Guideline Sensors for Industrie 4.0
Options for cost-efficient sensor systems
Innovations, problem-solving expertise and top quality are salient features of our sector. Those are also the attributes Industrie 4.0 precisely stands for. Key terms are digitalization and networking. Information and internet technologies are integrated into products and processes step by step.

As both, provider and user of Industrie 4.0, German machinery and plant engineering takes on a key role. It integrates new technologies into products and processes. At the same time, it serves as a data source for Industrie 4.0: It performs the task of data recording, interpretation, using it for innovation and for developing new business models. Sensors play a central role in implementing Industrie 4.0 since they are the connecting elements between the digital and the real world.

However, the right sensors are required for being able to correctly interpret data and thus to innovate. Yet, the costs of the suitable sensor technology often hamper implementing technological innovations in machinery and plant engineering.

It is against this backdrop, that this guideline provides assistance: Users and manufacturers of sensor systems are supported in defining the requirements and in developing cost-efficient sensor systems. This guideline formulates seven guiding questions sensor users shall contemplate. They comprise basic and cost-determining matters. Five thematic tool boxes lend support for answering the guiding questions.

With this guideline, the Mechanical Engineering Industry Association VDMA implements a further module in the process of practical implementation and extends its successful VDMA guideline series. Furthermore, the VDMA Forum Industrie 4.0 offers its members a platform for dialogue and for exchanging experience, also on this topic.

Special acknowledgment goes to Prof. Dr.-Ing. Jürgen Fleischer of the Karlsruhe Institute of Technology and his team for scientifically preparing this guideline. Moreover, thanks to all VDMA member companies involved for the commitment to the project-accompanying working group.

We wish you an interesting and inspiring reading.
Sensor technology for Industrie 4.0 — Guideline for cost-efficient sensor systems

Sensors are the connecting elements between the digital and the real world and thus one of the most crucial elements for implementing Industrie 4.0. Without the right sensors, all superordinate systems for data interpretation are blind. When it comes to applications in the industrial environment, costs for “industrially-suited” sensor technology, however, often hamper the implementation of innovation functionalities. In particular with respect to new products or new product features, end users often do not demonstrate a high willingness to pay. After all, the economic benefit of the own application cannot yet be precisely assessed. Consequently, the quantities of many sensor systems on the heterogeneous market remain at a low level for industrial applications. Thus, costs for sensor systems stay high and potential new applications cannot be tapped – a vicious cycle.

However, examples of other sectors show that high-quality sensor systems must not necessarily be expensive. Enormous volumes in the consumer electronics sector or the automotive industry lead to significantly reduced manufacturing costs and a situation which allows to allocate development cost to many applications. In certain applications of consumer electronics, it goes as far as to integrate sensor elements into the product that are not yet assigned to a particular application at product launch. As Industrie 4.0 develops, the call for sensor systems able to capture different measurements also grows louder – users see the potential of a profitable data analysis, yet they are unable to examine it without a comprehensive use of sensors.

Even if not all aspects of the consumer or automotive sector can be transferred to industrial applications, it is worth to think outside the box: How can users of industrial sensor technology be assisted in enabling them to develop solutions just as quickly as developers of smartphone apps? What other cost reducing levers exist for today’s sensor systems?

These and other questions have led to elaborating this guideline, which shall at the same time provide assistance and generate ideas. Sensor users shall be supported in the development process of their own, sensor-based applications. The objective is to become aware of the costs drivers of the own applications, to consider them at an early stage or to completely avoid them. To this end, this guideline defines guiding questions for the user on one hand and on the other hand it arranges tool boxes which shall support the user in answering the guiding questions.
However, neither now nor in the future will sensor users be able to do without the know-how and expertise of sensor manufacturers. This guideline thus takes on the position of sensor manufacturers by spelling out recommendations for actions and discusses levers as well as the relation to the consumer sector.

Industrie 4.0 can only revolutionize the industry, if comprehensive sensors serve as the data basis for new applications. However, only the specific application cases of the sensor users define the requirements for these sensors. That is exactly where this guideline comes in. It provides a tool for an even better alignment of applications and sensor systems.

Even if not all aspects of the consumer or automotive sector can be transferred to industrial applications, it is worth to think outside the box.

Prof. Dr.-Ing. Jürgen Fleischer
wbk Institute of Production Science,
Karlsruhe Institute of Technology (KIT)
Sensor components employed in consumer electronics or automotive production for transforming measurands into electric signals are mass-produced and thus available at low unit prices. Furthermore, these components may often be used for more than just one specific application. However, when sensor components are used in the machinery and plant engineering industry, they have to be integrated into a sensor system featuring the appropriate electric, mechanic and software components that meet the specific requirements of this industrial application.

In discussions with sensor manufacturers, it soon becomes clear why the technology cannot be compared to the low-cost sensor technology applied in the consumer or a sector: The much smaller number of sensor systems in industrial applications lead to the fact that development costs must be allocated to the few units sold. In production, there are also far less repetition effects than there are for sensors in the automotive sector – resulting in much higher costs.

This guideline asks seven guiding questions and provides five corresponding tool boxes. The guiding questions support users in focusing on all aspects that potentially increase costs of sensor application and to critically involve them in finding solutions. Five thematically arranged tool boxes lend support for answering the guiding questions by depicting technical options and approaches to different aspects of sensor systems in a tangible manner. Naturally, it cannot be guaranteed that this approach will produce a cost-efficient sensor system – however, if the application allows it, this guideline serves as a tool for harvesting this potential. Dealing with the guiding questions and the tool boxes shall exemplarily be described by using an example application (see page 20).

However, sensor users considering the cost drivers constitute just one step on the way towards implementing cost-efficient sensor technology. In closing, this guideline thus proposes recommendations that are specifically addressing sensor manufacturers.
What are the contents of this guideline?

Objective
This guideline pursues the objective of indicating levers and options to lower sensor costs for users and manufacturers of sensor systems. Sensor users are hence supported in the early development and evaluation process of their own application with guiding questions and assisting tool boxes. The way shall thus be paved for a cost-oriented requirements definition as well as the application of cost-efficient sensor technology. Furthermore, sensor manufacturers shall be supported with recommendations on collaborating with sensor users. Options on how to transfer aspects from other sectors to own products shall likewise be proposed.

Approach and structure
This guideline differs from common development approaches for mechatronic products or sensor systems. Mostly, they abstractly describe basic development methods. This guideline shall rather support users with different levels of knowledge in implementing their own sensor applications. Whether this development process is at first only approached by the user or in direct cooperation with the sensor manufacturers is initially irrelevant for the course of action. This guideline wants to support in formulating the correct questions – the answers must be elaborated on an individual basis.

Consequently, the guideline comprises seven guiding questions, sensor users shall deal with (see page 6). These guiding questions address the basic and cost-determining issues such as for example on the measurands, ambient conditions or number of applications to be implemented. However, merely formulating the correct questions does not suffice: Often, they stir up a whole series of other questions which are not easy to answer for many sensor users.

For this reason, five tool boxes have been developed (see page 10 ff.) that shall support in answering the guiding questions. The tool boxes are divided into five topic areas vividly portraying technical options and solutions. The tool boxes thus support the requirements definition and the selection of possible sensor systems.

The guiding questions and tool boxes support sensor users with different levels of knowledge in implementing their own sensor applications as cost-efficient as possible.

Project background
This guideline has been elaborated by the VDMA Forum Industrie 4.0 in cooperation with the wbk Institute of Production Science of the Karlsruhe Institute of Technology (KIT) and a project-accompanying VDMA working group. The VDMA working group comprises of 13 leading sensor manufacturers and users of sensor systems. The objective was to compare perspectives of sensor manufacturers and users in a direct exchange in forms of personal interviews, questionings and workshops and to provide assistance.
Guiding questions for users of sensor systems

To ask the correct questions at the outset is also crucial when it comes to sensor applications. Principally, there are many levers that have an impact on a sensor application’s performance and cost structure. However, considering only technical solutions at an early stage can block these levers. Thus, the formulated guiding questions aim at examining the different aspects of sensor application in an unbiased and balanced manner.

It depends on the development stage of the sensor application how profound each question must be answered. If an application shall partially be developed quickly for assessing the feasibility, cost structure and market acceptance, the level of detail differs from that of a scenario where a sensor solution shall be implemented in series. Consequently, each guiding question entails an arbitrarily long or short chain of follow-up questions which users must answer, possibly in cooperation with producers in a case-related manner. The individual guiding questions shall be outlined with explanatory accompanying texts in the following.

1. What benefit shall the sensor application generate?
The starting point of the guiding questions is ideally an unprejudiced examination of the planned core benefit of the new sensor application. Hence, it is important to part from thinking in technical solutions and to contemplate the added value for the target group of the application, instead. The precise technical configuration of the sensor solution thus has a decisive influence on the system’s costs, however, it is often only of minor importance to the customer. The benefit could, for example, constitute in higher machine availability, optimized process control or improved predictability of machine downtimes or material provision. New business models, for which the sensor system provides the data base, could also arise for machine manufacturers or users.

Enumerating the benefit for the user helps to specify the requirements of the sensor system more clearly – and to identify those that are secondary to the actual target group.

2. Are the measurands already known? Which ones shall be captured?
When a sensor application is discussed for the first time, it often apparently seems clear which measurands to capture. On the basis of the targeted benefit of the user (question 1) and the existing technical system, however, it is appropriate to discuss in a solution-neutral manner different measurands that could be suitable for implementation. This way, effects and conditions of a technical system can generally be recorded in various ways – directly or indirectly, by using a measurand or correlating a number of other parameters.

Subsequently, the tool box “Sensor Type” (page 11) can support in selecting possible sensor types for the measurands. It lists different processes and sensor types for determining common measurands used in industrial applications and thus points out alternatives with potentially different levels of accuracy, measuring ranges or costs.

The cost structure of sensor application has many influencing factors. However, considering only technical solutions at an early stage can block these levers.
Guiding questions and supporting toolboxes at a glance

1. What benefit shall the sensor application generate?

2. Are the measurands already known? Which ones shall be captured?

3. How much installation space and which interfaces are available for the sensor system?

4. To which ambient conditions is the sensor system exposed to?

5. Which characteristics shall the measuring signal have for the planned data interpretation?

6. What is the consequence of a sensor system failure / malfunction?

7. What is the target quantity for implementing the sensor system?

Figure 1: Five thematically structured tool boxes support in answering the guiding questions.
3. How much installation space and which interfaces are available for the sensor system?
Frequently, there are restrictions depending on the already existing technical system the sensor application shall be integrated into. For example, they affect the interfaces for communication, energy supply or mechanical mounting options as well as the available installation space. The possible measurands and sensor types (question 2) are frequently limiting the possibilities for positioning the sensor system and consequently the respective installation space available.

The tighter the restrictions for installation space and interfaces, the more likely that those sensor systems that are available on the market are not suitable for the application, that an existing sensor system must be adapted or that even a new one must be developed. Development costs and often low quantities (in particular in the area of machinery and plant engineering industry) thus lead to a profound increase of application’s costs. It is against this backdrop, that the interaction between measurand, sensor type and the resulting sensor position (tool box “Sensor Type”, page 11) with the mechanical integration that can be explained by the tool box “Mechanical Integration” (page 13) opens up options for implementing the sensor technology that is already on the market or for developing a new sensor system.

4. To which ambient conditions is the sensor system exposed to?
A major cost driver in the development and production process of sensor systems constitutes in permanently protecting sensor components with suitable housing against ambient conditions in industrial application and simultaneously providing a measuring signal of sufficient quality. However, external influences and its manifestations are as diverse as the application itself. It is thus important to define to which influences the sensor system would precisely be exposed to at the possible sensor positions and for how long it would have to resist this influence.

The interaction between the sensor type and the resulting sensor position (tool box “Sensor Type”, page 11) with the mechanical integration that can be explained by the tool box “Mechanical Integration” (page 13) opens up options for implementing the sensor technology that is already on the market or for developing a new sensor system.

5. Which characteristics shall the measuring signal have for the planned data interpretation?
The quality of the measuring signal is the basis for the technical implementability of the sensor application. At the same time, the high demands facing the measuring signal constitute a strong cost driver for the application: Large measuring ranges or high measuring accuracy and sampling rates have a major impact on a sensor system’s components, construction and development effort. Therefore, it is wise to test alternative solutions realistically and at an early stage to identify which minimal requirements the measuring signal must meet for the respective measurands. Must the measurand be recorded absolutely or does it suffice to capture the relative change of the measurand? How often must the measuring signal be processed or forwarded? The interpretation of the measuring signal or signals plays an important role in this regard. Consequently, it is worth testing the use

The more accurate the requirements for installation space and interfaces are, the more likely that available solutions on the market are not suitable for the application and new developments are necessary.
of measuring signals with different characteristics during the development phase to be able to later implement the most cost-efficient sensor system meeting all requirements.

The tool box “Information Generation” (page 17) shall present the approach as well as the technical options for tailoring the interpretation of the sensor data of the selected sensor type (tool box “Sensor Type”, page 11) to the specific application.

6. What is the consequence of a sensor system failure / malfunction?
The failure of a sensor system in industrial application can generally have more severe consequences than in the consumer sector. Tests and certifications specific to the application case and application area take this into account. With respect to the benefit of the user (question 1), it is thus important to discuss the failure of a sensor system. Thus, applications crucial to safety or process control face different demands than additional functions which cannot or only with delay interrupt the value-adding process. The discussion of these aspects is particularly important given the fact that Industrie 4.0 applications often entail additional functions with an added value for the user.

Answering the guiding question allows to estimate the effort which is required for avoiding failures on one hand and for qualifying the system’s functionality on the other hand. When avoiding failures, the selected sensor type (tool box “Sensor Type”, page 11), mechanical integration (tool box “Mechanical Integration”, page 13) as well as the robustness of data interpretation (tool box “Information Generation”, page 17) play a central role.

7. What is the target quantity for implementing the sensor system?
A look at the consumer and automotive sector reveals that quantities, due to the effects of scale, constitute a significant adjusting lever for the sensor system’s costs. Thus, the application’s economic efficiency is highly intertwined with the quantity in which the sensor system can be released. In particular, when dealing with novel additional functions that are based on sensor systems, there is, however, hardly any empirical knowledge on marketable quantities. Therefore, it is appropriate to seek dialogue with potential users at an early stage. First functional sensor systems allow to test the application with pilot customers or key users and to quantify the benefit of the sensor application more precisely.

The five tool boxes of this guideline shall help to quickly find first functional applications and to generate early knowledge on the technical and economic implementability.

In consultation with sensor manufacturers, a scenario should be elaborated which describes how the cost structure of the targeted sensor system can change depending on the assumed quantity.

In consultation with sensor manufacturers a scenario should be elaborated which describes how the cost structure of the targeted sensor system can change depending on the assumed quantity.
The tool box “Sensor Type” aims at supporting the complex decision-making process for the selection of the sensor types or measuring principles that are suitable for the own application. Sensor types frequently used in industrial applications and measuring principles (columns of the tool box) are listed in a structured manner according to individual measurands (rows of the tool box).

Measurands particularly focused on are those that are often of major interest in industrial application: temperature, flow rate, force (including pressure and torque), acceleration, audible sound and structure borne sound, position / distance / angle and their alterations over time, fill level as well as the identification of objects. It is striking that many measurands are related to one another or that they can indirectly be determined by other measurands. Consequently, some measuring principles are listed next to different measurands.

The depicted sensor types and measuring principles each feature different measuring ranges, measuring accuracies, hardware costs and other parameters which are important for the application. The suitability as well as the respective advantages and disadvantages can only be evaluated in an application-specific manner. The tool box paves the way for this evaluation. Testing different measuring principles of the own application is responsibility of the user. The aim should be to proceed, on one hand, unbiased as to the result and on the other hand, by keeping an eye on the application’s future cost structure.

MEMS Sensors (micro-electro-mechanical systems) are not explicitly listed in the tool box. However, many of the outlined sensor types and measuring principles are also available as MEMS, meaning in very compact dimensions and typically at lower costs for the respective components.

Furthermore, due to the dynamic development of the sensor market no claim to comprehensiveness can be raised, neither for measurands nor for measuring principles.
## Tool box “Sensor Type”

<table>
<thead>
<tr>
<th>Measurands</th>
<th>Sensor types and measuring principles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature / Thermal radiation</td>
<td>Resistance thermometer</td>
</tr>
<tr>
<td>Flow rate</td>
<td>Impeller flow meter</td>
</tr>
<tr>
<td>Force (incl. pressure, torque)</td>
<td>Piezoresistive sensor</td>
</tr>
<tr>
<td>Acceleration</td>
<td>Piezoelectric sensor</td>
</tr>
<tr>
<td>Audible sound / structure borne sound</td>
<td>Piezo microphone</td>
</tr>
<tr>
<td>Position / distance / angle and their alterations (e.g. speed)</td>
<td>Linear / rotatory encoders (e.g. potentiometer/ optical)</td>
</tr>
<tr>
<td></td>
<td>Optical sensor for example light grid / light barrier</td>
</tr>
<tr>
<td>Fill level</td>
<td>Float gauge / float switch</td>
</tr>
<tr>
<td>Identification of objects</td>
<td>Capacitive sensor</td>
</tr>
</tbody>
</table>

Figure 2: Tool box “Sensor Type”
Tool box “Mechanical Integration”

The tool box “Mechanical Integration” examines aspects of sensor positioning as well as the integration of the sensor components into sensor housing. The tool box shall in particular be used when considering the development of a new sensor system. For example, this can be the case if the application has specific technical requirements or if existing sensor systems cannot be implemented economically. It should be noted that newly developing or adapting an existing development can only be attractive if the expected quantity is high enough. High costs for development, tests and certifications can then be allocated to large quantities. Typical users of sensors usually do not possess the respective know-how for developing their own sensor system. This is the core competence of the sensor manufacturers. The tool box rather provides a basis for first internal steps as well as discussions with sensor manufacturers when considering developing or adapting a specific sensor system.

The first row, however, examines the aspect of sensor positioning for the purpose of determining the measurand. This fundamental question can have a major impact on the design and thus the costs of the sensor’s housing. Consequently, it must be weighed between the direct measuring of the respective measurands directly in the effective working area and the indirect measuring of secondary effects. This decision can have a significant influence on the quality of the measuring signal as well as on the constructional effort for the sensor housing. Different influences then impact the sensor, depending on its positioning, against which the sensor housing should protect it. The second row shows possible influences that must be considered.

The housing itself, however, frequently affects the measuring result. Thus, the housing’s mechanical damping for example impacts an acceleration sensor’s measured values. This aspect shall be taken into account accordingly when designing sensor and sensor housing.

It might be worthwhile to consider further housing alternatives: Could the sensor be integrated into already existing housing for electric devices? Or could a sensor component be mounted on an already existing or encapsulated board (see row “Housing integration”)?

The housing can then protect the sensor or the electric components in different ways. For example, the components can be fixed by foaming or casting or be protected by a suitable positioning and orientation inside the housing (see row “Mechanical sensor protection”).

The manufacture of the housing is closely intertwined with the expected sensor quantities as well as the materials to be used and the housing geometry. In addition to the conventional casting and shaping processes as well as metal-cutting, 3D-printed housing could be of interest, in particular for smaller quantities and evaluation purposes (see row “Manufacture of housing”).

The sensor system’s energy supply is to be located at the interface of mechanical integration and electrical construction. Conventional wired approaches, wireless transmission options, batteries or methods of energy harvesting are taken into consideration depending on the accessibility of the sensor’s position, the wiring effort and the required service life (see row “Transmission of energy”).
## Tool box “Mechanical Integration”

### Sensor positioning for determining measurand
- Measuring of primary effect at operating area
- Measuring of secondary effects at operating area
- Measuring of secondary effects outside the component / machine
- Evaluating further measuring data for interpretation (sensor fusion)

### External influences impacting sensor
- Temperatures
- Vibrations, impacts, forces
- Ambient pressure and pressure of liquids
- Radiation (e.g. ambient light, extraneous light)
- Contact with media (e.g. water, vapor, chemicals)
- Electromagnetic fields

### Interference with measurement through housing
- Mechanical effect / damping (e.g. vibration)
- Magnetic / electric shielding
- Thermal effect / damping

### Integration of housing

#### Additional housing
- New development of additional housing for sensor system
- Using existing products as part of sensor housing
- Integration of sensor elements into existing housing onto existing board

#### Integration into product housing

### Mechanical sensor protection
- Decoupling of housing and board from components
- Casting or foaming of components
- Positioning and orientation of components on board

### Manufacturing of housing

#### Smaller quantities
- 3D printing
- Machining in single-piece production
- Machining in series production
- Forming, e.g. deep drawing

#### Larger quantities
- Die casting / injection molding

### Transmission of energy

#### Supply required
- Wired energy transmission
- Wireless energy transmission (in particular inductively)
- Battery
- Lifetime-battery

#### Independent system
- Energy harvesting (e.g. solar/wind energy)

**Figure 3: Tool box “Mechanical Integration”**
Tool box “Data Processing”

The tool box “Data Processing” supports the design, processing and allocation of the processed sensor data on four levels. Factors influencing the required performance of data processing and possible locations for the processing and display of the data are described. The actual logic of the information generated from the sensor data is separately examined in the tool box “Information Generation”.

The computing power required for processing the sensor data determines the costs of the necessary hardware. Factors such as the sampling rate, the resolution of the measuring signal as well as the processing of the required arithmetic operations influence the required hardware performance and are thus portrayed in the row “Factors influencing the performance of data processing”.

Additional locations for data processing may be considered depending on the required computing resources, the real-time capability or aspects of data security.

Corresponding access rights are closely intertwined with the provision of data. In industrial application, they are traditionally often limited to the actual process and possibly installation operator. A discussion about additional access rights and thus usage possibilities might help to exploit further benefit of the data generated by the sensor and thus to justify the sensor system’s costs. Thus, sensor or installation manufacturers having an interest in field data and possessing the appropriate infrastructure could be allocated respective access rights (see row “Access rights to sensor data”).

After the sensor data has been processed, the result shall be made available to the user or the process. The level of provision of the generated data / information emphasizes the respective options. It covers the display or provision directly at the sensor, the communication with the system control as well as the locally independent availability in a cloud. Depending on the respective application case, the data or information can either be provided to a human user as edited data, or it can be fed back to a control system for direct further processing (see row “Provision of generated information / data”).

Different locations for data processing may be considered depending on the required computing resources, the real-time capability or aspects of data security.
### Tool box “Data Processing”

#### Factors influencing the performance of data processing

- **Resolution of measuring signal**
- **Sampling rate of sensor**
- **Required arithmetic operations of processing / interpretation**
- **Required real-time capability / cycle time**

#### Location of data processing

<table>
<thead>
<tr>
<th>At operating area</th>
<th>Outside the installation</th>
</tr>
</thead>
<tbody>
<tr>
<td>In the sensor component</td>
<td>In the sensor housing</td>
</tr>
<tr>
<td>In additional external evaluation module</td>
<td>In existing machine control or local server</td>
</tr>
<tr>
<td>In central server on site</td>
<td>In cloud</td>
</tr>
</tbody>
</table>

#### Provision of generated information / data

<table>
<thead>
<tr>
<th>At sensor</th>
<th>Across sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Display directly at sensor</td>
<td>Outside the installation (e.g. signal light)</td>
</tr>
<tr>
<td>Outside the installation (e.g. signal light)</td>
<td>At machine control or operating panel</td>
</tr>
<tr>
<td>At machine control or operating panel</td>
<td>Via central server on site</td>
</tr>
<tr>
<td>Via central server on site</td>
<td>Via MES / ERP systems</td>
</tr>
<tr>
<td>In cloud</td>
<td>In cloud</td>
</tr>
</tbody>
</table>

#### Access rights to sensor data

<table>
<thead>
<tr>
<th>Process only</th>
<th>Company wide</th>
</tr>
</thead>
<tbody>
<tr>
<td>For machine / process only (encapsulated)</td>
<td>System operator</td>
</tr>
<tr>
<td>System operator</td>
<td>All belonging to the IT network of the employing company</td>
</tr>
<tr>
<td>All belonging to the IT network of the employing company</td>
<td>Machine / installation manufacturer</td>
</tr>
<tr>
<td>Machine / installation manufacturer</td>
<td>Sensor manufacturer</td>
</tr>
<tr>
<td>Sensor manufacturer</td>
<td>External service provider (e.g. maintenance with sensor data)</td>
</tr>
</tbody>
</table>

Figure 4: Tool box “Data Processing”
The generation of information from sensor data for the user or a process usually constitutes the overall aim of the sensor system. Generating information has an indirect impact on sensor system costs: On the one hand the arithmetic operations needed for data processing determine the costs of the required computing resources and, on the other hand, the chosen approach for interpreting the sensor data has a great influence on the required data quality and therefore on the necessary sensor system. Inertial measurement units (IMUs) used for navigation purposes in robotics, for example, are only able to achieve highly accurate measurements by combining the signals of acceleration sensors, angular rate sensors and other sensors.

The tool box “Information Generation” structures the topics on the way towards gaining information from sensor data.

The tool box “Information Generation” structures the topics on the way towards gaining information from sensor data. The chosen approach for interpreting the sensor data has a great influence on the required data quality and thus on the necessary sensor system.

The first level describes the preparatory step of producing and understanding the data for preprocessing and creating the model to interpret the data. In most cases, only the preprocessing of sensor data with filters, for example, allows the “understanding of data” – either by people or by a learning algorithm. The range of options comprises linearization, FFT (Fast Fourier transform) or band pass filters.

The model for data interpretation to be created afterwards may now vary in complexity: Depending on the application, the complexity of the models ranges from a purely threshold-based action to machine-learning based process control. The modeling can build on the preprocessing conducted before and interacts with it. It is subdivided in the tool box into the areas: modeling by humans and machine learning.

Modeling by humans includes for example the definition and mathematical description of intuitively set rules as well as the definition of fixed or dynamically changeable intervention limits.

In contrast, there is machine learning. In this area, the tool box is divided into different relevant application cases: classification of subsets in datasets, detection of anomalies in datasets, description of correlations between measured and unknown quantities by regression as well as by reduction of dimensions for selection in order to interpret relevant data sources. Subsequently, the related algorithms and their implementations must be determined depending on the application case and, if necessary, need to be combined with an adequate preprocessing of the data.

After selecting the procedure for data interpretation, the generated information has to be evaluated. To this end, field tests of the application are carried out which critically analyze the provided data quality in terms of sensor system costs. In addition, potentially cost-cutting possibilities of data reduction can be discussed. Furthermore, it should be assessed to what extend the information generation system comprising of sensor and model can be transferred to related applications, thus allowing to potentially implement a system in higher quantities.
### Tool box "Information Generation"

<table>
<thead>
<tr>
<th>Steps towards generating and &quot;understanding&quot; data</th>
<th>Defining the procedure of initial data generation</th>
<th>Initial data generation</th>
<th>Processing and visualization of acquired data</th>
<th>Plausibility check of data</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Options for pre-processing sensor data</th>
<th>Linearization / error compensation of measured values</th>
<th>Structuring and chronological linking of acquired data</th>
<th>Analog-digital conversion (if necessary)</th>
<th>Transformation of data (e.g. transfer from time range to frequency range with FFT)</th>
<th>Filtering of data (e.g. band pass filter, noise suppression)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Options for modeling the correlation</th>
<th>Modeling by humans (e.g. statistically / physically / based on experience)</th>
<th>[ F = m \cdot a ]</th>
<th>Intuitive description of the correlation and definition of rules</th>
<th>Physical description of the process to deduce rules</th>
<th>Determining reference values for intervention limits (e.g. standard deviations)</th>
<th>Determining fixed upper / lower intervention limits</th>
<th>Determining control limits with variable reference values (e.g. mean value)</th>
</tr>
</thead>
</table>

| Machine learning (objectives)                   | Classification of datasets (e.g. as specific events) | Anomaly detection in datasets | Description of correlation btw. measured variables + unknowns w. regression | Dimensional reduction to select the data to be used |
|-------------------------------------------------|--------------------------------------------------|-------------------------|---------------------------------------------|--------------------------------------------------|--------------------------------------------------|

<table>
<thead>
<tr>
<th>Steps towards evaluation</th>
<th>Field testing of the sensor system with data pre-processing and interpretation model</th>
<th>Visualization of sensor data and the associated reaction of the interpretation model</th>
<th>Review of sensor data and the modeled correlation with system knowledge of the application</th>
<th>Assessment of the used data quality (e.g. poorer data or less data sufficient?)</th>
<th>Data reduction for a more efficient processing (e.g. reduction of sampling rate)</th>
<th>Evaluation of the transferability onto related applications (adaptation of parameters or new modeling required?)</th>
</tr>
</thead>
</table>

Figure 5: Tool box "Information Generation"
Choosing the communication technologies used for a sensor system does not only have an impact on the compatibility and performance of the data transfer but also on the costs of the entire system. Often, the choice of the technology or rather interface to be used is initially driven by the customer or sector. This way, the uncontrolled development of various systems for individual users or sectors can partly be contained but the complexity of different interfaces mostly remains unchanged for the sensor manufacturers. Consequently, there are higher costs for programming, electrical engineering and production, for example.

The dialogue between users and manufacturers of sensors shall be supported by the tool box “Communication Technologies”, in order to be able to discuss economical, technological and organizational aspects of the various technologies.

In case of less restrictions or the need to discuss other options, the tool box provides an overview of the different technologies and their characteristics. To this end, the overview lists the common communication technologies. To ensure comparability of the technologies portrayed in the tool box, communication protocols which can be used with different communication technologies are not identified separately. Such an example is represented by the frequently applied OPC UA in the context of Industrie 4.0.

The tool box compares different communication technologies by dividing them into seven categories. Besides the comparison of the fundamental topology of communication having a special influence on reliability (or failure safety), performance aspects are confronted in particular. That is why the other categories, as for example the achievable maximum line length (or the maximum transmission path in case of wireless transmission), are closely connected to the realizable transmission rates and cycle times. Moreover, the implemented methods for fault detection can ensure that occurring malfunctions are detected and that they will not cause successive errors.

Especially with regard to applications in the context of Industrie 4.0 it is worth discussing the actual cycle time, transmission rate or error rate to be ensured for the application. Thus, a number of “young” applications have lower requirements in terms of cycle times than classical sensor applications as for instance in automation engineering. This in turn can open up new data transmission possibilities with wireless communication, for example, or new data processing opportunities such as in cloud computing.

In addition to the resulting development cost for sensor manufacturers regarding the implementation of different communication technologies, subsequent costs may also incur for sensor users stemming from the application of specific technologies. Apart from the eventually required expansion of expertise for applying a new communication technology, additional hardware may be necessary. The category named “Required hardware” gives an overview.

Due to data transmission characteristics that are often heavily dependent on the limiting conditions of the application, such as attainable transmission rates and line lengths depend on existing electromagnetic disturbances, the characteristics indicated in the tool box can only be seen as a reference for realizable values. Considering the dynamic development in this subject area, there is no claim to completeness of the described technologies.
**Tool box "Communication Technologies"**

<table>
<thead>
<tr>
<th>Topology</th>
<th>Max. line length/ range*</th>
<th>Transfer rate*</th>
<th>Cycle time*</th>
<th>Fault detection</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS485</td>
<td>Multipoint connection, e.g. suitable for Profbus [1]</td>
<td>Up to 1200 m [1]</td>
<td>93.75 KBit/s [1]</td>
<td>n/a</td>
<td>Parity bit possible (see Profbus [2]) Simple and often cost effective, preferred for high transmission rates [2]</td>
</tr>
<tr>
<td>WLAN</td>
<td>Infrastructure net or ad-hoc net (meshed topology with a router) [6]</td>
<td>Approx. 10-20 m (for 11 Mbit) [7]</td>
<td>From 11 Mbit to max 6.9 Gbit/s at a 5GHz frequency band (depending on the used standard) [7]</td>
<td>n/a</td>
<td>Barker code (the conversion of 1 bit into 11 chips allows reading of faulty bits for an increased redundancy) [7] Wireless data transfer, requires encoding [7]</td>
</tr>
</tbody>
</table>

*The respective performance can be influenced by further factors. The figures indicated are meant for orientation.*
Using the guideline in a sample application from the textile industry

In production lines for fibers, as used for instance in the clothing industry or in industrial applications, plastic fibers are treated by a number of specific fast-moving rollers. Often, a whole range of machines is chained to each other with a multitude of these rollers, so called godets. Therefore, one malfunctioning godet could bring an entire module to a standstill. However, due to the continuous passing through of the thread, sometimes for days, maintenance can only take place between the individual batches. Consequently, the sample application needs a sensor system able to detect damages to the godets in time and thus helps to avoid consequential damage.

In the following, the guiding questions of the guide are described by using the sample application and the benefit of the individual tool boxes is outlined to explain the guideline’s approach.

The sample application was examined with the friendly assistance of Oerlikon Textile GmbH & Co. KG (Oerlikon Barmag).

1. What benefit should be achieved by using the sensors?
Damages to a godet can lead to reduced product quality as well as to a failure of the module for the user of a spinning plant. Furthermore, consequential damages to the module can occur because of the damaged godets and the vibrations caused by them.

In the sample application, an early detection of damages would allow to repair the godets during the planned downtimes and would help avoid further cost. Regular manual checking of the godets could also be reduced in certain circumstances.

2. Are the measurands already known? Which ones shall be recorded?
Damages to the godets manifest themselves, according to the experience of the equipment manufacturer, in the form of cyclical forces and vibrations due to the rotation of the godets.

The tool box “Sensor Type” therefore lists the measurands: force (including pressure and torque), acceleration, audible sound/structure borne sound. For this application, the audible sound is not applicable (due to the high and changing noise level in the production environment) as well as the structure borne sound (because of the currently substantial costs for sensor systems and data processing). The force is not measured since the large number of godets and possible force directions would require too great of an integration effort.

The measurands or measuring principles that remain eligible can be further evaluated by more investigations and preliminary studies. In the sample application, a series of acceleration sensors from the industrial sector have been tested as well as sensors with origins in the consumer area (see illustration on page 22).
3. How much installation space and which interfaces are available for the sensor system?

The available installation space for the sensor system and the existing interfaces result from the position of the sensor system which in turn depends on the type of sensor. In the sample application, various sensor types are at first tested in different positions in order to be able to evaluate the available installation space at these locations in a later step.

The connection between the sensors and the machine should be reversible for the testing of the different sensor types and be subject to minimal mechanical damping. That is why specific magnetic fixtures and adaptor plates are used. For the comparison, no data exchange with the machine itself is necessary at first. Interfaces, preferably quick to establish, between the sensors and the evaluation modules or the measuring PC are thus used.

As soon as the evaluation of the sensor types and measurement positions is terminated, it can be described which sensor type could be integrated at which cost at the possible measuring positions. If a newly developed sensor type is considered, the tool box “Mechanical Integration” shows the relative fundamental aspects. The tool box “Communication Technologies” gives an overview to the possible interfaces for connecting them to existing systems.

4. To which ambient conditions is the sensor system exposed?

During normal machine operation of the sample application, an acceleration sensor would be exposed to temperatures of up to 60°C and to chemically aggressive substances at the possible measuring positions. Moreover, this sensor would need to permanently withstand the operational vibrations of the machine (with or without damaged godets). These requirements need to be taken into account when selecting sensors available on the market. Once decided to embark on developing a new sensor system with a sensor manufacturer, respective tests and certifications must be executed. In this regard, the tool box “Mechanical Integration” demonstrates the basic viewpoints.

For evaluating the various acceleration sensors within the sample application, no additional safety measures are necessary (for the insufficiently protected sensor systems used) due to the short measurement times.

![Comparison of amplitude spectrum](image-url)

**Figure 8: Comparison of the amplitude spectrum**
Sample application of a tool box

**Tool box “Sensor Type”:**

For the implementation of the application, the measuring values of force, acceleration and audible sound and structure borne sound are considered. Due to costs and interfering factors of the application, the force and the audible sound/structure borne sound can initially be omitted.

1. **Force (ind. pressure, torque):**
   - Piezoresistive sensor: \( \Delta U \)
   - Capacitive sensor: \( \Delta C \)
   - Strain gauge: \( \Delta R \)
   - Pressure change of a fluid when a force is applied: \( \Delta p \)
   - Indirectly through measuring of other strains: see position

2. **Acceleration:**
   - Piezoelectric sensor: \( \frac{dU}{dt} \)
   - Capacitive sensor: \( \Delta C \)
   - Strain gauge: \( \Delta R \)
   - By changing the position: see position

3. **Audible sound / structure borne sound:**
   - Piezo microphone
   - Condenser microphone
   - Membrane/coil microphone

Level 2 remains with the acceleration as measurand. The usable sensor types for the application are selected and evaluated subsequently by further research and preliminary examinations. In the example, sensors from the industrial area and the consumer area are tested.

5. **Which characteristics shall the measurement signal have for the planned data interpretation?**
   For a sound statement about the characteristics of the measurement signal needed for data interpretation and the required data processing for it (tool boxes “Information Generation” and “Data Processing”), pre-examinations with different measuring systems are necessary. For comparing the sensors in the sample application, the sensors with the highest possible scan frequency and resolution are tested. The pre-tests with equipment according to industrial standards as well as with equipment from the consumer area help to identify the frequency ranges excited by faulty godets and the changes of the corresponding measurement signals. The tool box “Information Generation” shows a procedure and possible approaches for data interpretation.

In testing the acceleration sensors with intact and faulty godets, multiple godets excite the relative sensor with their oscillations. In order to compare the measurement signals with the intact and faulty godets, a fast Fourier transform (FFT) is applied in the sample application to interpret the frequency spectrum. Figure 8 shows the comparison of measured frequency spectrum and respective amplitudes in the range of 10 to 240 Hz. In doing so, higher amplitudes and additional peaks can be observed with a faulty godet, especially in the lower frequency range. The measurements were performed with a Bosch XDK multi-sensor system. Measurements with other sensors for industrial use show a similar behavior. As a next step, examinations with other faulty godets and introduced errors can be carried out and intervention limits for the respective frequency ranges can be defined.
6. What is the consequence of a sensor system failure / malfunction?
A malfunction of the sensor system can cause a wrong interpretation of the errors in the godets by the system during later operation and therefore a non-recognition of errors. This in turn might lead to downtimes of the machine and further consequential damages. On the other hand, unnecessary repair works could be executed due to false measure data or false interpretation. Possibilities for self-diagnosis and plausibility checks of sensor data can therefore be considered.

Tests with intact and faulty godets as well as longer field tests help to evaluate the robustness of the selected sensor systems and the data interpretation (tool box “Mechanical Integration” and “Information Generation”).

7. What is the target quantity for employing the sensor system?
The potentially marketable quantities can be estimated using the number of sold machines as well as the share of customers that can profitably implement the system. To this end, it must be examined whether the system can be transferred to related machines. Additional field tests and, if necessary, adaptations to the data interpretations (tool box “Information Generation”) shall provide respective insight. The share of machines that could be presumably equipped with the system results from the exchange of information between customers and the sales department. The fast implementation of the first functional system helps to demonstrate its usefulness and to create a solid basis for decision-making. Target prices for the sensor system may form part of the interactive dialogue with the sensor manufacturers.

Summary
The guiding questions and their respective tool boxes of the guide serve as supporting pillars for a systematic discussion of the sensor application. As in the sample application, they lead to a specification of requirements and help with the realization in the further steps.

The tool boxes show topic-wise options and procedures for the practical realization of the application - may it be for first tests or for series application. The degree of detail of the requirements specification and the work steps that are related to the individual guiding questions thus depend on the state of development of the application.

Often, it is sensible, as in the sample application, to strive for a quick and practical implementation of the application first and then, to confront various sensor systems with different cost structures and technical pros & cons. Building on that, a decision has to be made whether or not the sensors available on the market can be used in a technically and economically viable manner or if an adapted sensor system needs to be developed. And again, it is the expected marketable quantity that decides on the application’s profitability.
Identifying promising key users and leading-edge applications

It is not just since yesterday that the sensor industry has to deal with competition and cost pressures. The efficiency of developing and manufacturing sensor systems is as important to sensor manufacturers as the alignment of their own product portfolio in order to obtain a favorable ratio of quantities and yield per sold sensor system.

From the user perspective, this may lead to under or over designed solutions for special application cases. Not every user exploits the measuring range, measuring accuracy or protection class defined in the product specifications. For applications which at first do not reveal clear requirements and seem to have a niche character - as for instance the ones coming from the Industrie 4.0 sector - the development of customized sensor systems is often not appealing.

To address this dilemma, the guide starts with offering assistance to sensor users, so that they can evaluate concepts for sensor systems themselves and are able to estimate the technical requirements, the economic benefit and possible quantities ahead of time. Collaboration with sensor manufacturers, however, will not become obsolete in that matter. On the contrary: It is at an early stage that sensor manufacturers should deliberately seek cooperation with potential “key users” of tomorrow that will benefit from
the sensor manufacturer’s know-how in promising applications. New key users for new business areas then in turn help to find their own profile in the area of “young” applications and to integrate it into new sensor products. Cost sensibility should always be at the center of attention, in particular in the case of “young” applications as those, for example, from the Industrie 4.0 sector.

Sensor manufacturer now have to master the tightrope walk of untapping new market potentials and pulling apart or cannibalize their own product portfolio. A look at the consumer sector reveals a number of own approaches that shall be described in the following.

It is at an early stage that sensor manufacturers should deliberately seek cooperation with potential “key users” of tomorrow that will benefit from the sensor manufacturer’s know-how in promising applications.

Which aspects of the consumer sector can be transferred?
The starting point of the guide was the question, why sensor systems from the consumer sector can be offered at substantially lower cost than the ones for the industrial sector. An analysis showed that especially the higher requirements in terms of robustness and reliability as well as the lower quantities are driving the costs. Nevertheless, it is beneficial to look further beyond. Therefore, three partly contrary questions are formulated for the sensor manufacturers at the end:

1. Can compromises on robustness or reliability aiming at reducing costs be made for sensor systems of novel applications? The ambient conditions and the required reliability of sensor systems in the consumer sector are normally set lower than the ones for industrial applications. However, it can be questioned if such cost driving factors need to be considered for all applications in the same way.

2. What support do developers of industrial sensor applications need in the future to implement solutions quicker and easier? It is via development platforms for apps that producers of consumer electronics grant external developers of applications easy access to integrate, for example, existing sensors into smartphones. The development of apps is thus supported by “eco systems”. Developers can contribute their specific domain knowledge instead of concentrating on sensors. With this, applications can be launched earlier and their usefulness can be tested.

3. Can a further increased universality of sensor systems contribute to significantly broaden the application spectra and thus increase the respective quantities at little added cost? In the consumer sector, sensor systems often entail a variety of sensors. It is the respective app that later decides on the actual use of those sensors. Thus, the universality of the system grows and with it also the marketable quantity. This way, the sensor system as part of a smartphone for example, can be offered at a low price.

Finding solutions together
For Industrie 4.0 and the related networking of machines and their components, sensor costs quickly prove to be a knock-out criteria. In searching solutions, sectors that are already facing the IoT (internet of things) may provide ideas. Collaboration with innovative users and “young” industrial applications is gaining even more in importance because the concrete requirements of future sensor systems do not arise until implementation.
Industrie 4.0 in the VDMA

Digitalization is going to affect and shape all industrial areas. May it be a revolution or a evolutionary process – every company has to find its own path to Industrie 4.0. The VDMA accompanies and supports its members on this journey. In the Industrie 4.0 forum, the association is bundling up its various activities composed of the triad: information, knowledge transfer and networking.

Politics & networks
On the road to becoming a leading market and leading provider of Industrie 4.0, essential framework conditions need to be agreed upon with political and societal representatives. High requirements in the fields of research and development, education and qualification, norms and standards, legal and IT security must be complied with in order to lead Germany as an industrial location into the future.

Production & business models
Industrie 4.0 places high value on networking in production by using modern internet technologies. The objective is to facilitate communication between the operating equipment, products and its components to guarantee efficient and customer-specific production processes. Automation and products of batch size 1 will no longer be mutually exclusive. The potential for networking and customer-specific production resides in innovative business models covering the entire product life cycle – from conception to disposal.

Research & innovation
When implementing Industrie 4.0, the success in international competition and the competitiveness of industrial Germany mainly rests upon the research findings. Reliable funding tools in the research area of production and ICT as well as the consideration of requirements in machinery and plant engineering mainly operated by medium-sized businesses are particularly important in this regard. Major factors of success lie in the networking of all players and quickly transferring the research findings to all partners active in industrial operations.

Norms & standards
Industrie 4.0 allows cross-company networking and integration of various value-added networks. For this purpose, norms and standards are of fundamental importance since they define the mechanisms of cooperation and the information to be exchanged. It is thus essential to take part in the process of standardization and the shaping of open standards for the purpose of building a reference architecture and to engage all players in an active dialogue.

IT security & legal issues
In the context of Industrie 4.0, IT security is imperative for the secure operation of cross-company manufacturing processes. Automated data exchange of networked production systems must be secure and reliable. It is crucial to control the identification of the process players and to protect the know-how of products, machines and plants.

In the field of Industrie 4.0, legal repercussions can already be detected. Consequently, existing legislation need to be further developed and newly interpreted. This endeavor will constitute a central task when it comes to implementing Industrie 4.0 and incorporating it into the daily business of the company.

People & work
Industrie 4.0 will fundamentally change the work and its processes. In the future, the factory employees will have to take on more responsibility when it comes to coordinating the processes, steering communication and taking autonomous decisions. The tasks will be more challenging, technologically as well as organizationally, and interdisciplinary competences will gain in importance. The authorities, educational establishments and companies will have to adjust to these challenges.
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