4.2.1 Fibre optic sensors

A variety of road inspection tasks can be implemented using fibre optic sensors. The method is described here in general terms despite there being a broad range of fibre types and measurement principles available. Light is directed into and along a translucent fibre. This forms the fibre optic cable. Glass fibres are usually applied in communication networks, while polymer fibres are frequently used in non-destructive testing. The fibre transmits and reflects the light and reacts to external influences such as geometric changes, temperature, pressure, etc. This ultimately changes the light signal, which then serves as a measurement signal. Fibre optic sensors combine many advantages, especially for use in road construction: The fibres can be many kilometres long and are usually inexpensive. With the majority of measurement principles, the measurand is recorded distributed along the entire fibre length with high spatial resolution. Several measurands can be recorded with just one fibre, and the fibre is not susceptible to electromagnetic fields. The measuring unit for detecting the light signal depends on the method being used and is usually expensive. Automated switching between different fibres is possible with most devices.

4.2.2 Temperature measurement

- RFID-based sensors: Both active and passive RFID-based systems for component-integrated temperature measurement are currently being developed. A temperature probe is often already integrated in the RFID chip and can be called up using standardised communication protocols. High frequency RFID can be read directly using smartphones with NFC (near field communication). In addition to wireless networks, measurement data can also be transmitted via high-speed systems.
- Thermography: The surface temperature can be recorded across a wide area using thermography. The thermal imaging cameras optically detect the thermal radiation emitted. The method is technically advanced, but sensitive calibrated camera systems are usually very expensive. Further cost reductions would be desirable to ensure their wide-scale use in the construction industry.
- Fibre optic sensors: See general explanation above.

4.2.3 Component moisture

- RFID-based sensors: There are a number of sensor concepts for determining component moisture, e.g. resistive, capacitive, inductive or measurements of the corresponding relative moisture. A general approach is to further develop these measurement methods to ensure they can be installed directly within the component or construction material with very little effort, e.g. via RFID, Bluetooth, etc.
- Fibre optic sensors: Current developments include combinations of fibre and jacket materials that expand or contract in response to variations in moisture. The resulting stress in the fibre can be measured.

Calibration of the respective material is necessary to be able to measure component moisture quantitatively.

4.2.4 Deformation and expansion

- Ultrasonic sensors: Embedded, active ultrasonic sensors based on the piezoelectric principle can transmit and receive ultrasonic signals. The ultrasonic signal between the various sensors is measured. Static or quasi-static, elastic expansion and deformation lead to geometric changes in the material and/or to a change in the ultrasonic speed of the material and are, therefore, detected by ultrasonic sensors. Although well suited for local use, these sensors would need be developed more cost-effectively to guarantee large-scale use.
- Fibre optic sensors: See general explanation above.

4.2.5 Displacement/acceleration and vibration

- Piezoelectric sensors: These sensors have long been used for vibration measurements. The current trend is to embed them directly into the material.
- MEMS sensors: Micro-electro-mechanical systems are very small, low-cost sensors that offer low energy consumption. However, these sensors tend to experience sensor drift over time, meaning a sufficient level of measurement accuracy cannot be guaranteed in the long term. As such, they are rarely used in the construction industry to measure displacement and low-frequency vibration. However, considerable progress is being made at present in terms of temporal sensor stability, making these sensors increasingly interesting for the construction industry.
- Fibre optic sensors: The distributed measurement of the acceleration or vibration allows not only the frequency but also the mode of vibration and its higher harmonic components to be measured.

4.2.6 Cracks

- Camera systems: High-resolution cameras and accompanying software can automatically detect surface cracks above a certain size. The camera systems are usually very expensive, meaning further cost reductions must be addressed to facilitate their widespread adoption in the construction industry.
- Ultrasonic sensors: Embedded, active ultrasonic sensors can send and receive ultrasonic signals. The ultrasonic signal between the various sensors is measured. Cracks in the component lead to deformation of the ultrasonic signal. Crack measurement remains purely qualitative, as crack parameters, such as the crack shape or length, cannot be quantified. Although well suited for local use, this technology would need to become more cost-effective to enable its large-scale application.
- Fibre optic systems: When the fibre spans the crack, it experiences local expansion. This change in condition is then measured. Due to the potential for very high expansion rates in localised areas, polymer fibres are usually preferred over glass ones.

4.2.7 Crack growth

- Ultrasonic sensors: As cracks appear or expand, an acoustic signal is emitted naturally within the material. This signal can be recorded using passive ultrasonic sensors. This only requires ultrasonic receivers and a corresponding data recording system.
- Fibre optic systems: See above (Cracks).

4.2.8 Delamination (large-scale cracks/detachments parallel to the surface)

- Thermography: Delamination of the bond within a homogeneous material or layered composite results in a notable change in the thermal conductivity. Active and passive thermography can detect variations in the heating and cooling behaviour compared to intact areas.
- Fibre optic systems: As large-scale delaminations often substantially impact the elastic properties of the surrounding structure, delaminations can be detected by observing altered deformation or vibration behaviour, even when the fibre does not directly span or pass through the delamination. The greater the distance to the delamination, the smaller its influence.

4.2.9 Corrosion

- RFID-based sensors: Chloride ingress, carbonation and increased material moisture can cause corrosion. There are several laboratory-scale methods for determining chloride ingress and carbonation, primarily involving the installation of reference electrodes. In addition to further research into these methods, integrated active and passive systems are currently being developed (RFID, Bluetooth, etc.) to guarantee their large-scale use in the future.

4.2.10 Traffic loads

- Fibre optic systems: Distributed acoustic sensing can also be used to detect and characterise traffic. For details: See general explanation above.

4.3 Accuracy and quality assurance

Measurements are conducted to generate knowledge about a specific characteristic of interest. The objective is to determine the value of a measurand (see Fig. 2). Since the true value of the measured characteristic to be measured is unknown in principle, a certain measurement uncertainty must be attributed to the measurand. The measurement uncertainty can be understood as a measure of the quality of the measured information, thereby creating confidence in the measurement and ensuring the comparability of measurement results. Often, a measurement result is conveyed through a representative measured value that reflects the observations and is accompanied by the measurement uncertainty associated with this value.

In practical terms, measurement uncertainty typically comprises random measurement deviations and uncertainties resulting from the estimation of identified systematic measurement deviations. The estimated value of systematic deviations is also referred to as the bias of a measurement and must always be corrected. Reference information is required to determine systematic measurement deviations. If there are no systematic deviations or if they have been corrected, the measurement is deemed correct, i.e. an unbiased measurement.

In turn, a measurement is precise if the scatter of the values observed under similar conditions is low, i.e. indicating small random deviations. Measurement precision can be specifically quantified by the measurement uncertainty. A measurement that is both precise and accurate (see Figure 4) is often referred to as an exact measurement. If high measurement precision alone is the hallmark of high data quality, it can lead to a specific risk of misinterpreting measurement data, particularly with precise yet incorrect measurements. Systematic deviations and time-dependent effects (drift) must therefore be corrected – especially if the displayed values are close to defined threshold values.

The “Guide to the Expression of Uncertainty in Measurement” (GUM) provides recommendations that have been internationally agreed for the evaluation of measurement uncertainties. The core of the concept formulated in the “JCGM 100:2008” guide is the modelling of the measurement. This means that the measurand Y is obtained from estimates of a significant number of input quantities X_i. The input quantities are either required for the calculation of Y or influence the output of a measurement (often unintentionally). The relationship $Y = f(X_i)$ is also referred to as the (explicit) model equation. The input quantities X_i identified and categorised as relevant can be determined, i.e. quantified, using two equivalent methods. Like the measurand, they are often understood as random variables and described by distribution functions. An input quantity is quantified by evaluating several series of measurements using statistical methods (determination method A according to GUM).

Alternatively, input quantities can be determined using method B. The quantification is then based on non-statistical methods where physical evidence, including expert (group) opinions, is generally permissible. Use of method B is expected to yield more reliable results, especially when the number of measured values used to characterise the input quantity is unreasonably small.

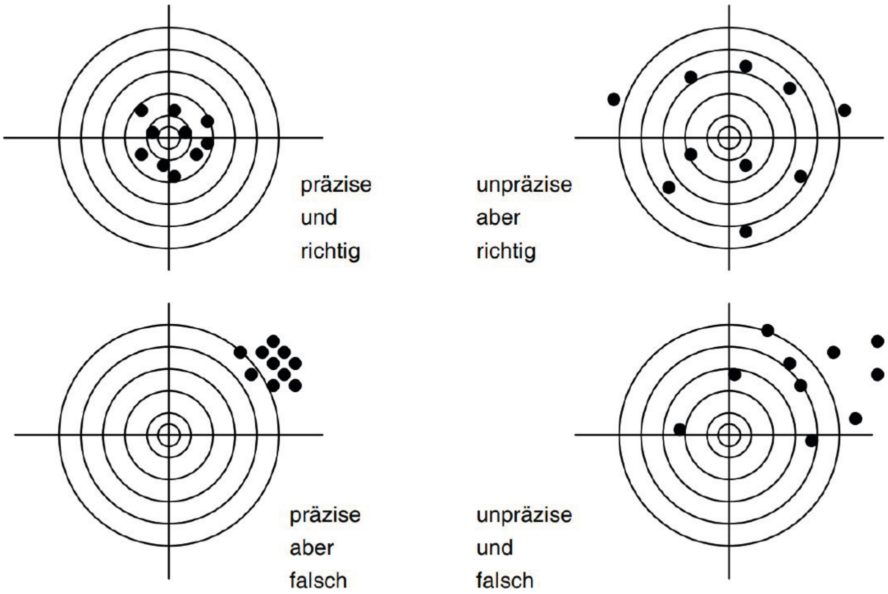

Figure 4: Measurement precision and accuracy (sources: Hässelbarth, Werner (2004), BAM-Leitfaden zur Ermittlung von Messunsicherheiten bei quantitativen Prüfergebnissen, 1st edition, Wirtschaftsverlag NW, Bremerhaven https://nbn-resolving.org/urn:nbn:de:kobv:b43-1850)

Once the measurement has been modelled, GUM rules can be applied to calculate the measurement result. The value of the measurand $\hat{y}$ is provided by inserting the best estimates of the input quantities $\hat{x}_i$ into the model equation. The combined standard uncertainty expresses the measurement uncertainty as a standard deviation and results from the application of Gauss' law of error propagation to the model equation. Optionally, the combined standard uncertainty can be converted into the expanded measurement uncertainty to determine coverage intervals, i.e. intervals that contain the required values with a predefined probability. A measurement result should be expressed in accordance with the GUM requirements and the International Vocabulary of Metrology (VIM) to ensure clarity and precision. The measured value $\hat{y}$, the combined standard uncertainty $u(\hat{y})$ and the distribution of the measurand Y are usually well suited for this purpose.

Quality assurance procedures for sensors in road construction have not yet been established. A comparison with reference values is therefore recommended prior to installation. This comparison should be documented. To identify data changes that are attributable to the actual sensor, standard loads, for example, may be suitable in the installed state. If suitable references are available, calibration and, if necessary, adjustment of the sensors is recommended.

5 Reconditioning

This section identifies additional elements of the measurement chain describing the path from the sensor to the measured value. The task of the measurement chain is to forward information obtained by the sensor and, if necessary, to recondition it. A common feature among all measurement chains suitable for automatic recording is their ability to convert the physical measurand into an electrical value. This interface can vary significantly.

Usually, the signal provided directly by the sensor is prone to interference, thus limiting its recording range to a short distance. Specialised amplifiers and filters can help solve the problem. An interface is not only responsible for forwarding information but also energises the sensor.

Since the information supplied by the sensor is ultimately to be recorded by a computer, the measurement chain normally includes an A/D converter. In most cases, it is necessary to consider aggregation and intermediate storage of data as an integral part of the measurement chain.

Figure 5 provides a general overview of measurement chain components. The numbers shown refer to the descriptive sections or subsections of this working paper.

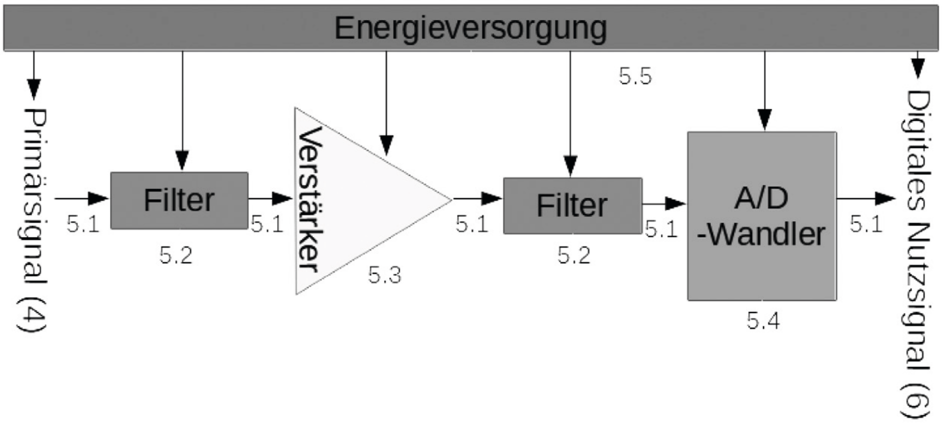

Figure 5: General measurement chain

Miniaturisation in the electronics sector, in particular, allows amplifiers and filters to be integrated directly into the sensor. This improves the quality of the signals and facilitates measured value recording, but may make it more difficult to recognise and understand the measurement chain.

Sensors with an integrated amplifier supply the analogue standard signal directly as an output signal, which corresponds to the output signal of the previously described variant with an external amplifier. Sensors with an analogue interface often lack the option of calibration (to the standard signal) after installation. This well known disadvantage can be offset by combined A/D interfaces (e.g. HART protocol)1).

An integrated microcontroller opens up further possibilities. In the case of analogue input signals, it is possible to switch directly to the digital environment (A/D conversion). Digital

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1) HART protocol: This is a control signal superimposed on the analogue output signal, which can be evaluated by the integrated amplifier and used for calibration activities. To accomplish this, a microcontroller is situated directly within the sensor alongside the amplifier. A corresponding control unit is necessary on the receiver side (control cabinet, measured value recording).

sensors are managed by the microcontroller using special bus systems. For instance, scheduled value retrieval, activation and deactivation of energy-saving intervals and the transmission of calibration values can be executed. Suitable protocols are I2C, SPI and UART.

5.1 Signal path/Signal transmission

Several processing blocks are run through from the primary signal to the digital useful signal. Ideally, the connections between these blocks should not cause any changes. Short connections generally offer better assurance of signal integrity compared to longer ones, irrespective of the signal type. For analogue signals, it is crucial for the impedances between the stages to match. Digital interfaces are versatile. The table in Annex 1 describes the typical values of some standard interfaces.

5.2 Filters

Figure 5 “General measurement chain” displays two blocks labelled “Filter”. When taking a closer look at the details of a measurement setup, this term appears in many components. Filters perform various tasks and are essential when it comes to recording measured values. In general, filters are required to transmit the information obtained without an interference. Filters are often an integral part of a component, optimised by the manufacturer and therefore unproblematic for the end user. Furthermore, filters impact the measurement result, and incorrect parameters can have a detrimental effect.

The primary signal is provided by a sensor. This sensor usually requires a supply voltage. Low-pass filters, e.g. a basic block-type capacitor in the simplest case, prevent or reduce this interference.

The output signal of the sensor, the primary signal, offers a specific bandwidth. The output signal is frequently directed through a band-pass filter, which specifically transmits this bandwidth while minimising external interference (left-hand filter in Fig. 5).

A downstream amplifier also requires an interference-free supply voltage. For its part, interference such as “noise” must be avoided as much as possible. This is usually guaranteed by the manufacturer. Low noise is a quality feature of all good amplifiers.

External amplifiers, in particular, provide end users with additional filter options, including choosing specific filter characteristics, manipulating cut-off frequencies or selecting the filter level. Any changes to these parameters require extensive expertise.

5.3 Amplifiers

Amplifiers are available in a range of designs: At their smallest they are integrated into the sensor and are, therefore, invisible to end users, while in their largest form they are offered as special amplifiers (costing several thousand euros), for example in 19-inch housings. In general, the task of an amplifier is to prepare its input signal for further transport of the information it contains.

Similar to the designs, the special properties also differ. For example, an integrated amplifier performs fixed amplification together with an impedance conversion. The signal becomes more robust. The end user has no influence.

An external amplifier may have a universal design. There is a wide range of options available to the end user here, from selection of the sensor signal (e.g. analogue voltage, analogue current, capacitance, inductance, various bridge signals, incl. definition of the bridge supply) through to selection of the output signal (often standard signals such as 0–10 V, 0–5 V, +/– 10 V, 4–20 mA, 0-20 mA or even digital signals if an A/D converter unit is part of the amplifier). Filters are frequently integrated within amplifiers, and their parameterisation should ideally be entrusted to experts.

5.4 A/D converters

The information collected by the sensor should be processed further and, in the simplest case, displayed somewhere. Nowadays, further processing is usually performed digitally. Ensuring the transition from analogue reality to digital processing is left to an A/D converter (analogue-to-digital converter).

Numerous variants of A/D converters are available. The choice of an appropriate type requires some specialist skills. The following outlines the terms for selecting an appropriate A/D converter:

– Sensing range
  The input of an A/D converter usually expects a voltage signal. This voltage signal must be located between the negative and positive reference voltage (reference value). This range may be identical to the supply voltage of the A/D converter.

– Resolution (quantisation)
  The value is specified in bits. A reference voltage (or the difference between the positive and negative reference) is divided into equal parts. Even modern-day microcontrollers have a resolution of 12 bits, which equates to $2^{12} = 4096$ parts. The input signal is compared with these parts and the number of the best matching part is the output signal of the A/D converter.
  The selected resolution must match the input signal. For instance, when recording the temperature of a road surface in Germany, the lowest expected temperature, even during a very cold winter, might be – 30 °C. In the summer, the road may heat up + 60 °C with the right amount of sunlight. If the amplifier used provides a signal corresponding to the negative reference voltage of the A/D converter at – 35 °C and a signal corresponding to the positive reference at 65 °C, then a temperature range of 100 °C is converted. Even with only 10 bits, this yields a resolution of $100\ °C / 2^{10} \approx 0.1\ °C$, which is likely adequate for the application discussed in this working paper. This resolution should not be confused with accuracy. Information on this matter is initially obtained from the sensor manufacturer, and finally for the entire system through calibration.

– Sampling
  Due to its design, an A/D converter has a maximum sampling frequency. This is basically information about how often the analogue input signal can be converted into a digital output signal. Lower frequencies (usually/2^x) can almost always be set. The minimum frequency must correspond to the Nyquist-Shannon theorem (twice the expected input frequency). The selected frequency must match the input signal. How fast does the input signal change? In the temperature example, recording every second is sufficient, usually even every minute. Dynamic signals in road traffic, such as expansion or acceleration, depend on the speed of the vehicles being recorded and the installation depth. For example, expansion caused by a lorry travelling at 80 km/h on the asphalt base course of an approx. 20 cm thick structure generates a signal lasting approx. 10 ms. If, for example, the maximum value is to be determined later on using this signal, a minimum sampling rate of 1,000 Hz is required, although 4,000 Hz are recommended.

– Synchronous
  If several sensors are to be recorded, a corresponding number of A/D converters is required. Low-cost systems use fast switches instead. In this case, the signals from the

various sensors are fed to an A/D converter one after the other. If the aim is to simultaneously compare signals, this method does not provide the desired result. If several A/D converters are present in one measuring system, it is referred to as synchronous recording.

- Sample and hold
  To ensure that the conversion described under “Synchronous” works with just one A/D converter, the signals are routed via a sample and hold element. This means that the A/D converter always records the signals under the same conditions not influenced by external factors. This is because the signal is disconnected from the element during the measurement. The signal and the A/D converter therefore never access the sample and hold element at the same time.

5.5 Power supply

All the components of the measurement chain need to be supplied with power. The requirements for the correct level and stability of the voltage supply for each individual part of the measurement chain must be taken into account.

Once the total requirement has been established in this manner, the next consideration is how it should be fulfilled. If the existing infrastructure includes a mains power supply, the solution is simple. If it does not, batteries and rechargeable batteries offer an alternative. A solution with an alternative energy source (solar cell, wind turbine, geothermal energy, fuel cell) is more independent. Possible costs for generating a mains power supply should not be underestimated.

6 Transport and storage

6.1 Data transmission/Transport

Section 5.1 focussed on signal transport up to the digital useful signal. This refers to further transport for final signal utilisation. Analogue signals are no longer used nowadays. In a typical case of using several/multiple sensors, initial bundling takes place in the local control cabinet. Using a USB flash drive for transmission is somewhat outdated and has the specific disadvantage of being unable to (promptly) react to potential failures of the measuring system. A permanent connection to the measuring point is more suitable. If a wired Internet connection is not available, transmission via mobile networks remains an option. Necessary data protection measures must be taken into account and encryption may be essential.

Due to rapid developments in mobile communications, any recommendations concerning a specific type of transmission would quickly become obsolete. The following factors must be considered individually:

- Volume of data being transmitted
- How much of a delay between sending and receiving the data is acceptable?
- How secure is transmission? (Is all the data received? Can third parties also read the data?)
- Transmission costs (should no longer be a critical factor).

6.2 Data storage

There are often several places where the data is saved or stored temporarily. As described above, the first collection point is often the local control cabinet. A computer collects the data transmitted to it via its interfaces. Standard interfaces are used here, for example an A/D converter in the form of a multifunction card supplies data via a USB interface, while more specialised interfaces utilise corresponding adapters, such as a CAN bus module, to enable data transmission from a connected process.

This data is usually initially saved or stored temporarily on a hard drive. Moreover, systems with a high level of redundancy can be set up for critical data. Significant advancements in computer performance allow for storage in a human-readable format, like XML or JSON, facilitating manufacturer-independent and standardised further processing. Depending on the amount of data recorded, files should be created on an event-by-event basis or in suitable “time slices”, e.g. daily.

Further processing of the data occurs elsewhere. To do so, data must be transmitted appropriately (see the previous section).

Further use of the data includes visualisation, analysis and archiving.

6.3 Visualisation

The transmitted files can often be used directly for visualisation. In scenarios where an immediate response to incoming data is required (e.g., in traffic control), careful consideration must be given to transmission times and security measures.

In principle, various programs are suitable for visualisation, ranging from calculation program components within office suites (such as Excel in MS Office or Calc in LibreOffice/OpenOffice) to Matlab implementations for more complex tasks, as well as simple dashboards and specialised applications.

6.4 Archiving

In the simplest case, XML or JSON files, for example, are stored again at a central location. If data records from various files, either from different days or from different projects, are to be compared and analysed, this method of storage can swiftly become limiting. The suitable transmission to a database is more flexible. Numerous products are accessible, and many of them are freely available (Open Source: PostgreSQL, MariaDB, MySQL, SQLite, etc.).

Transmission to a database is highly advantageous for the application of big data approaches.

6.5 Analysis

Ideally based on a database, analysis begins with the comparison of suitable data records, the search for extreme points and similarities in behaviour for influences that are as reproducible as possible and ends with the creation of a model. Discover the basics for new findings, reports and final assignments here.

7 Constructional aspects and special features

The long service life of a road can only be achieved when quality is prioritised across all phases of its life cycle – from planning and construction to maintenance. When integrating sensors into road pavements, it is crucial to ensure that obtaining additional information does not compromise the quality of the actual structure.

Special sensor requirements must be meticulously addressed during the planning phase to ensure thorough consideration. For example, it must be clarified whether empty conduits need to be laid, whether an external power supply needs to be provided, etc. The position of the sensors should also be clarified prior to installation. This applies both to the courses (bonded or unbonded) in which the sensors are to be embedded and to the actual position of the sensors in the cross-section. The individual boundary conditions of the respective construction project must always be taken into account. Furthermore, failure rates must be considered when planning the number of sensors.

These requirements must be included in the tender documents – especially the technical specifications and the specification of works – to ensure that the contractor can adequately calculate any additional work required. Great care should be taken to explain the planned sensors in a thorough yet comprehensible manner, particularly as sensors are not typically within the day-to-day operations of construction companies.

The construction of a road is characterised by a high degree of mechanisation; with disruptions in the construction processes almost always leading to a loss of quality. Therefore, when using sensors during the construction phase, meticulous attention must be paid to avoid obstructions such as complete standstill or installation delays. Prior to installation, it is imperative to coordinate the construction sequence among all stakeholders, thereby ensuring perfect alignment with the planned sensors.

Efforts should be made to prevent the integration of sensors from increasing manual installation areas or compromising the integrity of the (bound) superstructure.

If possible, the actual height and position of the sensors should be determined after installation.

In road construction, installation quality is typically assessed through control tests, often necessitating destructive sampling methods (e.g. drilling cores). It is therefore necessary to record and document the exact position of the sensors, at the latest during installation, to ensure there is no destruction or damage – such as cutting through the power supply – during sampling. The same applies to maintenance during the utilisation phase.

At the end of the utilisation phase of a road pavement or a course of the road superstructure, individual courses are usually removed, including the entire bound and unbound structure. The very high recycling rates of road construction materials are of paramount importance. This is where the cycle is completed: At the latest during the planning phase of the fundamental renewal of a road equipped with sensors, it is crucial to establish clear contractual and structural guidelines for the removal of existing courses (e.g. layer-by-layer milling). This helps to prevent the minimisation of the recyclability of the materials being removed due to foreign components and to salvage any sensors for potential reuse.

8 Data security

Aspects of data security relate to security against data loss as well as security against the unauthorised access to or misuse of data. In road instrumentation planning, it is essential to ascertain beforehand

- the potential economic or scientific impact of data loss,
- to determine acceptable downtime and
- to assess the sensitivity of the collected data to potential misuse.

Depending on this risk assessment, the following measures can be taken:

- Creation of process descriptions to avoid operating errors that could lead to data loss
- Redundant data storage, for example on a second data medium
- Direct transmission of data to external systems or a data cloud
- Remote maintenance and alarm systems for diagnosing faults and failures
- Data encryption
- Mechanical protection against theft and vandalism

Information on data security is provided by the Federal Office for Information Security (BSI) and the information security standards defined at www.bsi.bund. de.

When incorporating additional systems alongside embedded sensors, i.e. systems that allow personal conclusions to be drawn, e.g. traffic surveillance cameras, the applicable legal regulations on data protection must be observed at all times.

9 Outlook

There is a growing demand for the structural assessment of roads. The use of sensors is one way of continuously and directly capturing data for structural assessment.

The use of sensors in the road structure to record measurement data that can be used for structural assessment is currently a special case. As such, the relevant processes have not yet been standardised. The ongoing advancements in digitalisation, coupled with the accessibility of durable and compact components, affordable self-sustaining energy sources and extensive high-speed mobile network coverage, contribute to a continuously evolving pool of global expertise, which complements the insights and technological landscape outlined in this working paper.

Within the context of further development, the following aspects, in particular, must be considered from the perspective of the structural recording:

- Quality assurance of measurement chain elements
- Standardisation of components, installation methods and calibration methods
- Definition of future-proof formats for data storage
- Creation of and linking with behavioural functions for structural assessment

10 Literature references

DIN	DIN 1319-1	Fundamentals of metrology – Part 1: Basic terminology	1)
	DIN 1319-2	– Part 2: Terminology related to measuring equipment	1)
	DIN 1319-3	– Part 3: Evaluation of measurements of a single measurand, measurement uncertainty	1)
	DIN 1319-4	– Part 4: Evaluation of measurements, measurement uncertainty	1)
	DIN EN 15518-1	Winter maintenance equipment – Road weather information systems – Part 1: Global definitions and components	1)
FGSV		Notes on detection technologies in road traffic (FGSV 312)	2)
		Guidelines for road construction test routes (FGSV 440)	2)
	RiLSA	Guidelines for traffic light systems – traffic lights for road traffic (FGSV 321)	2)
	RSO asphalt and RSO concrete	Guidelines for the assessment of the structural substance of the superstructure of traffic surfaces (in preparation)	
BASt	TLS	Technical delivery terms for route stations (FGSV 3049)*)	2), 3)
JCGM	JCGM 100	Evaluation of measurement data (draft)	4)
	JCGM 101	Supplement 1 – Propagation of distributions using a Monte Carlo method	4)
	JCGM 102	Supplement 2 – Extension to any number of output quantities	4)
	JCGM 104	An introduction to the “GUM” and related documents	4)
	JCGM 106	Evaluation of measurement data – The role of measurement uncertainty in conformity assessment	4)
	JCGM 200	International vocabulary of metrology – Basic and general concepts and associated terms (VIM)	4)
	JCGM GUM-6	Guide to the expression of uncertainty in measurement – Part 6: Developing and using measurement models	4)

*) The title featuring this FGSV no. is also available in the FGSV Reader “Premium”

Reference sources

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Address: Burggrafenstrasse 6, D-10787 Berlin
Tel.: +49 30 / 26 01-13 31
E-Mail: kundenservice@beuth.de, Internet: www.beuth.de

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Address: Wesselinger Str. 15-17, D-50999 Cologne
Tel.: +49 22 36 / 38 46 30
E-Mail: info@fgsv-verlag.de, Internet: www.fgsv-verlag.de

3) **Federal Road Research Institute (BASt)**
Address: Brüderstrasse 53, D-51427 Bergisch Gladbach
Tel.: +49 22 04/43-0
E-Mail: info@bast.de, Internet: www.bast.de

4) **Joint Committee for Guides in Metrology (JCGM)**
JCGM – BIPM www.bipm.org/en/committees/jc/jcgm/

Annex 1

Exemplary explanation of the terms using various measurement chains

Example 1: Simple measurement of the length of an object

This example is intended to illustrate how the basic terminology can be applied to a simple example. The terms can best be understood when using the right-hand side of Figure 2.

The aim of the measurement is to determine the length of an object. The (abstract) measurand is therefore the length of the object. The (specific) measured value consists of a real number and a dimensional unit (“centimetre”). The measurement principle involves comparing the length of the object using the calibrated centimetre scale of a measuring unit, which is held alongside the object being measured. The sensor comprises the scale and a device for holding it properly next to the object being measured as well as the human eye and perceptual system to compare the length with the scale and to determine the numerical value assigned to the measure value. To record the measured value (“indicator”), it should be noted on a piece of paper in this example.

In this case, the measurement chain consists only of the sensor (scale, eye and perceptual system of the person performing the measurement) and the indicator (writing ability of the person performing the measurement, plus pen and paper).

While not crucial for understanding the actual example, it is important to acknowledge the complexity of the measurement task, requiring consideration of the accuracy and potential sources of error, to effectively demonstrate it. Depending on the characteristics of the object being measured and of the scale, it is easier or more difficult to hold the two objects next to each other in such a way that the length of the object can be reliably assigned to the scale. Factors such as scale reading accuracy and potential viewing angle errors, etc. further complicate measurements. Consequently, each measured value typically comes with an assigned level of accuracy.

Example 2: Simple measurement of an object temperature

This example highlights how an indirect measurement method adds to conceptual complexity. A liquid thermometer is under consideration here.

The aim of the measurement is to determine the temperature of an object using a liquid thermometer. The measurement principle relies on the expansion of a suitable liquid, thermally coupled to the object, within a narrow tube (capillary). The length of the liquid in the capillary is then a measure of the temperature. The length can be measured according to example 1; in this case, the scale is divided into °C, for example. The (general) measurand is the temperature, while the special measurand is ultimately the length. However, due to the calibration of the scale in °C, the numerical value of the measured value indicates the temperature.

The measurement principle here utilises the fact that the relationship between two physical variables, i.e. temperature and volume, is governed by the laws of physics. Rather than directly measuring the one variable, which is difficult to determine, the method captures the other one and deduces the value of interest using the laws of physics.

This example clearly shows that it is not easy to differentiate between measuring equipment. The sensor in the truest sense of the word is the liquid that is thermally coupled with the object being measured. The sensor in the broadest sense of the word or the measuring instrument is the entire liquid thermometer, i.e. the combination of the sensor in the truest sense of the word with further processing steps, namely the expansion capillaries and scale as well as with the eye and perceptual system of the person performing the measurement.

In any case, the indicator is the writing ability of the person performing the measurement, plus pen and paper. The measurement chain thus comprises the thermal coupling, measuring fluid, measuring capillaries, scale, eye, perceptual system of the person performing the measurement, writing ability of the person performing the measurement, pen and paper.

Example 3: Measuring the temperature of an object with electrical transmission

This example is intended as an introduction to electrical data processing. Depending on the depth of analysis, a simpler or more intricate perspective of the measurement chain can be adopted or deemed beneficial.

The aim of the measurement is to once again determine the temperature of an object (measurand). This time, however, the temperature value is to be transmitted electrically.

A thermocouple has been chosen as the measurement principle. A thermocouple consists of two conductors of different materials that are interconnected. A temperature difference between the conductors generates a (very small) voltage (a few μV per K temperature difference) between the unconnected ends of the conductors. A voltmeter is used to measure this voltage. The temperature can be inferred from this relationship between voltage and temperature difference, given their known correlation.

Since a thermocouple is only able to measure a temperature difference and not an absolute temperature, one end of the element is connected to the object being measured and the other to an object of a known temperature2).

The measurement chain comprises: Temperature, thermocouple with comparative temperature generation, voltmeter, readout.

This example is also be used to explain the hierarchical gradation of measuring equipment. The voltmeter, briefly mentioned in the example above, represents a sophisticated piece of measuring equipment in its own right. From the outside, it appears to be a homogeneous unit (measuring instrument) that (more or less) reliably measures a voltage (black box). While on the inside, it has its own measurement chain, whose aim is to measure voltage. It consists, for example, of a voltage amplifier (as the voltage being measured is very small), a conversion from electrical voltage to electrical current (e.g. via known reference voltages and resistors) and a current measuring instrument (black box within the voltmeter). The actual current meter uses the internal measurement principle of converting an electric current into a magnetic field, the measurement principle of converting a magnetic field into a force, the interaction of this force with a spring, which ultimately results in the movement of a pointer, the comparison of the pointer position with a scale, which – because of its ultimate use as a "voltmeter" – is suitably divided into V. If used permanently as part of a temperature measuring instrument, the scale could also be calibrated in °C.

Ultimately, a geometric length is measured that depends on a force generated by magnetic action as a result of a magnetic field in a coil. The magnetic field is induced within a coil by an electric current, whose strength correlates with a voltage amplified from a measurement voltage by a voltage amplifier. The measurement voltage was generated by the thermocouple in relation to the temperature variance from a reference temperature.

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2) For example, if the temperature of mixed asphalt (≈150 °C) is to be determined with an accuracy of ±10 °C, the estimated air temperature of approx. 10...30 °C is sufficient as a reference temperature. If a higher accuracy is demanded, a more stable and well-defined reference temperature source, e.g. ice water, should be chosen.

What is actually the sensor here? The thermocouple, the thermocouple with reference temperature, the thermocouple with reference temperature and measuring amplifier or the entire measuring instrument described?

Example 4: Complex temperature measuring field of a road section

This example is intended to illustrate how the temperature distribution across the asphalt courses of a road section should be measured.

In the simplest scenario, the distributed sensors are integrated in the asphalt course and their connections are routed as cable connections in small shafts next to the carriageway and connected to connection devices (on the left in Figure 6). To conduct the measurement, take the best suited measuring instrument (depending on the sensor type, a voltmeter, ohmmeter, laptop) to the designated road section, connect the measuring instrument to the sensor connections, carry out the measurement and document the results appropriately. Setting up this type of measuring point is relatively simple, but reading the result is very time-consuming.

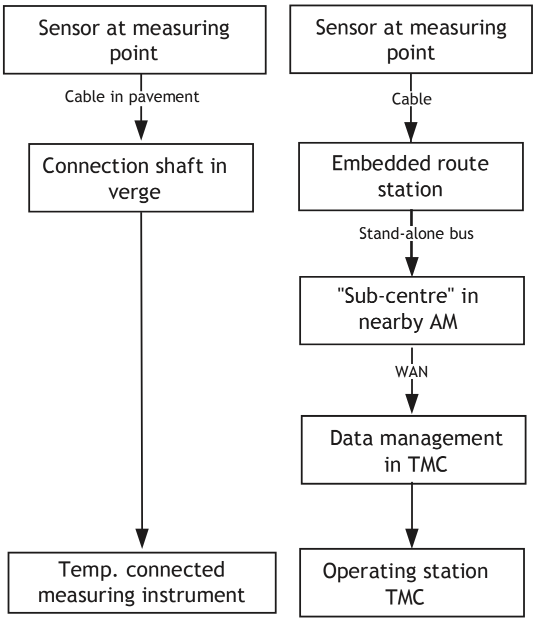

Figure 6: Example of temperature measuring instrument at a road section

The opposite end of the spectrum involves integrating the measuring field into a telematics system in accordance with the “Technical delivery terms for route stations” (TLS), which either already exists in the said area or is set up specifically for this measurement. In this case, the connections of the sensors are routed to a “route station” (usually in a switch box) in close proximity to the measuring field. The measurement signals are digitalised, temporarily stored, if necessary, and aggregated in this route station. This usually requires a suitable power supply (mains power supply, solar panels, etc.). Moreover, the required instruments must be set up in such a way that they remain fully functional even under extreme conditions (temperature, lightning strike). The route stations are interconnected and linked to their “sub-centre” via a “stand-alone bus”, which enables various transmission speeds and thus data volumes based on the equipment applied (route telecommunications cable, fibre optic cable). However, the transmission capacity of this bus is typically restricted (although this limitation should not pose an issue in the example due to the relatively gradual temperature changes anticipated). As a rule, most of the data reconditioning takes place in the sub-centre. It is also where (remote) configuration of the system occurs. Sub-centres are usually located in a nearby road maintenance facility. The sub-centres are linked via a “wide area network” to data centres, which allow remote operation of the systems and house extensive databases along with archiving facilities. Typically, the described temperature measuring instrument is evaluated on-site (or remotely from the responsible person’s office workstation). Setting up the described measuring instrument can be complex, particularly without access to an existing infrastructure (route stations, stand-alone buses, sub-centres). However, it offers significant advantages, especially for regular readouts (time series), monitoring conditions and for integrating with other data (e.g. weather or traffic data) already recorded in such systems.

Annex 2

Table of data transmission details

The table values are for information purposes only. When planning and configuring complex instrumentation, it is recommendable to consult relevant specialists.

Interface	No. of wires	Cable requirement	Voltage level	Direction	Range	Transmission rate	Connection	Protocol
RS232	2 + GND (+ hand-shake)	None	+/– (3 to 15 V)	Full duplex	900 m	2,400 Bd	1:1	No
					< 2m	115,200 Bd		
RS485	2	None, twisted wires recommended	Differential > +/– 200 mV	Half duplex	< 12 m	12 M Bd	n:n, n < 32	No
	4			Full duplex	1,200 m	100 k Bd		
CAN	2	Twisted wires	Differential > +/– 1,000 mV	Full duplex	500 m	125,000 Bd	n:n, n < 128	Yes
					40 m	1,000,000 Bd		
LIN	1 + GND	None	wired-AND, open Collector	Full duplex	40 m	19,200 Bd	1:n, n < 16	Yes
USB	2 + GND + 5V	Twisted, symmetrical	Differential	Full duplex	3 m (5 m)	1.0 : 12 M Bd	1:n, n < 128	Yes
						2.0 : 480 M Bd		
						3.1 : 10 G Bd		
						3.2 : 20 G Bd		
Ethernet	2 x 2	Twisted wires (copper)	Differential	Full duplex	100 m	10 M Bd		Yes
						100 M Bd (fast)		
	4 x 2	Shielded, twisted wires				1 G Bd (gigabit)		
	2	Glass fibre	Light signal		10 km	400 G Bd		

Explanation of some terms from the table above

- Twisted wires: To suppress interference, wires that belong together are twisted. The inductive voltages caused by electrical (interference) fields are thus almost cancelled out.
- Differential transmission: Transmission takes place via two lines with opposite signs. Interference is thus easy to detect.
- Duplex: Bidirectional transmission is essential for communication with the sensor, e.g. during calibration.
- Transmission rate: The value is specified in bits per second (bits/s). The value must not be confused with the sensing rate of an A/D converter. A sampling rate there of 1,000 Hz, for example, provides 1,000 measured values in one second with a resolution determined by the converter being used, e.g. 16 bits. If the same amount of data is to be transmitted digitally, at least 16,000 bits/s are required.
- Many digital interfaces transmit further information in addition to the measured value. This includes security codes through which data transmission errors can be recognised and corrected, as well as device addresses and time information. It is not unusual for this additional information to account for more than 50% of the data volume, especially when (communication) protocols are being used.

Remarks on the system of technical publications of the FGSV

R stands for regulations:

These publications either specify the technical design or realization (R1) or give recommendations on the technical design or realization (R2).

W stands for information documents:

These publications represent the current state-of-the-art knowledge and define how a technical issue shall be practicably dealt with or has already been successfully dealt with.

Category R1 indicates 1st category regulations:

R1-publications contain the contractual basis (Additional Technical Conditions of Contract and Directives, Technical Conditions of Delivery and Technical Test Specifications) as well as guidelines. They are always coordinated within the FGSV. R1-publications – in particular if agreed on as integral part of the contract – have a high binding force.

Category R2 indicates 2nd category regulations:

R2-publications contain information sheets and recommendations. They are always coordinated within the FGSV. Their application as state-of-the-art technology is recommended by the FGSV.

Category W1 indicates 1st category documents of knowledge:

W1-publications contain references. They are always coordinated within the FGSV but not with external parties. They represent current state-of-the-art knowledge within the respective responsible boards of the FGSV.

Category W2 indicates 2nd category documents of knowledge:

W2-publications contain working papers. These may include preliminary results, supplementary information and guidance. They are not coordinated within the FGSV and represent the conception of an individual board of the FGSV.

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