



Classification and examples of next generation machine elements

G. Vorwerk-Handing¹ · T. Gwosch² · S. Schork¹ · E. Kirchner¹  · S. Matthiesen²

Received: 8 July 2019 / Accepted: 9 October 2019 / Published online: 28 October 2019
© The Author(s) 2019

Abstract

In order to fully exploit the potential of the rapidly progressing digitalisation of technical systems, it is necessary to provide reliable and significant process and condition related data. In this context, solutions are especially aspired to allow a simple integration into the surrounding system and to influence it as little as possible. The main challenges regarding the measurement of process and condition data in the operation and control of technical systems as well as in test environments are identified and presented at the beginning of this article. A promising approach to meet the resulting requirements is the integration of sensory functions into simple standardised machine elements. In order to facilitate the discussion and interdisciplinary development of machine elements with sensory functions, an extension of the existing classification of mechatronic machine elements is introduced and illustrated with examples. The introduced classification takes into account the classification according to Stücheli and Meboldt and is based on a comparison of conventional and mechatronic machine elements on a functional level with regard to the function structure. As a result, the three classes *sensor carrying machine elements*, *sensor integrating machine elements* and *sensory utilizable machine elements* are introduced and subsequently discussed in more detail on the basis of examples. Finally, an outlook is given on the main research areas with regard to the development of mechatronic machine elements. Key aspects include working principles and effects for application in mechatronic machine elements, system analysis with regard to load conditions, power supply of sensor and data processor in the environment of the machine element as well as data processing and signal transmission under typical environmental conditions of mechanical engineering.

✉ E. Kirchner
kirchner@pmd.tu-darmstadt.de

¹ Technische Universität Darmstadt, Darmstadt, Germany

² Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany

Klassifizierung und Beispiele der nächsten Generation von Maschinenelementen

Zusammenfassung

Um das Potential der rasch voranschreitenden Digitalisierung technischer Systeme vollständig auszunutzen, ist es notwendig aussagekräftige Prozess- und Zustandsgrößen bereitzustellen. Hierzu werden insbesondere Lösungen angestrebt, die eine einfache Integration in das Umgebungssystem ermöglichen und dieses möglichst wenig beeinflussen. Die wesentlichen Herausforderungen hinsichtlich der Erfassung und Regelung von Prozess- und Zustandsgrößen im Betrieb technischer Systeme sowie in Testumgebungen werden erfasst und zu Beginn des Beitrags dargestellt. Ein vielversprechender Ansatz um den daraus resultierenden Forderungen gerecht zu werden, stellt die Integration von sensorischen Funktionen in standardisierte Maschinenelemente dar. Um die Diskussion und die interdisziplinäre Entwicklung von Maschinenelementen mit sensorischen Funktionen zu erleichtern, wird im Folgenden aufbauend auf der bestehenden Klassifizierung mechatronischer Maschinenelemente eine Erweiterung dieser eingeführt und an Beispielen verdeutlicht. Die eingeführte Klassifizierung berücksichtigt die Klassifizierung nach Stücheli und Meboldt und basiert auf einem Vergleich von konventionellen und mechatronischen Maschinenelementen auf der Funktionsebene unter Betrachtung der Funktionsstruktur. Als Ergebnis werden die drei Klassen *Sensor tragende Maschinenelemente (sensor carrying machine elements)*, *Sensorintegrierende Maschinenelemente (sensor integrating machine elements)* und *Maschinenelemente mit sensorisch nutzbaren Eigenschaften (sensory utilizable machine elements)* eingeführt und im Anschluss anhand von konkreten Beispielen näher diskutiert. Abschließend wird ein Ausblick auf die wesentlichen Forschungsbereiche hinsichtlich der Entwicklung mechatronischer Maschinenelemente gegeben. Wesentliche Aspekte sind unter anderem Funktionsprinzipien und Effekte zur Anwendung in mechatronischen Maschinenelementen, Systemanalyse hinsichtlich der Belastungszustände und Energieversorgung von Sensor und Datenprozessor im Umfeld des Maschinenelements sowie Datenverarbeitung und Signalübertragung unter typischen Umgebungsbedingungen des Maschinenbaus.

1 Introduction

In the current situation of a rapidly progressing digitalisation of technical systems, the demand of reliable and significant process and condition data is increasing [2, 3]. Mechanic components and devices become intelligent systems via mechatronic and smart systems (Fig. 1). Main objectives of the development towards smart systems are self-diagnosis, self-correction and self-calibration, for example

in form of electronic wear compensation in drive units. In the next step intelligent systems enable a cooperation and communication with the user and operator, e.g. in a smart drive unit with a display indicating the remaining useful life (RUL) based on measured operational data and not just on operational hours [1]. Further objectives of this development trend are condition monitoring, predictive maintenance or the demand- and energy-efficient control of non-stationary working processes. The commonality of all these

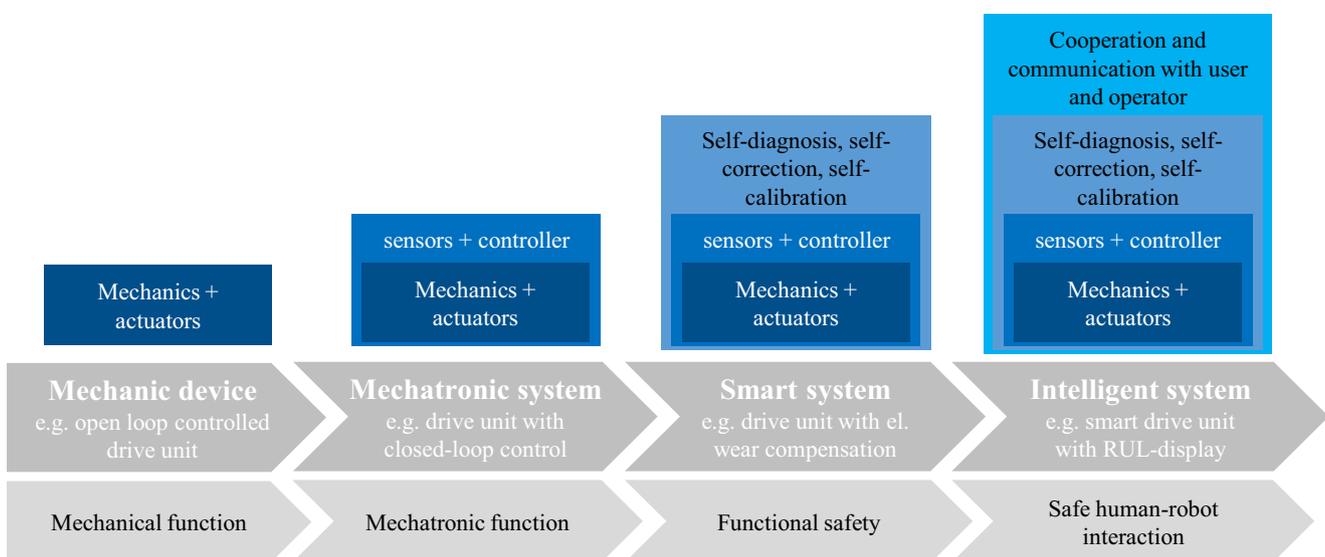


Fig. 1 From mechanic devices to intelligent Systems. (Own figure, following [1])

objectives is the demand of reliable and significant process and condition data, which need to be measured by sensors and processed in controllers. For this reason the monitoring and control of technical systems is the basis for each of the mentioned development steps (cf. Fig. 1). The architecture of the individual sensors amongst all development steps remains approximately the same. In order to realise the potential of digitalisation and interconnecting machine systems, solutions are needed that can be easily integrated into machine systems and at the same time have as little influence as possible on the surrounding system. In order to understand the essential boundary conditions for gathering reliable and significant process and condition data, the current challenges regarding the measurement of process and condition data in the operation of technical systems as well as in test environments are identified and presented below. This is done on the basis of a literature research, extended by experiences gained in industrial cooperation projects and during the construction and operation of test benches.

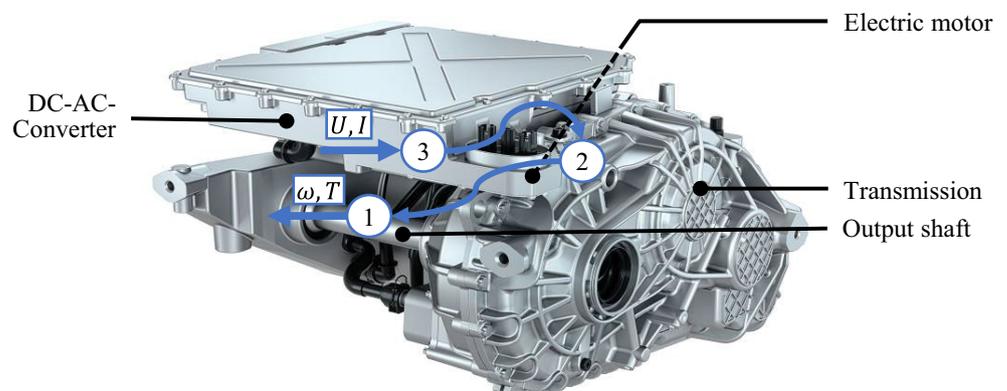
1.1 Challenges in monitoring and control of technical systems

Against the background of this contribution, the challenges in monitoring and control of technical systems can be identified in the requirement of a reliable and significant database. This requirement can be satisfied by using sensors and the processing of the measured data in controllers. State of the art for gathering process and condition related data of individual technical systems are two different approaches: On the one hand it is feasible to develop individual measuring solutions for systems [4], on the other hand process and condition related data of a system may be measured by standardised components [5]. Each approach has a reason for existence but also some drawbacks. The development of an individual measuring solution enables a high adaptability of sensors, models and data analysis to the original system. These solutions offer the possibility to place sensing devices close to the point of interest.

The models which characterise the correlation between the measurand and the required information can be simplified and the model uncertainty can be reduced. In this way the quality of the gained information can be maximised but the effort for sensor integration and thus the costs are relatively high. Such an approach is typically applied in small quantities or test benches. Using standardised measuring solutions instead can reduce the effort for sensor integration and thus the costs. However, this restricts the opportunity of adapting sensors to the original system. Therefore the sensing devices must often be placed further away from the point of interest. Correspondingly the effort to characterise the correlation between the measurand and the required information in models increases. Due to the more complex models, the model uncertainty increases and the quality of the gained information tends to lessen. Because of lower individual costs for the sensing devices and higher general costs for modelling the correlation between the measurand and the required information, this approach is typically applied in large quantities.

The two described approaches are explained in detail using the example of an electric drive unit shown in Fig. 2. The target quantity is the output torque at the axle shaft. In the example three different measuring positions are compared. Using standardised sensing devices the converter current can be measured (position 3). In this case a model correlating the current fed into the power electronics converter to the output torque at the shaft is required. Because of the distance, in terms of the signal flow, between the measuring position and the point of interest is relatively large, the model has to take several effects into account. If occurring effects like conversion losses, thermal losses or bearing and seal ring friction are neglected or only insufficiently or erroneously considered, the quality of the gained information about the output torque is relatively low or rather the uncertainty is relatively high. Shifting the measuring position to the motor currents, position 2 in Fig. 2, eliminates the uncertainty related to the electric power conversion but still leaves copper and magnetic losses as well as the influence

Fig. 2 Comparison of different measuring positions in an electric drive unit. (Image courtesy of Valeo Siemens eAutomotive Germany GmbH)



of the electromagnetic circuit. To consider the mentioned effects in a sufficient way, great effort in system modelling is necessary. Measuring position 1 in Fig. 2 is directly located at the output shaft. Currently there are no standardised torque measuring instruments with standardised mechanical and electrical interfaces available for this position. For this reason an individual solution in the shaft connection needs to be developed. The model which characterises the correlation between the measurand and the output torque would be, compared to positions 3 and 2, significantly less extensive because the measuring position and the point of interest are the same. The number of effects which have to be considered are lower and therefore the quality of the gained information about the output torque is higher or rather the uncertainty lower in relation to the aforementioned positions. These characteristics can also be found in other system variables such as vibrations [6–8]. Furthermore in the state of research many topics regarding bearing actuation with the goal to reduce the vibration of the powertrain are found [9–13]. These approaches and control concepts focus on control strategies. They use different types of actuators based on magnetic and piezo technologies which are included in the bearing seat. All these approaches require the acquisition and processing of measurement data as described above. Integrated sensor and actuator functionality holds the potential for easy integration in technical systems which reduces the effort in the design process and provides additional functionality in mechatronic systems [14].

1.2 Challenges in testing activities during product development

State of the art in testing activities during product development is the usage of application-specific measurement technologies such as force and torque sensors. The use of additional internal electronic quantities such as bus values or overcurrent and undervoltage measurement is common in mechatronic systems. The application-specific measurement technology enables the data acquisition of the system behaviour. Often, the tests have to be performed under realistic conditions. One challenge is to limit the change in system behaviour caused by sensor integration.

To explain these challenges of mechatronic systems in detail the example of a hand-held power tool is given. Acceleration sensors on the housing can measure the vibration of the power tool and enable the easy investigation of the dynamic behaviour of an angle grinder. This procedure is equivalent to the approach in the example with the electric drive unit in Fig. 2 (position 3). But there is also an increase of uncertainty in the easily measurable values. This is especially visible in the higher frequency range [15, 16]. Similar to predictive maintenance approaches there are efforts to determine the condition of a power tool system with-

out internal system parameters [17, 18]. A major challenge in this regard is the uncertainty in data quality resulting from the usage of external measurement positions. Better results may be achieved by measuring internal system variables such as torsional vibrations or force quantities [15]. In order to quantify the component load of the power train without strongly influencing the power train, non-contact measurements such as displacement sensors can be used. The measurement of the load depended deformation of the power train enables the indirect acquisition of forces [19].

2 Classification of mechatronic machine elements

Components of technical systems can be clustered in two groups. On the one hand there are machine elements as recurring components which are used several times to fulfil the same basic function. On the other hand there are individual components which are developed to fulfil a specific function under specific requirements. A promising approach to integrate sensory functions in technical systems is the development and application of Mechatronic Machine Elements (MME). MME are standardised parts which are derived from conventional machine elements but extended in their function by implementing for example sensory components [5, 14]. In this way, measurement functions could be realised by substituting conventional machine elements by MME. In order to facilitate a cross-location and interdisciplinary discussion of this approach, a common understanding of MME has to be established. Otherwise, there is a risk of ambiguity and communication difficulties. Especially in the research and development of mechatronic machine elements this common understanding forms the basis for a successful cooperation between various disciplines, such as mechanical engineering, electrical engineering and computer science. In order to facilitate the discussion and the interdisciplinary development of machine elements with sensory functions, the following attempt is made to classify the respective machine elements. In addition, this classification and discussion of MME also offers an added value with regard to the dissemination of this approach and thus also to the application of MME in technical systems. Finally, the desired goal of gathering and providing reliable and significant process and condition data in the operation of technical systems and in test environments as a basis for digitalisation is only achieved through the application of MME. Before this classification can be made, it is necessary to define machine elements. For this purpose, parts of the established WiGeP¹ definition are adopted. *Machine elements*

¹ Wissenschaftliche Gesellschaft für Produktentwicklung, www.wigep.de.

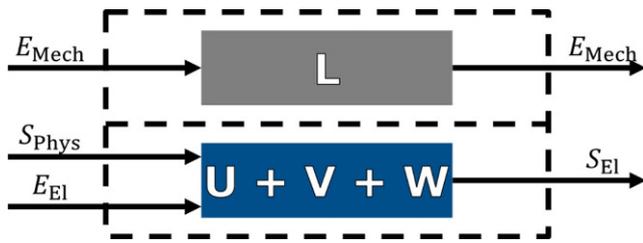


Fig. 3 Function structure of ScME

are basic elements or simple systems in mechanical engineering, which are often generally available as purchased parts, such as screws, pins, seals, roller bearings or shaft couplings. [...] In order to fulfil their function, they must be constructively integrated into superordinate systems, e.g. machines, systems, devices. Thus they become construction elements [20]. A classification is generally based on the identification and definition of characteristics and/or properties that are fulfilled by all objects within a class. Characteristics and/or properties of objects in a class that differ from each other are not considered. In order to identify and subsequently define such characteristics and/or properties, it is necessary to identify common (and differing) characteristics and/or properties of MME. Stücheli and Meboldt suggests to consider the following properties of MME for classification purposes: “Sensor output”, “Change mechanical properties” and “Add mechanical energy” [14]. Based on this they propose three types of MME: “Sensor-integrated machine element”, which is a conventional passive machine element with deeply integrated sensing capabilities; “Semi-actuator”, which have a basically passive mechanical behaviour but is actively adjustable; “Sensor-actuator Fusion”, which combine all mentioned properties and therefore show a deep integration of actuator and sensor functions into the single element [14]. This description is the first and currently sole approach to classifying MME. The orientation of the classification is generally valid and represents the basis for the following. In the existing classification it is not possible to distinguish within the group of *Sensor-integrated machine elements*. However, this is useful and necessary for the reasons introduced above, especially in the context of the development of such machine elements. For this reason, the existing classification will be extended by a subdivision at this point. In order to identify generally valid similarities between different *Sensor-integrated machine elements*, the *Sensor-integrated machine elements* have to be considered abstractly. As abstraction level the consideration on the function level is suggested and applied in the following. Accordingly, the following classification is based on the correlation between the mechanical functions of conventional machine elements and the extended functions of *Sensor-integrated machine elements*. For this purpose the function structures of different

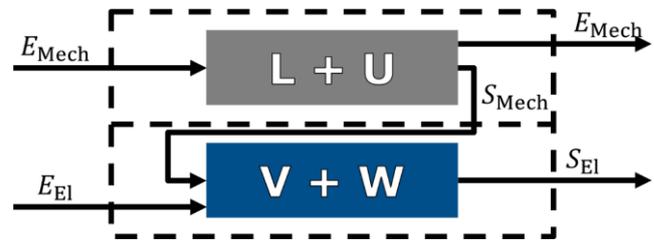


Fig. 4 Function structure of SiME

machine elements with measurement functions are identified and analysed. In Figs. 3, 4 and 5 the German abbreviations for channel (L–leiten), transform (U–umformen), connect (V–verknüpfen) and change (W–wandeln) according to Pahl and Beitz [21] and Roth [22] are used. The main results of this analysis are commonalities and differences between various machine elements with measurement functions. To achieve a common understanding in the following a differentiation between the target quantity, which is actually the quantity of interest and therefore the general objective of all efforts, and a variety of quantities which are unequivocally related to this target quantity and therefore potential measurands is used.

2.1 Sensor carrying Machine Elements (ScME)

In the category of ScME, the target quantity of the measurement is unrelated to the mechanical functions of the machine element. The machine element is therefore only carrying the sensor. In this way it channels (L) the mechanical energy (E_{Mech}) as conventional. The sensor transforms (U) the physical signals (S_{Phys}), connects (V) them with electric energy (E_{El}) and changes (W) them into an electric signal (S_{El}) (cf. Fig. 3).

2.2 Sensor integrating Machine Elements (SiME)

In this category, the target quantity has a relation to the mechanical functions of the conventional machine element. Sensors are integrated in the machine element and the relevant sensor signals depend directly on the channelled (L) and transformed (U) mechanical energy (E_{Mech}). The integrated sensor module connects (V) the mechanical sig-



Fig. 5 Function structure of SuME

nals (S_{Mech}) with electric energy (E_{El}) and changes (W) them into an electric signal (S_{El}) (cf. Fig. 4). Since a sensor element has to be integrated into the machine element, changes or adaptations of the conventional machine element are necessary. The machine element may also host further sensors as an additional information source, for example a thermal sensor. In the context of the classification and designation according to Stücheli and Meboldt [14], the category introduced here is not synonymous with *sensor-integrated machine elements*. Because Stücheli and Meboldt describe this category as *machine elements with deeply integrated sensor functions*, *sensor-integrated machine elements* are a more superordinate group compared to SiME and therefore similar to the third level in Fig. 15, paraphrased by *extension with sensor functions*.

2.3 Sensory utilizable Machine Elements (SuME)

The third category, sensory utilizable machine elements, are directly using the electric characteristics of the conventional machine element. Since no additional sensor element has to be integrated into the machine element, changes or adaptations to the conventional machine element are not necessarily needed. The SuME is machine element and sensor at once. It channels (L) mechanical energy (E_{Mech}), transforms (U) mechanical energy (E_{Mech}) into mechanical signals (S_{Mech}) and connects (V) those signals with electric energy (E_{El}) to change (W) them into electric signals (S_{El}) (cf. Fig. 5).

Based on these definitions, a series of examples of mechatronic machine elements is explained in the following to demonstrate the usefulness of the classification and to inspire further development of new concepts for machine elements with any kind of sensory functions. A distinction regarding the (additional) necessary installation space is consciously excluded in the proposed general distinction. Accordingly, each of the three introduced categories can be subdivided regarding the installation space requirements. A seemingly useful distinction is to consider the neutrality of the installation space.

3 Examples of mechatronic machine elements

The previous sections focussed on an abstract distinction of different mechatronic machine elements on a functional level, leading to the introduction of different categories of mechatronic machine elements. Those include a broad range of machine elements combined with potential sensor types such as thermocouples, strain gauges, accelerometers and magneto resistive sensors to name but a few. To give some tangible examples, the following section discusses

different mechatronic machine elements and their allocation in the introduced categories exemplary. In order to present the state of development and the potential research and development demand, the classification according to the Technology Readiness Level (TRL) is used [23].

3.1 Sensor carrying Machine Elements

3.1.1 Sensor carrying bolt

Fig. 6 shows a bolt in combination with a thermocouple (TRL 9). In this case the target quantity is the temperature at the screw tip. The bolt channels the axial forces needed for the bolt connection. This bolt is influenced by the axial force, for example in terms of deformation and elongation but this does not affect the integrated sensor. The sensor transforms the physical signal, which is the temperature, transforms it and connects it with electric energy to change it into an electric signal. This signal is unaffected by the primary mechanical function of the machine element, so the bolt only carries the sensor (cf. Fig. 6).

Provided that the target quantity of the measurement has no relation to the mechanical function of the machine element, any conventional machine element can potentially be further developed to a sensor carrying machine element by attaching a sensor.

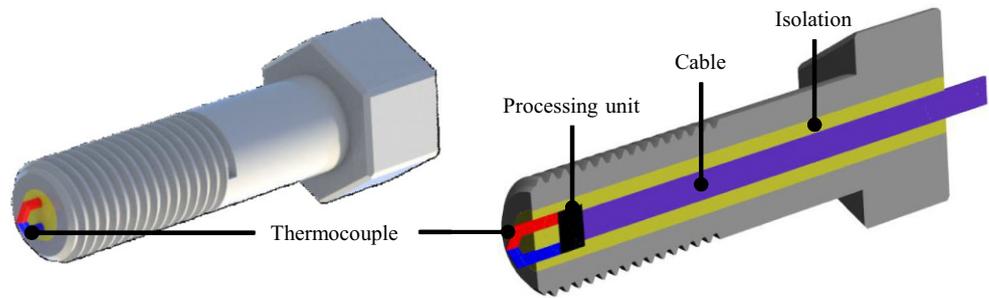
3.2 Sensor integrating Machine Elements

3.2.1 Sensor integrating fastening bolt

Sensor integrating fastening bolts (TRL 9) enable the monitoring of pretension and operational forces in mechanical connections between components (cf. Fig. 7). Those forces lead to an elongation of the bolt. Depending on the concept, the mechanical signal in form of an elongation or a force change in the bolt is connected with electric energy and changed to an electric signal by strain gauges or piezo elements [24]. The sensor integrating fastening bolts can be applied in the same way as a conventional fastening bolt.

Another option of monitoring the load in the bolt connection is a washer with an integrated sensor [25, 26]. It can be mounted between the head of the bolt and the fastened part. The sensor is based on a fibre optic principle which measures the stress-induced birefringence in an optical fibre embedded in a washer. Another method is the measurement of the bolt length based on the time-to-flight method [27, 28]. Measuring the displacement between bolt and concrete is suggested in [29]. In the state of the art, sensor technologies and the sensor application in the fastener are described. Primary research activities show the potential of sensor integrating fastening bolts [30].

Fig. 6 Sensor Carrying Bolt



The use of fastening bolts as sensor integrating machine elements allows the opportunity of monitoring the load in the fastening bolt. This is relevant for the failure of the fastening when tensile strength is too high, but also with regard to fatigue under alternate loads. In research, the knowledge about causes of failure and their investigation are important for the further product development of fasteners [31].

3.2.2 VarioSense bearing

The VarioSense bearing represents a sensor bearing commercially developed and distributed by Schaeffler Technologies AG & Co. KG. It has a modular design consisting of a sensor unit which is fitted on the side of the bearing (cf. Fig. 8). This design allows a flexible configuration of the sensors. Sensors for speed, temperature and displacement can be integrated in the sensor unit. The speed sensor records signals from a magnetic scale that is connected to the inner ring of the bearing. The temperature is measured at the outer ring of the bearing. Based on the measured displacement of the inner ring in comparison to the outer ring, information about the bearing load can be derived. The displacement is mainly caused by the radial load but is also subject to other influences such as axial load, tilting and temperature. These influences must be taken into account in the interpretation of the measured displacement. For the moment only the speed measurement is commer-

cially available (TRL 9). The measurement of temperature and displacement are available as prototypes [32]. The VarioSense bearing is classified as SiME based on the determination of the radial load via the displacement. This is directly related to the mechanical function of the bearing. The sensor unit represents an extension of the conventional machine element. The other measured variables (temperature, speed) are required to be able to determine the relationship between the displacement and the radial load. Furthermore, they represent additional sources of information.

3.2.3 Sensor integrating toothed belt

Toothed belts are used to transmit torque between belt pulleys. To run smoothly, the belt needs a certain amount of pre-tensioning. This system measures the longitudinal forces in a toothed belt with a segment specific resolution and sends the measured values to an external device during operation of the toothed belt. The aim of the integrated sensor is to support condition monitoring of the belt. The pre-tensioning force of the toothed belt, which can be indirectly determined from its natural frequency, acts as an indicator of wear. The acceleration as a result of vibrations is a mechanical signal, which can be measured with an accelerometer inside the teeth of the belt. The sensor connects the mechanical signal with electric energy and changes it to an electric signal. The sensor integrating toothed belt (cf.

Fig. 7 Sensor bolt. (Image courtesy of ConSenses GmbH)

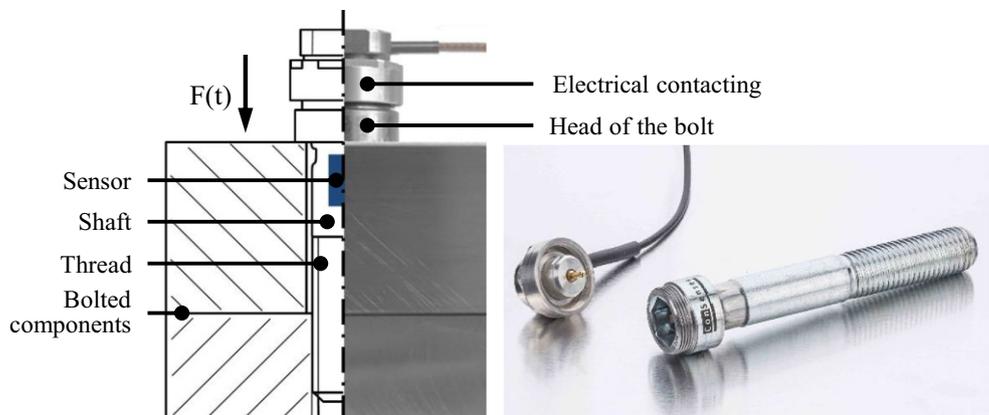


Fig. 8 Schaeffler VaroSense Bearing. (Image courtesy of Schaeffler)

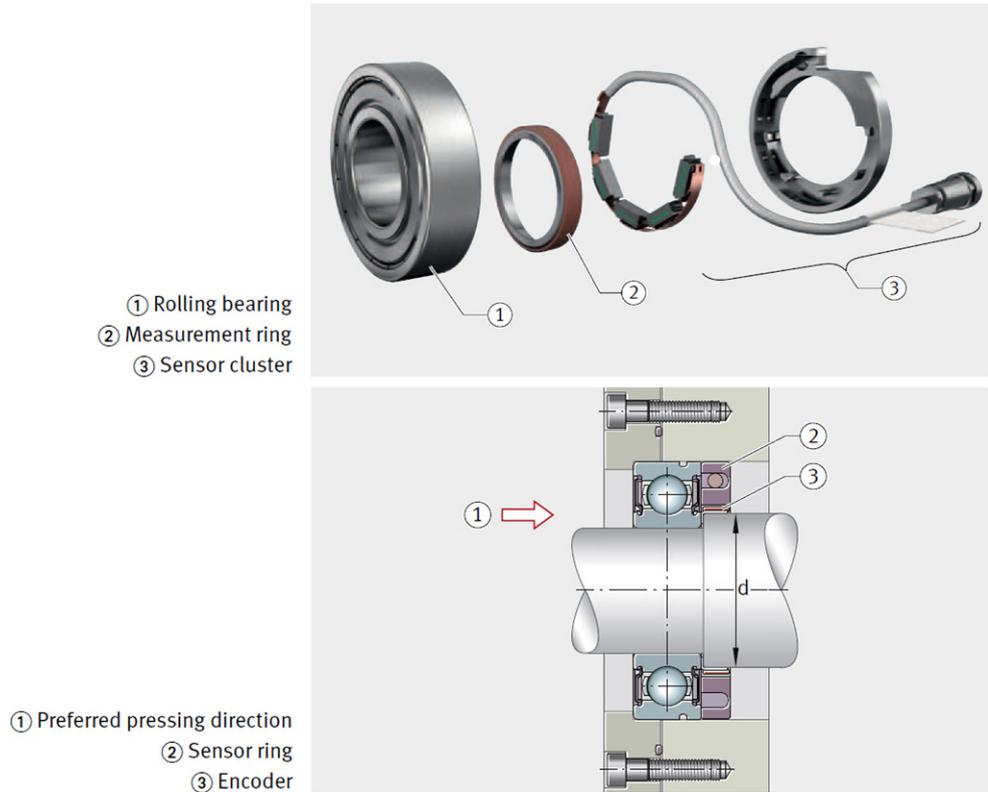


Fig. 9) has the same dimensions and characteristics as the conventional belt and can therefore be applied in the same way. The functionality is validated in an experimental setup on a laboratory scale, which corresponds to a TRL of 4.

3.2.4 Sensor integrating elastic claw coupling

To connect two shafts, for example the shaft of an engine and a transmission, a coupling is needed. The mechanical function of the coupling is to channel the torque from one shaft to the other. In most cases, there is some form and quantity of misalignment between the shafts which would cause additional loads on the system if a rigid coupling

is used. Therefore, elastic couplings, like elastic claw couplings are used. Transmitting torque via the coupling leads to a deformation of the elastic element. This deformation is a mechanical signal. In the example of the sensor integrating elastic claw coupling, a strain gauge applied to a bending plate inside one of the elastic elements is used to connect the mechanical signal with electric energy and to change them to an electric signal to determine the deformation of the elastic element (cf. Fig. 10). This deformation correlates via the torsional stiffness with the transmitted torque. In this case the target quantity of the measurement has a direct relation to the mechanic function of the conventional elastic claw coupling and adaptations of the conventional coupling are necessary. The described sensor integrating elastic claw coupling is on a prototype level which is corresponding to TRL 2–3.

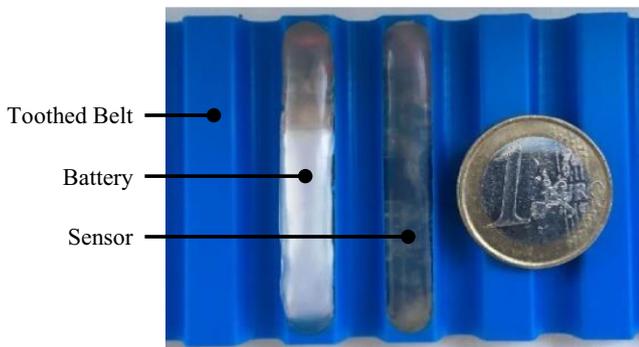


Fig. 9 Prototype of a sensor integrating toothed belt

3.2.5 Sensor integrating feather key

Fig. 11 shows a prototype (TRL 2) of a sensor integrating feather key, developed by Schäfer [34]. A feather key is part of shaft-hub connections to transmit torque. The feather key transmits the torque by channelling circumferential forces. Those forces lead to a deformation of the feather key. This deformation is a mechanical signal, which can be connected with electric energy and changed to an electric signal by an integrated sensor. A conventional feather key is therefore

Fig. 10 Prototype of a sensor integrating elastic claw coupling [33]

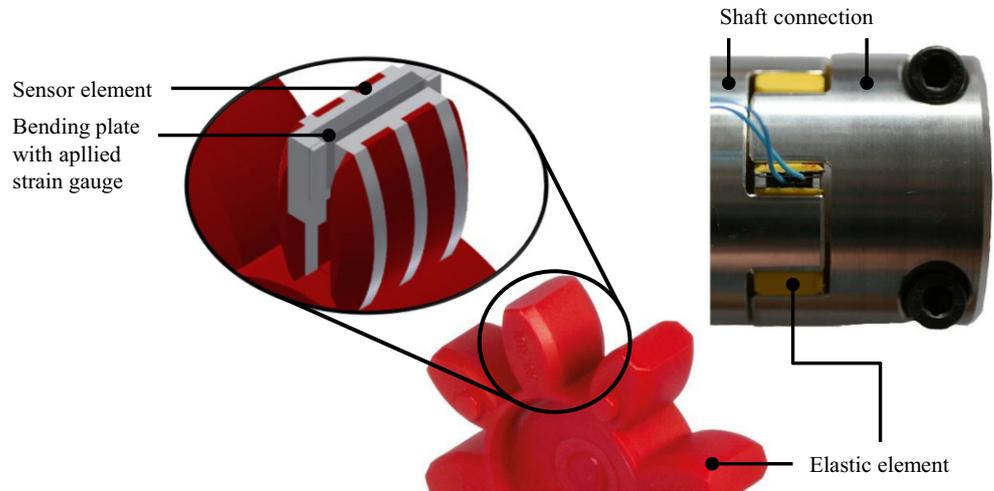
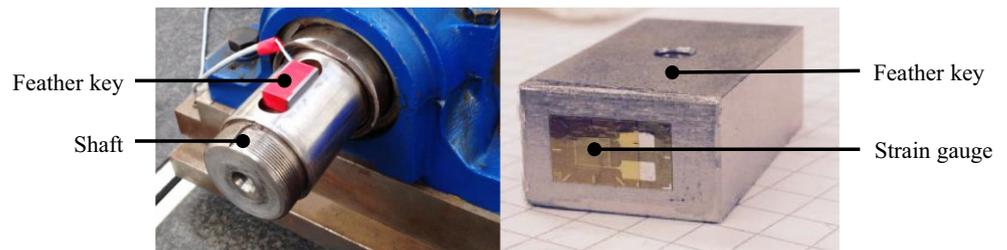


Fig. 11 Prototype of a sensor integrating feather key [34]



equipped with a strain gauge at the end face. By measuring the deformation of the feather key under load, the torque transferred via the shaft-hub connection can be determined. The sensor integrating feather key fits in standardised keyways and can be applied in the same way as a conventional feather key. Regarding the example shown in Fig. 2, this prototype is an option to measure the transferred torque directly in the shaft-hub connection (position 1). It is also an approach to develop standardised torque measuring instruments with standardised mechanical and electric interfaces.

3.3 Sensory utilizable Machine Elements

3.3.1 Sensory utilizable roller bearings

The sensor bearing concept [35, 36] utilizes the effect shown by Furtmann [37] and Gemeinder [38] that the roller and raceway behave like a plate capacitor with the lubrication film as a dielectric in between, see Fig. 12. The capacity depends on the Hertzian contact area and the lubrication film thickness. Since the elasto-hydrodynamic effect is a basic feature of grease or oil lubricated roller bearings, the sensory effect exploits a physical effect of the roller bearing, hence it can be classified as a sensory utilizable machine element. Since manufacturing tolerances and operational parameters need to be considered as disturbances having the same order of magnitude as the

lubrication film thickness the sensory effect is limited to the fully developed hydrodynamic state.

The load-dependent capacity change is an existing characteristic of the rolling bearing. The impedance between the inner ring and outer ring of the bearing is measured. This is possible due to the electrical isolation of the bearing against the housing and the shaft as well as a contact between the bearing inner ring and outer ring via an external impedance measuring device (cf. Fig. 13). In order to derive a conclusion about the bearing load from the measured impedance, it is also necessary to measure the temperature. The measured quantities (impedance and temperature) are

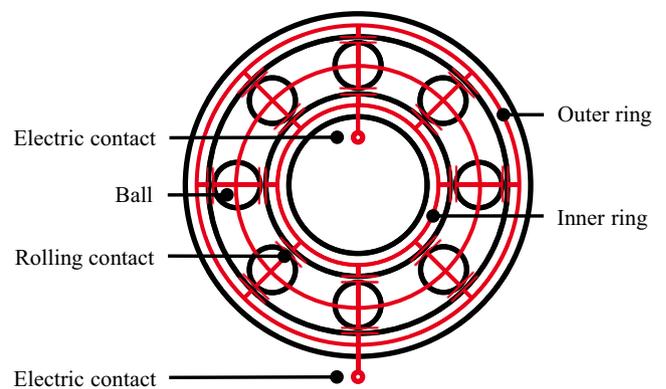
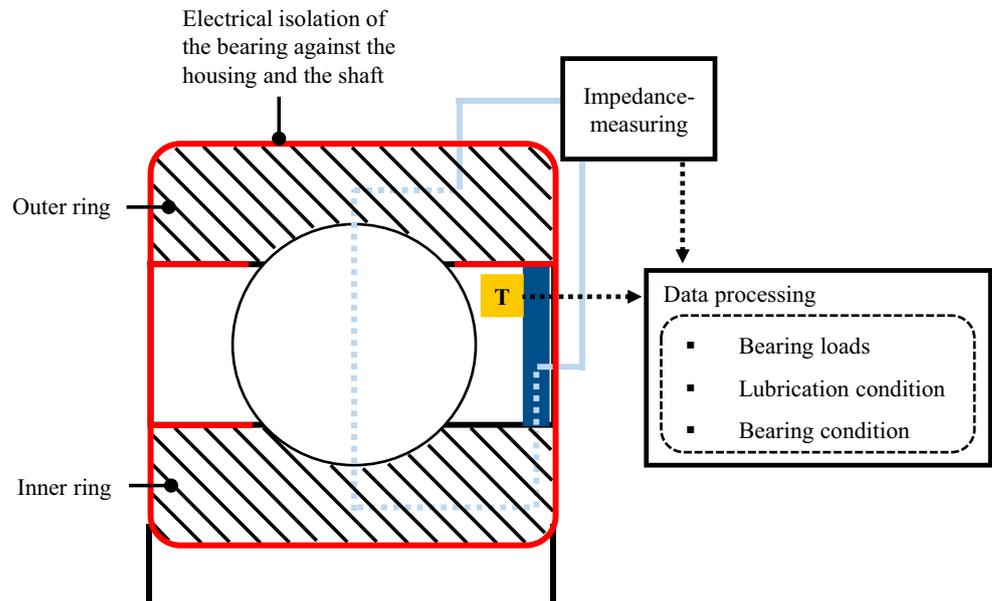


Fig. 12 Sensor bearing concept [35, 36]

Fig. 13 Setup and measuring principle of the sensor bearing



transferred to an external data processing system and can be analysed with regard to bearing load, lubrication conditions and bearing condition. The sensory utilizable roller bearing has a TRL of 4, what means that it is validated in a laboratory environment.

3.3.2 Sensory utilizable plain bearing

Plain bearings operated in the hydrodynamic range, see Fig. 14. Because the dependency between the eccentricity of the plain bearing and the load conditions can be used to measure the latter, hydrodynamic plain bearings can be used as sensory utilizable machine elements (TRL 2). Therefore the bearing is modelled as an eccentric cylindrical capacitor with the lubrication film as a dielectric. By measuring the capacity it is possible to calculate the eccentricity and therefore the load conditions of the bearing [35].

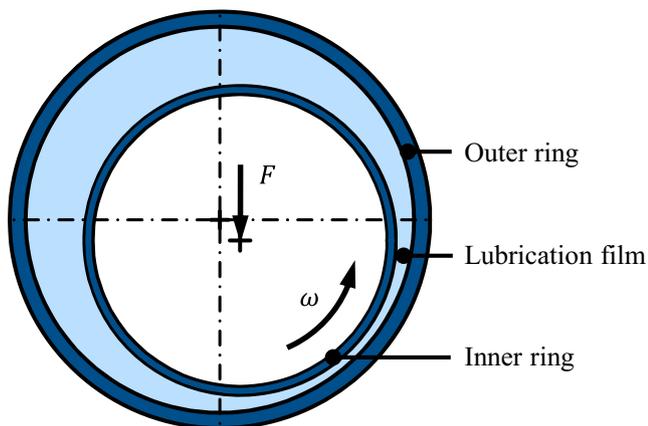


Fig. 14 Sensory utilizable plain bearing concept

4 Discussion

The main results of this contribution are the analysis and description of commonalities and differences between various machine elements with measurement functions and based on this, the distinction of three categories of mechatronic machine elements extended with sensor functions. The introduced classification takes into account the classification according to Stücheli and Meboldt [14]. In the existing classification it is not possible to distinguish within the group of *Sensor-integrated machine elements*. However, this is useful and necessary, especially in the context of the development of MME. For this reason, the existing classification is extended by a subdivision at this point. In order to identify generally valid similarities between different *Sensor-integrated machine elements*, the *Sensor-integrated machine elements* have to be considered abstractly. As abstraction level the consideration on the function level is suggested and applied successfully. Through the establishment of a unified understanding, the risk of ambiguity and communication difficulties between various disciplines, such as mechanical engineering, electrical engineering and computer science can be reduced. However, it has not been validated yet whether the introduced classification effectively facilitates a uniform understanding in practical application and whether the classification will be established. Both could be verified by empirical investigations, e.g. in the form of surveys within the context of the work on corresponding projects. Furthermore a distinction regarding the (additional) necessary installation space is excluded in the proposed general distinction. Accordingly, each of the three introduced categories can be subdivided regarding the installation space requirements. A seemingly useful distinc-

tion is to consider the neutrality of the installation space. The examples in Sect. 3 show that package-efficient solutions can be developed which facilitate retrofit solutions to digitalise e.g. existing production equipment.

5 Conclusion

In order to fully exploit the potential of digitalisation and crosslinking of machine systems, sensor solutions are needed that can be easily and cost-effectively integrated into mechatronic systems. Mechatronic machine elements are a viable option for this task. In this way, a reduction of the former disadvantages of a measurement with standardised components while retaining the benefits can be achieved. The sensing device can be placed closer to the point of interest and the needed changes in system behaviour caused by sensor integration can be limited to a minimum. Correspondingly, the effort to characterise the correlation between the measurand and the required information in models decreases. Due to the less complex models, the model uncertainty decreases and the quality of the gained information tends to be higher. Because of lower individual costs for the sensing devices, the approach can also be applied in systems of small quantities.

A common understanding of MME is established in order to facilitate a cross-location and interdisciplinary discussion of this approach. This reduces the risk of ambiguities and communication difficulties between different disciplines such as mechanical engineering, electrical engineering and computer science. The introduced classification is based on the correlation between the mechanical functions of conventional machine elements and the extended func-

tions of mechatronic machine elements. For this purpose the function structures of different machine elements with measurement functions are identified and analysed. Based on this, the three categories: *sensor carrying machine elements*, *sensor integrating machine elements* and *sensory utilisable machine elements* are formed. A summarising description is given in Fig. 15. In the category of mechatronic machine elements, Fig. 15 also contains an outlook on the integration of actuator functions into machine elements and thus refers to the class of *Semi-actuators* according to Stücheli and Meboldt [14]. This is intended to enable an influence on the system.

6 Outlook

The increasing miniaturisation of electronics as well as new possibilities in data pre-processing and improvements in measuring principles provide the basis for the development of mechatronic machine elements. On this basis, the following areas of research need to be addressed to advance the development of mechatronic machine elements:

- Working principles and effects that enable the development of mechatronic machine elements
- System level analysis of the effects of sensor integration into machine elements, e.g. mechanical loading conditions of machine elements and integrated sensors
- Solutions for energy supply of sensor and data processor in the machine element environment
- Data processing and signal transfer under typical environmental conditions of mechanical engineering, e.g. oil dust, closed metal housings, elevated temperature, electromagnetic compatibility etc.

Further research is required, however, to arrive at minimum energy consumption or even energy autonomous sensor systems that reduce the integration effort by reducing the energy supply requirements. Furthermore, research is required to integrate not only sensory functions into machine elements but also data processing instances in order to reduce the overall integration effort. Also, the development of mechatronic machine elements supporting in-situ measurements by their integrated sensors as well as the integration of these mechatronic machine elements in a technical design needs improvement. Currently, not only a lack of feasible concepts but also of development methods for sensor integrating machine elements themselves as well as for their successful integration into mechatronic, smart and intelligent systems needs to be taken as a challenge for future research.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted

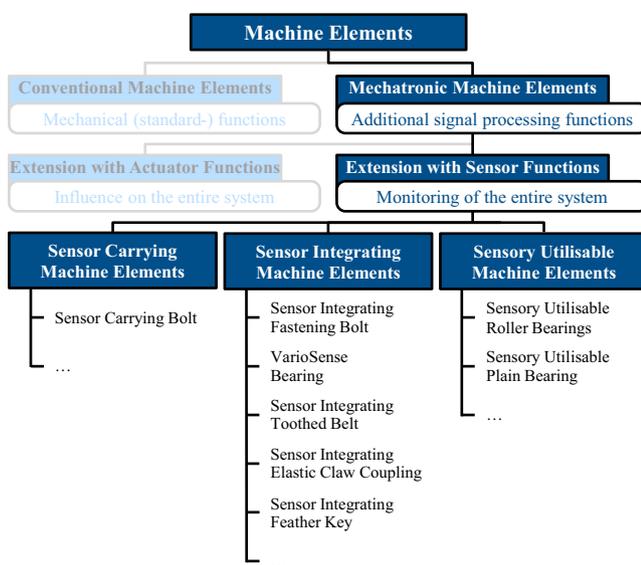


Fig. 15 Classification of machine elements

use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Anderl R et al (2012) Smart Engineering – Interdisziplinäre Produktentstehung. DISKUSSION. acatech – Deutsche Akademie der Technikwissenschaften, München
- Abramovici M, Herzog O (2016) Engineering im Umfeld von Industrie 4.0: Einschätzungen und Handlungsbedarf. Utz, München
- Bundesministerium für Wirtschaft und Energie (2016) Forschungsagenda Industrie 4.0 – Aktualisierung des Forschungsbedarfs. BMWi, Berlin
- Vorwerk-Handing G, Martin G, Kirchner E (2018) Integration of measurement functions in existing systems—retrofitting as basis for digitalization. In: Ekströmer P, Schütte S, Ölvander J (eds) NordDesign 2018. Linköping
- Martin G et al (2018) MME – Potentiale durch mechatronische Maschinenelemente. Konstruktion 70(01/02):71–75
- Trilla A, Gratacòs P (2016) Maintenance of bogie components through vibration inspection with intelligent wireless sensors: a case study on axle-boxes and wheel-sets using the empirical mode decomposition technique. Proc Inst Mech Eng Part F J Rail Rapid Transit 230(5):1408–1414
- Gao RX, Sahay P (1998) Miniaturized sensor module for a mechatronic bearing. Proc SPIE. <https://doi.org/10.1117/12.332799>
- Petko M, Uhl T (2004) Smart sensor for operational load measurement. Trans Inst Meas Control 26(2):99–117
- Jung D, DeSmidt H (2018) A new hybrid observer based rotor imbalance vibration control via passive autobalancer and active bearing actuation. J Sound Vib 415:1–24
- Tüma J et al (2017) Piezoelectric actuators in the active vibration control system of journal bearings. J Phys Conf Ser 870:12017
- El-Shafei A et al (2015) Test rig characterization and dynamic testing of a smart electro-magnetic actuator journal integrated bearing. Springer, Cham
- He Y et al (2019) Active vibration control of motorized spindle based on mixed H ∞ /Kalman filter robust state feedback control. J Vib Control 25(6):1279–1293
- Ambur R, Rinderknecht S (2018) Unbalance detection in rotor systems with active bearings using self-sensing piezoelectric actuators. Mech Syst Signal Process 102:72–86
- Stücheli M, Meboldt M (2013) Mechatronic machine elements. On their relevance in cyber-physical systems. In: Abramovici M, Stark R (eds) Smart production engineering. Proceedings of the 23rd CIRP design conference, Bochum, Germany, March 11th–13th, 2013. Springer, Heidelberg, pp 263–272
- Matthiesen S, Gwosch T, Bruchmüller T (2017) Experimentelle Identifikation von Schwingungsursachen in Antriebssträngen von Power-Tools. In: V.D.I.W. GmbH (ed) VDI-Fachtagung Schwingungen 2017. VDI Verlag, Düsseldorf, pp 311–322
- Matthiesen S, Gwosch T, Wettstein A (2017) Torsional vibration measurement of an angle grinder in real life applications. In: Torsional vibration symposium
- Dörr M et al (2019) Recognizing product application based on integrated consumer grade sensors: a case study with handheld power tools. In: CIRP design
- Heinis TB, Loy CL, Meboldt M (2018) Improving usage metrics for pay-per-use pricing with IoT technology and machine learning. Res Technol Manag 61(5):32–40
- Matthiesen S et al (2016) Experimentelle Ermittlung von Bauteilbelastungen eines Power Tool Antriebsstrangs durch indirektes Messen in realitätsnahen Anwendungen als ein Baustein in der Teilsystemvalidierung. Forsch Ingenieurwes 80:17
- Binz H, Bartholdt M (2014) Universitäre Lehre in der Produktentwicklung – Leitfaden der Wissenschaftlichen Gesellschaft für Produktentwicklung (WiGeP). Konstruktion 66:74–79
- Pahl G, Beitz W (2007) Konstruktionslehre: Grundlagen erfolgreicher Produktentwicklung, 7th edn. Springer, Berlin u. a.
- Roth K (2000) Konstruieren mit Konstruktionskatalogen
- Mankins JC (1995) Technology readiness levels (White Paper)
- Groche P, Brenneis M (2014) Manufacturing and use of novel sensoric fasteners for monitoring forming processes. Measurement 53:136–144
- Odoni W, Daendliker R, Schad H, Schweizer E (1992) Offenlegungsschrift DE 4037077 A1
- Lüthje H (2006) Die intelligente Kraftmessung: Innovativer diamantartiger Kraftsensor für Verschraubungs- und Spanntechnik – DiaKra (Abschlussbericht zum Verbundprojekt IN 3594 im Rahmen des Programms „Förderung von innovativen Netzwerken“ (InnoNet) des Bundesministeriums für Wirtschaft und Arbeit; Laufzeit des Vorhabens: 01.08.2003 bis 31.10.2005)
- Malicki R (1985) US Patent 4553124
- Widin Klasen L (2015) International Patent WO 2015/150544 A2. <https://depatisnet.dpma.de/DepatisNet/depatisnet?action=pdf&firstdoc=1&docid=WO002015150544A2>
- Teufelhart S (2018) Europe Patent EP 3 290 721 A1. <https://depatisnet.dpma.de/DepatisNet/depatisnet?action=pdf&firstdoc=4&docid=EP000003290721A1>
- Chorzewski D, Hofmann S (2015) Messverfahren zur Ermittlung der Schraubenvorspannung mittels Dehnungsmessstreifen
- Horn S et al (2019) Experimentelle Untersuchung von Versagensvorgängen an Verbundankern mit einem In-Situ-Versuchsmodell. Beton Stahlbetonbau. <https://doi.org/10.1002/best.201900013>
- Schaeffler (2019) Schaeffler VarioSense—Modular sensor bearings. Schaeffler Technologies, Schweinfurt
- Schork S (2015) Schlüsseleigenschaften und Erfolgsfaktoren von Smart Machine Elements. In: Mechanical engineering. TU Darmstadt, Darmstadt
- Schäfer K (2015) Entwicklung und Bewertung von Smart Machine Elements. In: Mechanical engineering. TU Darmstadt, Darmstadt
- Neu M, Harder A, Kirchner E (2019) Sensorische Eigenschaften von Wälz- und Gleitlagerungen – Beherrschen von Unsicherheiten von und durch Zusatzfunktionen. In: 13. VDI-Fachtagung – Gleit- und Wälzlagerungen 2019. VDI Wissensforum, Schweinfurt
- Schirra T, Martin G, Kirchner E (2019) Feasibility study of impedance analysis for measuring rolling bearing loads. Society of Tribologists and Lubrication Engineers (STLE), Nashville
- Furtmann A (2017) Elektrisches Verhalten von Maschinenelementen im Antriebsstrang. Maschinenbau. Leibniz Universität Hannover, Hannover
- Gemeinder Y (2016) Lagerimpedanz und Lagerschädigung bei Stromdurchgang in umrichter gespeisten elektrischen Maschinen. Elektrotechnik und Informationstechnik. TU Darmstadt, Darmstadt