DEVELOPMENT OF A GENERAL SENSOR SYSTEM MODEL TO DESCRIBE THE FUNCTIONALITY AND THE UNCERTAINTY OF SENSING MACHINE ELEMENTS

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ABSTRACT

Sensor integration as close to the process as possible provides advantages in the quality of the measurement results as well as the possibility to implement completely new sensor principles and to measure novel quantities of interest. Sensor integration at positions close to the process can be made possible, for example, through the development and application of Sensing Machine Elements (SME). In the first part of this contribution, a general sensor system model is proposed. It is based on the concept of measuring chains and allows the uniform description of functions and uncertainties within a conventional sensor or SME application. For this purpose, essential quantities are defined, which are required for a uniform understanding. In the second part, the presented sensor system model is applied to a load measuring strain gauge on a drive shaft. This enables the condition monitoring of the shaft and drive train by measuring the electrical resistance of the strain gauge and thus allowing conclusions about the acting drive torque. The individual functions and uncertainties of the strain gauge integration are presented in the system model. This example shows the applicability of the presented system model for sensors and SME.

Keywords: Industry 4.0, Product modelling / models, Uncertainty, Metrology, Sensing Machine Elements

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1 INTRODUCTION

The vision of the current megatrend Industry 4.0 describes a comprehensive digitalisation of production and technical systems with the aim to provide a complete integration of information, communication and technology, whereby large amounts of data serve as cornerstones for achieving these objectives. The required data is obtained from the technical systems itself with the goal, for example, to implement condition monitoring or predictive maintenance approaches. (Hirsch-Kreinsen *et al.*, 2019; Zhou *et al.*, 2015)

In the framework of digitalisation, sensors are used in order to obtain the required data from a technical system. Based on a possible sensor position, different approaches for sensor integration can be distinguished, with specific advantages and disadvantages. A common approach is the use of conventional standardised sensor solutions, whose direct integration into the system is often challenging. Reasons for this are, for example, installation space restrictions or the consideration of environmental influences. Since these sensors are often placed further away from the point of origin of the quantity of interest – a so-called ex situ measurement –, the measured data is associated with high uncertainty due to a longer transfer path of the measurand and thus a more complex model of its description. However, the current focus of research is on the integration of sensors as close to the point of origin of the quantity of interest as possible to decrease the associated uncertainty – a so-called in situ measurement. This can be achieved, for example, by using Sensing Machine Elements (SME). SME extend the mechanical primary functions of conventional machine elements with suitable measuring functions. (Vorwerk-Handing *et al.*, 2020; Hausmann *et al.*, 2021)

The development of SME and their application in technical systems require suitable development approaches including supporting models and methods. So far, literature does not provide a general applicable system model for SME applications, that describes not only the structure of a system containing SME, but also the therewith associated uncertainty. Furthermore, definitions of relevant quantities in terms of measuring are not sufficiently defined in literature for the description of a mechatronic system with SME. Therefore, this paper proposes a general system model for sensor applications using a uniformly defined vocabulary based on international standards. This system model also facilitates the representation of SME. In addition to the functional description of the sensor and the signal transfer, the focus of the system model is on the support of the identification, evaluation and consideration of uncertainty in the system with suitable approaches, such as the Uncertainty Mode and Effect Analysis (UMEA) and Robust Design. Finally, the presented system model is applied to an exemplary torque measuring strain gauge on a drive shaft. This example illustrates the applicability of the presented system model for sensors and SME.

2 BACKGROUND

The sensor system model presented in this paper is based on the state of the art of sensor technology and metrology. It illustrates the processes within a sensor system in a suitable block diagram. The definitions of quantities used in the system model are taken from or based on internationally valid standards and publications in order to enable a uniform understanding in terms of working with sensors and SME.

In metrology, it is common to represent the sensor function in a measuring chain. The measuring chain is the sequence of elements on the path from the measurement object to the measurement value output. This representation is often illustrated using a block diagram, as seen in Figure 1. Thereby, each block represents an element of the measuring system or a measuring instrument, such as a sensor or a signal processing unit. Each block has a defined input quantity, which is transformed within the block into a corresponding output quantity. This transformation is defined by the underlying transfer behaviour. (Joint Committee for Guides in Metrology, 2012; Deutsches Institut für Normung, 1995)

The underlying transfer behaviour of a model can, on the one hand, be completely determined, e.g. in form of a mathematical relation, or, on the other hand, it can be subject to uncertainty, e.g. when the transfer behaviour is based on an incomplete observation (Deutsches Institut für Normung, 1995). Depending on the used physical principles, the model of the transfer behaviour can be highly complex. This complexity can have a serious impact on the development process as well as on an error- and interference-free application. The quality of the information received from the measuring chain is consequently dependent on the completeness of the description of its underlying transfer behaviour. (Schork *et al.*, 2016)

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Besides the individual elements, the different quantities within a measuring chain are also of great importance. In international standards, the measurand is defined as the quantity to which the measurement applies, whereby the measurand can be measured directly or indirectly (Joint Committee for Guides in Metrology, 2008, 2012; Deutsches Institut für Normung, 1995). In literature, the term quantity of interest is used synonymously (Czichos, 2018). This is plausible in this respect, as the quantity to which the measurement applies is of interest for the measurer. Standards continue to define the measurable quantity as distinct from the measurand. The measurable quantity can be qualitatively differentiated and quantitatively determined (Joint Committee for Guides in Metrology, 2008). Thus, in contrast to the measurand, the measurable quantity is always directly measurable, but not always of immediate interest. It can serve as an intermediate quantity for determining the measurand respectively quantity of interest. Physical effects typically describe the relation between the quantity of interest and the measurable quantity (Vorwerk-Handing *et al.*, 2019). These definitions often do not allow a clear differentiation between measurand and measurable quantity, which can lead to difficulties in communication as well as in use. For this reason, a uniform vocabulary for the system model is proposed in Section 3 of this paper.

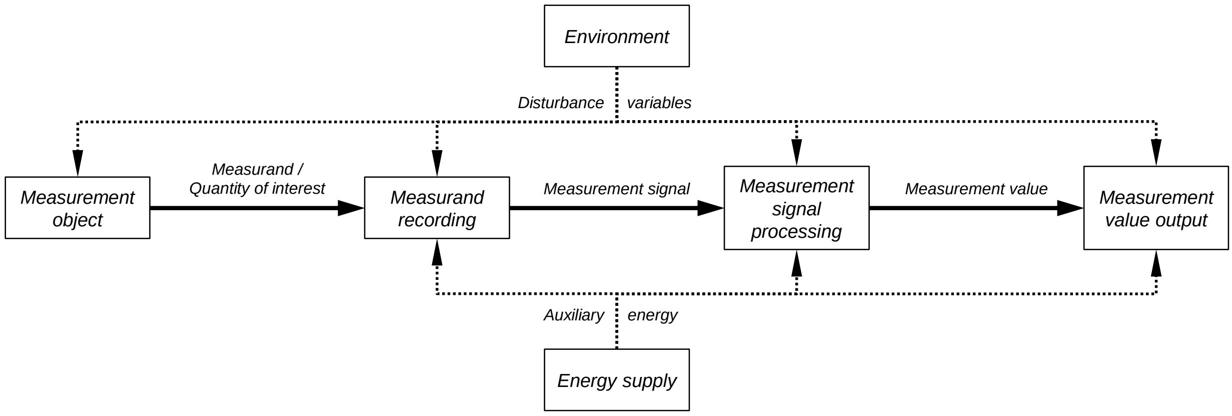

Figure 1: General structure of a measuring chain (based on Czichos and Daum, 2018)

In addition to the concept of a measuring chain mentioned above, the representation of a mechatronic system chain using a SME according to Schork *et al.* (2016) is also a basis of the presented system model. A mechatronic system chain can be visualised in a block diagram. In the mechatronic system, the SME serves as a sensor in the mechanical path and transmits the measured signal directly to an evaluation or control unit. Disturbance variables are therein considered as an influence on the actuating variable, no further uncertainty is taken into account. However, sensors and SME are not limited to an application in a control process. Furthermore, the elements within the system chain are not described in detail in the present state and serve only as an overview but not as a tool for a detailed description of the sensor system or for the identification of uncertainty. The sensor system model proposed in Section 3 is intended to address these deficits.

3 DESCRIPTION OF THE SENSOR SYSTEM MODEL

The basic structure of the sensor system model is based on the abstracted structure of a general measuring chain (see Figure 1). Therein, each block represents a model-based quantity relation between a defined input and output quantity. These mentioned quantities are represented using an arrow between two blocks. An extension compared to a conventional measuring chain is the representation of the occurring uncertainty U_i in each model-based quantity relation. Figure 2 shows the three-staged structure of the system model. The three levels provide a subdivision of the system depending on the specific area of interest. The first level is the overall system level, on which the whole mechatronic system is under consideration. It consists of an auxiliary energy source, the actual sensor as well as a data processing unit and serves as a representation of the superordinate aim of the analysis. This perspective is of particular interest for system development, where a sensor is acquired as an existing purchase part and is used in the technical system. The development of the actual sensor does not take place at this level but on the second level, the sensor level. Hereby, the overall system is no longer of direct interest. Instead, processes and functions within the sensor unit are considered. The

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deepest level is the sensor principle level, where the basic physical effects used to fulfil the measuring task within the sensor are addressed. On this level, new sensor principles are developed. Since the scope of this paper is on the description of the sensor integration into technical systems and not on the development of new sensor principles, this level is only briefly outlined. In the following, the levels and their elements are introduced and described in detail. The different blocks are therefore numbered consecutively in Figure 2.

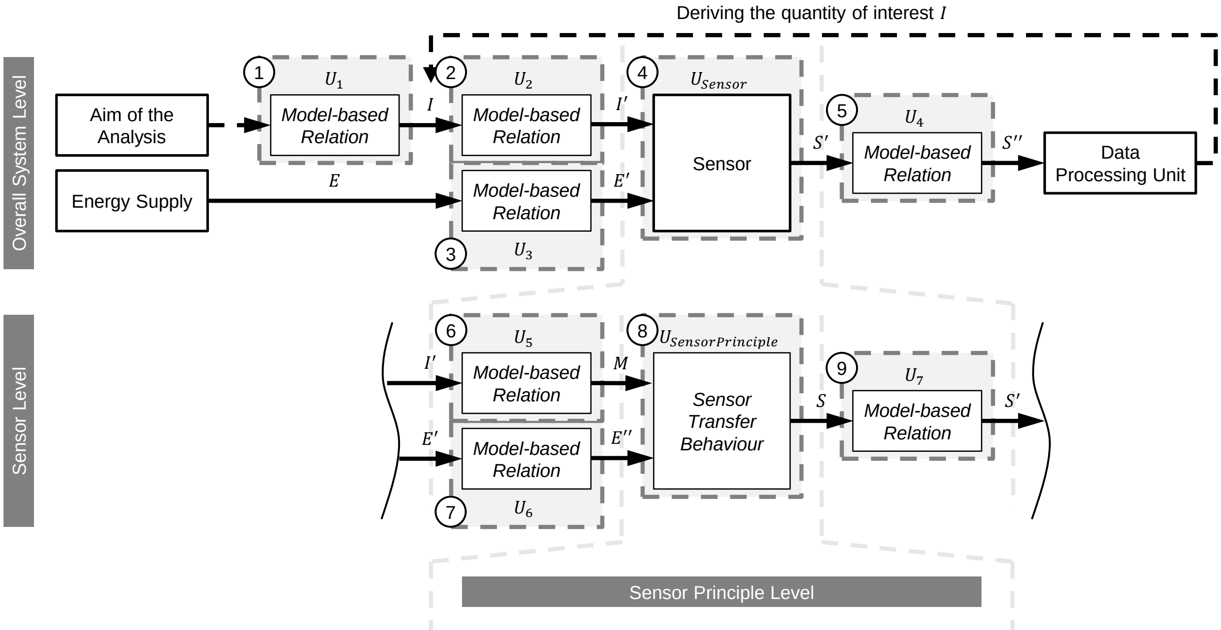

Figure 2: General sensor system model with a simplified view of the sensor principle level

1. The aim of a sensor application is basically defined by the aim of the analysis. This specifies the data or information to be obtained from the system under consideration. Through a model-based relation, a physical quantity can be derived from this objective, the quantity of interest I. According to literature, this quantity can also be called the measurand (see Section 2). However, in order to make clear that this quantity is not necessarily measured itself, but that the user is rather interested in it in order to achieve the specific aim of the analysis, the term quantity of interest is chosen. The model-based relation between the quantity of interest I and the aim of the analysis is associated to the model uncertainty U_1. The model uncertainty is based on simplifications or errors in the modelling, which lead to an incomplete or deficient representation of the reality.
2. In many applications, the quantity of interest I must first cover a transfer path before the sensor can measure it. This path ranges from the actual point of origin of the quantity of interest I within the system under consideration to the integrated sensor. On this path, various disturbances can affect and influence the quantity of interest I, such as temperature or electromagnetic influences. In addition, the model-based description of this path can also be associated with uncertainty, e.g. if the flux of forces or losses are not modelled precisely. For this reason, the quantity of interest I' entering the sensor may differ in terms of its absolute value from the initial quantity of interest I. By managing this occurring uncertainty U_2, the deviation can be reduced.
3. A second input of the sensor is the auxiliary power supply. It is typically required in sensor applications to be able to generate an electrical signal. Starting from an energy source, the required auxiliary electric energy E is transferred to the sensor via a specific path, for example, wireless or by wire. The model of the transfer behaviour of this path, like the path of the quantity of interest I, is linked to an uncertainty U_3. For example, disturbances from the outside may affect the transfer behaviour of the path or the electrical properties of the elements included in the path may be inadequately described. For this reason, the auxiliary electric energy E' entering the sensor may differ from the initial auxiliary electric energy E. Depending on the sensor used, this uncertainty can have a significant influence on the functionality of the sensor or the properties of the sensor signal.

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4. As in the descriptions of Block 2 and Block 3 already mentioned, the quantity of interest I' and the auxiliary electric energy E' represent the actual input quantities of the sensor. On the second level, the sensor level, the functionality and the transfer behaviour within the sensor are described in detail. On the overall system level, however, the sensor is only considered as a black box with the inputs I' and E' and the sensor signal S' as output quantity. The sensor behaviour and thus the relation between the input quantities and the output quantity is again linked to an uncertainty, that is described as U_{Sensor}. This uncertainty represents the uncertainties occurring on the second level. Guidelines for controlling or at least minimising this uncertainty are defined during the sensor development at the sensor level and can be considered on the overall system level when integrating the selected sensor solution.
5. The sensor signal S' emitted by the sensor is forwarded to the data processing unit. This transfer of the sensor signal is again subject to uncertainty, described as uncertainty U_4, resulting in the sensor signal S'', which is the input quantity of the data processing unit. The modelling of the signal path as well as external disturbances can influence the sensor signal received at the data processing unit. In the data processing unit, the incoming sensor signal S'' is used to derive the quantity of interest I in order to fulfil the overall aim of the analysis. The model-based description of this relation must take into account all the uncertainties present in the system in order to be able to make an accurate and error-free statement.
6. As shown on the overall system level, the quantity of interest I' enters the sensor on the second level, the so-called sensor level. Since the quantity of interest I' is not directly measurable in all cases, the measurable quantity M is derived from the quantity of interest I' using one or more physical effects (cf. Vorwerk-Handing, 2021). Between the quantity of interest I' and the measurable quantity M, several intermediate quantities can exist, which are necessary for the description of the physical principles. The measurable quantity M is the directly measurable input quantity of a specific sensor, e.g. in the case of a strain gauge the strain of the carrier material. The model-based relation between the quantity of interest I' and the measurable quantity M is linked to the uncertainty U_5, which can, for example, again result from the model description or external disturbance variables.
7. Analogous to the overall system level, the auxiliary electric energy E' is transferred to the sensor element on the sensor level. This energy path is linked to an uncertainty U_6, meaning that the possible further influenced auxiliary electric energy E'' is entering the actual sensor element.
8. The selected sensor is essentially based on a sensor principle and thus has a characteristic transfer behaviour. The measurable quantity M and the auxiliary electric energy E'' serve as input quantities for this sensory function. The sensor signal S represents the output quantity of the sensory function. The transfer behaviour of the sensory function is associated to the uncertainty $U_{SensorPrinciple}$. This results from uncertainties regarding the modelling of the transfer behaviour as well as from the incomplete observance of disturbance variables on the transfer path. Typically this uncertainty $U_{SensorPrinciple}$ is already identified and also quantified by the sensor manufacturer. The transfer behaviour in form of the underlying sensor principle is described on the next level, the sensor principle level. As there is a large number of different sensor principles, the transfer behaviour cannot be described here in a general way.
9. The last block can be described in the same way as Block 7. The sensor signal S is conducted out of the sensor itself, whereby the signal path may be subject to uncertainty. For this reason, the uncertainty U_7 can have an influence on the sensor signal S', which leaves the sensor.

4 MODELLING SENSOR APPLICATIONS WITH THE SENSOR SYSTEM MODEL

Following the description of the basic structure of the sensor system model, the procedure for an application in practice is briefly outlined. For the procedure presented below, separate methods and procedure models are required. This contribution does not focus on a complete process model itself, as the scope is the consideration of the:

- Differentiation of relevant quantities for sensor applications
- Transfer behaviour between quantities within the sensor system model
- Locations of occurrence of uncertainties

The system model can be used to describe existing sensor applications as well as those under development. Various objectives can be addressed in this context. For existing applications, the description with the help of the system model can support the identification of uncertainty, while for applications under development, it can additionally contribute to the selection of potential quantities of interest, measurable quantities as well as measuring locations.
The initial step is to define the aim of the analysis of the sensor application. This is derived from the initial requirements, defined at the beginning of the product development process. Based on this aim, a quantity of interest I can be derived in the next step. With the defined quantity of interest I, a measureable quantity M can be identified, for example, with the help of suitable effect catalogues (cf. Vorwerk-Handing, 2021), for which in turn a suitable sensor concept and thus a suitable sensor must be selected. Finally, the auxiliary energy supply required for the selected sensor and the signal path for the data acquisition must be designed.
In all these steps, the uncertainties that can occur must always be taken into account with suitable methods in order to obtain a sufficient sensor application. To control occurring uncertainty, for example, the UMEA can be used. This methodology consist of the following steps (cf. Engelhardt *et al.*, 2009):

1. Analysis of the target and the environment
2. Identification of uncertainty and their causes
3. Detection of effects of uncertainty
4. Evaluation of effects of uncertainty
5. Decision about measures regarding the uncertainty

In the following, an example of an SME application is described with the help of the proposed system model. For further information about SME, please refer to the classification of SME according to Vorwerk-Handing *et al.* (2020).

5 APPLICATION OF THE SENSOR SYSTEM MODEL

In order to demonstrate the validity of the sensor system model and its applicability for sensor as well as SME applications, the concept of a torque measuring strain gauge on a drive shaft for condition monitoring purposes is described in the following by using the proposed system model (cf. Figure 3). A strain gauge changes its electrical resistance in proportion to the strain acting on its carrier material. This allows the conversion of the torsion of a drive shaft, caused by the torque load, into an electrical voltage signal. Since the drive shaft carries the strain gauge and the drive torque as quantity of interest is directly dependent on the technical function of the drive shaft, this application can be classified according to Vorwerk-Handing *et al.* (2020) as a Sensor integrating Machine Element (SiME).

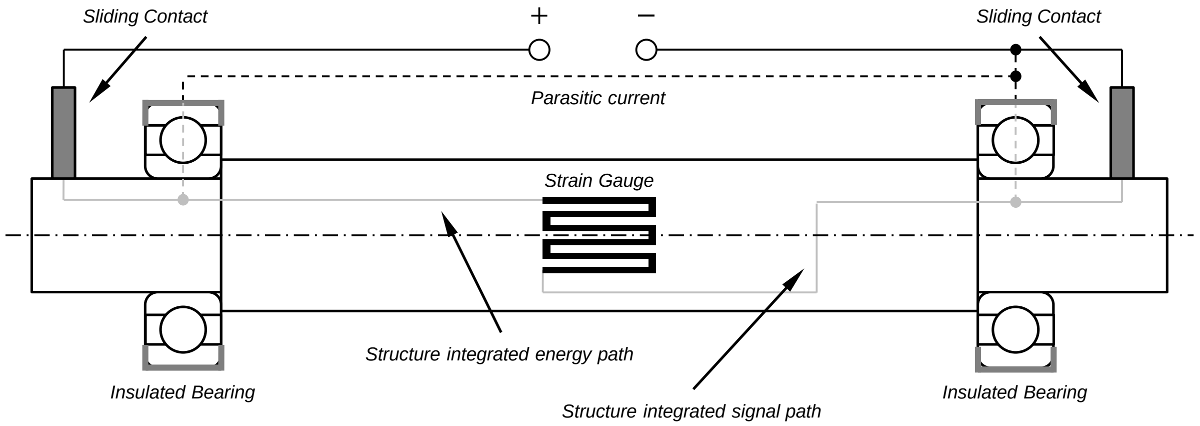

Figure 3: Strain gauge applied to a drive shaft for condition monitoring

The system model of the torque measuring strain gauge is shown in Figure 4. In addition to the basic framework of the system model from Figure 2, the occurring quantities as well as exemplary uncertainties are now included.

1. The overall aim of the exemplary sensor application is to monitor the condition of the drive shaft. Based on the damage accumulation approach, the condition of the drive shaft can be derived from the torque load on the shaft. Hence, the shaft torque is considered as the physical quantity

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of interest I. The model-based relation between the condition of the drive shaft and the torque load is associated with the uncertainty U_1. For example, simplifications in modelling can have an influence on the validity of the measurement. To be able to make a quantitative statement on the shaft condition, the underlying model and disturbance variables must be known.

2. In contrast to many applications in which the quantity of interest I is not measured directly at its point of origin but at a different location, the shaft torque as quantity of interest I is directly measured at its point of origin in this concept. However, uncertainty regarding the load distribution or the flux of forces as well as disturbance variables, such as external forces, can still occur at this point. This uncertainty is summarised in U_2.
3. The auxiliary electric energy E for the strain gauge is a specific direct current, which is applied to the shaft from the outside through an electric sliding contact. It then flows via a defined path to the strain gauge. The cables outside the mechanical system can be described without significant uncertainty, since shielded cables are used. However, the sliding-contact, the structure-integrated energy path via mechanical elements, such as the shaft, external disturbance variables, such as temperature, as well as parasitic currents through other components (dashed lines in Figure 3), result in an uncertainty U_3, which must be taken into account. The auxiliary electric energy E' enters the strain gauge and enables the sensor function.
4. The sensor block receives the mentioned shaft torque as quantity of interest I' and the auxiliary electric energy E'. The SME outputs, following the underlying transfer behaviour, an electric voltage as the sensor signal S'. The entire SME transfer behaviour is subject to the uncertainties of the lower levels, the uncertainty U_{SME}. When integrating the drive shaft with applied strain gauge into a mechanical system, it is necessary to manage these uncertainties in order to achieve the desired functionality of the sensor concept and ensure a high quality and reliability of the measurement data.
5. The sensor signal S' in form of an electric voltage is transmitted from the strain gauge via a defined path over the shaft, a sliding contact and shielded cables outside the system to the data processing unit. However, the signal S'' reaching the data processing unit is subject to the uncertainty U_4. This uncertainty results, similar to Block 3, for example, from the description of the transfer behaviour of the cables, the structural elements and the electric contacts. In addition, external disturbance variables, such as parasitic currents or electromagnetic fields, can also influence the quality of the signal.
6. The strain gauge cannot measure the shaft torque directly. Instead, the load can be determined with the help of a suitable measurable quantity M. In case of the strain gauge, the measurable quantity M is the shaft strain respectively the torsion of the shaft caused by the applied torque. The relation between strain and load can be described by *Hooke's Law*. The description of this relation is subject to an uncertainty U_5. This uncertainty is caused, for example, by an unknown or not precisely describable load distribution, shaft geometry or material properties. Furthermore, disturbance variables, such as the temperature of the shaft, may as well have an impact.
7. Analogous to Block 3 on the overall system level, the auxiliary electric energy E' continues its path through the sensor. Thereby the transfer behaviour can be subject to the uncertainty U_6, caused by insufficient knowledge about the electrical transfer behaviour or external disturbance variables, resulting in the auxiliary energy E'' supplying the sensor.
8. The measurable quantity M in form of the shaft strain and the auxiliary electric energy E'' serve as input quantities of the sensor transfer behaviour. The shaft strain ε has a direct influence on the electric resistance of the strain gauge. This relation is shown by the equitation in Block 10. On the basis of *Ohm's Law* (cf. Block 11), the resulting change in electrical resistance ΔR leads to a change in voltage. This change in voltage can be measured as signal S. These mentioned processes and models are subject to the uncertainty $U_{SensorPrinciple}$. It results, for example, from uncertainties regarding the true geometry of the strain gauge under the influence of the torque, but also from disturbance variables, such as external frequency influences.
9. The last block described is similar to Block 5. The voltage signal in form of the signal S is now routed to the signal path outside the strain gauge. This transfer is structure-integrated, that means no cables are used and the signal is directly routed over the structure of the components of the strain gauge. Since the elements in this path also have an influence on the signal S, there is an uncertainty in regards to the electrical transfer behaviour. Furthermore, disturbance variables,

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such as parasitic currents or electromagnetic fields, can influence the signal transfer behaviour. Finally, the signal S' leaves the strain gauge under an uncertainty U_7.

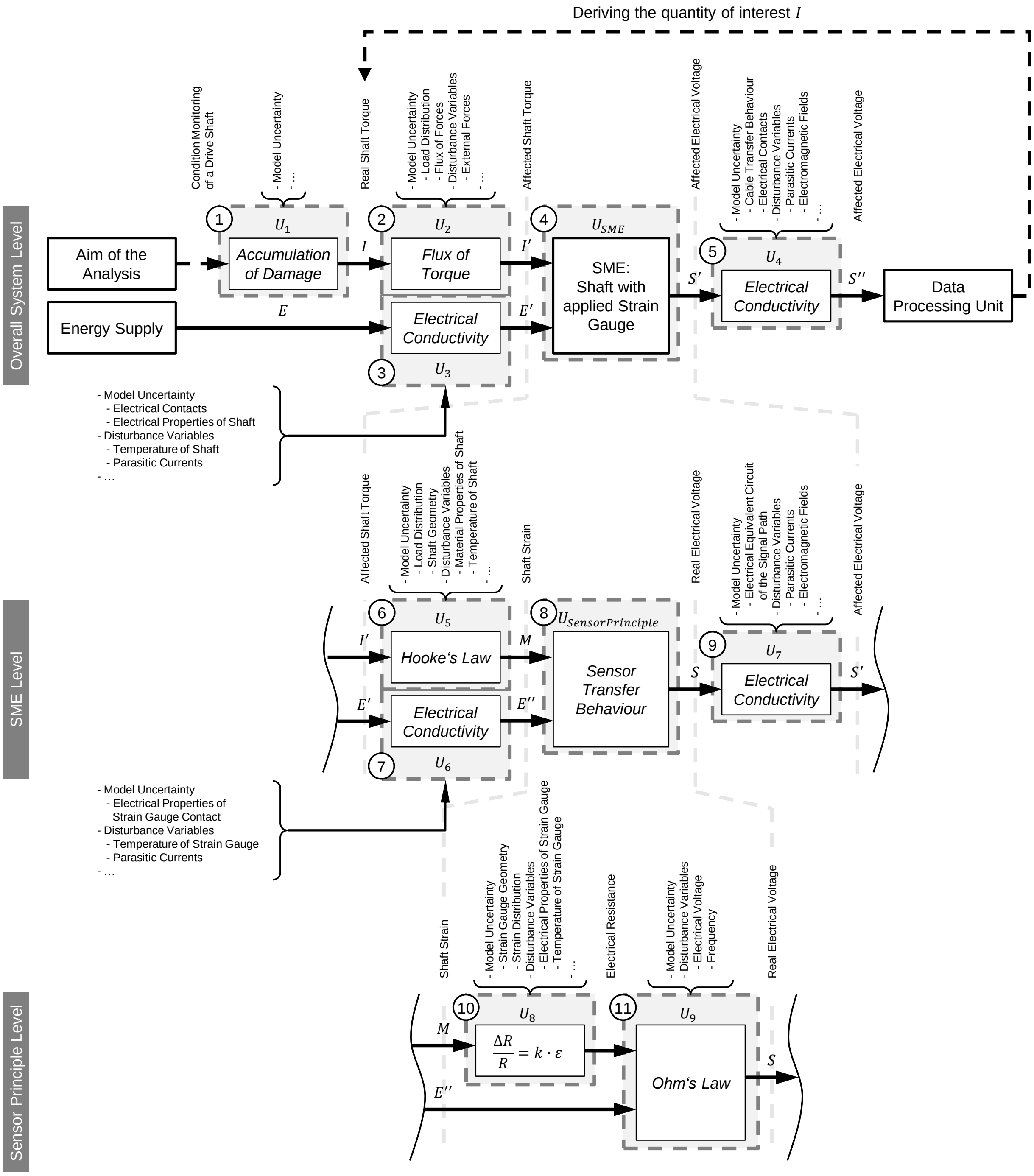

Figure 4: Sensor system model for the example of torque measurement by a strain gauge applied on a drive shaft

6 CONCLUSION

In this paper a general sensor system model is proposed, that allows a description of the functions, processes and locations of occurrence of uncertainty within a sensor system. The system model is based on the procedures commonly used in metrology, such as the measuring chain or the block diagram. Furthermore, it suggests a uniform understanding of terms used in metrology for the different quantities based on their individual function, as these are not yet clearly differentiated or defined in literature. The focus of the system model is on the flow of different quantities of a measuring function through the system. Starting from the aim of the analysis, the physical quantity of interest is derived. In the sensor,

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the quantity of interest is converted into an actual measurable quantity that can be measured by the selected sensor principle and output as a corresponding sensor signal. Due to its general applicability, the system model, as presented in Section 3 and Section 4, is applicable to SME applications.
Each step in the system model can be associated with a certain degree of uncertainty. The system model shows at which locations in a measuring system uncertainties can occur, so that they can be identified, described, evaluated and later controlled with the help of methodical approaches, such as the UMEA and Robust Design. While, for example, energy paths by wire leading to a conventional sensor can be described with a high degree of certainty, since the underlying models are well known and influencing variables can be taken into account, high uncertainty occurs especially in the context of structure-integrated energy and signal transfer as well as structure-integrated sensor functions. In this context, a high demand for further research exists.

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